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I-DIRECTIONAL HEAT

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RTG PARAMETRIC

STUDY VOYAGER TASK C (U)

LOG-D00150

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1.0 INTRODUCTION AND SUMMARY

The weight, size, operating conditions, and performance of RTG's designed for uni-directional heat rejection and intact re-entry are presented in this report. The previous report, on the characteristics of finned cylinder RTG designs (VOY-CI-TRI), is supplemented by the inclusion in this report of the re-entry heat shield weights. The RTG design for uni-directional heat rejection is illustrated in Figure 1. The fuel capsule and thermopile are based on SNAP-27 technology. The headlight shaped appearance is a result of an attempt to minimize thermal interactions between the RTG and the spacecraft body.

The range of RTG's considered in this report is between 50 watts (electrical) and the largest size which can be accommodated within a 48-inch diameter envelope. This upper limit corresponds roughly to a 100 watt (e) size. The maximum size was limited to that RTG which could be efficiently integrated into the Voyager Task C vehicle.

The RTG weight and performance results were obtained by performing a parametric study of an RTG model. The model includes significant conceptual detail for spacecraft integration purposes, but it does not provide an RTG design.

The parametric study covers the same range of hot junction temperatures as the previous report. For the cold junction temperatures, the range was extended to higher temperatures to reduce radiator area, since the heat rejection area was severely limited.

As indicated in the report covering the finned cylinder RTG's, the use of a 1600⁰F hot junction temperature for the SiGe system would represent an advance in the state-of-the-art of fuel capsule design and materials application. Therefore, additional development work would be required to assure fuel capsule safety. Although the study indicates that SiGe systems operating with a hot junction of 1600⁰F are lightest, the uncertainties associated with the higher temperature operation should be noted.

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The lightest units for both the SiGe and PbTe systems are obtained at the highest hot junction temperatures, and this result applies both with and without the additional weight for re-entry protection. The minimum system weights for the uni-directional case always occur with the smallest (50 watt) units. The lowest system weights are summarized below:

<u>Type of Thermopile, No. and Size of Unit</u>	<u>Hot Junction Temperature °F</u>	<u>Approximate RTG Wt.</u>	
		<u>Without Re-entry Protection</u>	<u>With Re-entry Protection</u>
PbTe: 8-75W	1100	71	100
SiGe: 8-75w	1600	38*	66*
SiGe: 8-75w	1400	51	85

*No allowance has been included for increased weight which may be necessary to accommodate the high-temperature fuel capsule.

These results are based on consideration that the 75-watt unit is best suited to the 12-sided spacecraft (eight units required).

The previous report on finned cylinder RTG's addressed itself to the problem of the design of a minimum weight RTG, independent of re-entry shielding. This report includes an analysis of the re-entry shielding for the finned cylinder RTG, as well as for the uni-directional heat rejection RTG. The results have shown that the ability to radiate heat from the sides of the RTG is a distinct performance advantage. The uni-directional heat rejection type of RTG sacrifices RTG weight in order to eliminate the side thermal radiation, and at the same time requires only a modest re-entry heat shield.

A combination of advantages for the two types of RTG's is shown in Figure 1A. The re-entry heat shield and annular fin outer diameter have been reduced and radial fins added. The radial fins radiate heat sideways, thereby increasing the effective heat rejection area of the

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RTG. It is believed that the small amount of heat radiated in the direction of the spacecraft will not impose any thermal restrictions. Since the fraction of heat radiated sideways, and the total amount of heat is less than that examined in the preliminary spacecraft thermal analysis (150 watt finned cylinder RTG's) which concluded that no thermal interactions sufficient to cause problems would develop. It is anticipated that this type of RTG will operate at higher efficiency than the current "headlight" design and require a lighter re-entry heat shield. This concept is being investigated in an attempt to arrive at a recommended Voyager Spacecraft RTG concept.

2.0 CONFIGURATION SELECTION

2.1 OBJECTIVES AND CONSTRAINTS

The uni-directional RTG design was selected to meet the objective of heat rejection in one direction only, while conforming to the following constraints:

- a. Maximum outside diameter of 48 inches
- b. Integration within an established re-entry vehicle shape
- c. Use of proven fuel capsule designs for Pu-238
- d. Use of SiGe and PbTe thermoelectric materials within known temperature limitations
- e. Application of state-of-the-art re-entry protection materials
- f. Incorporation of mounting concepts compatible with a jettison system for aborts
- g. Easy loading of fuel capsules into the generator without complex handling devices
- h. Life of re-entry protection material compatible with the longest decaying orbit which can be established by the mission mode
- i. Generator arrangement compatible with prelaunch checkout using electric heaters

2.2 CONFIGURATION DEVELOPMENT

Several configurations were laid out in development of the final choice.

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The conceptual thinking behind this evolution is described below. In preparation of an RTG design to conform to objectives and constraints, the physical arrangement is an over-riding factor. Therefore, preparation of a drawing for a particular concept is essential in evaluating its potentialities and problems. In the early phases of the study, the power rating of the units was not precisely determined, but the heat rejection area and capsule sizes were selected to fit the range of 75 to 100 watts electrical output. It had been determined previously that this range was within the region of optimum size for Voyager. Therefore, the ability of the designs to meet the objectives and constraints could be evaluated, and the configuration which is ultimately selected may then be studied in greater detail to accurately define the dimensions and weights necessary to deliver the required power. The detailed study of the selected generator is not considered to be within the scope of the present work, but would be the subject of a future study.

2.3 CHARACTERISTICS OF SPECIFIC TRIAL CONFIGURATIONS

The first design is shown in Figure 2. This design uses an Apollo-type re-entry vehicle with a combined heat shield and radiator of beryllium. The sides of the Apollo shape are insulated to meet the uni-directional radiation objective.

The fuel capsules for this design are mounted on a hot frame assembly which then mates and latches with the cold frame and re-entry vehicle assembly. This design has the following disadvantages which precluded further consideration:

- a. The generator must be supported from the hot frame assembly to allow removal of the heat shield-radiator-thermopile assembly for access to the thermopile.
- b. The hot frame assembly will be heavy and awkward to handle, necessitating somewhat complex equipment.
- c. Disassembly of the generator and probable disconnection of the power connector will be necessary to replace the electric-heated test unit with the fuel capsules.
- d. The jettison mounts must be within the circle described by the rear side of the re-entry vehicle to maintain the aerodynamic shape. Therefore, these mounts are relatively inaccessible after the generator is placed on the spacecraft.
- e. Circumferential variation in fuel capsule temperature, introducing capsule hot spots.

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Figure 3 is a variation of the design of Figure 2, but it reduces the structural mounting problems for the capsules by locating them in a ring rather than having four capsules located near the center of the disk. The thermopile is also ring-shaped. However, the problems attendant to Figure 2 design are also present here, eliminating further consideration.

Figure 4 is similar in concept to Figures 2 and 3, but the capsule handling problem is simplified by using a straight radial location. The thermopile arrangement is also simplified, becoming simply a radial array. It was considered that the fuel capsules could be loaded into the generator in place of the electrical units after the generator was installed, with this arrangement. However, the other difficulties remained, and a different concept was next tried as shown in Figure 5.

In Figure 5, a Mark II-type re-entry body is used. The radiator and heat shield are now separate, and materials such as ESM or 3DGFM graphite (which are lighter than beryllium) would be used for the heat shield.

The fuel capsules are short ($L/D = 1$) cylinders which are mounted in a beryllium heat block or disk. The short cylinders allow the maximum thermal loading to be placed within a disk of given diameter, without considering an unrealistic pie-tin shaped capsule. Heat rejection is from the rear face of the generator, which is actually a sculptured beryllium fin.

This design comprises three separate parts:

- a. The hot frame (heat block)
- b. The cold frame assembly
- c. The re-entry vehicle

Some of the objections to the previous designs which were met are as follows:

- a. The generator can now be supported by a ring clamp around its periphery. Hence, the jettison mechanism problem is simplified.
- b. The thermopile end of the generator is now turned outward from the vehicle, which increases the accessibility of the thermopile.
- c. The heat disk reduces the circumferential temperature variation of the fuel capsules.

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However, the awkward fuel assembly and the difficulty in installing and removing electrical test heaters remain a problem. Consequently, a further iteration (Figure 6) was performed. This design uses the Mark-II shape but the thermopile and fuel capsule arrangement have been changed to an axial design similar to the SNAP-27. The heat rejection is from a conical surface lining the rear side of the re-entry shield. Heat is conducted to this surface by six ribs connecting it to the cold frame. The generator comprises only two parts: a re-entry vehicle-thermopile-radiator assembly, and a fuel capsule. This design meets all the constraints and objectives as follows:

- a. Fuel capsule insertion is very easy, since only a straight axial insertion into the outward end of the generator is required.
- b. The generator may be mounted by its periphery
- c. The fuel capsule will be light because a complex support structure is unnecessary.
- d. The thermopile is accessible for removal or service
- e. Electrical heaters can be installed and removed without disassembly of the generator.
- f. Circumferential temperature gradients in the fuel capsule are eliminated

From a size and weight standpoint, improvements in the arrangement are desirable to reduce the overall unit weight and increase the power range. The design of Figure 7 incorporates four small units within one re-entry vehicle. This concept reduces the re-entry protection and structure per watt of electrical output. However, a void space (shown occupied by a power-conditioning unit) is inherent in this arrangement, and an uneconomical use of material therefore results. Since this problem will always occur with this concept, it will not be pursued further.

To obtain more radiating area (and larger electrical output) within the same diameter re-entry vehicle, the configuration of Figure 8 was studied. This design incorporates an integral capsule-thermopile-radiator assembly which is mounted within the re-entry vehicle by a linkage mechanism. The heat rejection ability is improved since direct radiation from half the thermopile is obtained. Also, the length of the conduction path is reduced compared to the designs of Figures 6 and 7, resulting in better overall fin efficiency. This design has a

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drawback (The fuel capsule must be inserted at right angles to the axis of the generator, rather than axially. This significantly complicates the loading mechanism.) which overcomes its attractive features.

A study was made to determine whether the capsule could be pivoted to allow insertion in the axial direction, and it was determined that this could be accomplished only with significant penalties in heat rejection area, because it is considered that the conduction across a hinge would be poor. Hence, the use of a hinge would reduce the radiation area, and a long, strong hinge would reduce the area more than a short hinge. The capsule arrangement shown allows use of an essentially one-piece fin, with a removable piece to allow passage of the capsule.

- a. The linkage and locking arrangement to allow fueling without disassembly of the generator is complex, adds weight, and might be an additional source of prelaunch reliability problems.
- b. It is impossible to combine the back side of the re-entry shell with the radiating surface to reduce the structural weight, because the radiating surface must be self-supporting when drawn out.
- c. A circumferential gradient will exist in the fuel capsule.

Considering these integration and performance limitations, an improved design combining the best features of the preliminary designs was prepared. It is shown in Figure 9. This design employs the axially-inserted capsule and thermopile reminiscent of the SNAP-27. However, the cold frame is increased in thickness from either end toward its center, and a conical fin is attached at the thickest point. Analysis showed that a longitudinal temperature gradient along the thermopile does not seriously decrease the efficiency. Hence, the conductive path is shorter, compared to the designs of Figures 6 and 7.

Because the conical fin need not be separated from the re-entry shell after assembly, it can be used as a structural support for the shell, minimizing the combined weight of these two components.

All the advantages of accessibility, easy loading, and easy testing are obtained with this design. Also, the circumferential temperature variation of the capsule, which would very likely exist because of the six radial fins of the design of Figure 6, is eliminated.

This design is more efficient as a heat rejection system because nearly all of the fin material has an unrestricted view of space, whereas the radial ribs of the design of Figure 6 are restricted in their view by each other.

Because the configuration of Figure 9 meets all the objectives and constraints of the design ground rules, it has been selected as the reference design for parametric performance studies and vehicle integration studies.

3.0 ASSUMPTIONS

Assumptions used in this study are as follows:

Fuel - Pu-238 microspheres
Thermoelectric materials - PbTe and SiGe
Configuration - Body of revolution; maximum diameter limited to 48 inches
Heat rejection - uni-directional
Fin materials - Beryllium

Temperature range:

PbTe		SiGe	
Hot Junction Temperature, °F	Cold Junction Temperature, °F	Hot Junction Temperature, °F	Cold Junction Temperature °F
1000	400	1200	500
1100	500	1400	550*
	550*	1600	600
	600		650*
			700

*Cases calculated at these intermediate temperatures when required to meet either the heat rejection area limit (within 48-inch diameter) or the 2000°F central fuel temperature limit.

Sink temperature: -50°F

Spacecraft electrical requirement: 600 watts (preliminary)

Power range: 50 to 100 watts (e)

End-of-Life Thermopile Condition Specifications:

PbTe Thermopile 20% Extraneous Resistance
SiGe Thermopile 10% Extraneous Resistance

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Minimum Length of Thermocouple Legs:

PbTe: 0.4 inch

SiGe: 0.5 inch

Minimum cross-sectional characteristic dimension of thermocouple legs:

PbTe: 0.125-inch diameter

SiGe: 0.125-inch side of square

Density of thermocouple legs:

PbTe: N-leg 0.2945 lb/in.³

P-leg 0.2421 lb/in.³

SiGe: Both legs 0.1156 lb/in.³

Generator heat loss (bypassing thermopile through exposed end)

PbTe and SiGe: 10%

Hot frame hot junction temperature drop:

PbTe: 30°F

SiGe: 20°F

Cold junction - cold frame temperature drop:

PbTe: 20°F

SiGe: 50°F

Longitudinal cold frame temperature drop (end to fin base)

PbTe and SiGe: 50°F

Voltage: 15v and 28v

Capsule Parameters:

Fuel - Thermal conductivity = 1.3 Btu/hr-ft-°F
Density - 0.279 lb/in.³
Heat generation - 51 watts/in.³

Clad - Thickness - 0.06 inch
Density - 0.330 lb/in.³

Liner - Thickness - 0.02 inch
Density - 0.330 lb/in.³

Void volume - 45%

Maximum capsule diameter - 4 inches

4.0 PARAMETRIC MODEL

A sketch of the parametric model used in the study is shown in Figure 10. The characteristics of the model were investigated over the ranges of power, temperature, voltage, type of thermoelectric material, and diameter, as listed in the previous section. Weights were calculated for the capsule, thermopile, end plate support and fin. The cold frame thickness was selected to permit heat flow from the thermopile to the fin, which was located at the thermopile midplane, without excessive temperature drop. A description is given in the next section of the procedure used to determine the optimum cold frame temperature drop. Weight of the additional beryllium necessary in the cold frame is calculated.

The capsule model used was the same as that described in the previous report describing the finned cylinder RTG parametric study performed for the Voyager program (VOY-CI-TRI). The thermopile model also was described in that report.

The fuel capsules used Pu-238 fuel arranged in an annular cylinder with 45% void volume. Maximum capsule diameter was four inches, which required leaving larger radiation gaps in some cases. This design results in an additional 50° rise in capsule temperature.

The fuel capsule L/D ratio was considered as a variable parameter in the initial part of the study, but it was found that total RTG weight was relatively insensitive to variations in aspect ratio. The fuel capsule aspect ratio was therefore not considered as an important parameter. The overall fuel capsule length was constrained such that the RTG would fit within the re-entry shell.

The fuel capsule diameter was limited to a practical maximum limit of four inches. The capsule size was reduced to the minimum diameter compatible with the 45% void volume, keeping length constant.

The weight of the end plate, which is used both as a cover and for support of the capsule and thermopile, was taken to be a function of only the thermopile diameter squared, and was based upon the weight of the end plate support of the SNAP-27 RTG.

The heat rejection was based on the thermopile performance and assumed that 10% of the fuel capsule heat bypassed the thermopile and was radiated directly to space. No heat loss

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through the re-entry shield was assumed. For PbTe, a 70°F drop from cold junction to fin base was assumed; for SiGe this drop was taken as 100 degrees. This drop accounted for thermal contact losses as well as the additions to the cold frame required to channel the heat from the cylindrical cold frame to the inner ring of the annular fin.

In the fin analysis, a fin outer diameter is assumed, and a fin efficiency determined from the charts of Mackay*, assuming the use of the minimum weight fin. It was further assumed that the incident radiation was zero. For a Mars mission, where the average sink temperature never exceeds -50°F , such an assumption will not affect the fin design. The fin efficiency is then corrected to account for a 25% taper of the fin cross-section (fin tip thickness is 25% of fin base thickness). This correction was found to be essentially constant at an efficiency change of -1.5%. The amount of heat rejected by the fin was the total heat to be rejected less the heat rejected by the cold frame cylinder. The fin area is determined by the heat to be rejected by the fin, the fin efficiency, the fin emissivity (constant at 0.85), and the fin base temperature. This area, however, is based upon an annular plane fin. Since the proposed fin design incorporates a conical fin area, a connection was made to account for the reduced view factor from the fin to space. From the corrected fin area and the diameter of the cold frame cylinder, the outer diameter of the fin is calculated. This diameter is then compared to the initial assumption and the process is then repeated if required. Finally, the fin base thickness is calculated from the inner and outer fin diameters, fin base temperature, fin material emissivity, fin material thermal conductivity, and the profile number. The study assumed that beryllium was used as the fin material, with an emissivity, $E = 0.85$. Having all the fin dimensions, and with a density, $p = 0.067 \text{ lbs/in.}^3$, the weight of the fin is then calculated.

The calculated weights of the components are added to give total generator weight. This weight does not include the weight of the re-entry vehicle on the insulation and support structure packed behind the re-entry shield.

* Mackay, D.B., Design of Space Powerplants, Prentice-Hall, 1963.

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5.0 GENERATOR WEIGHT OPTIMIZATION

A detailed calculation was performed for one particular hot and cold junction temperature combination to determine the existence of an optimum temperature drop along the cold frame from cold junction to the fin base. For a given heat generation rate, power and capsule-thermopile length, weights were calculated for thermopile capsule, cold frame thickening, fin, and re-entry shell with varying cold frame temperature drops (from 10°F to 100°F). It was found that for all temperature drops, fin weight changed very slightly in comparison to RTG weight and the same was true for the re-entry shell. The material required to be added to the cold frame did not change significantly and was the dominating factor. For example, to maintain a temperature drop of 10°F, 39.5 pounds of additional beryllium would be required on the cold frame. This value drops to four pounds for a 100°F drop. The total weight dropped sharply as the additional cold figure temperature drop is increased by 10°, then the rate of descent slows and a broad minimum is observed between 35°F and 60°F. It is for this reason that the entire study was performed for a 50° drop along the cold frame.

Optimization of the entire generator was possible only within the 48-inch outer fin diameter limit. It was found that cases which could not meet this limit had either too low a fin base temperature to reject the heat or a very inefficient thermopile which results in large heat rejection rates.

Total weight varied by only small amounts between short, large diameter thermopiles and long, small diameter thermopiles. This result was brought about by a decrease in fin weight and fuel capsule support with decreasing thermopile diameter, whereas the cold frame weight increased at the same time because of increasing length and the correspondingly greater thickness required at the center.

Optimized results discussed in the next section are for the basic RTG and do not include re-entry vehicle weights.

6.0 RESULTS OF THE PARAMETRIC RTG STUDY

The model of the uni-directional heat rejection RTG was analyzed with both PbTe and SiGe thermopiles over the power range from 50 to 100 watts. A maximum RTG diameter of 48 inches was used as a design limit, and this was reached or exceeded for most of the 100-watt units.

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The results of the study of generators with PbTe thermopiles are presented in Figures 11 and 12. The RTG weight is shown as a function of the cold junction temperature in Figure 11. A broad minimum is seen. Since the fuel inventory decreases with reduced cold junction temperature, a design would probably be based on a low heat rejection temperature. The 75-watt unit would exceed the 48-inch limit if it were to be designed with a 450°F heat rejection temperature. Similarly, all of the 100-watt units exceeded this size limit. If the PbTe thermopiles were to be operated at a hot junction of 1000°F instead of the 1100°F reference value, then the size limit would be exceeded by the 75-watt units.

The RTG weight is shown as a function of power rating in Figure 12. Little difference is seen between the RTG's with 500°F and 600°F cold junction temperatures. The specific power is basically of one watt per pound, decreasing very slightly with increasing power.

The results for RTG's with SiGe thermopiles are presented in Figures 13 and 14. The influence of cold junction temperature is seen in Figure 13. The broad minimum is again seen, with little difference in RTG weight for cold junctions above 650°F. The higher optimum cold junction temperature is due to the facts that the SiGe thermopiles operate with hotter hot junction temperatures, and have a lower material efficiency.

The dependence of RTG weight on power is shown in Figure 14. The specific power varies from 0.9 watt/lb at 1200°F hot junction temperature, 1.3 watts/lb at 1400°F hot junction temperature, and 1.8 watts/lb at 1600°F hot junction temperature. The specific power of the generator with SiGe thermopiles increases with increased power level so that the use of a greater number of smaller generators is indicated. The inclusion of re-entry heat shield weight brings the specific weight of the various sized generators nearer, so that no optimum power size is seen in the 50-to 100-watt range.

The 48-inch limit on the thermopile diameter limited the power available from a 1200°F hot junction SiGe thermopile to 50-watts. The fuel inner liner temperature limit limited the size of the fuel capsules for the generators with a 1600°F hot junction temperature to 75 watts.

The total fuel inventory is shown in Figure 15 as a function of cold junction temperature. The total fuel inventory shown is for a 600-watt system. When the cost of the fuel, which is between 500 dollars to 1000 dollars per thermal watt, is realized, it becomes apparent that

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a cost differential of about four million dollars per launch results from a lowering of the cold junction temperature by 100°F . In light of the small weight differences associated with lower cold junction temperatures, the associated cost savings are worthy of consideration. Fuel inventory is lowest for highest power ratings because the heat leaks from the ends of the fuel capsule are a lower percentage of the total fuel requirement for the larger sized units.

The relationship between the diameter of the RTG and the RTG size is shown in Figure 16. Extrapolation of the calculated curves shows that the 48-inch limit will accommodate RTG sizes from 65 to 110 watts for thermopile hot junction temperatures of 1200°F to 1400°F . RTG's with PbTe thermopiles are limited to power ratings below 90 watts in order to fit into the 48-inch envelope.

The re-entry shield weights are combined with the basic RTG weights to give the weight of complete RTG's with re-entry shielding. These results are presented in Figures 17 through 20. The re-entry shield weights were obtained using the techniques described in Section 7. Figure 17 shows the total weight of RTG's with PbTe thermopiles as a function of cold junction temperature. The minimum total weight RTG has a higher cold junction temperature than that of the optimum weight bare RTG. This is due to the weight penalty as imposed on the radiator area imposed by the heat shield. Figure 18 shows a similar trend for RTG's with SiGe thermopiles.

The summary of the minimum total weight RTG's is shown in Figure 19 as a function of power rating for RTG's delivering power at 28 Volts. RTG's designed for 15 volt operation would be about 10% lighter. It is seen that the PbTe thermopile generators with 1100°F hot junction temperatures fall between those of the SiGe thermopile with 1200°F and 1400°F hot junction temperature. The specific weight (lbs/watt) of the RTG's does not vary appreciably with power rating. The relationship of average specific power to hot junction temperature is shown in Figure 20. A 200°F shift between the curves for the two materials is seen. This results from the different thermoelectric material efficiency of the two materials.

7.0 RE-ENTRY VEHICLE WEIGHT AND CONSIDERATIONS

7.1 DIRECTED HEAT REJECTION RTG APPLICATION

A study was made concerning the re-entry vehicle heat shield requirements for the Uni-directional heat rejection RTG presented in this report. The constraints placed upon this study are listed in Table 1.

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The primary consideration is to return the radioisotope fuel to earth without dispersion of the isotope.

7.1.1 Re-entry Shapes

There are a number of re-entry shapes suitable for the application. Of the various available aerodynamic R/V shapes, the sphere cone (Mark II shape) is of prime importance for this application since its aerothermodynamic characteristics are well known, therefore, a minimum of development work is required. The detailed shape (cone angle and nose to base radius) will determine the drag and the overall performance of the vehicle. The lower the drag, the higher the heating and the more controlled is the flight path. The blunter the vehicle, the higher the drag, the thermal environment is lower and the less sophisticated becomes the heat protection system requirement. A blunt vehicle like the Mark II, which has been adequately flight and ground tested, appears to offer many advantages over other shapes.

Sphere cone cylinder flare shapes are of particular interest when payload shape is long and slender. The flare portion is required for stability purposes and is a relatively critical portion of the vehicle from both a weight and stability stand-point.

The flat plate shape is of interest when it is required to provide high drag and low heating for a given overall frontal area. The prime disadvantage of the shape is that it will produce oscillations and/or tumbling since it is unstable. The tumbling will require heat protection on all surfaces and will significantly increase the re-entry dispersion. The addition of a flare can provide adequate stability but this will offset the prime advantage from a heating and drag standpoint. The use of a flat plate is not believed desirable for this application.

There are many other possible shapes capable of re-entry which consist of both symmetrical and asymmetrical bodies. The symmetrical bodies can have forebodies made to a power law for specific advantage either to minimize drag, heating or to maximize payload placement for special applications. There are various asymmetrical bodies which can provide special re-entry characteristics especially when lift is required. For the present application none of these specialized shapes, which require considerable development work from an aerothermo standpoint, are desirable for this application.

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7.1.2 Heat Protection Systems

The heat protection systems of possible interest for this application include both passive and active systems. The passive systems include re-radiation, ablation, heat sink, liquid metal cooling and transpiration cooling. The active cooling systems include transpiration and film cooling systems. The transpiration, film and liquid metal cooling systems are particularly attractive for applications which have high heat flux and which require minimum shape change. The heat sink system can be used for this application but due to the long flight time and relatively high total heating the system is quite heavy even when a very efficient material such as Beryllium is used. The systems that are most applicable are both the re-radiation and ablation systems.

7.1.3 Re-Entry Materials

The re-entry materials required for this application are somewhat different than the usual re-entry materials. The relatively long re-entry time-low heat flux-low shear type of environment, typical of the decay type re-entry, will require in general a certain type of re-entry material. The use of ablation materials for this environment is limited due to the orbital requirements (long duration at 500 to 700⁰F and the particle radiation from the RTG). Of the ablation materials available ESM (a flight proven material) utilizing a mechanical bond is most suitable.

The requirements for the application show that metallic or graphite materials are most suitable for the application. The operating temperature limit of some of the materials can readily establish their desirability of operation. The materials such as Beryllium can be taken up to about 2000⁰F, but in addition it is a very good heat sink material. Rene' 41 can be operated to about 2000⁰F, TAM can be raised to 3000⁰F and Ta-Hf can operate around 4000⁰F. These materials are generally considered for Re-radiation application. The graphites can be utilized to temperatures in the 5000 to 6000⁰F range and is a good material for combined re-radiation/ablation application. The graphite materials are well suited especially for the form suggested by this application. It can be utilized essentially as a re-radiator with no shape change, and it is adequate for this re-entry application. The material is called three dimensional graphite fibrous material which obtains support from the basic vehicle structure. The basic material can be made by various methods of weaving

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and/or sewing individual layers of graphite cloth to the desired thickness as required. This material is presently under development. Preliminary ablation performance tests have shown that the material behaves as a re-radiator with no surface recession in the thermal environment of interest for this application.

7.1.4 Heat-Shield Requirements

The heat shield weight was determined for re-entry vehicles having an outside diameter varying from 25 to 48 inches and for total vehicle weight from 50 to 150 pounds. The re-entry vehicle shape utilized for the application has a nose to base radius ratio (r_n/r_b) equal to 0.50 and a half cone angle of 50 degrees. The re-entry conditions were given to be $U_E = 26000$ ft/sec and $\gamma_E = 0$ degrees. The heat shield weight required to meet these conditions is shown on Figure 21 as a function of base diameter for two material systems namely: 1) three dimensional graphite fibrous material (3DGFM) which is a combined re-radiator/ablator and 2) ESM an ablation material. The 3DGFM material acts essentially as a re-radiator for this re-entry environment with no surface erosion. The material can operate continuously during orbital operation at the required temperatures without any change in properties or performance. The ESM ablation material will degrade somewhat when exposed to temperature during orbital operational and would have to be attached to the structure by mechanical means for this application. Surface erosion will occur during re-entry since this material acts like an ablator for this application.

The shield weight for the 3DGFM material (Figure 21) is somewhat lower than that for ESM. The shield weight increases with an increase in base diameter. It is noted that for a given base diameter, the increased vehicle weight will increase the unit heat shield weight requirement. For a given vehicle weight, the local heating rate will decrease as the base diameter is increased. The lower local heating decreases the unit heat shield weight, but the total shield surface area increases faster than the reduction due to heating, therefore, a net increase occurs.

The total vehicle weight shown on Figure 21 includes as shown the weight of the heat shield, thermopile, fins, structure plus insulation and auxiliary equipment. Figure 22 shows typical structure weights for two vehicle concepts. The vehicle which has a structure plus insulation separate from the RTG and fins will have a total re-entry vehicle weight appreciably

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greater than that for the vehicle which uses the fin as the structure eliminating the need for the additional structure weight. It is noted that the added structural weight is of the same magnitude as the heat shield itself.

7.1.5 Conclusions

The re-entry vehicle for the Uni-directional RTG that appears most attractive for this application may be summarized as follows:

a. Sphere cone shape

Nose to base radius (r_n/r_b) = 0.50

Half cone angle = 50 degrees

b. Heat shield material

Three DGFM (graphite tape)

c. Shield weight

100 lbs. total vehicle weight

14.5 lbs. for 28-in. diameter

37 lbs. for 48-in. diameter

d. Desirable R/V design

Utilize the Fin and RTG as structure for minimum weight.

Table 2 illustrates typical point re-entry conditions.

7.2 FINNED CYLINDER RTG APPLICATION

A study was also made to determine the re-entry vehicle shield requirements for a finned cylinder RTG. The finned cylinder RTG's were studied parametrically and previously reported in VOY-CI-TRI, "RTG Parametric study report for the RTG study Voyager Task C", September, 1966. Again, the primary consideration is to return the radioisotope fuel to earth without radioisotope exposure. The restraints imposed upon this study were as listed in Table 3.

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7.2.1 Re-entry Shapes

The shapes considered for the finned cylinder RTG's were essentially the same as those specified in Section 7.1.1. The sphere cone cylinder flare shape was of particular interest, and it was eventually selected because of its ideal adaptability to the RTG shape.

7.2.2 Heat Protection System

The heat protection system most applicable for this particular application is again the re-radiation and ablation systems. The three dimensional graphite fibrous material is also preferred for this application because of its light weight, excellent high temperature properties, and insensitivity to radiation.

7.2.3 Heat Shield Requirements

Figure 23 is a sketch of the finned cylinder RTG with a sphere cone nose and aft flare attached to provide re-entry protection. This type of configuration is similar to the SNAP-27 LEM fuel shipping cask.

The sphere cone nose diameter is sized such that the separated flow leaving the trailing edge of the nosepiece will not intersect the cylindrical portion of the RTG outer case. The aft flare is sized to place the center of pressure aft of the center of gravity. This design concept prevents the air which is shockwave heated by the nose and body of the RTG from causing the thermopile from melting and subsequent fuel capsule melting and exposure of fuel. The presence of the fins may cause fin induced shock waves to impinge on the RTG body and result in local melting. The extent of augmentation of body heating by fin induced shockwaves is currently under investigation as Task 3.7 of the SNAP-27 program. The work which is being performed on this task is directed at solving the unusual heat transfer phenomenon associated with the hypersonic flight of a finned cylinder. Preliminary qualitative tests have indicated that during directed flight with the flight vector parallel to the RTG axis that the fin base heat transfer problem is manageable.

In addition to the heat transfer uncertainty associated with the fin base heat transfer augmentation the fins themselves present an aerodynamic lift problem. Re-entry flight at appreciable angles of attack may result in asymmetrical fin heating which is expected to result in a non-uniform rate of fin melting. The resulting body would then develop a finite lift

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coefficient and would possess a stable flight attitude at a finite angle of attack. This flight mode would result in significant increased heating of the underside of the RTG cylindrical body. Offsetting this behavior is the fact that in hypersonic flow aerodynamic forces are directly related to heat transfer, and therefore as soon as a fin begins to develop lift it will be severely heated and melt rapidly. This increased fin heating with angle of attack will tend to stabilize the body.

The complex coupled aerodynamics and hypersonic heat transfer should be analyzed in detail for a significant set of re-entry trajectories. The forces and heat fluxes must be simultaneously evaluated in a consistent manner in order to provide a meaningful result. Until such an analysis is performed the accompanying weight estimate for the re-entry protection for a finned cylinder RTG must be considered preliminary. Fin release techniques initiated by command or by the re-entry heat pulse itself acting on fusible link brazes at the fin root would separate the fins prior to the development of any fin augmented heat transfer. Such fin release techniques are possible and would have to be examined in a detailed re-entry design. A 20% weight allowance has been included in the weight presented here as an estimate of the additional re-entry system weight allocated to the solution of the problems resulting from the presence of the fins. Figure 24 relates the resulting heat shield weight to the length and diameter of the thermopile.

7.2.4 Weights of Finned Cylinder RTG's with Re-entry Heat Shielding

Figure 25 shows the weight of finned cylinder RTG's with PbTe thermopiles and re-entry heating shielding as a function of cold junction temperature. The smaller sized, 50-watt units show a definite optimum cold junction temperature, while the larger, 125-watt, units show a dependence of optimum cold junction temperature on hot junction temperature. This is due to the RTG length limit placing a premium on radiator area. Figure 26 shows a similar plot for RTG's with SiGe thermopiles. For these generators it is seen that the optimum cold junction is at or in excess of 600°F, which is the temperature limit of the previous study. The high cold junction temperature results in more compact RTG's which in turn reduce heat shield requirements. In general the addition of a re-entry heat shield to an RTG will cause the minimum weight configuration to have a higher cold junction temperature, and smaller size, than an optimum bare RTG.

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The minimum weights of finned cylinder RTG's with re-entry shielding are shown in Figures 27 and 28 for PbTe and SiGe thermopiles respectively. The specific weights vary from 1.15 to 0.85 lbs/watt for RTG's with PbTe thermopiles, and between 0.90 to 0.55 lbs/watt for RTG's with SiGe thermopiles, depending on thermopile hot junction temperature.

8.0 ANALYSIS OF PERFORMANCE MARGINS

In the design of a generator, it is always proper to speak in terms of the conditions existing at the Beginning Of Life (BOL) and End Of Life (EOL). Design margins are included to account for both known degradation and performance uncertainties. The performance uncertainties of RTG's cannot be generalized accurately, since every RTG design will have different sensitivities to material properties, tolerances, etc. Table 4 is a compilation of the uncertainties and known degradation and their effects on RTG performance.

It is seen that the major performance margin item is the degradation allowance. Thus, power conditioning equipment must be sized to handle up to 22% additional power above that required at the end of a 10,000 hour operational period. The total degradation allowance variation is linear with time for PbTe in the range between one to one and a half years. For SiGe thermopiles, the power degradation rate is logarithmic with time at the rate of 5% per extension in generator life by a factor of 10 beyond 10,000 hours.

8.1 THERMOELECTRIC MATERIAL DEGRADATION

The SNAP-27 design incorporates a contact resistance of 9.25 milliohm/couple to allow for thermopile degradation. The performance history of previous PbTe thermopiles of the type used in SNAP-27 have been correlated with the development of such an extraneous resistance during 10,000 hours of operation. This degradation amounts to a 15% increase in leg resistance in 10,000 hours. The parametric model used in this VOYAGER study was based on a 20% additional resistance over that of the legs, thereby combining the degradation of a 14-month operational period, the cold junction connector straps, and hot junction electrodes into a single parameter. It is believed that this technique is as accurate as one can use without resorting to a detailed thermopile design. The SiGe studies included a 10% extraneous resistance after the 1500 hour burn-in period to account for the same items (including the resistance of the shoes).

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8.2 FUEL LOADING UNCERTAINTIES

An uncertainty exists for both the power density and specific power. A variation in power density affects the volume of fuel required and consequently the fuel capsule internal hot spot temperature. Variations in specific power affect the fuel weight. The ^{238}Pu fuel form presently being used has a power density of $2.6 \pm 0.2 \text{ w/cm}^3$ and a specific power of $0.40 \pm 0.01 \text{ w/gm}$. Variations in power density are accommodated by basing the fuel capsule design on the lowest values of power density and thermal conductivity and manufacturing a number of fuel capsule inner liners to accommodate this range. The small temperature distribution variations resulting from fuel skimming do not affect the generator performance. The variation in specific weight results in a fuel weight which has uncertainties of $1/2\%$.

The techniques of fuel loading includes a calorimetric determination of the thermal loading. With proper instrumentation and procedures, the thermal loading can be kept to within 2% .

Since Voyager launch dates would be known in advance, the fuel loading would incorporate the small decay of the plutonium (89.6 half-life). Fuel power density and specific power would decay at a rate of roughly 1% per year from the time of fuel preparation. Since these factors would be known once an RTG program is initiated a small uncertainty must exist in the fuel capsule weight prior to program commencement. Fuel trim can be accomplished, to within 2% , to adjust the fuel capsule to individual generator variations, determined from performance testing with electrical heaters.

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8.3 SENSITIVITY TO THERMOELECTRIC MATERIAL PROPERTIES

The design conditions are such that the figure of merit of the thermoelectric materials is a maximum. The property values selected for use in the design are based on measured material properties with the measurements performed on samples of all which were taken from the same batch. The set of properties used therefore represents those properties associated with a specific doping level and metallurgical composition. The doping variations primarily affect the Seebeck coefficient and resistivity. Since the figure of merit is even though individual variations in S and ρ are found. The lattice contribution to the thermal conductivity predominates over the electronic portion and hence it has been found that no significant variation in measured thermal conductivity results from process doping variations. The combined variations in all three properties affecting the figure of merit result in a performance uncertainty of less than 1%.

A thermo pile test evaluation is included in the SNAP-27 generator program. Ten and 104 couple instrumented thermopile modules are delivering from 99% to 114% of design power, based on the material property values used in the SNAP-27 generator program and in the PbTe thermopile portion of the VOYAGER parametric study. The variations in 10 and 104 couple module performance is in part due to a lower insulation thermal conductivity, uncertainties in module and heat leaks, instrumentation uncertainties, and in part due to the fact that a small fraction of the thermoelements may have figures of merit, measurably above the minimum acceptance specifications and this increased performance of individual couples is more easily seen in the thermopiles employing few legs. As in all doped semiconductor products, the possibility exists for a tightening of manufacturing specifications in an attempt to purchase only the high performance tail of the product distribution.

8.4 SENSITIVITY TO FUEL LOADING

The generator output can be expressed by:

$$\text{Power} = \eta_{\text{carnot}} \eta_{\text{material}} Q$$

where

$$\eta_{\text{carnot}} = \frac{\Delta T}{T_{\text{hot}}} = \frac{T_{\text{hot}} - T_{\text{cold}}}{T_{\text{hot}}}$$

A reduction in the heat input, Q , has two effects; by definition, it lowers the amount of heat available for conversion into electric power, and it also reduces the temperature drop across the thermopile. A change in heat flux also results in a change in heat rejection temperature since

$$Q_{\text{Rejected}} = \sigma \left(T_c^4 - T_s^4 \right) A$$

For a fixed value of the materials efficiency

$$\frac{dP}{P} = \frac{d\eta_c}{\eta_c} + \frac{dQ}{Q}$$

Since the temperature difference is proportional to the heat flux

$$\Delta T = CQ$$

it can be shown that

$$\frac{d\eta_c}{\eta_c} = (1 - \eta_c) \frac{dQ}{Q}$$

for fixed T_c . And

$$\frac{d\eta_c}{\eta_c} = \frac{3}{4} (1 - \eta_c) \frac{dQ}{Q}$$

for a variable T_c with a sink temperature of absolute zero. For a finite sink temperature

$$\frac{d\eta_c}{\eta_c} = \left(1 - \eta_c - \frac{1}{4} \left(\frac{T_c^4 - T_s^4}{T_h T_c^3} \right) \right) \frac{dQ}{Q}$$

For typical values of T_h , T_c , and T_s

$$\frac{dP}{P} = K \frac{dQ}{Q}$$

CONDITION	K
Fixed to	1.55
Variable T_c , $T_s = 0^\circ\text{R}$	1.41
Variable T_c , $T_s = -50^\circ\text{F}$	1.43

Indicating that typically a 1% variation in heat input results in a 1-1/2% variation in power output. Detailed generator analyses have verified this analytical result of a power variation 50% in excess of the heat input variation.

Increases in heat input over the design point would result in an increase in hot junction temperature in excess of the design point. This in turn would impair the generator life. Excess heat input would be prevented from overheating the generator by shifting the operating point to that of a higher current. This results in an increase in internal dissipation. A series of point analyses were performed on overfueled generators with operating temperatures limited to design conditions. It was found that the penalty for maintaining a constant hot junction temperature with excess fuel loading was again 1-1/2% power loss per 1% fuel variation.

8.5 SENSITIVITY TO OUTER COATING EMISSIVITY

The SNAP-27 outer coating is designed for an emissivity of 0.85. Measured values of this coating vary from 0.88 to 0.92 as fabricated and a 1% to 3% loss in thermal vacuum for one

year is predicted. The cold junction temperature will drop by $2\frac{1}{2}^{\circ}\text{F}$ per 1% increase in emissivity in excess of 0.85. The change in temperature is felt throughout the generator and affects a change in power since the material properties are temperature dependent. The corresponding power variation prediction is 0.016% per 1°F lowering of the cold junction temperature. The variation in emissivity will result in a loss in power which should not exceed 1/3%, and based on measurements of currently produced outer coatings should be less than 0.04%.

8.6 OPEN AND SHORT CIRCUIT ALLOWANCES

The thermopile consists of a two-way ladder arrangement to allow for open circuit of individual elements. The loss of a single thermocouple would result in a power loss of 1/2%.

8.7 COLD FRAME THERMAL CONTACT RESISTANCE

The total thermal contact resistance temperature drop from the cold junction to the outer case is predicted to be 20°F . Measurements in an instrumental mock-up of this section have shown a 13°F to 26°F temperature drop attributable to contact resistance. The sensitivity to contact resistance temperature drop is due to the temperature variation in material properties, and, like the sensitivity to emissivity, is predicted to be 0.016%/°F.

9.0 CONCLUSIONS

The weight of RTG's designed for unidirectional heat rejection are presented in Figure 29. The weight of both the basic RTG and the re-entry shielded RTG are presented. A small increase in specific weight with increasing power level is seen. This is attributal to the fact that the weight of the annular heat rejection Fin increases at a more rapid rate than the RTG power. The effect of the 48-inch diameter constraint is to limit the RTG size to about 90 watts. The optimum cold junction temperatures are about 150°F above those found for the finned cylinder configuration. This is due to the constraints on radiator area. The heat shield weights amount to 0.2 to 0.5 lbs/watt.

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TABLE 1. RE-ENTRY VEHICLES CONSTRAINTS

RTG Radioisotope	Pu-238
Cooling Fin OD range	25 - 48 inches
RTG and fin weight range	23 - 90 pounds
Re-entry conditions U_E	26,000 ft/sec
γ_E	0 degree

TABLE 2. TYPICAL POINT RE-ENTRY CONDITIONS

R/V Characteristics

Diameter (D_B) - inches	26	31	39
Total weight - lbs	61	70	88
R_N/R_B	0.538	0.455	0.359
$W/C_D A$ - lb/ft ²	13.4	11.0	8.9
Required Center of Gravity location - X/D_B	0.56	0.57	0.58

Stagnation Conditions

$\dot{q}_{s_{max}}$ - Btu/ft ² sec	108.2	98.3	88.1
Q_s - Btu/ft ²	24,100	21,900	19,660

Heat protection requirements at stagnation point - Trailing edge thickness is 85% of thickness at stagnation point.

A - 3 DGFM - graphite tape material at stagnation point

thickness - inches	0.715	0.696	0.676
weight - lb/ft ² surface area	2.61	2.54	2.46

B - ESM - mechanical bond. Material thickness at stagnation point

thickness - inches	1.19	1.10	1.00
weight - lb/ft ² surface area	3.58	3.29	3.00

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TABLE 3. FINNED CYLINDER RE-ENTRY VEHICLE CONSTRAINTS

RTG diameter range	6 - 12 inches
RTG length range	18 to 24 inches
RTG power range	50 to 150 watts
RTG weight range	25 - 50 lbs
Re-entry conditions U_E	26,000 ft/sec
γ_E	0 degree

TABLE 4. RTG's DEGRADATION AND PERFORMANCE VARIATIONS

<u>Source</u>	<u>Effect on Performance</u>
S^2/ρ Variations	Less than 1% change in Power
Material degradation and development of contact resistance	
Pbte Thermopile	BOL power 22% greater than EOL
SiGe Thermopile	BOL power 14% greater than EOL
Fuel Loading	+0, -3% Power uncertainties
Emissivity Variation	+0, -3% Power uncertainties
Open Circuit Contingency	1/2% of Power
Thermal contact resistance	$\pm 0.1\%$ power uncertainties

TABLE 5. MOD5 GENERATOR PERFORMANCE
(1442 WATTS INPUT)

Theoretical Material*	69.5 watts
As Assembled (New)	68.5 watts
At 300 hours	67.5 watts
Predicted with 5.75 mohm/couple additional resistance	61.5 watts
Predicted with 9.25 mohm/couple additional resistance**	57.0 watts

* Zero contact resistance

** End-of-Life (10,000 hrs.) degradation allowance

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Figure 1. Unidirectional Heat Rejection RTG Configuration

Figure 1A. Small Diameter "Headlight" Type RTG

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Figure 2. Preliminary Concept RTG Unit in a Re-entry Vehicle Application: Voyager Concept No. 1

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Figure 3. Preliminary Concept RTG Unit in a Re-entry Vehicle Application: Voyager Concept No. 2

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Figure 4. Preliminary Concept RTG Unit in a Re-entry Vehicle Application: Voyager Concept No. 3

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Figure 5. Preliminary Concept RTG Unit in a Re-entry Vehicle Application: Voyager Concept No. 4

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PRELIMINARY CONCEPT
R.T.G. UNIT
IN A RE-ENTRY VEHICLE
APPLICATION: VOYAGER
OCT. 20, 1966

Figure 6. Preliminary Concept RTG Unit in a Re-entry Vehicle Application: Voyager Concept No. 5

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PRELIMINARY CONCEPT
R.T.G. UNIT
IN A RE-ENTRY VEHICLE
APPLICATION : VOYAGER
OCT. 22, 1966

Figure 7. Preliminary Concept RTG Unit in a Re-entry Vehicle Application: Voyager Concept No. 6

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Figure 8. Preliminary Concept 60 Watt RTG Unit in a Re-entry Vehicle for Application on Voyager

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PRELIMINARY DESIGN:-
R.T.G. UNIT IN A RE-ENTRY VEHICLE
MSC-178
Jan 28th 1966

Figure 9. Preliminary Design RTG Unit in a Re-entry Vehicle

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Figure 10. Parametric Model

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Figure 11. RTG Weight As a Function of Cold Junction Temperature PbTe Thermopiles

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Figure 12. RTG Weight As a Function of the RTG Power Rating PbTe Thermopiles

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Figure 13. RTG Weight As a Function of Cold Junction Temperature SiGe Thermopiles

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Figure 14. RTG Weight As a Function of Power Rating SiGe Thermopiles

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Figure 15. Total Fuel Inventory As a Function of Cold Junction Temperature

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Figure 16. Relationship Between RTG Diameter and Power Size of RTG's With Uni-directional Heat Rejection Capabilities

Figure 17. Total Weight As a Function of Cold Junction Temperature PbTe Thermopiles

Figure 18. Total RTG Weight As a Function of Cold Junction Temperature SiGe Thermopiles

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Figure 19. Total RTG Weight As a Function of Power Rating SiGe Thermopiles

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Figure 20. Relationship of Total RTG Weight and Thermopile Hot Function Temperature

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Figure 21. Voyager RTG Re-entry Package Heat Shield Weight vs. Base Diameter

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Figure 22. Structure and Insulation for Two Voyager Re-Entry Concepts

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Figure 23. Finned Cylinder RTG with Re-entry Protection

Figure 24. Re-entry Protection for Finned Cylinders

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Figure 25. Total RTG Weight As a Function of Cold Junction Temperature PbTe Thermopiles

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Figure 26. Total RTG Weight as a Function of Cold Junction Temperature SiGe Thermopiles

Figure 27. Total RTG Weight As a Function of Power Rating PbTe Thermopiles

Figure 28. Total RTG Weight As a Function of Power Rating SiGe Thermopiles

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Figure 29. Specific Power of Uni-directional Heat Rejection RTG's

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