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General-Purpose Heat Source Development

Phase I—Design Requirements

University of California

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GENERAL-PURPOSE HEAT SOURCE DEVELOPMENT

PHASE I--DESIGN REQUIREMENTS

by

E. C. Snow and R. W. Zocher

ABSTRACT

Studies have been performed to determine the necessary design requirements for a $^{238}\text{PuO}_2$ General-Purpose Heat Source (GPHS). Systems and missions applications, as well as accident conditions, were considered. The results of these studies, along with the recommended GPHS design requirements, are given in this report.

1.0. INTRODUCTION

In the past, there have been a number of space and terrestrial applications of radioisotope-fueled heat sources.¹ For most of these applications, the heat source and the conversion system required to produce electrical power were designed for a specific mission or series of missions. The only method available to change the total electrical power output within these power systems was to add integral numbers of complete conversion systems, which often results in weight and volume penalties. As each of these designs evolved, considerable time and money were spent on the development and qualification of each different heat source. A rationale for the development of the General-Purpose Heat Source (GPHS) is that if a modular heat source can be developed and qualified to meet the needs of existing and future systems, a great deal of time, money, systems weight, and volume can be saved.

The general goals of the GPHS development project are to develop a heat source with the following attributes.

Modular. A modular heat source will have the geometric flexibility to be compatible with the various static and dynamic conversion systems. If the modules are relatively small, it will also have the versatility of affording small changes in electrical power with little or no weight and volume penalties.

High-Power Density. A design goal for power density of the GPHS modules is to be at least 75 thermal watts per pound. Maximum power density of the modules would result in minimizing the overall size and weight of the conversion systems.

Improved Safety. The development of the heat source will be guided by safety testing to ensure that maximum safety index is achieved for both the individual modules and a heat source consisting of an array of modules.

Lower Cost. In addition to the time and money savings associated with not having to requalify the heat source for each use, efforts will be made to minimize the production costs of the GPHS modules.

In order that the GPHS meet the needs of the various dynamic and static conversion systems and display the desired safety attributes, studies have been performed to determine the GPHS design requirements. The primary static system considered was the Selenide Isotope Generator (SIG) being developed by Teledyne Energy Systems (TES) for the NASA Solar-Polar 1983 flight. This is also scheduled to be the first use of the GPHS. The dynamic systems that were considered in these studies are the Brayton Isotope Power System (BIPS) being developed by AiResearch, the Rakine Cycle Turbine System (KIPS) being developed by Sundstrand, a Stirling Cycle System (SIPS) being developed by General Electric (GE) and Philips Laboratories, and a Free Piston Stirling Engine being developed by Mechanical Technology Incorporated (MTI). Missions applications and accident conditions considered were all space launched except SIPS. These launches will be mainly on the NASA Space Transportation System (STS), commonly known as the Shuttle and shown in the artist's concept given as Fig. 1-1. The accident conditions and abort environments for the Titan IIIC launches were also included in these studies.

2.0. SYSTEMS APPLICATIONS

2.1. Static Systems

2.1.1. Selenide Converter. The SIG, being developed by TES and the 3M Company, is a device that utilizes the thermoelectric effect to convert the thermal energy from a radioisotope heat source to useful electrical power. This is the basic conversion method used on all flight systems in the past. In general, if two conductors of different materials are joined at one end to form a junction and that junction is then heated to a temperature higher than the other ends of these conductors, an electrical potential is produced between the two cold ends of the conductors. The magnitude of this potential is dependent on the type of material in the two conductors and the temperature difference between the hot and cold junction. The device created by two conductors, a hot junction and a cold junction, is called a thermocouple and should be recognized as a device often used in remote temperature measurements. In the SIG system, the two legs of the thermocouples are in the form of ceramic cylinders and have a current strap at the hot end to form a junction. Figure 2-1 shows an exploded view of a typical selenide thermocouple, in which GdSe is used as the material for the N-leg, and 3M's TPM-217 is used in the P-leg. These thermocouples can be stacked in modular arrays and connected in series or parallel circuits to produce the desired voltage and subsequent power output.

In the current SIG design, the hot junction is to operate at approximately 900°C with the cold junction at 150°C. At these temperatures, the flight design SIG for the NASA Jupiter Orbiter Probe (JOP) mission is expected to operate with an approximate conversion efficiency of 10%. It is hoped that this efficiency can be improved to about 11% by 1983 and as high as 13.5% in 1985. In the flight design for the 1981 mission, the Multihundred Watt (MHW) heat source

Fig. 1-1.

Artist's concept of the STS (Schuttle) in earth orbit, while launching a space-lab.²

will be used. In this configuration, the fuel clad operating temperature is expected to be approximately 1300°C .

Studies by TES as to what would be the best configuration for a selenide converter, utilizing a high thermal density modular heat source, have produced a design as shown in Fig. 2-2. As can be seen in this figure, the heat source modules, in the form of blocks, are stacked in a long parallelepiped arrangement. This appears to be one of the most favorable configurations for minimizing heat loss, getting the maximum efficiency from the fins used to radiate excess heat, and keeping the overall weight of the system at a minimum.

The staff at TES has expressed a desire to see a modular heat source like GPHS with a maximum thermal density and geometries that would allow stacking in a parallelepiped, similar to that shown in Fig. 2-2. The square cross section of this stack does not seem to be as significant as the small dimension and high thermal density; however, there would seem to be some advantages in having flat

Fig. 2-1.

Exposed view of a selenide thermocouple assembly for the SIG system.³

electric device much the same as the selenide converter. The only real difference in the two systems is in the materials used to make up the thermocouples, as shown in Fig. 2-3. Several of these converters are currently in service with MHW heat sources on both the LES 8/9 and the Mariner Jupiter Saturn (MJS) missions. A typical MHW heat source, SiGe converter setup is shown in Fig. 2-4.

In the current design, the SiGe converter operates with a hot junction temperature of approximately 1000°C and a cold junction temperature of about 300°C. At these temperatures, this system operates with a conversion efficiency of about 6.25%.

As far as interfacing with GPHS directly, this system is not expected to be used for missions beyond 1981, since it is being replaced by the more efficient selenide converter system. However, if problems with the selenide system should force future use of a SiGe converter, it would probably be constructed in a geometry very similar to that proposed for the 1983 selenide system. That is, to use the heat source in the form of a long parallelepiped of small cross section and high thermal density.

2.2. Dynamic Systems

2.2.1. Brayton Isotope Power Systems. The BIPS, being developed by AiResearch, is a closed-cycle gas-turbine system that will use a $^{238}\text{PuO}_2$ fueled isotopic heat source. The system consists of a heat source assembly, a radiator, a turbine generator called the Mini-Bru, and a recuperator as shown in Fig. 2-5. As indicated in the flow schematic shown in the lower right of that figure and in Fig. 2-6, the working fluid is heated as it passes through the heat exchanger surrounding the heat source assembly. The heated gas then passes through the turbine end of the Mini-Bru, where the work is done by the hot gas in turning the rotator of the alternator and thus producing electrical power. The hot gas then proceeds to the recuperator, where some of the heat is transferred to the cold return gas, preheating it prior to its interaction with the heat source. The gas then goes to the radiator, where most of the remaining heat is radiated to

surfaces to interface with this thermocouple configuration, such as use of parallel thermocouple clusters that use a common loading spring, ease of machining flat-face hot shoe assemblies, etc.

In a thermocouple conversion system like the SIG, the useful increments of thermal power are dictated by the size of a complete thermocouple assembly. That is, we would like to see the modules of the GPHS sized so that each additional module in the heat source stack could be accommodated by a thermocouple assembly or assemblies as an integral unit. Otherwise, the addition of a module may result in wasted or insufficient thermal power for the increment of optimum electrical conversion system available and would possibly result in a volume or weight penalty.

2.1.2. SiGe Converter. The Silicon Germanium converter is a thermo-

Fig. 2-2.

Design concept of a GPHS-type modular heat source in use with a selenide conversion system.³

space. The now cool gas goes through the compressor end of the Mini-Bru, is pressurized, flows through the recuperator, where it is preheated, and ends up back at the heat source heat exchanger for final heat-up prior to the start of another cycle. All movement of gas through the cycle, including flow-through bearings and alternator for cooling, is completely contained within the closed system, and working fluid loss during normal operation is held to a minimum.

The current BIPS design operates at a maximum hot gas temperature of approximately 790°C as the gas enters the turbine end of the Mini-Bru. At this operating temperature, the BIPS system is expected to operate at about 27% efficiency.

Fig. 2-3.
Silicon germanium thermocouple as used
in the MHW converter.⁴

Because the system is currently designed to use the MHW heat source, the MHW fuel clad would normally operate at approximately 1260°C.

The staff at AiResearch would prefer a modular heat source with a high thermal-power density and of the size and shape proposed by TES in their Low-Cost High-Power Generator (LCHPG) design. Such modules could be stacked in an array similar to that preferred for the selenide system, as shown in Fig. 2-2. This would maximize the surface area of the heat source exposed to the heat exchanger while holding end losses to a minimum. This would also reduce the cross section of the heat exchanger, which in turn would tend to reduce the weight and fabrication difficulties associated with this type of pressure vessel. It is also possible that such a configuration will result in lower thermal resistance between the fuel and the working fluid, thus allowing either a higher working temperature for the hot gas or a lower fuel clad operating temperature. Both cases have some advantages in systems performance and safety.

In short, the preferred heat source geometry to interface with the BIPS system would appear to be one that could be used as a long parallelepiped with a small cross section, maximum power density, and minimum end exposures. This, of course, is very similar to the geometric preference described for the selenide system above.

2.2.2. Rankine Cycle Turbine System. The KIPS, being developed by Sundstrand Energy Systems, is also a closed-cycle gas-turbine system that uses a $^{238}\text{PuO}_2$ fueled isotopic heat source. This system, as shown in Fig. 2-7, consists of heat source assemblies, a radiator, a turbine generator, and other working fluid handling and heat transfer components. As indicated in the flow schematic in Fig. 2-8, the KIPS operates in much the same way as the BIPS. The one basic difference is that, unlike the BIPS cycle, in the KIPS the working fluid operates in both the liquid and vapor phases. In this system, instead of a heat exchanger around the heat source, the heat source is surrounded by boiler pipes. The working fluid enters these boiler pipes as a preheated liquid and leaves in the vapor phase. This hot vapor is then passed through the turbine end of the generator unit, where it performs the work of turning the rotator of the alternator, thus producing the desired electrical power. The hot vapor then passes through the jet condenser and is returned to the liquid phase and remains a liquid for the rest of the cycle.

The current KIPS design operates with a maximum hot vapor temperature of approximately 340°C at the inlet side of the turbine. At this maximum operating temperature, the KIPS is expected to yield a 19.4% conversion efficiency. In its current design configuration, using three MHW heat source assemblies, the fuel clad temperature during normal operation is kept at approximately 1040°C.

Fig. 2-4.
MHW Radioisotope Thermoelectric Generator.⁴

Fig. 2-7.
KIPS flight system with the LCHF heat source.⁶

Fig. 2-8.
KIPS flight system cycle schematic.⁶

As to the interfacing between the KIPS and a modular heat source like GPHS, the Sundstrand staff would mainly like to see a geometry that would allow stacking that results in flat surfaces of the proper length on which the KIPS boiler pipes could be easily attached. The high power density is always desirable to maximize the performance while keeping the size and weight to a minimum.

Again, the preferred heat source geometry to interface with the KIPS would appear to be similar to the preferences expressed for both the BIPS and the selenide system, that is, the parallelepiped with a small cross section, maximum power density, and minimum end exposures.

2.2.3. Stirling Isotope Power System. The Stirling heat engine, being developed by Philips Laboratories and GE, operates on a thermodynamic cycle consisting ideally of two isothermal and two constant volume processes. A working gas is compressed isothermally, then heated at constant volume. The hot gas is then allowed to expand isothermally and reject heat at constant volume. The work performed by the gas during its expansion, less the work done on the gas during its compression provides a net work output by the cycle. The pressure/volume relationship required by the cycle can be achieved theoretically by the sequenced operation of two pistons in a single cylinder: a displacer piston and a power piston. The displacer piston is used to move the working gas at constant volume between the hot and cold sections of the cylinder. The power piston is used to compress the gas during the compression operation and to remove the work done by the gas during the expansion process. In addition to the two pistons and cylinders, a heater section, regenerator, and cooling section are needed, as shown in Fig. 2-9, to achieve the necessary heat input and heat rejection during the cycle. The four processes of the Stirling cycle are illustrated in Fig. 2-9. Of course, the reciprocating motion of these two pistons is synchronized through a rotating drive system in a crankcase below the engine cylinder. The rotating drive system is also used to extract work from the engine to turn the rotator of an alternator unit, thus producing the desired electrical power.

In SIPS, the current Stirling engine system design, the minimum hot gas temperature is approximately 725°C. At this operating temperature, this system is expected to achieve a 30% thermal conversion efficiency. The current SIPS is designed primarily for terrestrial use but could be converted to space applications with an appropriate heat source and heat rejection system. In the first use of

Fig. 2-9.
Diagram illustrating the four phases of the Stirling cycle.

SIPS, the heat source will be made up using the Fueled Sphere Assemblies (FSAs) from the MHW heat source placed in an annular array, with a fuel clad temperature of approximately 960°C during normal operation.

The interfacing of the Stirling engine with an isotopic heat source is considerably different from that encountered with the selenide system or BIPS and KIPS. In this system, the efficiency is very dependent on the heat source being in near proximity with the hot end of the engine cylinder. In the current SIPS design, it has been established that the preferred geometry would be to stack the heat source modules in an annular array around the engine cylinder. For maximum efficiency, this would indicate that the modules of GPHS should be relatively small and display a very high volumetric power density.

Apparently, the only thing in common between the SIPS requirements and the other systems would be the need for high thermal-power density. However, if the modules used for stacking in a parallelepiped arrangement are small enough, they could probably also be arranged in an annular array that would be suitable for use with a Stirling engine system.

2.2.4. Free Piston Stirling System. The Free Piston Stirling Engine, being developed by MTI, is a thermally driven mechanical oscillator operating on a Stirling engine cycle, deriving power from heat flow between a source and a sink. The desired displacer motion in this engine is produced by gas forces rather than kinematic linkages, as is the case in most commonly known Stirling engines such as SIPS. In this system, the reciprocating motion of the engine is coupled directly to a linear alternator to produce the desired electrical power.

At this early stage in the development of the Free Piston Stirling System, the operating temperatures have not been set, nor have the system efficiencies been completely determined. However, it is expected that this system will operate with approximately the same temperature and efficiencies as SIPS. It is also expected that the heat source interface will require approximately the same heat source geometry as SIPS. Of course, new heat source requirements that may evolve from the development of this system will be taken under consideration.

2.3. Summary of Systems Requirements

The GPHS interface requirements for the various conversion systems are summarized in Table 2-1. In the table, T_1 is the "hot shoe" temperature for the static systems and the maximum working fluid temperature for the dynamic systems. In essence, T_1 is the interface temperature between the heat source and the conversion system. T_2 in the table is the Post-Impact Containment Shell (PICS) temperature for the various systems as used with the MHW, which has a thermal power density of the heat source of approximately 27.7 W_T/Kg (61 W_T/lb) for space systems. This number should help give some feeling for what clad operating temperatures are being experienced in the current systems, and what order of temperatures might be anticipated in a GPHS configuration. The conversion efficiencies listed in the table are those associated with current configurations, most of which utilize the MHW heat source. However, the use of the GPHS with these systems would be expected to increase these efficiencies in most cases. Listed under W_T in the table are the ranges of thermal watts of power for each conversion system that would be required to produce a range of electrical power from 50 to 5000 W. The low end of each range of thermal power gives an approximate measure of the maximum power per module that would be required for the GPHS, to allow the electrical power of each system to be varied in increments of as low as 50 W. The last column in the table gives an indication of the main geometric interface requirement for each of the various conversion systems. These are only general indicators of the geometry required. In the final analysis,

TABLE 2-1
GPHS SYSTEMS INTERFACE SUMMARY

<u>System</u>	<u>T₁ (°C)</u>	<u>T₂ (°C)</u>	<u>Conversion Efficiency (%)</u>	<u>W_T(500-5000 W_E)</u>	<u>Interface Requirements</u>
SIG ^a	900	1300	11	450-45 000	Small cross section
SiGe ^b	1000	1200	6.25	800-80 000	Small cross section
BIPS ^c	790	1260	27	185-18 500	Maximum surface exposed to heat exchanger
KIPS ^d	345	1040	19.4	260-26 000	Flat surfaces for attaching boiler pipes
SIPS ^e	725	960	30	167-16 700	Small modules to fit into annular volume around engine head
Free Piston ^f Stirling	≈ 700	N/A	≈30	167-16 700	Small modules to fit into annular volume around engine head

T₁ ≡ Systems high operating temperature

T₂ ≡ PICS temperature for MHW

a Reference 3

b Reference 4

c Reference 7

d Reference 6

e Reference 8

f Reference 9

consideration will have to be given to each of the GPHS designs being considered with each of the conversion systems in some detail.

From the information in Table 2-1 and consultation with the various prospective users of the GPHS, we conclude that the GPHS design geometry should be one that produces the maximum thermal-power density, has a total power inventory per module in the range of 150 to 300 W, and is a relatively simple geometry that can be stacked or arranged in a variety of arrays.

3.0. MISSIONS APPLICATIONS

The mission applications affect the GPHS design only indirectly through the conversion system and the accident conditions that are possible because of the

launch vehicle configuration. The accident conditions are covered in Section 4.0 of this report, so only the mission applications' influence on the normal operation of the heat source and conversion system will be discussed here.

3.1. Solar-Polar Mission (1983)

The Solar-Polar is a NASA mission scheduled for launch in 1983 and is the first mission for which the GPHS is scheduled to be used. This mission will be a dual Jupiter swingby by two spacecraft launched simultaneously on the STS (Shuttle). Each spacecraft will have an end of mission power requirement of 161 W electrical. To provide this power, each spacecraft will be equipped with two Radioisotope Thermoelectric Generators (RTGs), each of which will have a capacity to produce 100 W of electrical power, resulting in 200 W per spacecraft at the start of the 4 1/2-year mission.

The conversion system to be used for this mission is to be the TES SIG, designed to use the GPHS modules. With the overall system conversion efficiency of approximately 11%, each RTG will require a power inventory of about 1000 W thermal. Since there is a critical weight requirement for this mission, it is important to provide the required thermal inventory per RTG without imposing any weight penalties. This suggests that one would like to have a GPHS module that has a maximum power density from a weight consideration and can be arrayed to give just the required power without any excess. For the latter requirement, ideally, one would design a module that was very small with a minimum thermal-power inventory, on the order of less than 100 W. However, due to the packaging and other safety requirements, this would undoubtedly reduce the power density to an unacceptable level. These are two "tradeoff" requirements that will have to be considered during the design and development of the GPHS.

3.2. Future Missions (Beyond 1983)

Beyond 1983, the mission that will use RTGs as a source of electrical power will be using the GPHS as the source of thermal power. Many of these will be deep space missions with small spacecraft requiring electrical power in the 200- to 400-W range.¹⁰ Most of these types of missions are weight critical and require the GPHS to be designed to minimize the RTG weight for the power needed. This suggests a need to look at the tradeoffs between the minimum size for the GPHS module design and the maximum thermal-power density that can be achieved.

On some future space missions, where electrical power requirements are in the kilowatt range, it is expected that dynamic conversion systems will be used. In these cases, the need to exactly match the thermal requirements will not be critical. However, the requirement for maximum thermal-power density will still exist.

4.0. SAFETY REQUIREMENTS

There are possible accident conditions associated with the application of the GPHS that produce environments requiring protective members to be included in the module design. A typical radioisotopic heat source has three basic protective members, the fuel containment clad member, the impact attenuation member, and the reentry or ablation member. These basic members and their functions will be discussed later in this section, relative to the various accident environments.

The space- and terrestrial-use accident conditions and their associated environments and occurrence probabilities used for the GPHS design are covered in the "Safety Specification of Plutonium-238 Developmental Heat Sources."¹¹ When considering the relative severities of the environments and the limitations of

size and weight placed on the heat source, the space-use accident conditions are more difficult to protect against and will, therefore, be the ones discussed here. The most severe of these environments are reviewed, along with some discussion as to what type of protection may be required in the GPHS design. The accident conditions that are discussed are those of blast overpressure and fragments, solid-propellant fire, reentry, and impact.

4.1. Launch Abort

During the prelaunch, launch, and early ascent stages of a space mission, there exists the possibility of a catastrophic abort, which will result in an explosion of the launch vehicle. In these situations, a radioisotopic heat source could be exposed to a severe overpressure environment and an impact by fragments of the launch vehicle and the spacecraft. Such explosions could be followed by an impact and possible exposure of the heat source to a solid-propellant fire environment. In order that the protective members of the heat source be properly designed to contain the PuO_2 fuel, all four of these environments must be considered as occurring in a sequence. The possible clad failure modes produced by these environments are due to breaches as a result of deformation, penetration by a sharp fragment, and melting of the clad material.

In the blast overpressure environment, the deformation of the clad will be decreased by the presence of the impact member and the reentry member. The conversion system would also add some protection, but several systems are to be considered, and none are actually designed at this time. The effects of the presence of such systems are unknown at the present, so no credit will be taken for their presence in the GPHS design analyses and testing. If considering only the blast environment, we see that as long as the deformation of the clad member was not severe enough to cause a breach, we would not be concerned about the final condition of the other two members. However, removal of either the impact or the reentry member at this time could have a significant effect on the vulnerability of the clad member to the subsequent fragments, impact, and solid-propellant fire.

In the case of fragments, as with the overpressure, we need to be concerned not only with the protection against the penetration of the clad by the sharp missile, but because of the impact and the solid-propellant fire exposure that could follow, we would like to see the impact and reentry members stay as nearly integral as possible.

The impact environment referred to here is not as severe as that experienced at terminal velocity after reentry, which will be discussed later. This impact environment is the result of the heat source being released from the conversion system by the overpressure or fragments during a catastrophic launch abort, and of falling to the launch pad from its position on the launch vehicle. Since such a release of the heat source will usually be from only 30 m (100 ft) or so above the pad, the module impact velocity should be on the order of about 30 m/s (~ 100 ft/s). At this low velocity, earlier tests¹² on MHW FSAs indicate that survival of the fuel clad should be no problem. These tests also indicate that retaining the impact member and possibly the reentry member during such an impact should not pose too much of a design or materials problem. Of course, after launch, when the launch vehicle has attained some altitude, there is the possibility of an abort, where the impact velocity of the module would approach the terminal velocity. However, at these altitudes, the STS would probably be over water, the impact effects on the module would be minimal, and the possibility of contact with solid-propellant fire would be all but nonexistent.

In the solid-propellant fire environment, previous tests¹³ have shown that in a single proximity encounter, the iridium clad of an MHW FSA will survive as

long as it is afforded the protection of the MHW impact member. These results indicate that the impact member of the GPHS module will probably afford a similar protection for iridium clad in a GPHS design. Currently, there are no data on the survival of a Pt-3008 clad in this environment. However, temperatures of the iridium clad inside an MHW impact member measured during the MHW tests referenced above indicate the need for additional thermal protection, if the Pt-3008 clad material was to be used.

4.2. Reentry

The reentry environment results when the spacecraft reenters the atmosphere, burns up, and releases the GPHS modules at high altitude. The effects of this environment on a GPHS module will be surface ablation, high temperatures, thermal stresses, and mechanical loading. There are essentially two reentry trajectories that will result in maximum effects on the heat source. The first is the shallow angle reentry that produces maximum surface ablation and the highest temperatures at the clad. The second is the steep angle reentry that produces maximum thermal and mechanical stresses in the reentry member.

Though the geometries of the fuel, clad member, and impact member enter into the analyses of the GPHS module during reentry, the main design restrictions imposed by the reentry environment are those imposed on the reentry or ablation member. This member must be designed to remain integral during the reentry with its associated ablation, high thermal stresses, and mechanical loading. For the most part, the ablation is handled by making the reentry member thick enough and of the proper material for the module geometry. The safety specifications¹¹ require that the ablation remove no more than one-half the minimum thickness of the reentry member. On the other hand, the thermal stress and mechanical loading influence the design details as well as material selection, such as the closure design and associated threads, where localized stresses can become large.

Of the effects posed by the reentry environment, the high clad temperature is probably the most difficult to deal with. According to the safety specifications, one must design the thermal protection within the module so as to limit the temperature of the clad material during the reentry event to stay 200°C below the melting point of the material or the temperature at which it reacts catastrophically with the adjacent materials, whichever is lower. At the same time, one must design the GPHS module for a reasonable range of clad operating temperature, when in use with the various systems. Due to the clad-graphite eutectics, the maximum temperatures allowed for iridium and Pt-3008 during reentry are approximately 2000°C and 1650°C, respectively. The operating temperatures should be maintained below approximately 1300°C for iridium, because of grain growth and 1100°C for Pt-3008, because of observed graphite interactions and the fact that long-term data are currently unavailable above this temperature.

4.3. Impact

The impact environment is the result of a terminal velocity encounter with the earth's surface, following the reentry event. The major effect of this environment on the module will be the deformation of the fuel capsule or clad member. In the GPHS design effort, one must design the module and especially the impact member so that the clad deformation is less than that required to breach it and release the fuel to the atmosphere.

There are several ways of reducing the probability of fuel capsule breach. One method is to increase the thickness and subsequent strength of the clad significantly. The major drawback to this approach is that the weight of the module is increased and the mass power density is significantly reduced. A second

method would be to provide impact protection in the form of an impact attenuation member. If of proper character and design, this member would not only absorb a large portion of the kinetic energy during impact but would also serve as additional thermal protection against reentry and solid-propellant fires. This is the method used in current heat source design and that concept will be used in GPHS. A third method, which will also be employed in GPHS, is to design the module geometry so that its terminal velocity is as slow as possible. A fourth method, which will also be used in GPHS is to strengthen the fuel so that the deformation of the clad is minimized in any impact event.

Since tests¹⁴ on the LCHP have shown that the impact velocities for a GPHS-type module should be in the range of 46 m/s (150 ft/s) to 61 m/s (200 ft/s), most of the impact testing for design and safety analyses will be done in this range. However, impact tests of velocities up to 91 m/s (300 ft/s) will be used to evaluate the impact capabilities of the GPHS design.

Additional parameters in the impact environment that affect the design of both the impact and reentry member are those of orientation, fuel and capsule geometry, and clad temperature. Of these, the clad temperature at impact can be the most difficult to cope with if one is to use iridium clad material. Iridium loses some ductility below about 1000°C and does not deform well without increased possibility of cracking. This means that if iridium is to be used, one must not only be concerned with holding down the operating and the peak reentry temperatures, but he must also design the module so that the clad temperature is on the order of 1000°C or higher at impact. Pt-3008 does not seem to suffer this impact embrittlement at low temperature but does have a much lower operating and reentry range than iridium.

5.0 GPHS DESIGN REQUIREMENTS SUMMARY

The GPHS design requirements, as covered in this report, will be discussed in two parts. The first part will cover the requirements that affect the performance and geometry as they relate to normal operating conditions. The second part will discuss the requirements that affect the safety performance of the module as it relates to the more severe accident conditions associated with the space use of the GPHS. Due to the universal use requirement placed on the GPHS, the design requirements can only be defined in a general way and within ranges of design parameters.

5.1. Performance and Geometry

The performance of a radioisotopic heat source like the GPHS depends primarily on the thermal-power density of the design and the temperature at which it can safely operate. Reliability is also a measure of performance, but in a heat source like the GPHS, this is determined primarily by the compatibility of materials and depends only indirectly on the design. As far as thermal-power density is concerned, all of the conversion systems seem to require the maximum power density possible (see Sec. 2.0.). In all of the conversion systems being developed, maximum thermal-power density of the heat source reduces the overall system size and weight. Therefore, the GPHS design will be aimed at achieving as high a thermal-power density as possible, consistent with safety considerations, with a current goal of 34 W/kg (75 W/lb) and 0.46 W/cm³ (7.5 W/in.³).

The highest systems operating temperatures are about 900 to 1000°C on the system side of the heat source system interface, as shown in Table 5-1. With the current MHW heat source design, the operating temperature at the clad can be as high as 1300°C, which requires the use of iridium. If the GPHS is designed

TABLE 5-1

GPHS SYSTEMS REQUIREMENTS

System	Conversion Efficiency (%)	Operating Temperature ^a (°C)	$W_T(50 W_E)$	$W_E(250 W_T)$	Preferred Geometry for GPHS
SIG	11	900	450	27.5	A block about 10 cm by 10 cm by 5 cm (4 in. by 4 in. by 2 in.) that can be stacked in a long parallel-piped of small cross section.
KIPS	19.4	345	260	48.5	A small regular shape that can be arrayed to produce a flat surface of the proper length on which the boiler pipes can be attached.
BIPS	27	870	185	67.5	A small regular shape that can be arrayed to require the smallest heat exchanger pressure vessel and minimize heat loss.
SIPS ^b	30	725	167	75.0	Small modules that can be arrayed in the minimum annular volume around the head of the engine.
Free Piston Stirling	~30	~700	~167	~75.0	None expressed, but probably the same as for the SIPS

^a High temperature on system side of heat exchanger, not surface of heat source.

^b Currently being designed for terrestrial use.

to minimize the thermal resistance between the fuel and the system interface, one may be able to maintain a clad operating temperature of 1100°C or less and consider Pt-3008 as a clad material candidate, as well as iridium.

In considering the geometry of the GPHS module as it relates to normal operating conditions, the overall size and shape of the module are of the most interest. Of course, the size is related to the module shape, but it depends more significantly on the thermal inventory and protection needed for it. This, in turn, relates to the missions requirement that each module be kept as small as possible to minimize the amount of excess power that has to be carried on any one mission. A goal of the GPHS design is to allow addition of thermal power in small enough units to change the electrical power output of the system by as little as 50 W. The values in Table 5-1 indicate that the thermal inventory for the GPHS module should, therefore, range from 170 W for the most efficient dynamic system, to as high as 450 W thermal for the selenide static system. However, one must realize that the more efficient dynamic systems are only useful for large amounts of total power, where the size of the additional increments of power becomes less important. With this in mind, and the fact that the SIG system is considered to be the static conversion system of the future, the range of thermal inventory for the GPHS module is planned to be between 250 and 350 W.

The shape of the GPHS module is dictated by the need to interface with all of the various conversion systems. The information given in Table 5-1 indicates that the only specific geometry preference was expressed by the SIG static conversion system. The other systems require only that the GPHS modules be kept relatively small and be of a simple regular shape, so that they can be stacked in a usable array.

5.2. Safety

The performance and geometry of the GPHS would present little or no problem if it were not for the need to meet the various safety criteria, as related to accident conditions and the subsequent environments. The safety goal for the

GPHS is to have a safety index for all viable accident conditions of less than 10^{-6} Ci, where the safety index is defined as the probability of an accident condition occurring times the probability of the release of PuO_2 as a result of that accident times the amount of respirable fines that would be released, measured in curies.

The accident conditions that are of the primary concern in safety design are those that are most probable and with severe associated environments. Those that will be considered in the design and testing of GPHS are as follows.

1. The blast overpressure and fragments created by a launch pad abort and subsequent launch vehicle explosion. This environment is currently not defined for the STS. Current indications are that the STS accident conditions and associated environments will be defined before the Trial Designs phase of the GPHS development project is completed in October 1978. In the interim, the capabilities of the GPHS designs to survive the blast overpressure and fragments will have to be determined by using the Titan IIIC launch vehicle abort environments and independent estimates of the most severe case that could be expected with an STS launch abort.

2. The solid-propellant fire that can occur as a result of a catastrophic launch pad abort. Since the composition of solid propellant is to be essentially the same as that used in the Titan IIIC boosters, the environment associated with a Shuttle launch should be very much like that of the UTP-3001 solid propellant. The only significant differences should be in the total burn time being slightly longer for the Shuttle propellant, because of a 10% increase in the web thickness of the Shuttle boosters over the Titan IIIC boosters.

3. The reentry environments for both steep and shallow angle reentries. The safety specifications define these reentry trajectories as $V \leq 11\,000$ m/s (36 000 ft/s), $\gamma \leq 90^\circ$ and $V \leq 13\,400$ m/s (44 000 ft/s), $\gamma \leq 15^\circ$, respectively, where V is the velocity at the time the heat source is released from the conversion system, and γ is the angle of attack, relative to the earth's atmosphere. The GPHS reentry analyses will be done by Battelle Columbus Laboratories (BCL) for $V = 11\,000$ m/s (36 000 ft/s), $\gamma = 89.9^\circ$ and $V = 11\,000$ m/s (36 000 ft/s), $\gamma = 5.3^\circ$. These trajectories have been defined by BCL as the ones that will produce the maximum stresses and highest peak clad temperatures. These environments create conditions of ablation, high clad temperatures, and high thermal and mechanical stresses.

4. The terminal velocity impact on a hard surface that occurs after reentry.

Any module design for the GPHS will have to be analyzed and tested for these accident conditions as well as their normal operating conditions. Account must also be taken for the fact that these accident conditions are sequential, in that the solid-propellant fire is usually preceded by exposure of the module to overpressure and fragments, and the terminal velocity impact is usually preceded by exposure to the reentry environment. In addition, it must be considered that most of the components of the GPHS module will be multipurpose, in that the reentry member will also serve as protection from overpressure and fragments, both the reentry and impact members will provide some thermal protection for the solid-propellant fire, as well as during the reentry event.

In general, we conclude that no one design criterion, whether related to operating performance or safety, can be considered completely independent of the other criteria. This requires the design effort to be an iterative process consisting of design, redesign, testing and analyses, tradeoffs, and compromise. The aim of the GPHS development project is to produce a final design that will meet or surpass all of the design requirements.

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