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THERMAL ANALYSIS OF CONCEPTUAL DESIGNS FOR GPHS/FPSE POWER SYSTEMS OF 250 W_e AND 500 W_e

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Final Report

By

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ABSTRACT

Thermal analyses were performed for two distinct configurations of a proposed space nuclear power system which combines the U.S. Department of Energy's (DOE) General Purpose Heat Source (GPHS) modules with state-of-the-art Free-Piston Stirling Engines (FPSE). The two configurations correspond to systems with power levels of 250 W_e and 500 W_e. The 250 W_e GPHS/FPSE power system utilizes four GPHS modules and one FPSE, and the 500 W_e contains eight GPHS modules and two FPSEs. The configurations of the systems and the bases for selecting the configurations are described. Brief introductory sections are included to describe the GPHS modules and free-piston Stirling engines.

The primary focus of the thermal analyses is on the temperature of the iridium fuel clad within the GPHS modules. A design goal temperature of 1573 K has been selected as upper limit for the fuel clad during normal operating conditions. The basis for selecting this temperature limit is discussed in detail.

Results obtained from thermal analysis of the 250 W_e GPHS/FPSE power system indicate fuel clad temperatures which slightly exceed the design goal temperature of 1573 K. The results are considered favorable due to the numerous conservative assumptions used in developing the thermal model and performing the thermal analysis. To demonstrate the effects of the conservatism, a brief sensitivity analysis is performed in which a few of the key system parameters are varied to determine their effect on the fuel clad temperatures. It is concluded that thermal analysis of a more detailed thermal model would be expected to yield fuel clad temperatures below the design goal temperature limit of 1573 K.

Thermal analysis of the 500 W_e GPHS/FPSE power system yields fuel clad temperatures slightly greater than those obtained in the analysis of the 250 W_e power system, yet still close enough to the design goal temperature limit to consider the results favorable. Analysis of a more detailed thermal model would be expected to yield fuel clad temperatures closer to, or lower than, the design goal temperature.

An additional analysis is performed for the 500 W_e GPHS/FPSE power system. Since the 500 W_e system has two Stirling engines, the effects on fuel clad temperatures of losing one engine are analyzed. It is found that the fuel clad temperatures rise significantly when one engine is lost. The results are not too unfavorable due to certain ambiguities associated with the design goal temperature limit.

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1.0 INTRODUCTION

This report presents the results of a thermal analysis performed by the University of Florida's Department of Nuclear Engineering Sciences for NASA Lewis Research Center (Contract # NAG3-1123). The primary intent of this study is to demonstrate by thermal analysis the feasibility of developing radioisotope-fueled dynamic space power systems of 250 W_e and 500 W_e which combine the U.S. Department of Energy's (DOE's) General Purpose Heat Source (GPHS) modules with state-of-the-art Free-Piston Stirling Engines (FPSE). Feasibility of each system is based solely on meeting the temperature constraints for the radioisotope fuel clad under normal operating conditions. Other general design criteria, such as requirements for specific mass (kg/kW_e) and structural design, are given consideration in this study, but can be addressed in full detail only as design of the system progresses beyond the conceptual stage.

2.0 OBJECTIVES

2.1 Overview

This study consisted primarily of the performance of thermal analyses of the proposed GPHS/FPSE power systems using thermal models representative of the system configurations at power levels of 250 W_e and 500 W_e. Development of the thermal models and the results of the thermal analyses performed with these models are described in this report. The thermal models were created using NASA's thermal analysis computer codes, TRASYS and SINDA. These codes were used together to generate the steady-state temperature distribution throughout the enclosures of the power generation systems, including the interior components of the GPHS modules.

The primary focus of the thermal analysis with the thermal models is the temperature of the iridium fuel clad in the GPHS modules. Temperature constraints and other design considerations are addressed in detail in the following subsections.

2.2 Temperature Constraints

The temperature limits are imposed on the clad to ensure the integrity of the fuel capsule in the event of an aborted mission in which the GPHS modules reenter the earth's atmosphere and impact the surface. For the cladded fuel pellet to survive impact, the iridium clad must retain its ductility. To ensure adequate ductility, the fuel capsules must impact with a relatively high clad temperature and a reasonably fine grain size. The fine grain size can be assured only if the fuel clad temperature during normal operating conditions has been below a prescribed temperature limit and the peak reentry temperature of the clad has also been below a specified temperature limit.

To meet the temperature requirements of the iridium clad in the GPHS/FPSE power system, there are two primary design concerns: (1) under normal operating conditions, the iridium clad temperature must be below the maximum allowable, and (2) the system must be designed such that, upon accidental reentry, the power system will break apart, allowing the GPHS modules to reenter the atmosphere individually. Design considerations associated with this second concern are given in the next section.

The first design concern, the maximum permissible temperature for the iridium clad under normal operating conditions, was initially thought to be straightforward. The temperature limits of the clad for normal operating conditions and for extended transient conditions were identified in a 1986 Rockwell International Corporation BSTS (Boost Surveillance and Tracking System) power system definition study (reference 1). These temperature limits, given in Table 2.1, are almost identical to, but slightly more conservative than, the initial temperature constraints used in the design of the GPHS modules (reference 2). The requirements given in Table 2.1, although slightly ambiguous, were interpreted to impose the following fuel clad temperature limits: (1) a maximum of 1300° C for normal operation and (2) a minimum of 950° C for reentry and earth impact. The temperature ranges listed for transient conditions would only apply to the GPHS/FPSE system if mission lifetimes for the power system were to be within the time intervals listed for 'transient' conditions.

Table 2.1 GPHS Temperature Design Requirements [1]

*PICS, operational	1300° C or less maximum long term
*PICS, impact	950° C minimum
Transient	Time at temperature (hours)
1600 to 1500° C	10
1500 to 1400° C	50
1400 to 1300° C	1000
1300 to 1200° C	100,000
1200 and below	indefinite

* Post-Impact Containment Shell [Iridium Fuel Clad]

The temperature limits used for design of the GPHS modules are given in reference 2 as: (1) a maximum of 1330°C for normal operation, and (2) 900°C for minimum impact temperature. In addition, a peak reentry temperature limit of 1800°C was also imposed.

The temperature limits interpreted from Table 2.1 seemed reasonable and were to be used as the design goal temperatures for the detailed thermal analysis. However, while on a trip to Mound Laboratories in Dayton, Ohio, where the GPHS blocks are assembled and tested, the Mound engineers expressed skepticism concerning the validity of these numbers. The minimum impact temperature was agreed upon as 950°C, but, the Mound engineers stated that the GPHS modules could be safely operated for extended periods (anticipated mission lifetimes) in the temperature range of 1573 K ±200 K (1100°C to 1500°C, 2012°F to 2732°F). Grain growth in the iridium clad, they suggested, had been overestimated when the temperatures limits listed in Table 2.1 were established.

Using the temperature limits as recommended by the Mound engineers would lead to much more flexibility in design of the GPHS/FPSE system. For example, a power system configuration with fuel clad temperatures of up to 1500°C would be allowed to operate for an indefinite period. If the values in Table 2.1 were used as the design criteria, the blocks could be operated with a clad temperature of 1500°C for only 50 hours.

Due to this confusion, the Astro Space Division of the General Electric Company (GE), which performed the Safety Analysis for the Galileo mission (which uses the GPHS-RTG), was contacted for their advice. According to Mr. John Loffreda of GE, there is an ongoing debate as to the effect on grain growth in the iridium clad of long term operation within the temperature ranges given in Table 2.1. Some feel that these temperature limits are conservative, and the GPHS blocks may be operated safely for longer periods in these temperature ranges. Others feel that there would be too much grain growth when adhering to these temperature constraints. The concerns, however, are more with the higher temperature ranges and the associated times of operation. Operation of the GPHS modules with the iridium clad temperature at or near the maximum long term operational temperature limit of 1300° C given in Table 2.1 is perfectly acceptable for indefinite operation. Thus, the design goal of this study is to produce thermal models of the GPHS/FPSE power systems which can be shown by thermal analysis to have iridium clad temperatures of 1300°C (1573 K, 2372°F) or below under normal, steady-state operating conditions.

2.3 Other Design Considerations

In developing the configurations for the GPHS/FPSE power systems, three design considerations were followed in addition to the primary objective of meeting the clad temperature requirement for normal operation. They are listed below with brief explanations.

(1) Structural design. Configuration of the power systems must allow for supports for the GPHS blocks (to be added to the design later) to fail upon reentry, allowing the GPHS blocks to reenter the atmosphere individually. This condition assures that temperature requirements are met for reentry and earth impact.

(2) Overall size of the power system enclosure. The power system enclosure for each configuration, consisting of the GPHS blocks, heat sink, structural supports, and multifoil insulation must be as small as possible to reduce the specific mass of the system.

(3) Symmetry. The GPHS modules must be arranged symmetrically without any large gaps to ensure uniformity of the heat flux into the heat sink. Uniformity of the heat flux into the Stirling engine heater head is critical to the successful operation of the free-piston Stirling engine.

Steps taken to ensure that these design considerations are followed are addressed in this report. The system configurations are described in Section 3.0. The GPHS modules and FPSE are described in Sections 4.0 and 5.0, respectively. Thermal modeling and analysis of the 250 W_e GPHS/FPSE power system are described in Sections 6.0 and 8.0, respectively. Thermal modeling of the 500 W_e GPHS/FPSE power system is described in Section 7.0 and results of the thermal analysis of the 500 W_e system are given in Section 9.0.

2.4 References

1. Brandewie, Dr. R., et al., "Lockheed Missiles And Space Company BSTS Power System Definition Study", Rockwell International Report #RI/RD86-188 Rev. 1, 1986.
2. Schock, A., "Design Evolution and Verification of the 'General Purpose Heat Source'," Proceedings of the 15th IECEC, Seattle, Washington, August, 1980.
3. Conversations with EG&G engineers at Mound Laboratories in Dayton, Ohio on February 6th, 1990.
4. Conversation with John A. Loffreda of General Electric Company's Astro Space Division on February 22, 1990.

3.0 GPHS/FPSE POWER SYSTEM CONFIGURATIONS

3.1 Introduction

For power levels of 250 W_e and 500 W_e, the basic configurations of the GPHS/FPSE systems used for thermal modeling and analysis are described in this section. The descriptions are very general. Detailed descriptions of each configuration and the bases for selecting these two configurations are included in Sections 6.0 and 7.0 where the thermal models for each system are described. Specific characteristics of the components, such as materials and thermal properties, are covered in the thermal analysis sections of this report.

3.2 The 250 W_e GPHS/FPSE Power System

3.2.1 Introduction

The general configuration for the proposed GPHS/FPSE 250 W_e power system is shown in Figures 3.1a and 3.1b. As indicated in the figures, the system contains a cylindrical heat sink (to simulate the FPSE heater head) surrounded by four GPHS modules, all encased in an insulated cylindrical outer structure. Since each GPHS block generates approximately 250 thermal watts, the total thermal power of the system is 1000 W_{th}.

An overall system efficiency of 25% has been assumed in order to produce 250 W_e. This

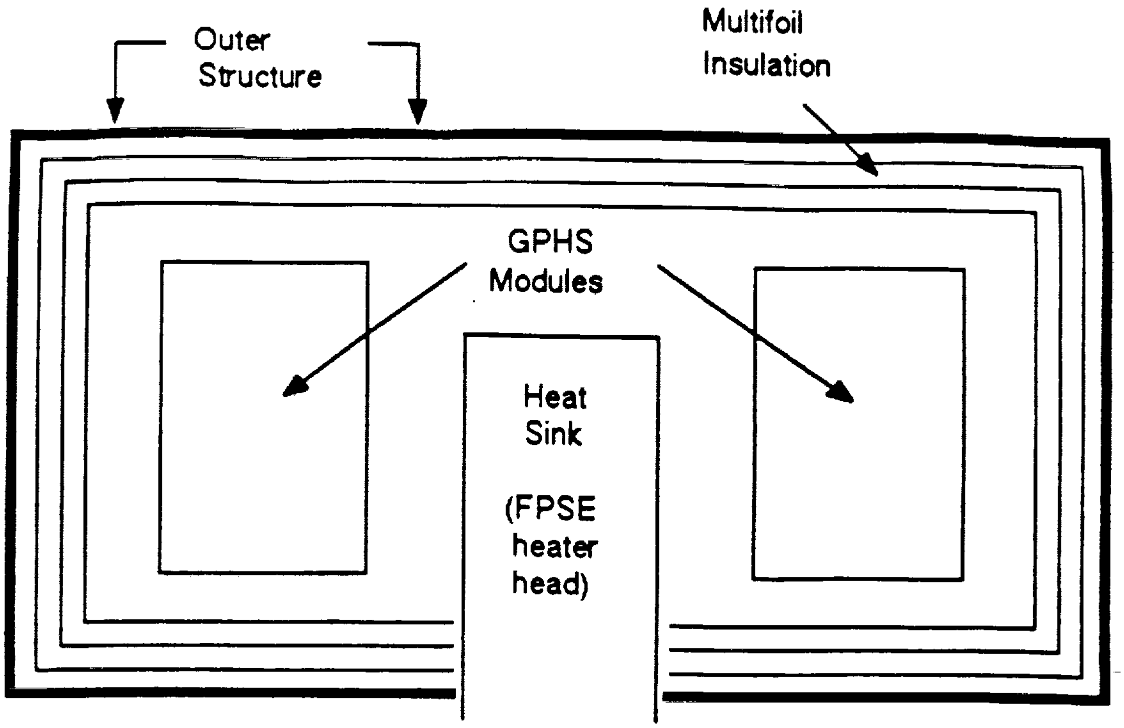


Figure 3.1a Side View of 250 W(e) GPHS/FPSE Power System

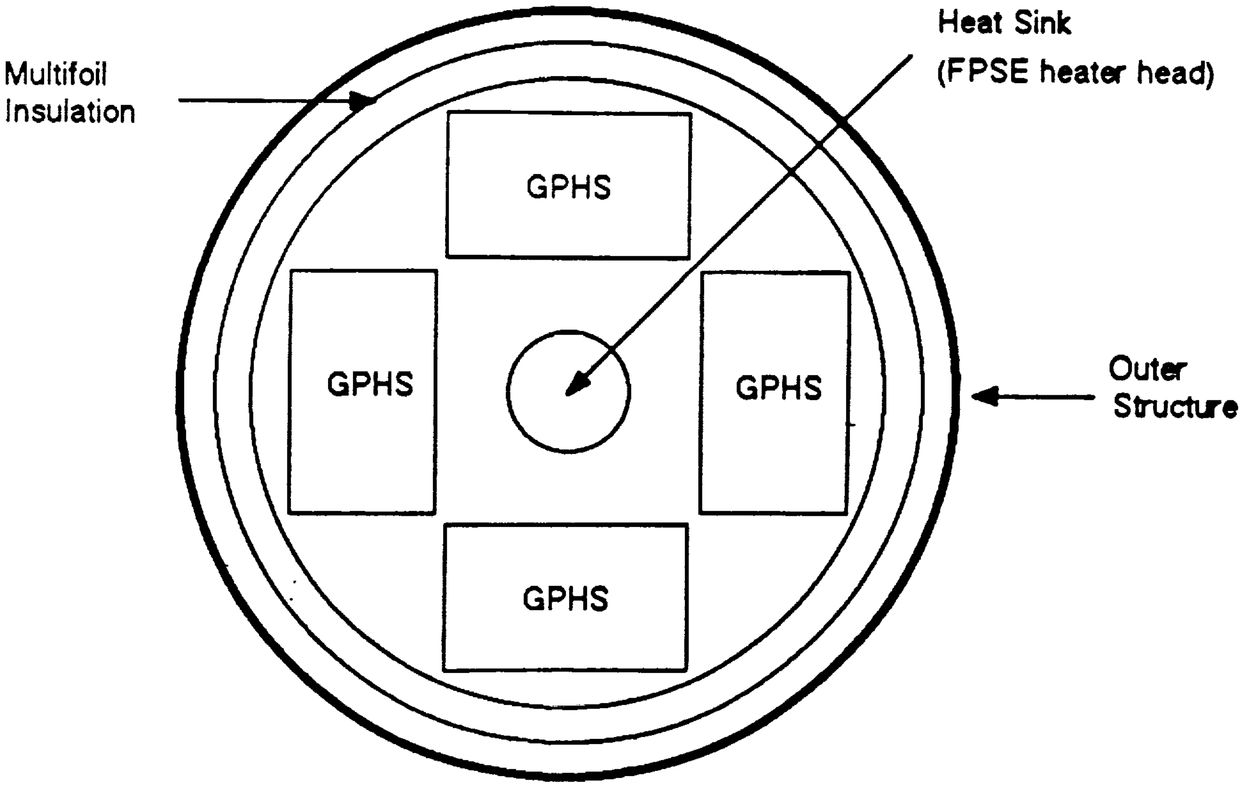


Figure 3.1b Top View of 250 W(e) GPHS/FPSE Power System

assumption is based upon discussions with engineers in NASA Lewis Research Center's (LeRC's) Power Systems Integration Office and Stirling Technology Branch. The 25% efficiency value is consistent with the design system efficiency for the 1.5 kW_e Solar Dynamic Space Experiment (SDSE).

The power level is comparable to that of the GPHS-RTG (General Purpose Heat Source - Radioisotope Thermoelectric Generator) which has a beginning-of-life output power of approximately 285 W_e. As design of the GPHS/FPSE system progresses, a comparison to the GPHS-RTG will be made based upon specific mass.

The power system components and their positioning with relation to each other are described below.

3.2.2 Configuration Description

The heat sink is centrally located at one end of the power system enclosure. It is cylindrically shaped with a radius of 1.0 inch and a length of 3.0 inches. The heat sink has a constant surface temperature of 1050 K. At the end of the cylindrical heat sink is a flat disk-shaped end cap which is thermally insulated from the heat sink. The disk is not considered a part of the heat sink. The basis for the heat sink design is given in Section 6.0 as part of the detailed description of the thermal model.

The GPHS modules are positioned symmetrically around the heat sink. The modules have dimensions of 3.826 inches (width) X 3.668 inches (height) X 2.090 inches (depth). Their largest surfaces (3.826 inches X 3.668 inches) face toward the heat sink with the height parallel to the length of the heat sink. The shortest radial distance between the heat sink and the GPHS modules is 1 inch. The modules are assumed to be 0.5 inches from both the top and the bottom of the enclosure. Thus, the modules are suspended in this configuration, and do not physically contact any other surfaces. The half inch gap is provided to allow for structural support which will be added later in the system design. The shortest edges of the GPHS blocks (2.090 inches) extend away from the heat sink.

The cylindrical outer structure is internally lined with multifoil insulation and contains the heat sources and the heat sink. The inner surface of the power system enclosure (the inner-most foil of the insulation) is cylindrically shaped with a radius of 4.8 inches and a length of 4.668 inches. The thickness of the foil and the external dimensions of the system will be determined as design of the system continues.

3.3 The 500 W_e GPHS/FPSE Power System

3.3.1 Introduction

As shown in Figures 3.2a and 3.2b, the general configuration for the 500 W_e GPHS/FPSE power system is very similar to the configuration described in the previous subsection for the 250 W_e system. Due to the increase in power level, however, there are a couple of

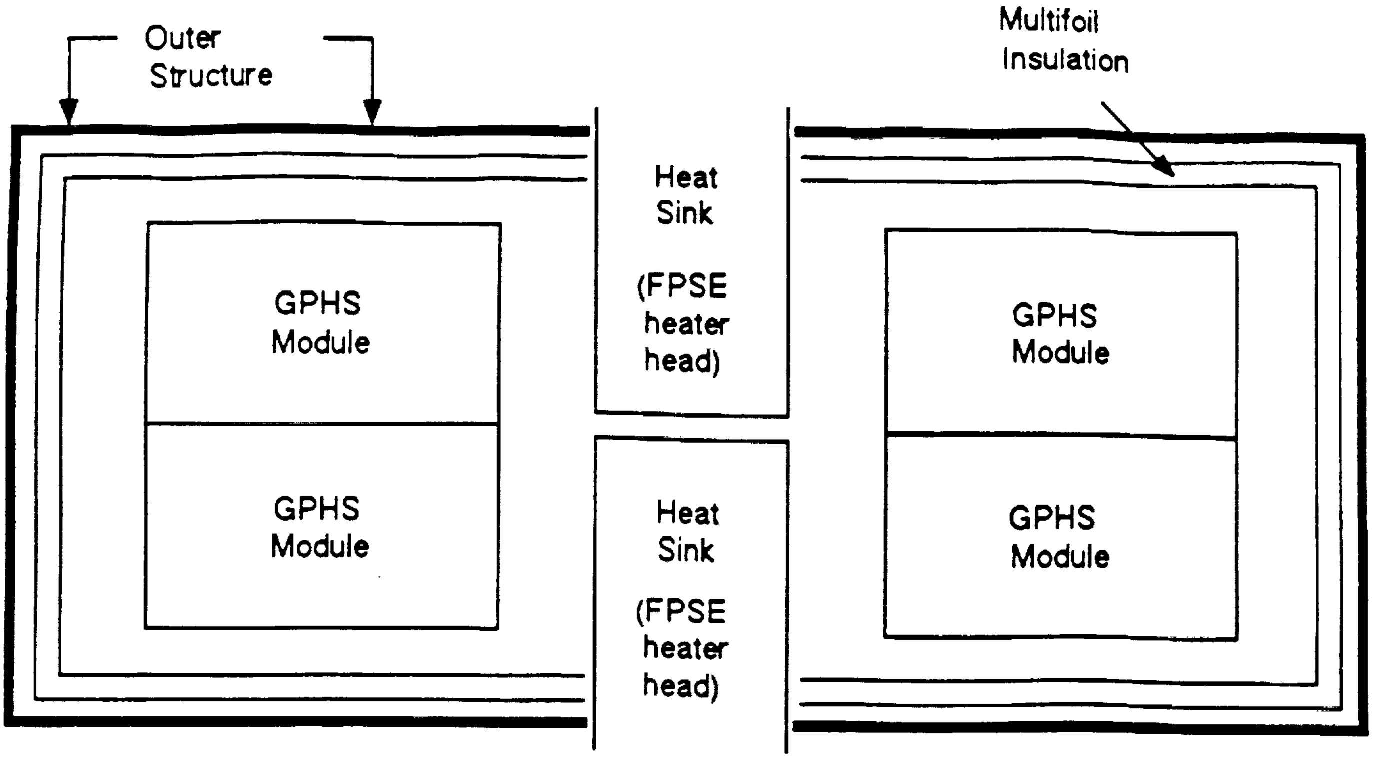


Figure 3.2a Side View of 500 W(e) GPHS/FPSE Power System

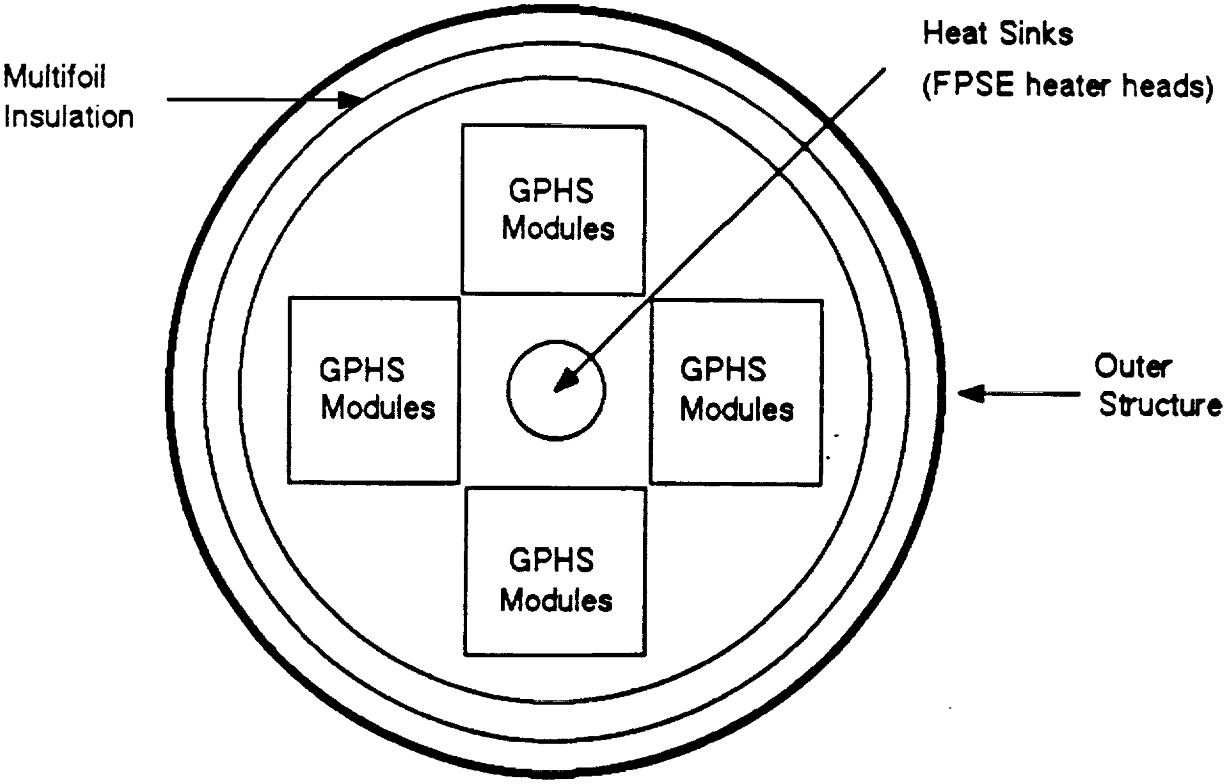


Figure 3.2b Top View of 500 W(e) GPHS/FPSE Power System

differences. Instead of having only one heat sink, this system utilizes dual, opposing heat sinks which represent two opposing FPSE heater heads. In addition, eight GPHS modules are required to supply 2000 watts of thermal energy. As with the 250 W_e system, an overall system efficiency of 25% has been assumed.

3.3.2 Configuration Description

The cylindrical heat sinks in the 500 W_e power system are similar but not identical to the one in the 250 W_e system. The radius of each sink is the same (1.0 inch) but in the 500 W_e configuration, the heat sinks have lengths of only 2.5 inches. This provides for the most compact configuration. Since the distance between the two ends of the enclosure is 5.18 inches, the ends of the heat sinks are separated by only 0.18 inches.

The heat sinks are centrally located at each end of the power system enclosure. The cylinder surfaces have a constant temperature of 1050 K. Like the heat sink in the 250 W_e system, a flat disk-shaped end cap is located at the end of each heat sink cylinder. The end caps are thermally insulated from the heat sinks. The basis for the heat sink design is given in Section 7.0 as part of the detailed description of the thermal model.

The eight GPHS modules are stacked symmetrically around the heat sinks in four sets of two (See Figures 3.2a and 3.2b). Each set of two can be viewed as a single block with dimensions of 3.826 inches (width) X 4.180 inches (height) X 3.668 inches (depth). The largest surfaces (3.826 inches X 4.180 inches) of each stack face the heat sinks with the height of each stack parallel to the lengths of the heat sinks. The shortest radial distance between the heat sink surface and the GPHS modules is 1.0 inch. A gap of 0.5 inches is left between the blocks and the ends of the enclosure to allow for support structures to be added later in the system design. The shortest edges of the stacks of GPHS modules (3.668 inches) extend away from the heat sink.

The cylindrical outer structure is internally lined with multifoil insulation and contains the heat sources and the heat sink. The inner surface of the power system enclosure (the inner-most foil of the insulation) is cylindrically shaped with a radius of 6.5 inches and a length of 5.18 inches. The actual thickness of the foil and the external dimensions of the system will be determined as design of the system continues.

3.4 References

1. Schreiber, J., et al., "SDSE Summary," NASA Lewis Research Center, Cleveland, Ohio, Summer, 1989.

4.0 GENERAL PURPOSE HEAT SOURCE

4.1 General Description

The General Purpose Heat Source (GPHS) module is a block-shaped hexahedron with overall dimensions of 9.317 cm X 9.718 cm X 5.308 cm (3.668 in. X 3.826 in. X 2.090 in.) and a mass of approximately 1.45 kg (3.2 lb). Each module contains four iridium clad fuel pellets, two graphite impact shells, two thermal insulation sleeves, and an outer aeroshell. Initially each block generates 250 ± 6 watts of thermal energy. Each GPHS module is completely autonomous including its own passive safety provisions. The internals of the blocks are illustrated in Figure 4.1. The major components are described in the following subsections.

4.2 Fuel Pellet

Each GPHS module contains four radioisotope fuel pellets (see Figure 4.1). The solid ceramic pellets are cylindrically shaped with an average diameter of 2.753 ± 0.025 cm (1.084 ± 0.010 inch) and an average length of 2.756 ± 0.038 cm (1.085 ± 0.015 inch). The fuel material is an isotopic mixture of plutonium in the form of the dioxide, PuO_2, containing 83.5 ± 1% $^{238}PuO_2$. Each pellet contains an initial thermal inventory of 62.5 ± 1.5 watts which corresponds to 1921 ± 46 Curies of ^{238}Pu and 152.4 ± 3.7 grams of PuO_2 per pellet. Heat transfer properties of the fuel are included in Appendix A.

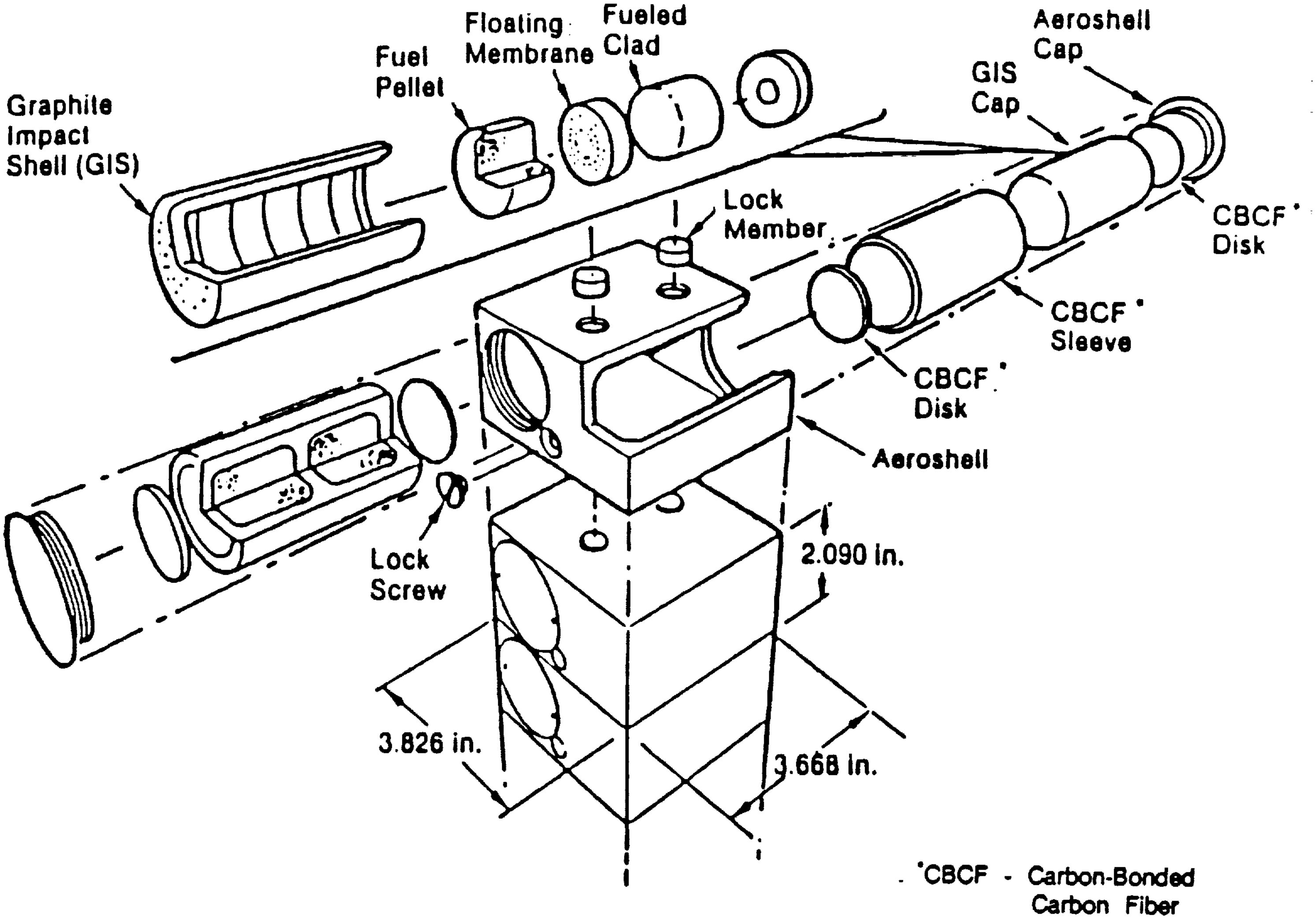


Figure 4.1 General Purpose Heat Source Module

4.3 Clad Material

From a nuclear safety perspective, the clad material is the most important feature of the GPHS module. The clad's primary function is to prevent the release of radioactive material under all anticipated operating and accident conditions. Such conditions include ground transportation and handling, launch operations, launch, ascent and orbital insertion, on-orbit operations, and reentry, impact, and post-impact environmental behavior. In order to perform its intended function, two primary technical objectives had to be satisfied: (1) the clad must be chemically compatible with the fuel material and the surrounding Graphite Impact Shell (GIS) in all anticipated environments; and (2) the clad must be resistant to long-term air oxidation at elevated temperatures after surviving reentry and earth impact.

The clad material chosen for use in the GPHS is the iridium alloy, DOP-26 Ir, developed by Oak Ridge National Laboratories. This alloy was already known to be compatible with PuO_2 and the GIS, and it had the best chance of meeting the second technical objective. Meeting the second objective was difficult due to temperature constraints imposed on the clad in order for it to retain adequate ductility to survive earth impact (See Section 2.2).

The clad surrounds the fuel pellet with a minimum thickness of 0.0559 cm (0.022 inches). At one end of the fueled clad is a vent hole with a diameter of 0.04445 cm (0.0175 inches) and a vent hole filter subassembly which allows the helium gas to escape but prevents the release of particles from inside the fuel pellet.

Heat transfer properties of DOP-26 Ir can be found in Appendix A.

4.4 Graphite Impact Shell (GIS)

As shown in Figure 4.1, there are two GIS's per GPHS module. Each GIS contains two iridium clad fuel pellets separated by a floating membrane. The GIS has a threaded end cap to secure its contents. The GIS, the floating membrane and the end cap are all constructed of fine weave pierced fabric (FWPF) graphite. FWPF is a composition of carbon-bonded carbon fibers which are layered to form a relatively dense, three dimensional structure. The cylindrical sides of the GIS have a density of 123.8 lb/ft^3 (1.98 g/cm^3). FWPF is extremely tough and has excellent thermal-shock resistance. The thermal conductivity and emissivity are anisotropic as indicated in Appendix A.

The GIS is designed to absorb energy and cushion the fuel capsule under earth impact conditions associated with GPHS module terminal velocity. The GIS also provides a protective shell against shrapnel which may penetrate the aeroshell and the CBCF sleeve.

4.5 CBCF Disk and Sleeve

Surrounding each GIS is a thermal insulating sleeve constructed of the carbon-bonded carbon fiber, CBCF-3. Developed by Oak Ridge National Laboratory, CBCF-3 has a density of only 14.4 lb/ft^3 (0.23 g/cm^3) and has a very low thermal conductivity normal to its deposition plane (see Appendix A). At each end of the GIS is an insulating disk made of the same material.

The primary function of the insulator is to prevent overheating of the fuel capsule during hypersonic reentry and overcooling during subsonic descent. It also provides protection against the heat from launch pad fires.

4.6 Aeroshell

Four cladded fuel pellets enclosed in two GIS's and surrounded by the thermal insulators are housed in the outer aeroshell as shown in Figure 4.1. Each of the two assemblies is held in place by an aeroshell cap and a lock screw. All aeroshell components are constructed of the same material as the GIS, FWPF graphite. Physical properties of the aeroshell FWPF graphite are included in Appendix A.

The aeroshell is the primary structural member of the GPHS module. Its primary function is to provide ablation protection during reentry, thus protecting the GIS's from the harsh environment encountered during reentry. It also serves as the outermost protective layer against shrapnel in the event of an explosion.

4.7 Nuclear Safety

Each heat source module contains its own passive safety provisions to immobilize the fuel under all credible accident conditions. The most severe accident would be atmospheric reentry followed by earth-impact. In order to guarantee containment of radioactive material after earth-impact, the design of the blocks requires the modules to reenter the atmosphere individually. Any power system design which incorporates the GPHS modules must allow for individual reentry.

Under all normal and accident conditions, there are two primary barriers to the release of radioactive material from the GPHS blocks. The first barrier is the ceramic fuel capsule itself. The ceramic material retains all solid decay products. The second barrier is the fuel clad with its vent hole filter subassembly which allows the escape of only the helium gas generated from the alpha decay. As discussed in earlier sections, the GPHS modules have been designed and tested to ensure that these two barriers prevent the release of radioactive material under all normal operating conditions and in all postulated accident and post-accident environments.

4.8 References

1. Schock, A., "Design Evolution and Verification of the 'General Purpose Heat Source'," Proceedings of the 15th IECEC, Seattle, Washington, August, 1980.
2. Angelo, Jr., Ph.D., J.A., Buden, D., Space Nuclear Power, Orbit Book Company, Inc., Malabar, Florida, 1985.
3. Final Safety Analysis Report For The Galileo Mission, Prepared for the U.S. Department of Energy by General Electric's Astro-Space Division Under Contract DE-AC01-79ET32043, May, 1988.
4. Glasstone, S., Sesonske, A., Nuclear Reactor Engineering, Third Edition, Van Nostrand Reinhold Company, New York, 1981.
5. Brandewie, Dr. R., et al., "Lockheed Missiles And Space Company BSTS Power System Definition Study," Rockwell International Report # RI/RD86-188 Rev. 1, 1986.

5.0 FREE PISTON STIRLING ENGINE

5.1 Introduction

For the purpose of the thermal analysis of the proposed GPHS/FPSE system, the Stirling engine is treated primarily as a heat sink which makes efficient use of the heat supplied from the decay of plutonium-238. When the system reaches the development phase, the cylindrically modeled heat sink may actually be a set of heat receptor fins, heat pipe(s) or the Stirling engine heater head itself. In any case, as development of this power system continues, the goal remains the conversion of the heat from radioactive decay to useful electrical output by a Free-Piston Stirling Engine (FPSE).

5.2 FPSE General Description

The FPSE is essentially a thermally driven mechanical oscillator which derives its power from the heat flow between a heat source and a heat sink. Using the Stirling cycle, the FPSE operates with the highest thermal efficiency of all known heat engines.

The three basic components of a FPSE are: (1) a relatively massive piston (the power piston), (2) a low mass piston (the displacer), and (3) a hermetically sealed cylinder. A typical configuration of a FPSE is shown in Figure 5.1.

The FPSE is chosen because the current technology status indicates that a light weight,

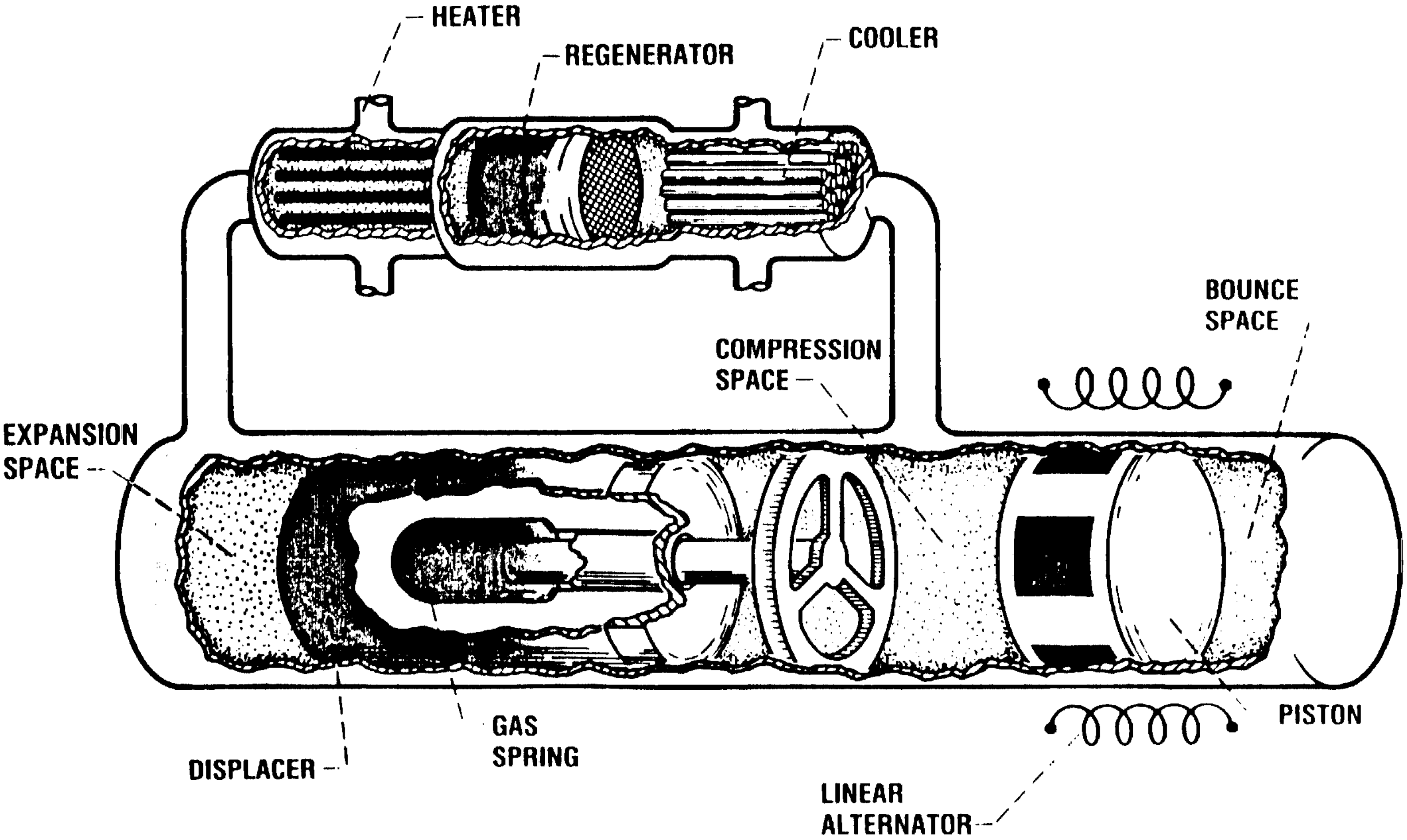


Figure 5.1 Free-Piston Stirling Engine With Linear Alternator

high efficiency, maintenance-free engine may be developed in the near future. The expected reliability of the FPSE is significantly higher than other dynamic conversion systems due to several unique features. Operating in a hermetically sealed cylinder, the FPSE has no mechanical linkages, no high pressure shaft seals and no contaminating lubricants; all of which tend to increase the probability of failure in a dynamic system.

5.3 References

1. Angelo, Jr., Ph.D., J.A., Buden, D., Space Nuclear Power, Orbit Book Company, Inc., Malabar, Florida, 1985.

6.0 THERMAL MODEL OF THE 250 W_e GPHS/FPSE POWER SYSTEM

6.1 Introduction

A general description of the 250 W_e GPHS/FPSE power system was given in Section 3.0. In this section, the detailed thermal model used for the thermal analysis is described. The bases for selecting the specific dimensions and physical properties for each of the nodes representing the power system components are given and the thermal connections between the nodes are also described. Figure 6.1 depicts the power system configuration including the components and their dimensions. Nodes of interest in the thermal analysis are identified in Figure 6.2.

The dimensions and physical properties associated with the nodes are given in Tables 6.1 and 6.2 for the heat sink cylinder nodes, Table 6.3 for the exterior GPHS module nodes, and Table 6.4 for the power system enclosure nodes. Nodes representing the fuel clad in the GPHS modules are described in Section 8.0 of this report. Additional information regarding the nodes representing the interior of the GPHS modules is given in Appendix B. Deep space, the external heat sink, is represented by a single boundary node (node # 99999) with a constant temperature of 0 K (-460 °F).

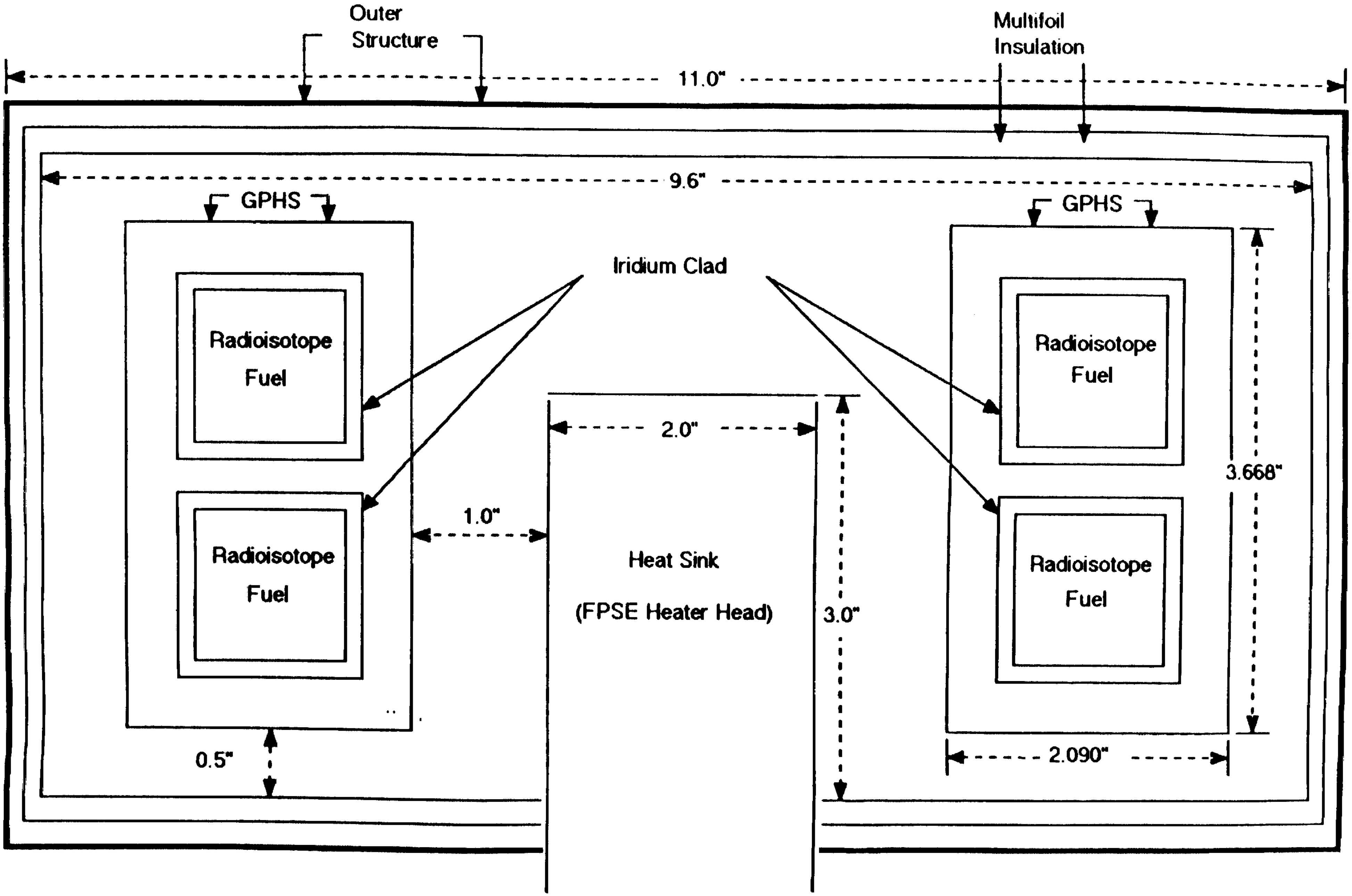


Figure 6.1 250 W(e) GPHS /FPSE Power System Configuration

6.2 Thermal Modeling of the Components

6.2.1 Heat Sink

6.2.1.1 Nodal Descriptions

The heat sink is situated at the center of one end of the power system. It is represented by a single cylindrical boundary node with a diameter of 2.0 inches, a length of 3.0 inches, a constant surface temperature of 1050 K, and an emissivity of 0.8.

At the end of the heat sink cylinder is a single arithmetic node (zero thermal capacitance) with a disk shape. This end cap has a diameter of 2.0 inches and an emissivity of 0.2. The end cap has not been assigned a thickness and it is thermally insulated from the heat sink. The heat sink cylinder and end cap nodal characteristics are summarized in Table 6.1.

Table 6.1 Heat Sink and End Cap Nodes

Node Number	Node Type	Node Shape	Dimensions (inches)	Emissivity
10100	Boundary	Cylinder	Radius: 1.0 Length: 3.0	0.8
10200	Arithmetic	Disk	Radius: 1.0	0.2

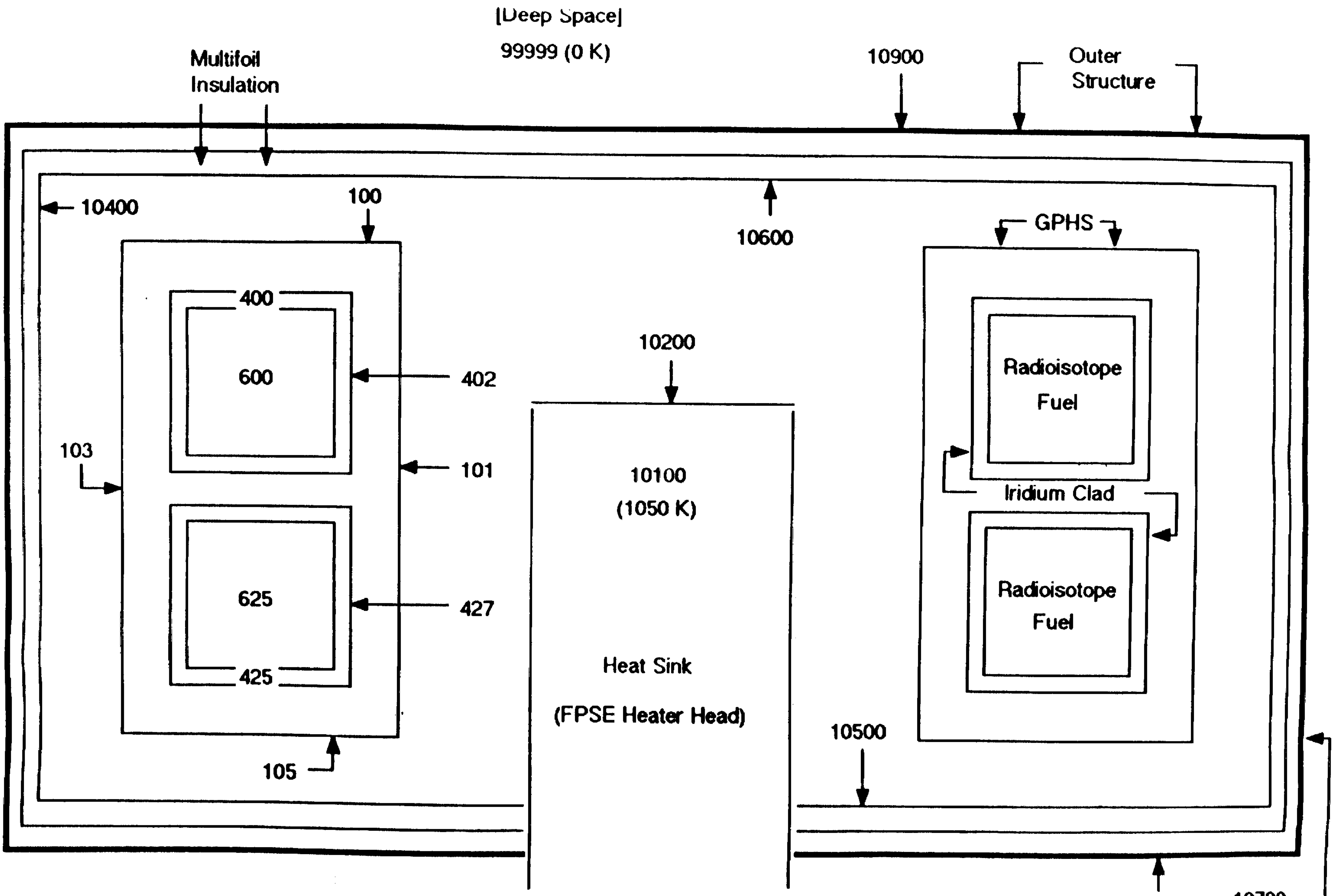


Figure 6.2 250 W(e) GPHS /FPSE Power System Nodal Arrangement

6.2.1.2 Basis for Heat Sink Parameters

The heat sink was initially to be modeled with heat entering through the sides and the end of the heat sink cylinder. The disk-shaped end cap was originally represented by a constant temperature boundary node. However, after discussion with Mr. Jeff Schreiber of NASA Lewis Research Center's (NASA LeRC's) Stirling Technology Branch, it was decided that this initial model would not be very accurate. He suggested that it would be more accurate to assume that heat enters only through the sides of the cylinder.

The basis for this assumption lies in the performance of the Stirling engine. If, in the final design of the GPHS/FPSE system, the heat sink is in fact a Stirling engine heater head, the performance of the engine would suffer considerably if heat were absorbed through the end of the heater head. The reasons for this drop in performance are beyond the scope of this project. Thus, in the thermal model, the flat disk representing the end of the heat sink is treated as an arithmetic node which is thermally insulated from the heat sink. The disk has not been assigned a thickness since no heat is conducted through it.

The heater head has been sized to have a heat flux consistent with the Solar Dynamic Space Experiment (SDSE) Stirling engine (reference 1). Determination of the SDSE heat flux value was not straightforward since the heater head heat flux is not one of the primary design parameters used when sizing the Stirling engine. In fact, an exact value of the heat flux into the heater head of the SDSE Stirling engine has never been determined. Due to the complex heater head design for the SDSE engine, the actual heat flux had to be estimated. NASA LeRC engineers estimated the effective heat flux into the engine to be approximately 70,000 W/m^2.

Using the dimensions given for the 250 W_e GPHS/FPSE power system and assuming that all of the heat generated by the GPHS modules (1000 W_{th}) is absorbed by the heat sink, the heat flux into the heat sink is calculated to be 82,230 W/m^2. According to NASA LeRC, this value is acceptable for this thermal model. Using a value slightly larger than the SDSE heat flux is, in fact, preferred. As design of the GPHS/FPSE system progresses, if it is found that the FPSE cannot accommodate this heat flux, the heat flux would be reduced by increasing the heat sink surface area. This increase would result in a lower surface temperature of the GPHS modules and, therefore, a lower fuel clad temperature. Thus, the correction of any error introduced by underestimating the heat sink size could only result in lower fuel clad temperatures, which is desirable.

The heat sink surface temperature value of 1050 K also has its basis in the SDSE engine design. Although the effective hot side temperature for the SDSE engine is approximately 1030 K (reference 1), the mean heater metal temperature for the SDSE engine is slightly higher, 1080 K. Because of the simplicity of the heat sink model for the GPHS/FPSE system relative to the SDSE heater head design, it was decided that a temperature of 1050 K be used for the heat sink surface temperature.

The emissivity value of 0.8 for the cylindrical heat sink was chosen after discussion with NASA LeRC engineers. It is based upon emissivity values for materials which would be used for a Stirling engine heater head. For the disk-shaped end cap, an emissivity of 0.2 was selected. This value was based on emissivities of polished metallic surfaces at temperatures expected for this surface.

The parameters of the heat sink and the disk end cap are summarized in Table 6.2.

Table 6.2 Heat Sink and End Cap Parameters

	Heat Sink	End Cap
Dimensions	Radius: 1.0 inch Length: 3.0 inches	Radius: 1.0 inch
Heat Flux	82,230 W/m^2	N/A
Temperature	1050 K	To be determined
Emissivity	0.8	0.2

6.2.1.3 Thermal Connections

The heat sink is thermally insulated from both the end of the enclosure through which it penetrates and the disk-shaped end cap. Therefore, the heat sink and the end cap exchange thermal energy with other nodes in the power system by radiative heat transfer only. The radiation conductor conductance values for the heat sink and end cap are generated by the TRASYS code and are included as part of the SINDA input deck in Appendix D.

6.2.2 GPHS Modules

6.2.2.1 Introduction

The GPHS modules were described in detail in Section 4.0. In this subsection a description is given of the nodes representing the exterior surfaces of the modules and the thermal connections of these nodes to the other surfaces within the power system. From this perspective, the GPHS modules can be viewed as blocked-shaped heat sources with generated heat radiating from all six external surfaces.

The thermal model representing the interior of the GPHS modules was produced specifically for this project by the Engineering Directorate of NASA Lewis Research Center (NASA LeRC). A description of the internal nodes of the GPHS thermal model and the SINDA input deck for the model can be found in Appendix B. The model contains 151 nodes with six nodes representing each fuel pellet and five nodes representing the clad of each fuel pellet. Nodes representing the iridium fuel clad are described in detail in Subsection 8.2.2 as part of the thermal analysis of the power system. The focus of the thermal analysis is on the steady-state temperature of the fuel clad nodes.

6.2.2.2 Nodal Descriptions

The GPHS modules are block-shaped with external dimensions of 3.668 in. X 3.826 in. X 2.090 in. The exterior of each GPHS module is represented in the thermal model by six rectangular arithmetic nodes corresponding to the six faces of each module. The modules are symmetrically positioned around the heat sink cylinder as described in Section 3.2. The nodes have an emissivity of 0.8. Measured radially from the center of the heat sink, the closest face of each block is one inch from the heat sink surface.

Table 6.3 summarizes the characteristics of the external nodes corresponding to one of the GPHS modules. These nodes exchange radiant energy with other surfaces within the power system enclosure. The node numbers corresponding to the other three GPHS modules are calculated by adding 2000, 4000, and 6000, respectively, to the nodes numbers given in Table 6.3. For example, nodes 101, 2101, 4101 and 6101 represent the largest face of each of the modules that faces the heat sink. Positioning of the surfaces within the enclosure is shown in Figure 6.2. Figure 8.2, included as part of the thermal analysis results, also depicts the positioning of the GPHS surface nodes relative to the heat sink cylinder.

6.2.2.3 Basis and Background for GPHS Thermal Model

For the 250 W_e GPHS/FPSE power system configuration, the GPHS thermal model (SINDA input deck in Appendix B) was duplicated four times and the nodes were renumbered to correspond to the four individual modules. The positions of the blocks relative to each other and to the other components of the power system are specified in the TRASYS input file (Appendix C).

Table 6.3 GPHS Module Surface Nodes

Node Number	Node Shape	Dimensions (inches)	Emissivity	Positioning
100	Rectangle	2.09 X 3.826	0.8	faces node 10600
101	Rectangle	3.668 X 3.826	0.8	faces heat sink
102	Rectangle	2.09 X 3.668	0.8	side facing GPHS module
103	Rectangle	3.668 X 3.826	0.8	faces node 10400
104	Rectangle	2.09 X 3.668	0.8	side facing GPHS module
105	Rectangle	2.09 X 3.826	0.8	faces node 10500

Due to the method used in TRASYS to generate the model of the GPHS blocks, the external surfaces of the blocks had to be assigned a constant emissivity. As indicated in Tables A.6 and A.7 of Appendix A, the emissivity of the aeroshell material is actually both temperature dependant and anisotropic. Since these properties were not incorporated into the TRASYS input, an appropriate average value for the emissivity had to be selected. The value was selected based upon the results from a NASA LeRC thermal analysis in which an individual GPHS module was analyzed in a vacuum environment, radiating to an external heat sink at a temperature of 1010° C (1850° F, 1283 K). In this environment, the GPHS surface temperatures were found to be approximately 1900° F (~1310 K). From Tables A.6 and A.7 of Appendix A, at 1900° F, an emissivity of 0.8 is a good approximation for a constant average emissivity value.

As stated in the introduction to this subsection, the thermal model representing the interior of the GPHS blocks was prepared as a precursor to this project. General Electric (GE) Company's Astro Space Division supplied values for the physical and thermal properties of the GPHS materials (Appendix A). GE has their own thermal model for the GPHS modules, but it was not available for use on this project. However, results from a thermal analysis using the GE model were available. These results were used to verify the accuracy of the model created at NASA LeRC.

As mentioned in Section 3.2, the GPHS modules are assumed to be suspended in the vacuum space in the power system enclosure. This assumption is conservative since any structure added to secure the blocks in place would provide a heat removal path superior to the exclusively radiative heat removal modeled in the analyzed configuration. Although this improved heat transfer path from the GPHS surfaces to the power system structure may degrade the overall system performance, its effect on the fuel clad temperature would be favorable. The fuel clad temperatures would be lower than indicated by the thermal analysis performed with the current thermal model.

6.2.2.4 Thermal Connections

In the thermal model, the external surfaces of the GPHS modules do not physically contact any other nodes in the power system enclosure. Thus, the exterior nodes of the modules are connected to each other and to the other surfaces in the power system enclosure with radiation conductors. The GPHS module radiation conductor conductance values are generated by the TRASYS code and are included as part of the SINDA input deck in Appendix D. The conductance values for the GPHS module interior nodes are included in both the GPHS Thermal Model (Appendix B) and the SINDA input deck (Appendix D).

6.2.3 Power System Enclosure

6.2.3.1 Nodal Descriptions

The power system enclosure is cylindrical with an internal radius of 4.8 inches, an internal length of 4.668 inches, an external radius of 5.5 inches, and an external length of 6.068 inches. The enclosure is represented by six arithmetic nodes; two of the nodes are cylindrical and four are disk-shaped nodes. Three of the nodes represent the inner surfaces of the enclosure and the other three represent the exterior of the power system which radiates directly to space. All nodes have been given emissivity values of 0.1. The enclosure has a thickness of 0.7 inches. The power system enclosure nodal characteristics are summarized in Table 6.4.

Table 6.4 Power System Enclosure Nodes

Node Number	Location	Node Shape	Dimensions (inches)	Emissivity
10400	Interior	Cylinder	Radius: 4.8 Length: 4.668	0.1
10600	Interior	Disk	Radius: 4.8	0.1
10500	Interior	Disk with hole	Inner Rad: 1.0 Outer Rad: 4.8	0.1
10700	Exterior	Cylinder	Radius: 5.5 Length: 6.068	0.1
10900	Exterior	Disk	Radius: 5.5	0.1
10800	Exterior	Disk with hole	Inner Rad: 1.0 Outer Rad: 5.5	0.1

6.2.3.2 Basis for Power System Enclosure Parameters

The power system enclosure was originally to be modeled with nodes and thermal conductor conductance values representative of specific physical and thermal properties of a selected multifoil insulation and an outer structural material. As work on this project continued, and a suitable insulation material had not been chosen, the decision was made jointly by the University of Florida and NASA LeRC to model the system with negligible heat loss through the enclosure, thus eliminating the need for selection of a specific insulation material. All of the thermal energy generated by the GPHS modules is assumed to enter the internal heat sink.

Using this assumption in the thermal analysis results in higher temperatures within the power system than if the model allowed for heat loss to space through the enclosure. The assumption is conservative since the project objective is to demonstrate fuel clad temperatures below a maximum temperature value. Any direct heat loss from the actual system will be detrimental only to the overall system performance and will not jeopardize the safe operation of the GPHS modules.

The interior dimensions of the power system enclosure have been chosen to ensure adequate space for GPHS module structural supports to be added later in the system design. At the same time, the overall system volume has been minimized to ensure the lowest possible specific mass (kg/kW$_e$) of the system.

The exterior dimensions of the power system were selected rather arbitrarily. An enclosure thickness of 0.7 inches was chosen only because this is the thickness of the multifoil insulation for the GPHS-RTG. The actual thickness of the enclosure does not impact the thermal analysis of the GPHS/FPSE system since there is negligible heat transfer from the interior to the exterior of the enclosure.

Since the system is modeled with no heat transfer through the power system enclosure, all thermal energy is retained within the enclosure and the emissivity values of the six enclosure nodes do not affect the results of the thermal analysis. The emissivity values are specified for computational purposes only.

An emissivity value of 0.1 was chosen for the interior and exterior surfaces of the enclosure to accommodate future thermal analyses in which a specific insulation material's properties and structural material's properties are included in the thermal model and analysis. The low emissivity value for the interior surfaces will ensure maximum reflection of thermal energy within the enclosure. A low emissivity value for the external nodes will ensure the minimum radiant heat loss from the exterior of the enclosure. Surface coatings can be used to achieve low emissivity values for all of the surfaces.

6.2.3.3 Thermal Connections

The interior nodes of the power system enclosure exchange thermal energy with each other and with other nodes within the enclosure by radiative heat transfer only. None of the other nodes within the enclosure are in direct physical contact with the enclosure's inner surface. As mentioned in Subsection 6.2.1.3, the heat sink is assumed to be thermally insulated from the enclosure. The radiation conductor conductance values for the thermal connections within the enclosure are generated by the TRASYS code and are included as part of the SINDA input deck in Appendix D.

As mentioned in the previous subsection, the thermal model does not allow for direct heat loss from the enclosure to space. The radiation conductors representing the heat flow paths from the inner enclosure surface nodes to the corresponding exterior nodes have been given thermal conductance values of 1 X 10^{-25} Btu/hr-ft·°F. Use of this value essentially eliminates any heat loss through the enclosure.

Since there is essentially no thermal conductance assumed in the enclosure itself, conduction conductors were not computed for heat transfer between the cylindrical nodes and the nodes representing the ends of the enclosure.

6.3 References

1. Schreiber, J., et al., "SDSE Summary," NASA Lewis Research Center, Cleveland, Ohio, Summer, 1989.
2. Conversations with Jeff Schreiber of NASA Lewis Research Center, February, 1990.

7.0 THERMAL MODEL OF THE 500 W_e GPHS/FPSE POWER SYSTEM

7.1 Introduction

As indicated in the description of the 500 W_e power system given in Section 3.3, besides the increase in overall size, there are only two primary differences between this system and the 250 W_e power system: 1) The 500 W_e power system has an additional cylindrical heat sink, and 2) it contains twice as many GPHS modules as the 250 W_e system. Because of the similarities between the thermal models of the two power systems, the following description of the 500 W_e power system thermal model details only the significant alterations made to the 250 W_e model to accommodate the higher power level.

Figure 7.1 depicts half of the power system configuration including the components and their dimensions. The nodes of interest in the thermal analysis are identified in Figure 7.2. The dimensions and physical properties associated with these nodes are given in Table 7.1 for the heat sink cylinder nodes, Table 7.3 for the exterior GPHS module nodes, and Table 7.4 for the power system enclosure nodes. Nodes representing the fuel clad in the GPHS modules are described as part of the thermal analysis in Section 9.0 of this report. Additional nodal descriptions representing the interior of the GPHS modules are given in Appendix B.

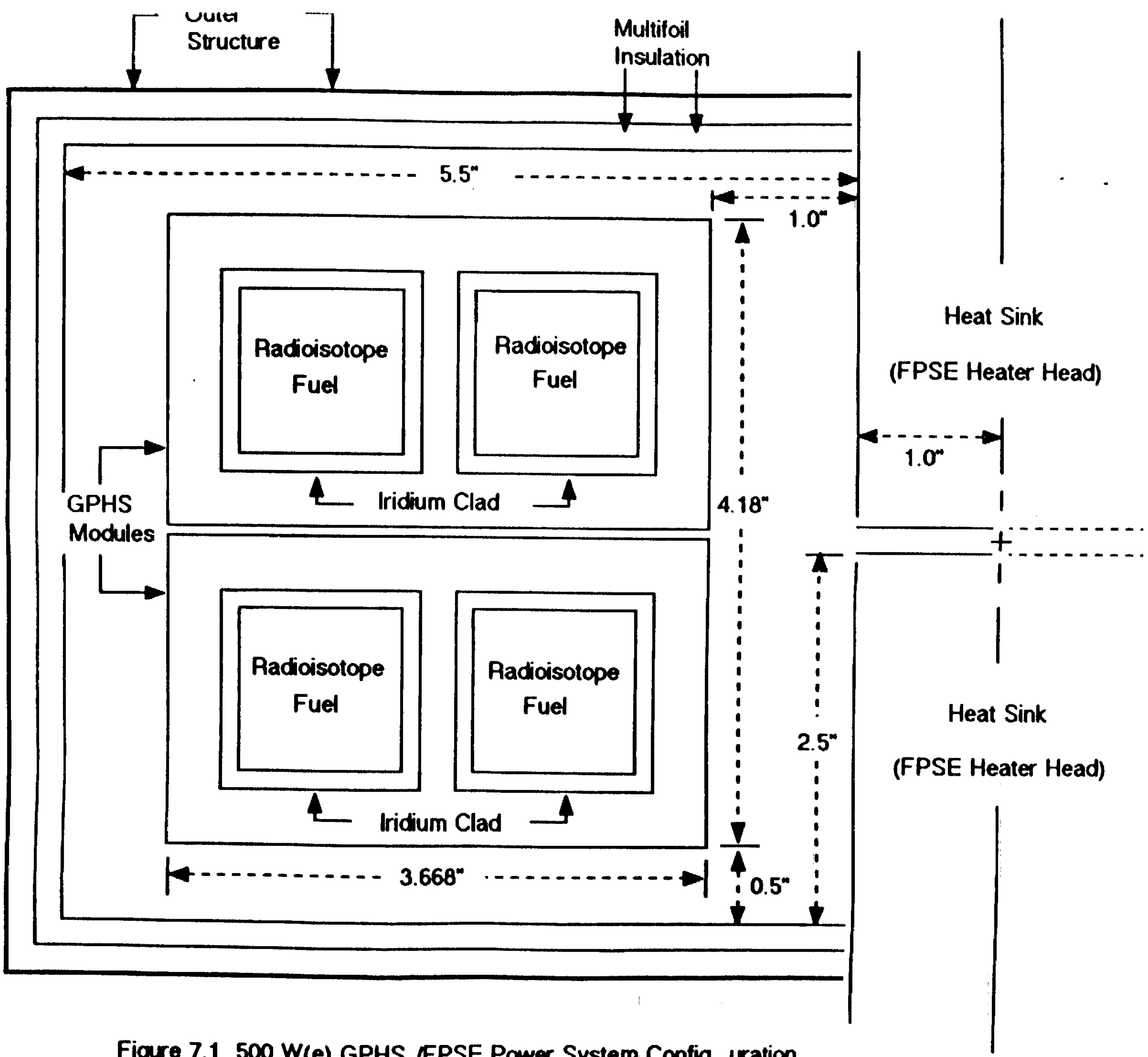


Figure 7.1 500 W(e) GPHS /FPSE Power System Configuration

7.2 Thermal Modeling of the Components

7.2.1 Heat Sinks

7.2.1.1 Nodal Descriptions

The heat sinks are situated at the center of both ends of the power system. They are each represented by single cylindrical boundary nodes with diameters of 2.0 inches, lengths of 2.5 inches, constant surface temperatures of 1050 K, and emissivities of 0.8.

At the end of each heat sink cylinder is a single arithmetic node (zero thermal capacitance) with a disk shape. The end caps have diameters of 2.0 inches and emissivities of 0.2. As in the 250 W_e system thermal model, the end caps have not been assigned thicknesses and they are thermally insulated from the heat sinks. The nodal characteristics of the heat sink cylinders and the end caps are summarized in Table 7.1.

Table 7.1 Heat Sink and End Cap Nodes

Node Numbers	Node Type	Node Shape	Dimensions (inches)	Emissivity
10100 11100	Boundary	Cylinder	Radius: 1.0 Length: 2.5	0.8
10200 11200	Arithmetic	Disk	Radius: 1.0	0.2

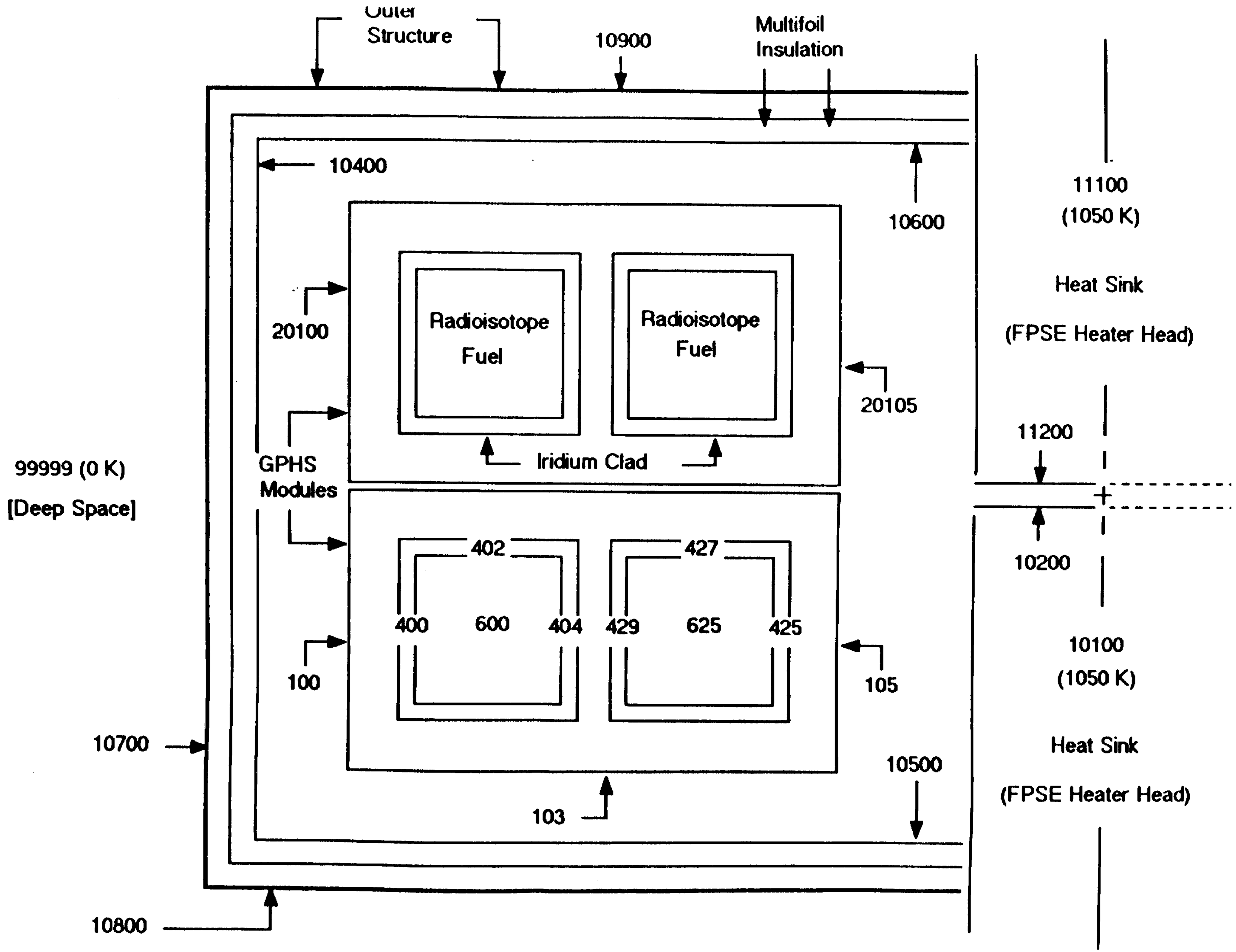


Figure 7.2 500 W(e) GPHS /FPSE Power System Nodal Arrangement

7.2.1.2 Basis For Heat Sink Parameters

The bases for selecting the heat sink parameters for the 500 W_e power system are identical to those used for the 250 W_e power system (See Subsection 6.2.1.2). However, in an effort to minimize the overall enclosure size, the lengths of the heat sink cylinders were reduced from 3.0 inches (250 W_e model) to 2.5 inches for the 500 W_e thermal model. This decrease in heat sink surface area results in an increase in the heater head heat flux from 82,230 W/m^2 to 98,676 W/m^2. The increased heat flux was reviewed and approved by NASA LeRC engineers for use in this thermal analysis. Parameters for the heat sinks and the disk end caps are summarized in Table 7.2.

Table 7.2 Heat Sink and End Cap Parameters

	Heat Sinks	End Caps
Dimensions	Radius: 1.0 inch Length: 2.5 inches	Radius: 1.0 inch
Heat Flux	98,676 W/m^2	N/A
Temperature	1050 K	To be determined
Emissivity	0.8	0.2

For the purpose of this thermal analysis, the increased heat flux (smaller heat sink) is a step in the more conservative direction. If thermal analysis of the present thermal model yields fuel clad temperatures which are too high, the model can be revised to increase the overall heat sink size. Thermal analysis using the larger heat sink surface area (lower heater head heat flux) would result in lower fuel clad temperatures.

7.2.1.3 Thermal Connections

As in the 250 W_e thermal model, the heat sinks are thermally insulated from the ends of the enclosure through which they penetrate and from the disk-shaped end caps. Therefore, the heat sinks and the end caps exchange thermal energy with other nodes in the power system by radiative heat transfer only. The heat sink and end cap radiation conductor conductance values are generated by the TRASYS code and are included as part of the SINDA input deck.

7.2.2 GPHS Modules

7.2.2.1 Nodal Descriptions

As in the 250 W_e power system thermal model, the exterior of each GPHS module is represented in the thermal model by six arithmetic nodes corresponding to the six faces of each module. All of the GPHS surface nodes have emissivities of 0.8. Measured radially from the center of the heat sink, the closest face of each set is one inch from the heat sink surface.

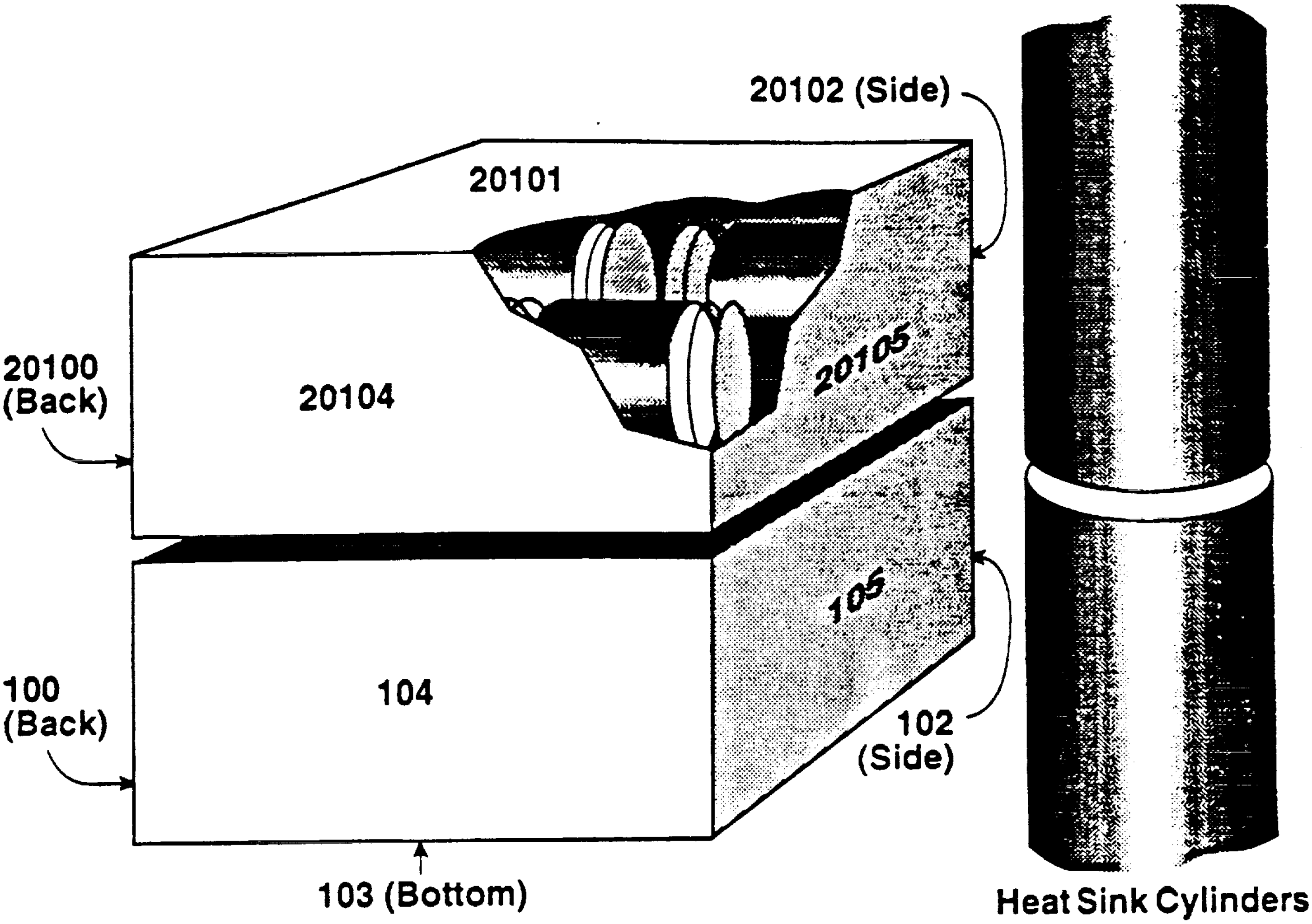
As described in Section 3.3, the eight GPHS modules are stacked symmetrically around the heat sinks in four sets of two. The thermal model representing each set consists of two complete models of a GPHS module. The external nodes of the GPHS modules in one set are shown in Figure 7.3. The characteristics of the external nodes are summarized in Table 7.3. The node numbers corresponding to the three other sets of GPHS modules are calculated by adding 2000, 4000, and 6000, respectively, to the nodes numbers given in Table 7.3.

The interior of each GPHS module is represented in the thermal model by the same model that was used for the GPHS modules in the 250 W_e system thermal model (See Subsection 6.2.2 and Appendix B).

7.2.2.2 Basis and Background for GPHS Thermal Model

For the configuration of the 500 W_e GPHS/FPSE power system, the GPHS thermal model (Appendix B) was duplicated eight times and the nodes were renumbered to correspond to the eight individual modules. The positions of the blocks relative to each other and to the other components of the power system are specified in the TRASYS input file.

The bases used for selecting the physical parameters of the GPHS modules and their positioning within the power system are the same as those used for the 250 W_e power system thermal model (See Subsection 6.2.2.2).



Not shown:
101 - top face of bottom module
20103 - bottom face of top module

Figure 7.3 GPHS Exterior Nodal Configuration for the 500 W_e Power System

Table 7.3 GPHS Module Surface Nodes

Node Number	Node Shape	Dimensions (inches)	Emissivity	Positioning
100	Rectangle	2.09 X 3.826	0.8	Faces node 10400
101	Rectangle	3.668 X 3.826	0.8	In contact with node 20103
102	Rectangle	2.09 X 3.668	0.8	Side facing GPHS module
103	Rectangle	3.668 X 3.826	0.8	Faces node 10500
104	Rectangle	2.09 X 3.668	0.8	Side facing GPHS module
105	Rectangle	2.09 X 3.826	0.8	Faces heat sink
20100	Rectangle	2.09 X 3.826	0.8	Faces node 10400
20101	Rectangle	3.668 X 3.826	0.8	Faces node 10600
20102	Rectangle	2.09 X 3.668	0.8	Side facing GPHS module
20103	Rectangle	3.668 X 3.826	0.8	In contact with node 101
20104	Rectangle	2.09 X 3.668	0.8	Side facing GPHS module
20105	Rectangle	2.09 X 3.826	0.8	Faces heat sink

7.2.2.3 Thermal Connections

In the 500 W_e system thermal model, the external surfaces of each set of GPHS modules do not physically contact any other nodes in the power system enclosure. However, since there are two modules per set, there are two GPHS surface nodes in each set that are in contact with each other. In the thermal model, these surfaces are connected by radiation conductors. In order to connect the surfaces radiatively, the thermal model had to include a small gap between the surfaces. The gap is only 0.006 inches; therefore, the surfaces exchange thermal energy only with each other.

As in the 250 W_e system thermal model, all other exterior nodes of the GPHS modules are connected to each other and to the other surfaces in the power system enclosure with radiation conductors. The radiation conductor conductance values connecting the GPHS module exterior surface nodes to the other surface nodes in the power system are generated by the TRASYS code and are included as part of the SINDA input deck.

7.2.3 Power System Enclosure

7.2.3.1 Nodal Descriptions

Similar to the 250 W_e system thermal model, the 500 W_e power system enclosure is represented by six arithmetic nodes. Two of the nodes are cylindrical and four are disk-shaped nodes. Three of the nodes represent the inner surfaces of the enclosure and the other three represent the exterior of the power system which radiates directly to space. All nodes have been assigned emissivity values of 0.1. The enclosure has a thickness of 0.7 inches.

There are only two differences between the power system enclosure nodes in the 500 W_e system thermal model and the 250 W_e system thermal model. The most significant difference is that instead of having a smooth disk-shaped node at one end of the enclosure as in the 250 W_e system model, both ends of the 500 W_e system enclosure have disk-shaped nodes with holes in the center to accommodate the additional heat sink. The other difference is, of course, the size of the nodes, which are larger due to the increased enclosure volume required to house the eight GPHS modules. The power system enclosure nodal characteristics are summarized in Table 7.2.

It is interesting to note that, even with the reduced heat sink size for the 500 W_e power system, the internal volume of the enclosure is still more than double the volume of the 250 W_e system; 687.6 in^3 for the 500 W_e system and 337.9 in^3 for the 250 W_e system.

7.2.3.2 Basis for Power System Enclosure Parameters

The bases for selecting the nodal representation of the power system enclosure are identical to those used for the 250 W_e system thermal model. And, as in the 250 W_e system model, the 500 W_e power system is modeled with no heat loss through the enclosure to space.

Table 7.4 Power System Enclosure Nodes

Node Number	Location	Node Shape	Dimensions (inches)	Emissivity
10400	Interior	Cylinder	Radius: 6.5 Length: 5.18	0.1
10600	Interior	Disk with hole	Inner Rad: 1.0 Outer Rad: 6.5	0.1
10500	Interior	Disk with hole	Inner Rad: 1.0 Outer Rad: 6.5	0.1
10700	Exterior	Cylinder	Radius: 7.2 Length: 6.58	0.1
10900	Exterior	Disk with hole	Inner Rad: 1.0 Outer Rad: 7.2	0.1
10800	Exterior	Disk with hole	Inner Rad: 1.0 Outer Rad: 7.2	0.1

7.2.3.3 Thermal Connections

As in the 250 W_e system thermal model, the interior nodes of the power system enclosure exchange thermal energy with each other and with other nodes within the enclosure by radiative heat transfer only. None of the other nodes within the enclosure are in direct physical contact with the enclosure's inner surface. The radiation conductor conductance values for the thermal connections within the enclosure are generated by the TRASYS code and are included as part of the SINDA input deck.

As mentioned in the previous subsection, the thermal model does not allow for direct heat loss from the enclosure to space. The radiation conductor conductance values representing the heat flow paths from the inner surface nodes to the corresponding exterior nodes are the same as those used in the 250 W_e system thermal model, 1 X 10^{-25} Btu/hr·ft··F. Use of this value essentially eliminates any heat loss through the enclosure.

As in the 250 W_e system thermal model, since there is essentially no thermal conductance assumed in the enclosure itself, conduction conductors were not computed for heat transfer between the cylindrical nodes and the nodes representing the ends of the enclosure.

8.0 THERMAL ANALYSIS OF THE 250 W_e GPHS/FPSE POWER SYSTEM

8.1 Description of Analysis

8.1.1 Introduction

The thermal analysis of the 250 W_e GPHS/FPSE power system is performed using the thermal model described in Section 6.0. The code, TRASYS, is used to generate conductance values for the radiation conductors which connect the surface nodes within the power system enclosure. The code, SINDA, is used to generate the steady-state temperature distribution throughout the entire thermal system.

8.1.2 TRASYS Analysis

The surface nodes are defined in the TRASYS input file (Appendix C). Dimensions are specified for the heat sink and end cap nodes, the exterior nodes of the GPHS modules and the nodes representing the inner surfaces of the power system enclosure. The positions of the components with relation to one another are also specified. The interior of the power system enclosure contains 29 surface nodes (24 faces of the GPHS modules, 3 power system enclosure surfaces, the heat sink cylinder and the heat sink end cap). Emissivity values for each node are specified.

Application of the TRASYS code to the 250 W_e GPHS/FPSE power system thermal model yields 406 radiation conductors connecting the surface nodes within the power system enclosure. The conductors are numbered 1 through 406 and are included as part of the SINDA input deck in Appendix D. For each radiation conductor number, the nodes which are connected are identified and the conductance value for the conductor is generated.

8.1.3 SINDA Analysis

The SINDA code is a thermal analyzer that utilizes resistor-capacitor (R-C) network representations of thermal systems. SINDA is used to generate the steady-state temperature within the GPHS modules and throughout the power system enclosure.

The bulk of the SINDA input deck is dedicated to defining the nodes and conductors in the thermal model. The radiation conductors and the corresponding conductance values which are generated by the TRASYS code are inserted directly into the conductor segment of the SINDA input deck. The remainder of the input deck is used to define the heat generation rates in the fuel pellet nodes and to specify the SINDA subroutines to be executed.

Three SINDA subroutines are used for the thermal analysis; STDSTL, TPRINT, and QIPRNT. STDSTL is a thermal network solution subroutine which calculates the finite difference steady-state solution. TPRINT is a printout subroutine which produces a printout of all the nodal temperatures in the steady-state solution. QIPRNT is also a printout subroutine; it produces a printout of the heat generation rate for each node in the thermal system. QIPRNT is used to verify the heat generation rates for the fuel pellet nodes and to verify that all other nodes have a heat generation rate of zero.

8.1.4 Initial Temperatures

All nodes in the thermal model of the 250 W_e GPHS/FPSE power system are given an initial temperature as a starting point for the iterative process used for the thermal analysis by the SINDA code. The boundary node temperatures and the initial temperatures for the arithmetic nodes are listed in Table 8.1.

Table 8.1 Initial Nodal Temperatures for Thermal Analysis of the 250 W_e GPHS/FPSE Power System

Node Numbers	Node Description	Node Type	Initial Temperature
10100	Heat Sink	Boundary	1430° F
99999	Deep Space	Boundary	-460° F
10200	Heat Sink End Cap	Arithmetic	1500° F
10400 10500 10600	Inner Surfaces of Power System Enclosure	Arithmetic	1500° F
10700 10800 10900	Outer Surfaces of Power System Enclosure	Arithmetic	200° F
	ALL Other Nodes	Arithmetic	2000° F

8.2 Results And Interpretations of Thermal Analysis

8.2.1 Introduction

The SINDA output file contains the steady-state temperature for each of the 609 nodes in the thermal model. For the purpose of this analysis, only the temperatures of selected nodes throughout the power system are presented.

8.2.2 Fuel Clad Temperatures

Examination of the fuel clad nodal temperatures is most important since the primary design objective is to demonstrate temperatures of the fuel clad below the design goal temperature limit of 1573 K under normal operating conditions. With 5 nodes representing the fuel clad of each fuel pellet, there are 80 fuel clad nodes in the thermal system.

Evaluation of the thermal analysis results is simplified considerably due to the symmetry of the system. From the top view of the power system shown in Figure 8.1, it can be seen that, since the thermal model representing each GPHS model is identical, analogous nodes in each of the modules should have similar temperatures when the system is in thermal equilibrium. In addition, analogous nodes on either side of each module should have similar temperatures. Accuracy of the analysis is verified by examining temperatures of the analogous nodes within the GPHS modules.

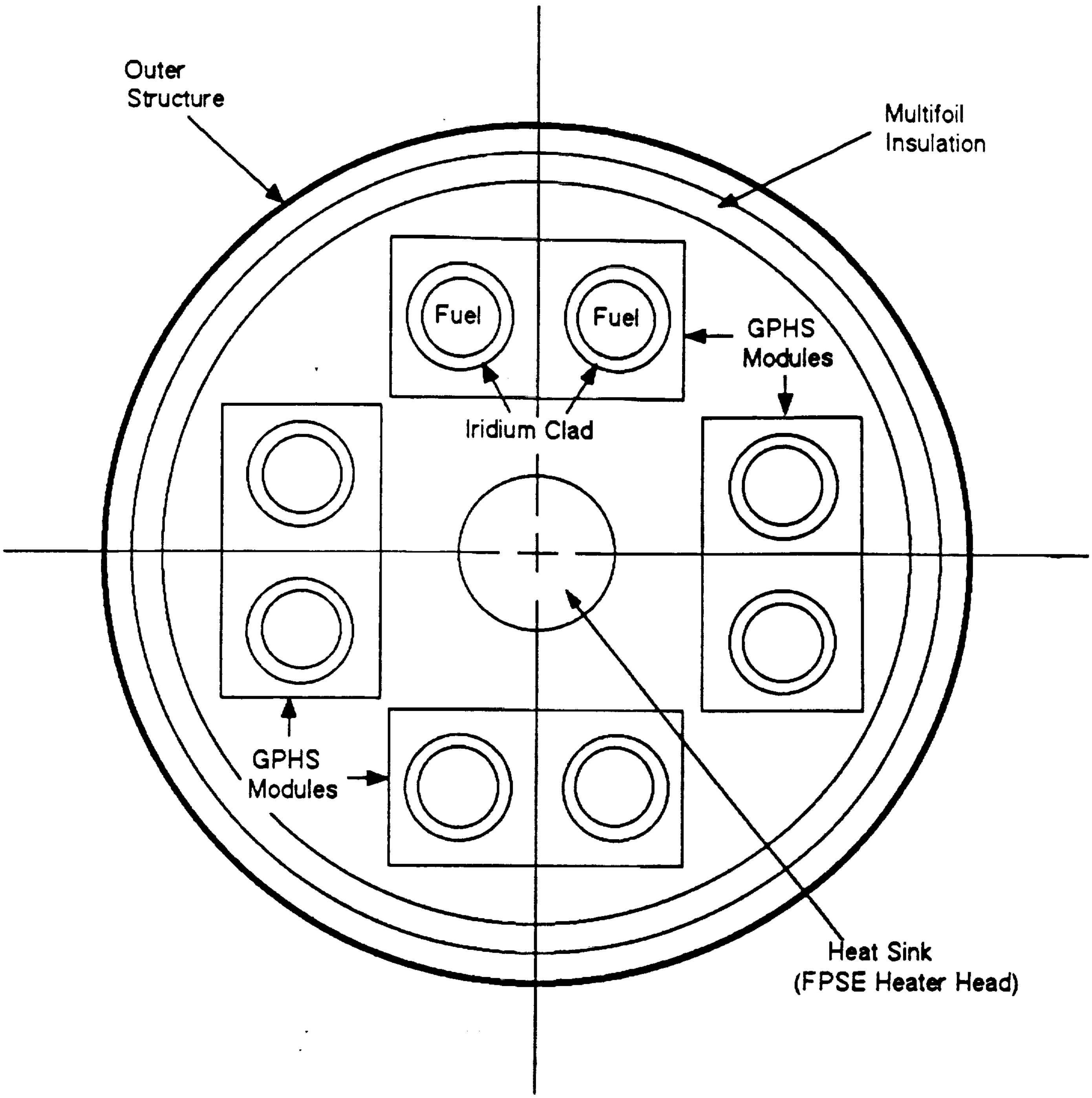


Figure 8.1 Symmetry of 250 W(e) Power System Fro m Top View

Before examining the temperatures of the analogous nodes, it is necessary to present a brief description of the nodes representing the fuel clad of each pellet. The nodes numbered 400 to 429 and 1400 to 1429 are identified in Figure 8.2. Analogous nodes in each of the other four modules are calculated by adding 2000, 4000, and 6000, respectively, to the node numbers shown in Figure 8.2. For example, nodes 427, 2427, 4427, and 6427 represent the cylindrical portion of the fuel clad for a fuel pellet in the identical quadrant of a GPHS module. Physical descriptions for the fuel clad nodes shown in Figure 8.2 are given in Table 8.2. The positioning of the GPHS modules within the power system was shown in Figure 6.2.

Table 8.2 Description of Fuel Clad Nodes

Node Numbers	Description of Nodes
400, 425, 404, 429 1400, 1425, 1404, 1429	Disk-shaped nodes which represent the ends of the fuel clad cylinders.
401, 403 426, 428 1401, 1403, 1426, 1428	Ring-shaped nodes which connect the disk-shaped end nodes to the cylindrical nodes.
402, 427, 1402, 1427	Cylindrical nodes which represent the cylindrical portions of the fuel clad.

A comparison of analogous nodal temperatures is contained in Tables 8.3 and 8.4; Table

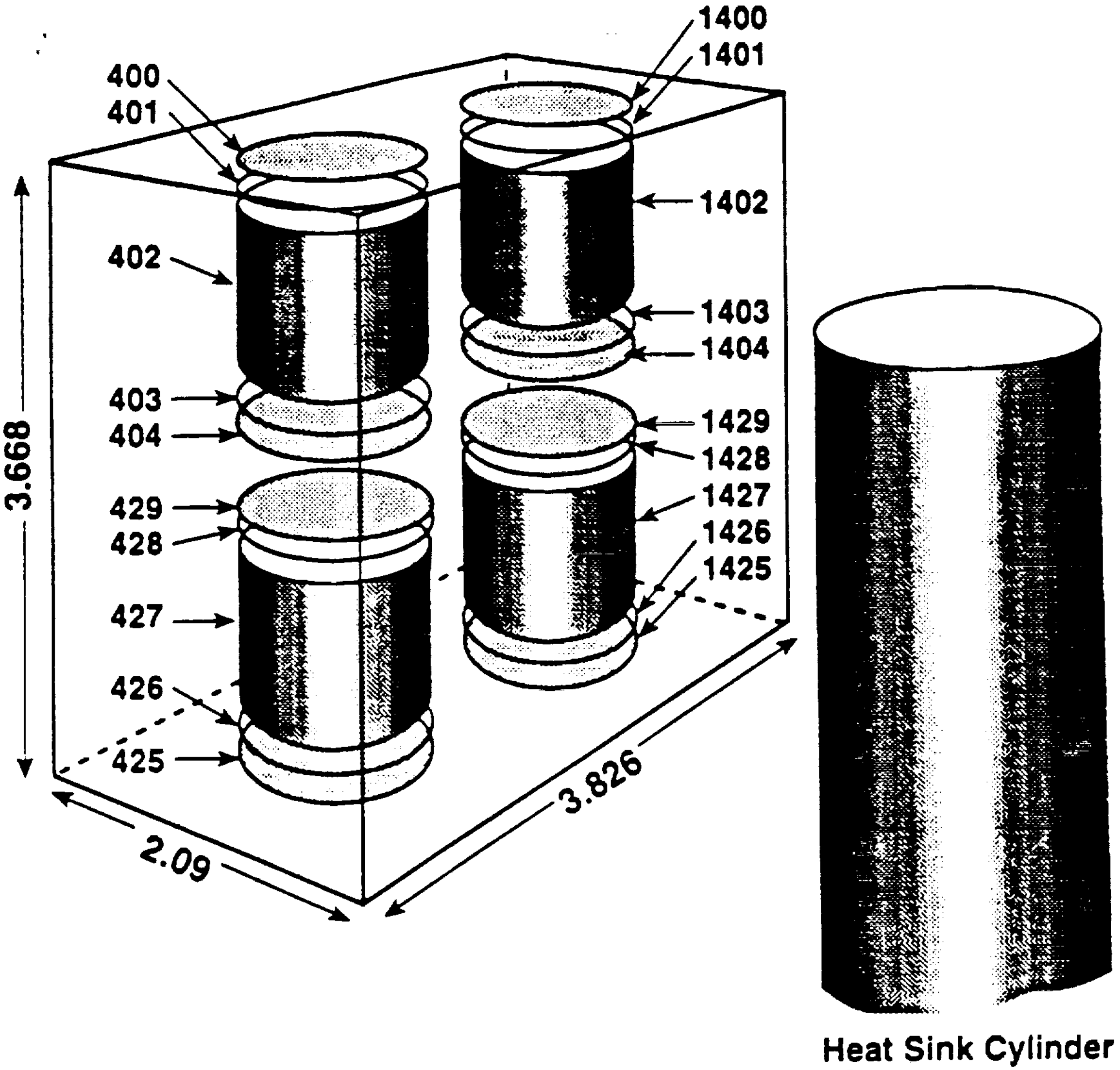


Figure 8.2 Iridium Fuel Clad Nodal Arrangement

8.3 compares the steady-state temperatures for a selection of analogous fuel clad nodes in each of the four GPHS modules and Table 8.4 compares the temperatures for analogous nodes within one GPHS module.

Table 8.3 Comparison of Temperatures For Analogous Fuel Clad Nodes in Different GPHS Modules

Node Number	GPHS Block	Temperature °F (K)
400	1	2406 (1592)
2400	2	2405 (1592)
4400	3	2405 (1592)
6400	4	2406 (1592)
404	1	2454 (1618)
2404	2	2453 (1618)
4404	3	2453 (1618)
6404	4	2454 (1618)
427	1	2456 (1620)
2427	2	2456 (1620)
4427	3	2456 (1620)
6427	4	2456 (1620)

As indicated in Tables 8.3 and 8.4, the thermal analysis has demonstrated nearly identical temperatures for the analogous fuel clad nodes in each of the GPHS modules and on either side of each module. Therefore, the number of nodal temperatures examined can be reduced to the ten nodes representing the fuel clad of two of the fuel pellets in one GPHS module.

Table 8.4 Comparison of Temperatures for Analogous Fuel Clad Nodes in One GPHS Module

Node Number	Temperature •F (K)
401	2447 (1615)
1401	2447 (1615)
403	2456 (1620)
1403	2456 (1620)
425	2404 (1591)
1425	2404 (1591)
429	2453 (1618)
1429	2453 (1618)

The fuel clad nodal temperatures determined by the thermal analysis for the ten nodes representing the fuel clad of two of the fuel pellets in one GPHS module are listed in Table 8.5 and shown in Figure 8.3.

As indicated in the Figure 8.3 and Table 8.5, the temperatures of the fuel clad nodes are slightly higher than the design goal temperature limit of 1573 K. After discussion with NASA LeRC engineers, it was decided that the temperatures shown by the thermal analysis are sufficiently close to the design temperature limit to warrant further investigation of the power system. This decision was based on the close proximity of the fuel clad temperatures to the temperature limit, the ambiguous nature of the limit itself,

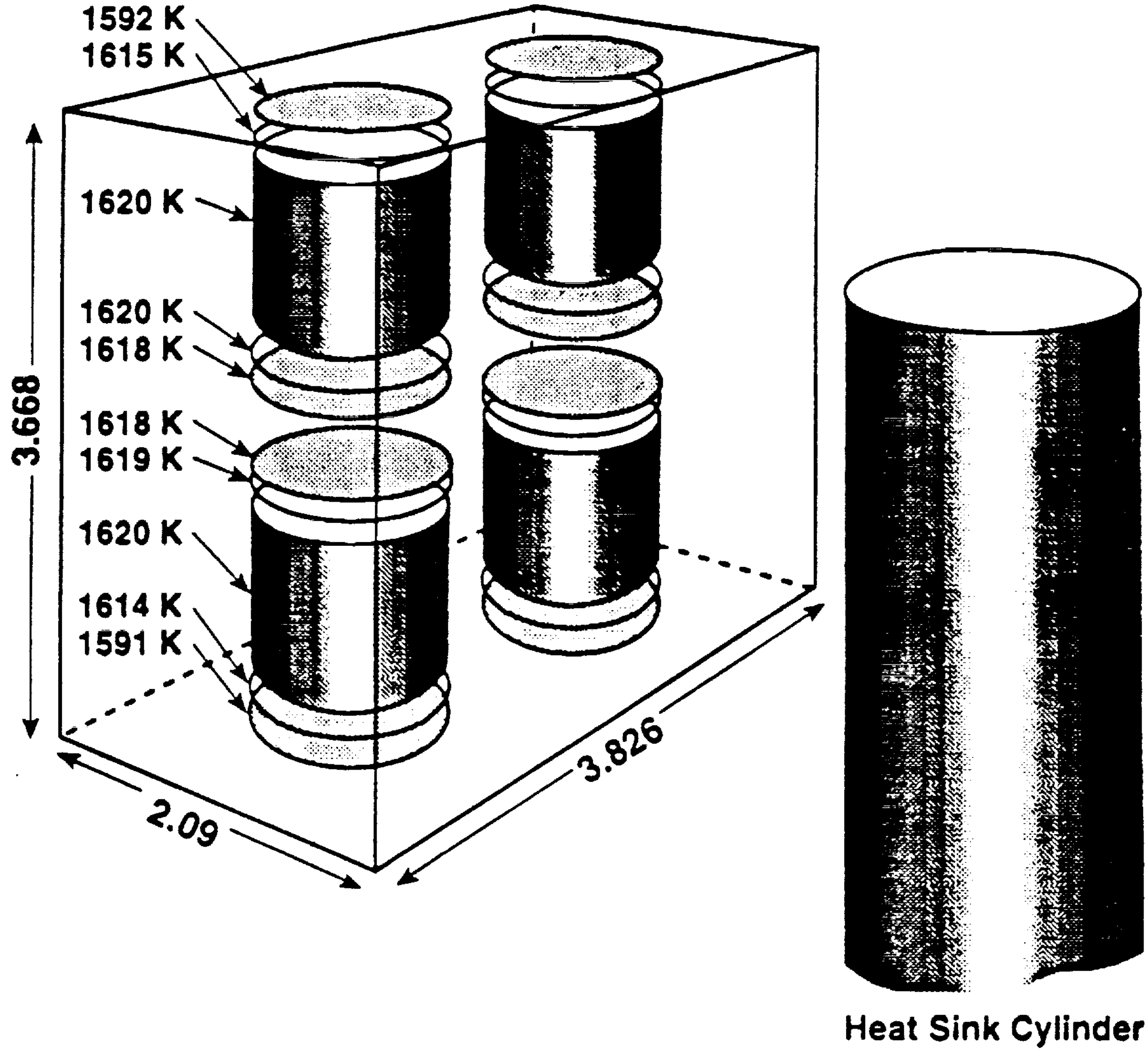


Figure 8.3 Iridium Fuel Clad Nodal Temperatures

and the conservative assumptions incorporated into the thermal model and used in the thermal analysis.

Table 8.5 250 W_e GPHS/FPSE Power System Fuel Clad Nodal Temperatures

Node Number	Temperature °F (K)		Node Number	Temperature °F (K)
400	2406 (1592)		425	2404 (1591)
401	2447 (1615)		426	2446 (1614)
402	2456 (1620)		427	2456 (1620)
403	2456 (1620)		428	2455 (1619)
404	2454 (1618)		429	2453 (1618)

As a more detailed design of the GPHS/FPSE system is established, the thermal model can be modified to remove some of the conservatism of the thermal analysis. Once an insulation material is selected, the nature of the heat sink is determined, and structural supports for the GPHS modules are added, a thermal analysis of the detailed system design should yield lower fuel clad temperatures.

8.2.3 Temperatures Throughout the Power System Enclosure

Temperatures generated for nodes representing other surfaces of the power system are shown in Figure 8.4. The components and node numbers corresponding to the indicated

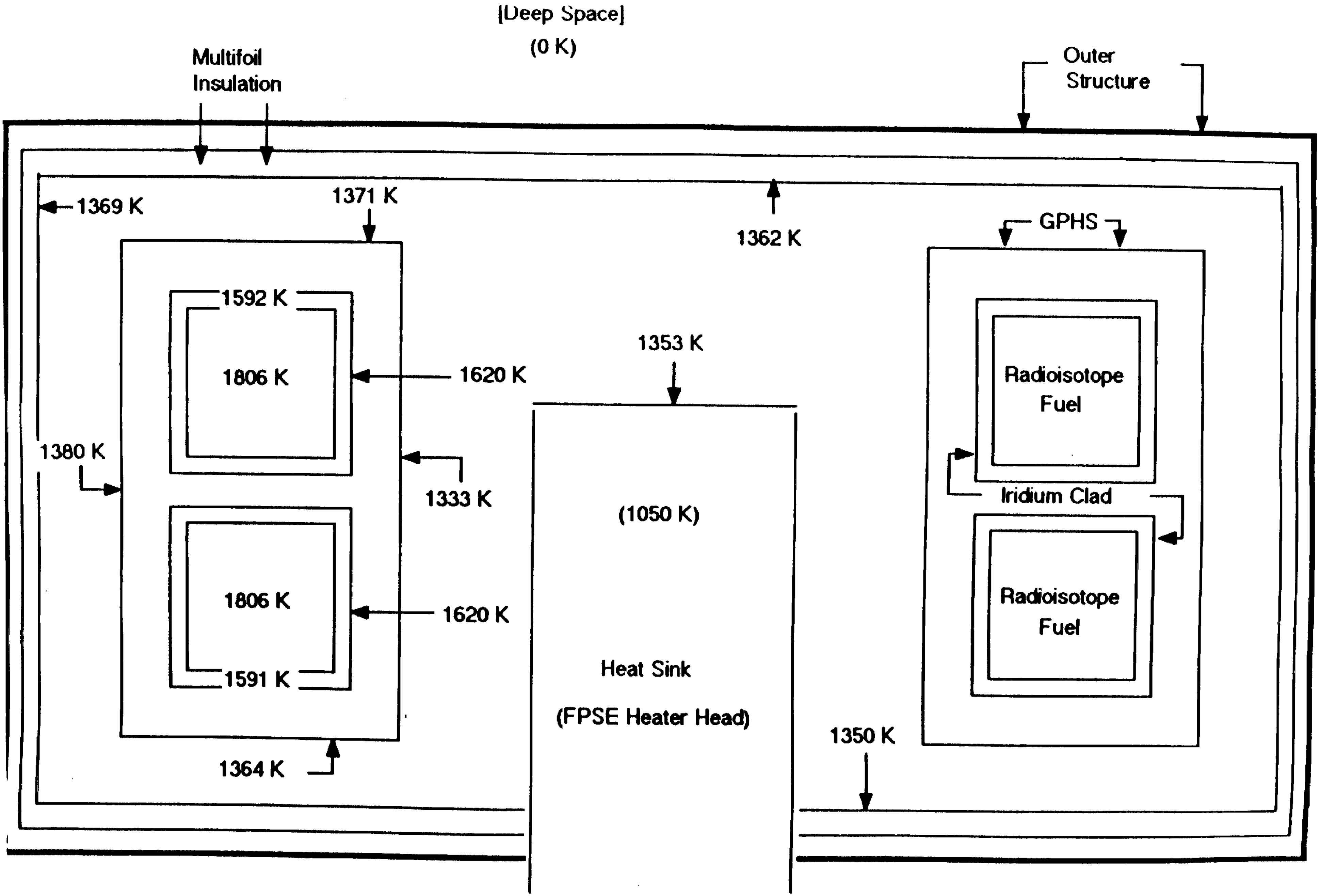


Figure 8.4 Nodal Tempera tures Throughout the 250 W(e) GPHS/FPSE Power System

temperatures were shown in Figures 6.1 and 6.2. Temperatures throughout the power system are certainly within acceptable ranges for materials considered for use in the power system.

An interesting observation is made concerning the temperatures of the nodes representing the power system enclosure inner surfaces. One would expect the inner surface temperature of the enclosure to lie somewhere between the heat source (GPHS modules' surfaces) temperatures (1333 K - 1380 K) and the temperature of the heat sink (1050 K). The thermal analysis has computed inner surface nodal temperatures (1350 K - 1369 K) that lie within the heat source temperature range.

At first glance, it appears that this solution indicates an error in the thermal analysis. Upon further examination, however, this apparent discrepancy can be easily explained.

To start, all of the surfaces within the enclosure can be placed in one of three categories; (1) heat source, (2) heat sink or (3) power system enclosure inner surface (enclosure node). Since radiative heat transfer is the only mechanism by which the surfaces in each category exchange thermal energy, heat transfer between the surfaces depends upon the size, temperature and emissivity of each of the surfaces and on the geometric view factors connecting the surfaces. Ignoring the emissivities and the view factors for now, an equivalent 'surface-area-averaged' temperature for each set of surfaces (heat source, heat sink, enclosure) is calculated and compared to demonstrate that the equivalent enclosure temperature does in fact lie between the equivalent heat source and heat sink temperatures. The surface emissivity values and the view factors connecting the surfaces are examined later since they help to determine whether the enclosure temperature is closer to the heat source temperature or the heat sink temperature.

The equivalent 'surface-area-averaged' temperatures for the heat source, heat sink and enclosure surfaces are calculated using the following equation:

$$T_{SA} = \frac{\Sigma A_i T_i}{\Sigma A_i}$$

where: T_{SA}= 'Surface-Area-Averaged' Temperature
A_i = Area of Surface i
T_i = Temperature of Surface i

The calculated 'surface-area-averaged' temperatures along with the total surface area for each element of the system are given in Table 8.6. From these temperatures, it is shown that the 'surface-area-averaged' temperature of the enclosure's inner surface is slightly lower than the heat source 'surface-area-averaged' temperature. The close proximity of the enclosure temperature to the heat source temperature can be explained by examining the heat transfer paths connecting the surfaces and the significant difference in surface area between the surfaces supplying heat to the system and the one surface removing heat from the system.

Table 8.6 'Surface-Area-Averaged' Temperatures For The Heat Source, Heat Sink, and Enclosure Surface

Surface	Total Surface Area, ΣA_i	'Surface-Area-Averaged' Temperature
Heat Source	237.6 in^2	1364.0 K
Power System Enclosure Inner Surface	282.4 in^2	1362.5 K
Heat Sink	18.9 in^2	1050.0 K

Examining the surface areas first, it is seen that the four GPHS modules have a total surface area of 237.6 in^2 and a 'surface-area-averaged' temperature of 1364.0 K, while the heat sink surface area is only 18.9 in^2 with a temperature of 1050 K. With greater than 12 times the surface area than the heat sink, and because radiative heat transfer is a function of temperature to the fourth power, the GPHS surfaces have a much greater influence on the inner surface temperature of the power system enclosure.

When looking at the heat transfer paths, it is seen that most of the heat sink surface is blocked by the GPHS modules from direct thermal energy exchange with the enclosure surfaces. Therefore, the values for the geometric view factors which connect the enclosure nodes to the heat sink node are very low, reducing the heat sink temperature's influence on the enclosure temperature. Since both the heat source and heat sink have emissivities of 0.8, the emissivities are not a factor when comparing the relative influence of each on the enclosure temperature.

From the above discussion, it can be concluded that a calculated 'surface-area-averaged' temperature of 1362.5 K for the enclosure surfaces is not unreasonable, as it may first appear.

8.2.4 Sensitivity Analysis

As a followup to the thermal analysis results presented in the previous subsections, a brief sensitivity analysis was performed to determine the effects of varying some of the key system parameters on the fuel clad nodal temperatures. The thermal analysis performed using the thermal model described in this report used conservative values for most of the system parameters. Understanding the effects of variations in these parameters is essential prior to further development of the power system.

Five system parameters whose variance would impact the clad temperatures have been identified for the sensitivity analysis; (1) direct heat loss to space (variance of the conductance through the power system enclosure), (2) the heat sink surface area, (3) the distance between the GPHS modules and the heat sink, (4) the emissivity of the inner surfaces of the power system enclosure, and, (5) the emissivity of the heat sink cylinder.

Three of the five key parameters were varied for this sensitivity analysis. The GPHS module positions were not varied since this requires a rather extensive revision to the current thermal model. Varying the distance between the modules and the heat sink and repositioning of the modules within the enclosure (turning them so different module surfaces face the heat sink) is recommended for future study. The emissivity values for the inner surfaces of the power system enclosure were not varied since, using the current thermal model (no heat transfer through the enclosure), the emissivity values have no effect on the thermal analysis results. Once an insulation material has been selected, this parameter should be varied to determine its effect on the fuel clad nodal temperatures.

The direct heat loss from the system to space was varied by selecting three different conductor conductance values connecting the interior nodes of the power system enclosure to the exterior nodes. The corresponding heat loss was calculated from the temperatures of the exterior nodes as predicted by the SINDA thermal analysis. The range of iridium clad temperatures for each of the three cases is shown in Table 8.7.

Table 8.7 Fuel Clad Nodal Temperatures as a Function of Heat Loss to Space

Heat Loss (W)	Iridium Clad Nodal Temperatures (K)
0.0	1591 - 1620
20.0	1588 - 1617
45.6	1584 - 1617
83.3	1578 - 1607

As shown in Table 8.7, as the heat loss through the enclosure increases, the fuel clad temperatures slowly decreases. Based upon the direct heat loss to space from the GPHS-RTG (see Reference 1), a heat loss of about 5% (50 W) could be expected for an actual GPHS/FPSE power system. From Table 8.7, a decrease in fuel clad temperature of 7 to 8 K could result from such a heat loss. However, a design which provides for increased heat loss from the system is not desirable since it will result in decreased system performance.

The heat sink size was varied directly by changing the input value in the TRASYS input file. Cylinder lengths of 2.5 and 3.5 inches were used for the analysis. The range of iridium fuel clad nodal temperatures for each heat sink size is shown in Table 8.8. The heat sink heat flux corresponding to each heat sink size is also given.

Table 8.8 Fuel Clad Nodal Temperatures as a Function of Heat Sink Size

Heat Sink Cylinder Length (in.)	Heat flux (W/m^2)	Iridium Clad Nodal Temperatures (K)
2.5	98,676	1615 - 1645
3.0	82,230	1591 - 1620
3.5	70,483	1571 - 1599

As shown in Table 8.8, increasing the heat sink cylinder length 0.5 inches results in a heat sink heat flux similar to the estimated Solar Dynamic Space Experiment (SDSE) FPSE heater head heat flux of 70,000 W/m^2 (see Section 6.2). The corresponding fuel clad nodal temperatures are lower and approach the design goal of 1573 K. Thus the design of the GPHS/FPSE system should strive for a heat sink heat flux value of 70,000 W/m^2 or below.

The heat sink emissivity value was also varied by changing the input value into the TRASYS input file. Emissivity values of 0.7 and 0.9 were used for the analysis. The range of fuel clad nodal temperatures corresponding to these emissivity values is shown in Table 8.9.

As shown in Table 8.9, a heat sink emissivity of 0.9 reduces the fuel clad nodal temperatures close to the design goal of 1573 K. Thus, a coating which could provide a heat sink emissivity greater than 0.8 is recommended for the system. A heat sink emissivity of 0.9 in combination with a larger heat sink size could reduce all fuel clad nodal temperatures to the design goal of 1573 K.

Table 8.9 Fuel Clad Nodal Temperatures as a Function of Heat Sink Emissivity

Heat Sink Emissivity	Iridium Clad Nodal Temperatures (K)
0.7	1610 - 1639
0.8	1591 - 1620
0.9	1576 - 1604

The sensitivity analysis has shown that varying the heat sink parameters has the greatest effect on the fuel clad nodal temperatures. As design of the 250 W_e GPHS/FPSE system continues, primary emphasis must be placed on incorporating as large a heat sink as possible with the lowest heat flux achievable. Direct heat loss from the system will tend to decrease the clad temperatures, but this mechanism should not be relied upon too strongly since it will adversely affect the overall system performance.

8.3 References

1. Final Safety Analysis Report For The Galileo Mission, Prepared for the U.S. Department of Energy by General Electric's Astro-Space Division Under Contract DE-AC01-79ET32043, May, 1988.

9.0 THERMAL ANALYSIS OF THE 500 W_e GPHS/FPSE POWER SYSTEM

9.1 Description of Analysis

9.1.1 Introduction

The thermal analysis of the 500 W_e GPHS/FPSE power system is very similar to the thermal analysis of the 250 W_e power system. The analysis was performed using the thermal model described in Section 7.0. The TRASYS code is used to generate conductance values for the radiation conductors which connect the surface nodes within the power system enclosure. The SINDA code is used to generate the steady-state temperature distribution throughout the entire thermal system. Due to the similarities between the TRASYS and SINDA input files for the 250 W_e and 500 W_e power systems, and the lengths of the files, the input files for the 500 W_e system are not included as appendices.

9.1.2 TRASYS Analysis

The surfaces within the power system enclosure are defined in the TRASYS input file. Dimensions are specified for the heat sink, the GPHS modules and the inner surfaces of the power system enclosure. The positions of the components with relation to one another are also specified. The interior of the 500 W_e power system enclosure contains 55 surfaces (48 faces of the GPHS modules, 3 power system enclosure surfaces, two heat sink cylinders and the two heat sink end caps). Emissivity values for each surface are specified.

Application of the TRASYS code to the 500 W_e GPHS/FPSE power system thermal model yields 1085 radiation conductors connecting the surfaces within the power system enclosure. The conductors are numbered 1 through 1085 and are included as part of the SINDA input deck. For each radiation conductor number, the nodes which are connected are identified and the conductance value for the conductor is generated.

9.1.3 SINDA Analysis

As in the 250 W_e SINDA input deck, the bulk input deck is dedicated to defining the nodes and conductors in the thermal model. The radiation conductors and the corresponding conductance values which are generated by the TRASYS code are inserted directly into the conductor segment of the SINDA input deck. The remainder of the input deck is used to define the heat generation rates in the fuel pellet nodes and to specify the SINDA subroutines to be executed.

The same three SINDA subroutines (STDSTL, TPRINT, and QIPRNT) used for the 250 W_e system thermal analysis are used for the 500 W_e system thermal analysis. STDSTL is a thermal network solution subroutine which calculates the finite difference steady-state solution. TPRINT is a printout subroutine which produces a printout of all the nodal temperatures in the steady-state solution. QIPRNT is also a printout subroutine; it produces a printout of the heat generation rate for each node in the thermal system. QIPRNT is used to verify the heat generation rates for the fuel pellet nodes and to verify that all other nodes have a heat generation rate of zero.

9.1.4 Initial Temperatures

As in the 250 W_e SINDA input deck, all nodes in the thermal model of the 500 W_e GPHS/FPSE power system are given an initial temperature as a starting point for the iterative process used for the thermal analysis by the SINDA code. The boundary node temperatures and the initial temperatures for the arithmetic nodes are listed in Table 9.1.

Table 9.1 Initial Nodal Temperatures for Thermal Analysis of the 500 W_e GPHS/FPSE Power System

Node Numbers	Node Description	Node Type	Initial Temperature
10100 11100	Heat Sinks	Boundary	1430° F
99999	Deep Space	Boundary	-460° F
10200 11200	Heat Sink End Caps	Arithmetic	1500° F
10400 10500 10600	Inner Surfaces of Power System Enclosure	Arithmetic	1500° F
10700 10800 10900	Outer Surfaces of Power System Enclosure	Arithmetic	200° F
	ALL Other Nodes	Arithmetic	2000° F

9.2 Results And Interpretations of Thermal Analysis

9.2.1 Introduction

The SINDA output file contains the steady-state temperature for each of the 1211 nodes in the thermal model. For the purpose of this analysis, only the temperatures of selected nodes throughout the power system are presented.

9.2.2 Fuel Clad Temperatures

As in the 250 W_e power system thermal analysis, examination of the fuel clad nodal temperatures is most important since the primary design objective is to demonstrate temperatures of the fuel clad below the design goal temperature limit of 1573 K under normal operating conditions. With 8 GPHS modules, 4 fuel pellets per modules, and 5 nodes representing the fuel clad of each fuel pellet, there are 160 fuel clad nodes in the 500 W_e power system thermal network. Again, evaluation of all the nodal temperatures is not necessary because of the symmetry in the system configuration.

Figures 9.1a and 9.1b, respectively, illustrate the symmetry of the 500 W_e from both side and top views of the power system. From the top view (Figure 9.1b), it can be seen that analogous nodes in each set of GPHS modules should have similar temperatures when the system is in thermal equilibrium. In addition, analogous nodes on either side of each set of modules should have similar temperatures. From the side view (Figure 9.1a), it

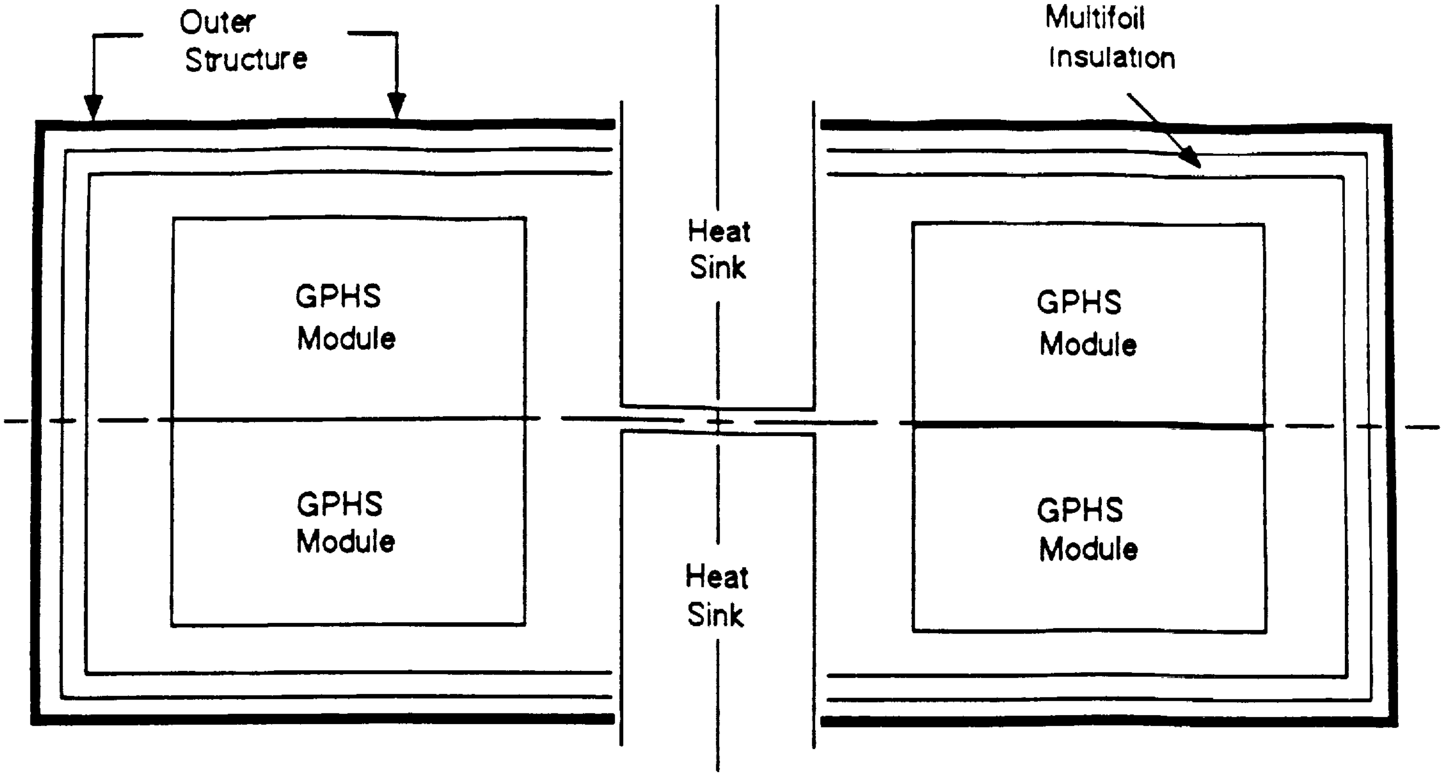


Figure 9.1a Symmetry of 500 W(e) GPHS/FPSE Power System From Side View

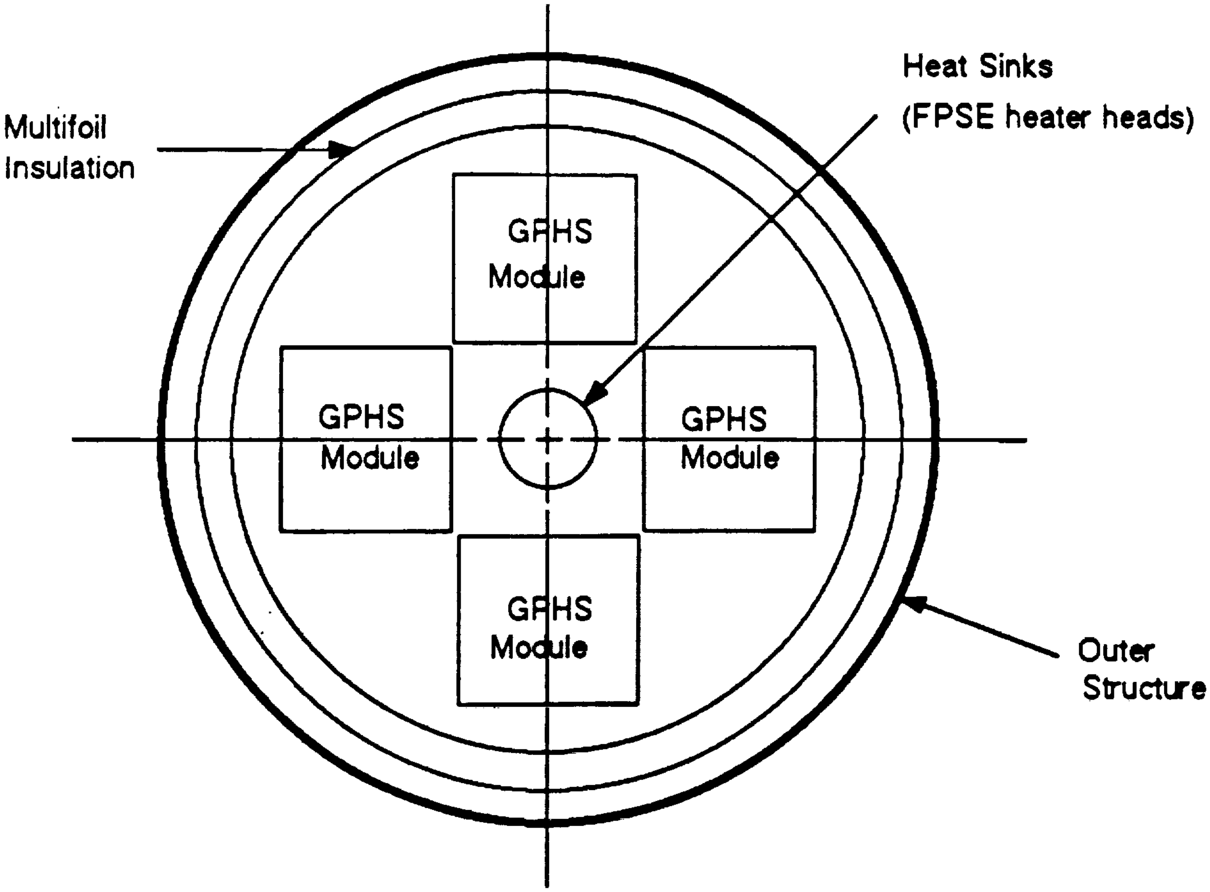


Figure 9.1b Symmetry of 500 W(e) GPHS/FPSE Power System From Top View

can be seen that analogous nodes in each GPHS module within each set of modules should have similar temperatures.

Temperatures of analogous nodes in each of the four sets of modules, and within each set of modules, were examined and found to be identical. Therefore, the number of nodal temperatures examined is reduced to the 10 nodes representing the fuel clad of the two fuel pellets on one side of one GPHS module.

Figure 9.2 depicts the arrangement of the fuel clad nodes in the 500 W_e power system configuration. The node shapes are identical to those described in Table 8.2 as part of the thermal analysis results for the 250 W_e power system. As shown in Figure 9.2, nodes numbered 425 to 429 represent the cladding of the fuel pellet closest to the heat sink and nodes 400 to 404 represent the cladding of the fuel pellet on the side of the GPHS module facing the power system enclosure.

The fuel clad nodal temperatures determined by the thermal analysis are shown in Figure 9.3 and listed in Table 9.2. As indicated in the figure and table, the temperatures of the fuel clad nodes are higher than the design goal temperature limit of 1573 K and higher than the fuel clad nodal temperatures determined for the fuel clad nodes in the 250 W_e system thermal model (See Figure 8.3 and Table 8.5).

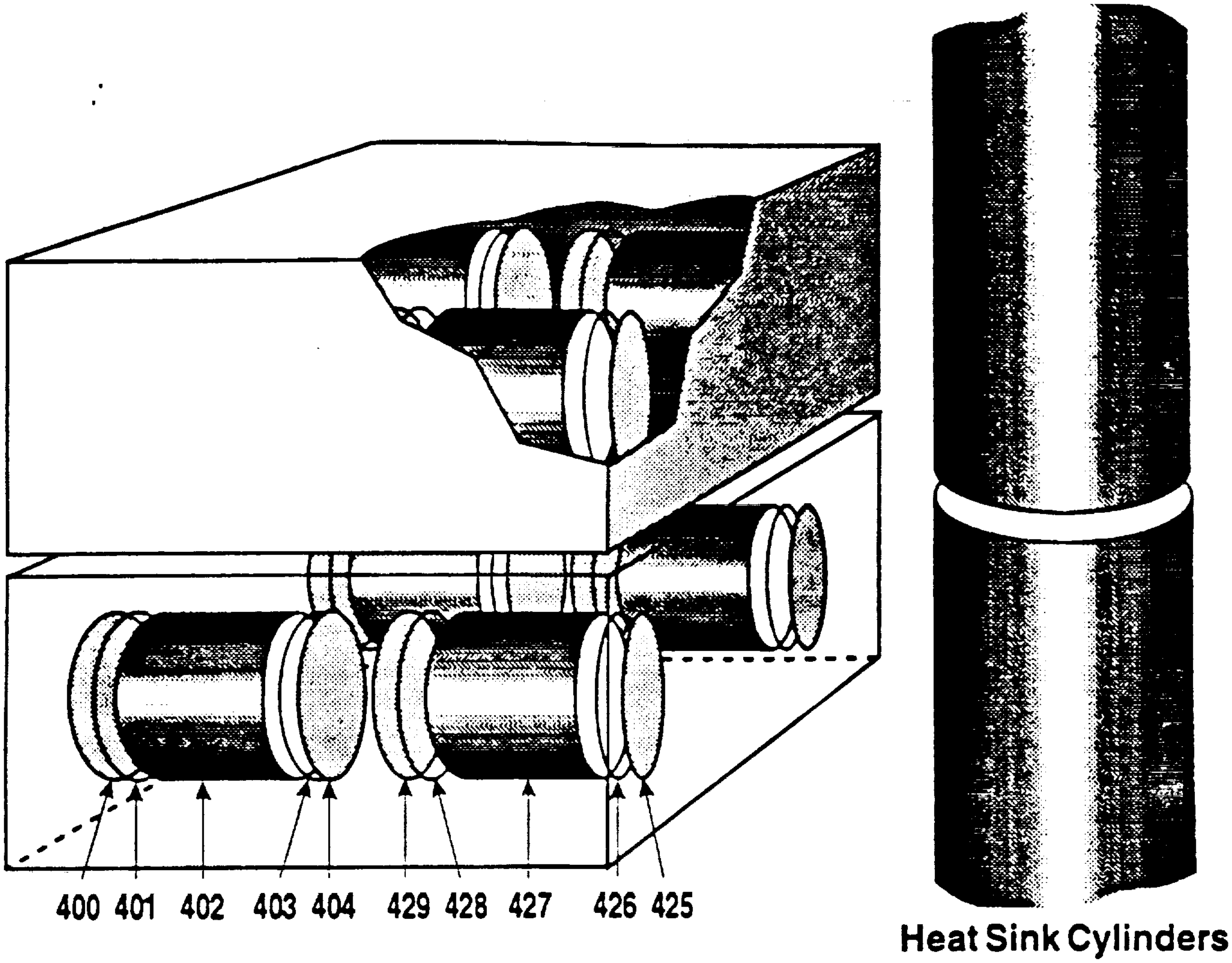


Figure 9.2 Iridium Fuel Clad Nodal Arrangement

Table 9.2 500 W_e GPHS/FPSE Power System Fuel Clad Nodal Temperatures

Node Number	Temperature °F (K)		Node Number	Temperature °F (K)
400	2461 (1623)		425	2449 (1616)
401	2503 (1646)		426	2497 (1642)
402	2512 (1651)		427	2507 (1648)
403	2511 (1651)		428	2507 (1648)
404	2509 (1649)		429	2507 (1648)

After discussion with NASA LeRC engineers, it was decided that the temperatures shown by the thermal analysis are sufficiently close to the design goal temperature limit to warrant further investigation of the 500 W_e power system. The basis for this conclusion is the same as for the 250 W_e power system. Due to the close proximity of the fuel clad temperatures to the temperature limit, the ambiguous nature of the limit itself, and the conservative assumptions incorporated into the thermal model and used in the thermal analysis, modifications to the current thermal model should yield lower fuel clad nodal temperatures.

9.2.3 Temperatures Throughout the Power System Enclosure

Temperatures generated for various nodes throughout the 500 W_e power system, including some fuel clad nodes, are shown in Figure 9.4. The components and node

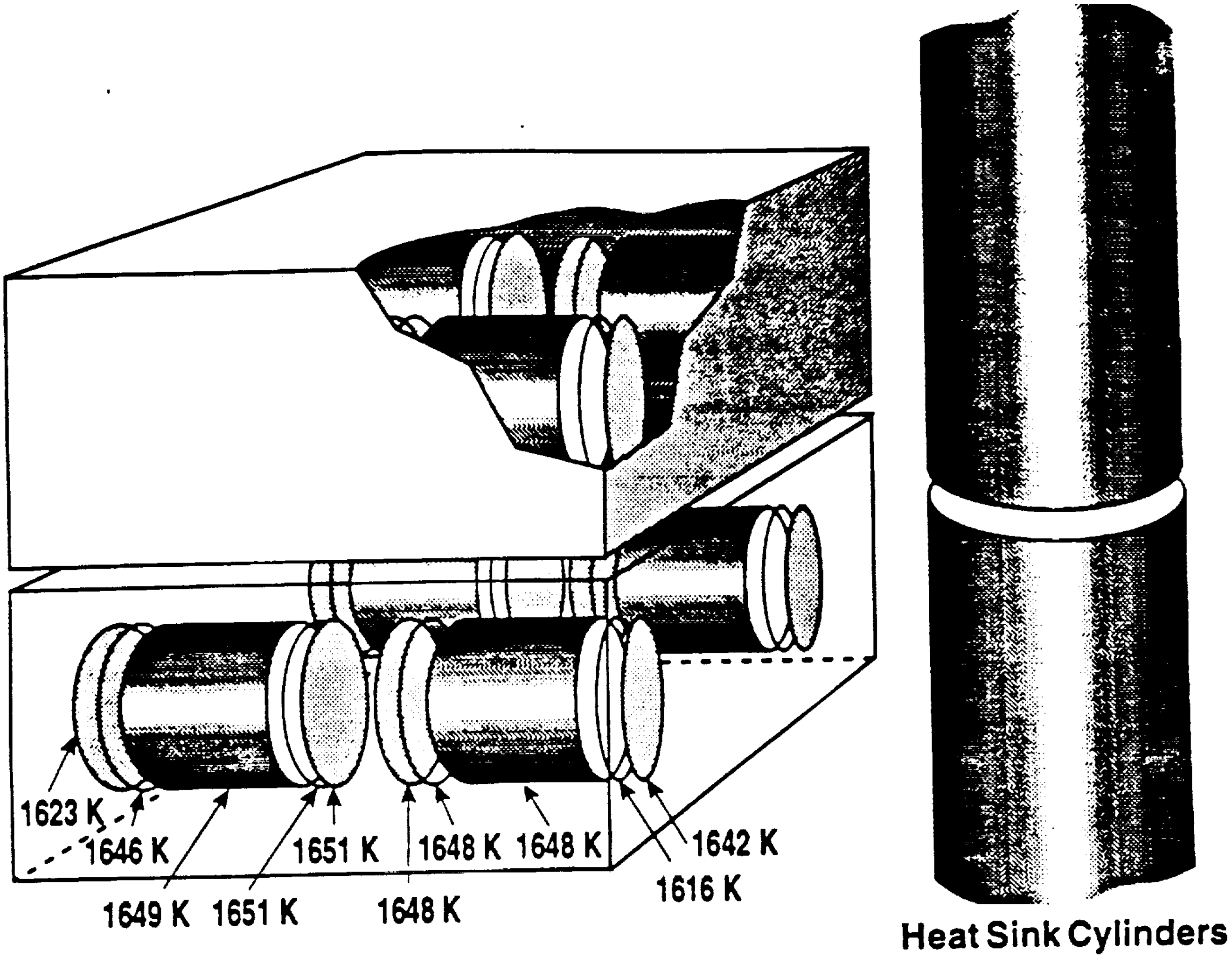


Figure 9.3 Iridium Fuel Clad Nodal Tempuratures

numbers corresponding to the indicated temperatures were shown in Figures 7.1 and 7.2. As in the 250 W_e system, temperatures throughout the power system are within acceptable ranges for materials considered for use in the power system.

A sensitivity analysis was not performed for the 500 W_e power system. Due to the similarities between the two system configurations, it is expected that variance of the same key parameters should have similar effects on the fuel clad nodal temperatures. Since the degree to which the temperatures are affected may not be the same, a sensitivity analysis is recommended for future study.

9.2.4 Loss Of One Heat Sink Thermal Analysis

9.2.4.1 Description of Analysis

Since the 500 W_e GPHS/FPSE power system has two heat sinks, an additional analysis was performed for this system in which one of the heat sinks is assumed to be lost. A significant assumption is necessary in order for the power system to continue operating under these conditions; each Stirling engine must be capable of handling the increased heat input that would be required to maintain the system in thermal equilibrium. With this assumption, under normal operating conditions, each Stirling engine would be operating at half its capacity. Whether or not Stirling engines could be developed to meet this requirement is beyond the scope of this analysis. Nevertheless, the analysis is performed and the fuel clad nodal temperatures are examined.

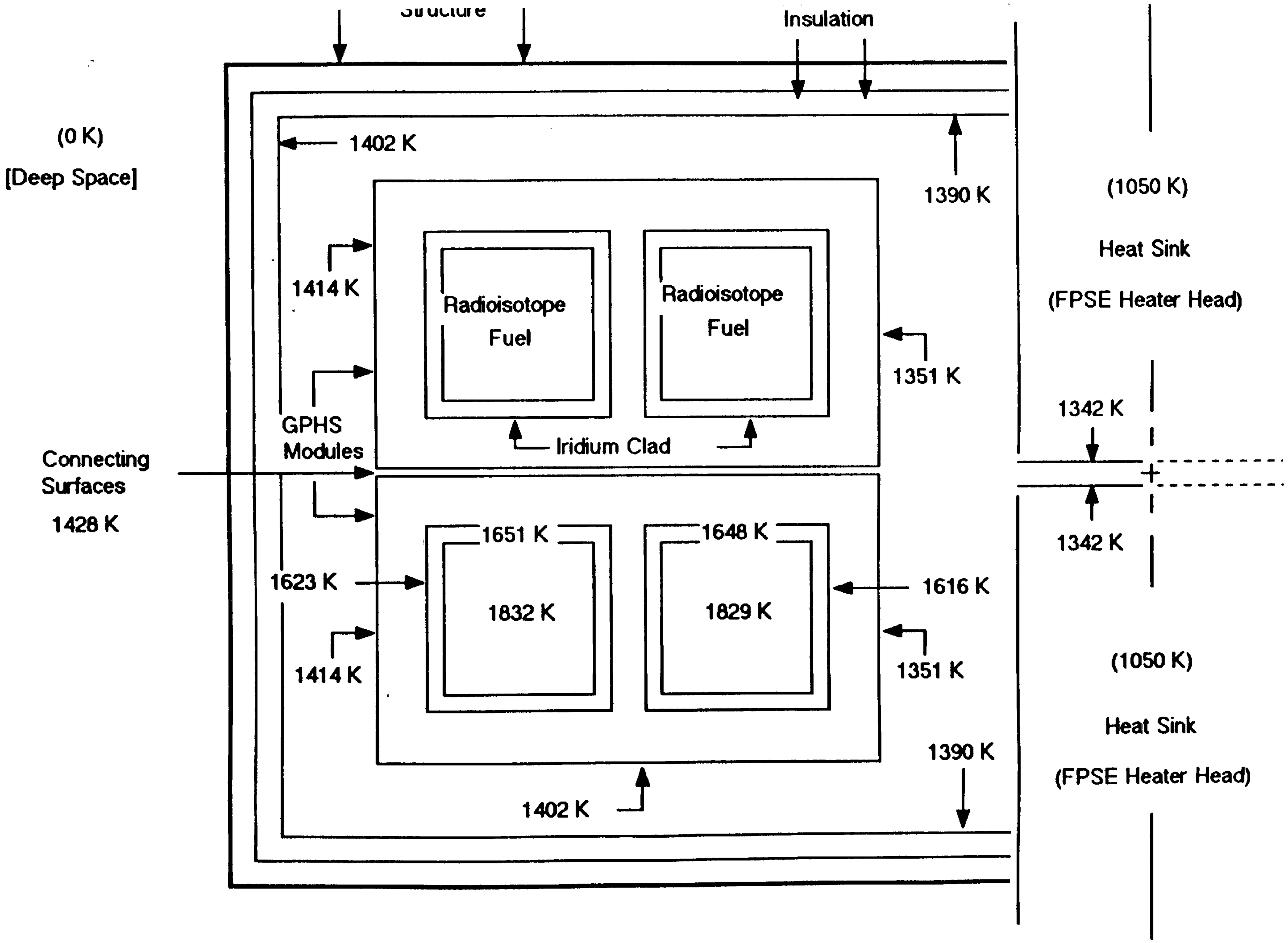


Figure 9.4 500 W(e) GPHS /FPSE Power System Nodal Temperatures

As an extension of the assumption described above, it is assumed that after failure of one of the heat sinks, the failed heat sink no longer removes heat from the system. The cylindrical node representing the failed heat sink is treated as an arithmetic node similar to the end cap nodes. The former heat sink node now reflects all thermal energy back into the power system enclosure.

9.2.4.2 Results From Loss of One Heat Sink Thermal Analysis

Since one heat sink is lost, the symmetry of the system shown in the side view of the power system (Figure 9.1a) is no longer applicable. Analogous nodes in each GPHS module within each set of modules are expected to have different temperatures. The symmetry shown in the top view of the power system (Figure 9.1b) still applies. Thus, the temperatures of the 20 nodes shown in Figure 9.2, which represent the fuel clad of the 4 pellets on one side of one set of the GPHS modules, are examined.

The fuel clad temperatures determined by the thermal analysis are listed in Table 9.3 and shown in Figure 9.5. As indicated in the figure and table, the temperatures of the fuel clad far exceed the design goal temperature limit of 1573 K. The temperatures, however, are not as unfavorable as they might first appear. If one were to use the temperature constraints suggested by the engineers at Mound Laboratories (See Subsection 2.2), the GPHS modules may be operated safely with temperatures as high as 1773 K. Using this criteria, the temperatures obtained from the thermal analysis are very close to falling

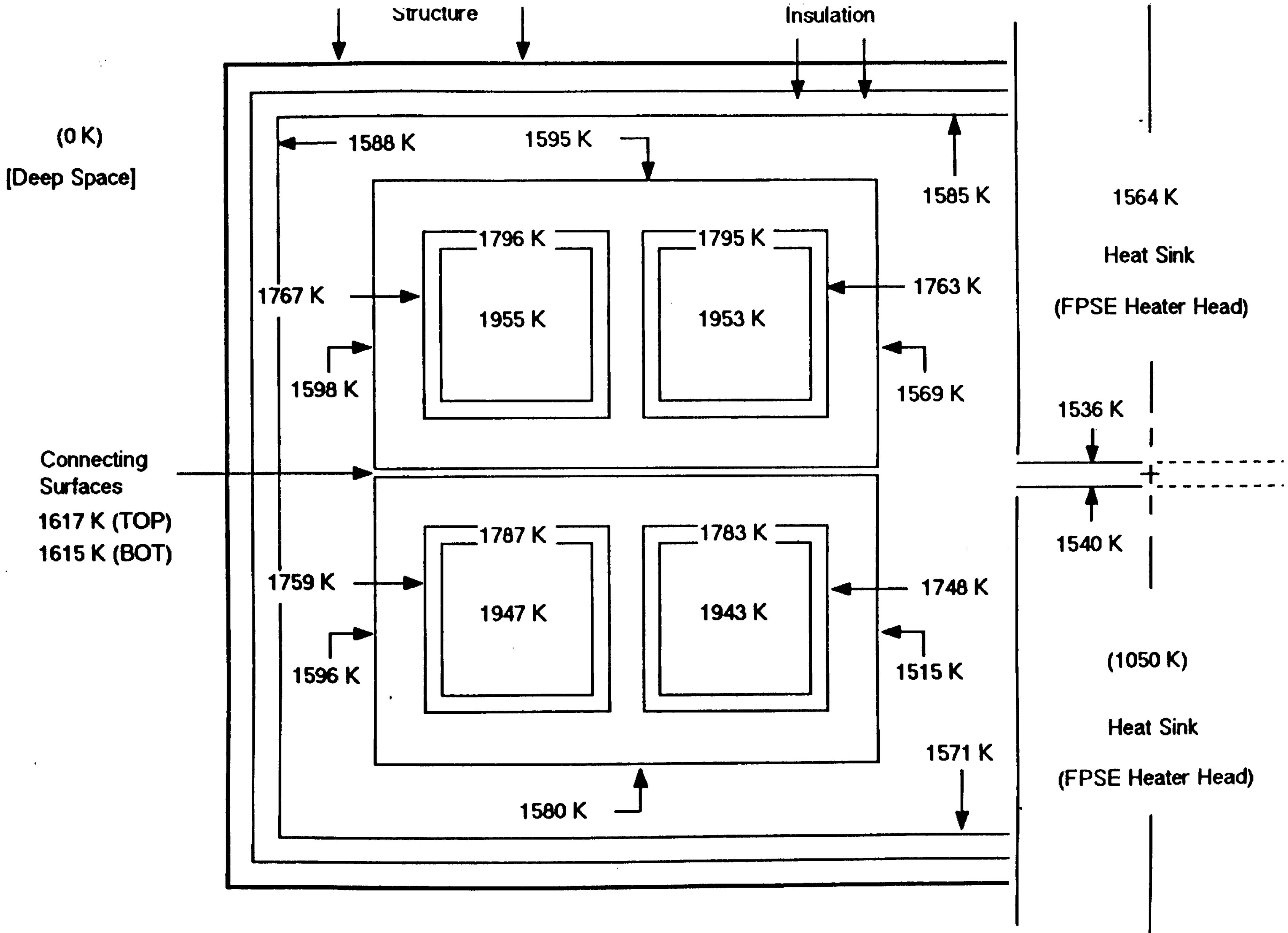


Figure 9.5 500 W(e) GPH S/FPSE Power System Nodal Temperatures
(Loss of One Heat Sink)

within the acceptable range.

Table 9.3 Fuel Clad Nodal Temperatures for the 500 W_e Power System After Failure of One Heat Sink

Node Number	Temperature °F (K)		Node Number	Temperature °F (K)
400	2707 (1759)		425	2686 (1748)
401	2748 (1782)		426	2739 (1777)
402	2758 (1787)		427	2750 (1783)
403	2757 (1787)		428	2751 (1784)
404	2756 (1786)		429	2753 (1785)
20400	2721 (1767)		20425	2713 (1763)
20401	2764 (1791)		20426	2760 (1789)
20402	2773 (1796)		20427	2771 (1795)
20403	2773 (1796)		20428	2771 (1795)
20404	2772 (1796)		20429	2771 (1795)

The temperature limits indicated in Table 2.1 also allowed for limited operation of the system with elevated fuel clad temperatures. The temperatures obtained from the thermal analysis indicate the system may be operated safely in this configuration for about 10 hours. It must be noted, however, that this thermal analysis has been a steady-state analysis. The time for the system to reach this steady-state has not been accounted for. If time constraints are applied, a transient analysis is necessary to determine the temperatures of the fuel clad nodes as a function of time as the steady-state conditions are reached.

From the preceding thermal analysis, it is clear that an incontrovertible temperature limit for the fuel clad under normal operating conditions needs to be established. Only after the ambiguity of the temperature limit is removed can a final judgement be made concerning the acceptability of running the 500 W_e GPHS/FPSE power system with only one engine.

10.0 CONCLUSIONS AND RECOMMENDATIONS

10.1 250 W_e GPHS/FPSE Power System

As discussed in Section 8.0, for the thermal system modeled for the 250 W_e power system configuration, the iridium fuel clad temperatures in the GPHS modules were shown to be slightly higher (~20 K to ~50 K) than the design goal temperature of 1573 K. Due to the conservative assumptions used for the thermal analysis and the ambiguity of the temperature limit, the results of the analysis are considered favorable.

The sensitivity analysis has shown the relatively strong dependence of the fuel clad nodal temperatures on the heat sink parameters. The use of heat receptor fins on the Stirling engine heater head may be beneficial to the system design. The fins could be used to supply a larger surface area for the heat sink, thus reducing the heat sink heat flux. However, the fin temperatures may be slightly higher than the temperature used for the heat sink in the thermal model, so the advantage may not be as great as may be expected.

Another feature which should be investigated is the addition of surfaces which block the direct heat transfer between the GPHS modules. The current thermal model allows for the portion of each GPHS module extending beyond the end of the heat sink cylinder to directly exchange radiant energy with the other modules in the enclosure. Blocking this heat transfer path should result in lower fuel clad nodal temperatures. If heat receptor fins which extend the length of the GPHS modules are incorporated into the heater head design, the fins would block a significant portion of the direct radiant heat transfer between the modules.

Before the model is revised to reflect the design changes mentioned above, it is recommended that a more detailed thermal analysis be performed with a modified version of the current thermal model. The modified thermal model should include nodes representing structural supports for the GPHS modules and nodes corresponding to a specific insulation material for the power system enclosure. As can be inferred from the heat loss variation performed as part of the sensitivity analysis, adding insulation to the thermal model should not significantly affect the fuel clad nodal temperatures. However, the impact of the added supports needs to be evaluated.

One of the primary assumptions used for the thermal analysis performed for this project was that the power system is operated in a vacuum environment (space). However, another potential mission application for the GPHS/FPSE power system may be use as the electrical power system for a Martian surface rover vehicle. Additional analysis would need to be done with the higher external heat sink temperature and the addition of the atmospheric gas in the power system enclosure. This would entail the addition of convective heat transfer inside and outside of the enclosure. In addition, since the Martian atmospheric gas is not transparent to thermal radiation, the affects of the reduced radiant heat transfer would need to be incorporated into the analysis.

10.2 500 W_e GPHS/FPSE Power System

The thermal analysis of the 500 W_e system thermal model has demonstrated fuel clad temperatures higher than then design goal temperature limit of 1573 K. Although the temperatures range from 43 K to 78 K higher than the design goal, the results of the analysis are considered favorable. These temperatures may prove to be perfectly acceptable once a firm operating temperature limit has been established. Even if the temperature limit is set at 1573 K, modifications to the current thermal model would be expected to yield temperatures below the prescribed limit.

The thermal analysis in which one of the heat sinks is lost has shown a significant increase in fuel clad temperatures from the normal operating temperatures. The fuel clad nodal temperatures range from 175 K to 223 K above the 1573 K design goal temperature limit. Based upon the criteria given in Table 2.1 of this report, indefinite operation of the system with fuel clad temperatures in this range is unacceptable. However, according to the same criteria, the system may be operated safely for a short time (~10 hours) with fuel clad temperatures in this range. It is also possible that these temperatures may be very close to being acceptable if the upper temperature limit for normal operation is set in accordance with the recommendations of the engineers at Mound Laboratories (see Subsection 2.2). They had suggested than the GPHS modules could be safely operated for extended periods (anticipated mission lifetimes) with fuel clad temperatures of up to 1773 K. If their assessment is accurate, minor modifications to the current 500 W_e system thermal model with only one heat sink should yield fuel clad temperatures below

1773 K.

The recommended modifications for future thermal analysis of the 500 W_e GPHS/FPSE power system are similar to those indicated for the 250 W_e power system. The modified thermal model should include nodes representing structural supports for the sets of GPHS modules and nodes corresponding to a specific insulation material for the power system enclosure. With two heat sinks in the 500 W_e system configuration, there is some blockage of direct thermal energy exchange between the sets of GPHS modules. Incorporating additional blocking surfaces should be investigated to determine the effect on the fuel clad temperatures.

Similar to the 250 W_e power system, if the 500 W_e GPHS/FPSE power system is considered for use as an electrical power system for a Martian surface rover vehicle, the current thermal model would need to be modified to reflect the changes described in the previous subsection.

Further analysis based on the results of this study should include investigation of even higher power level GPHS/FPSE systems. The higher power level systems should result in a lower specific weight (kg/kW_e) than the 250 W_e and 500 W_e power systems. The upper limit for the power level for a GPHS/FPSE power system remains to be determined. The limiting factors will be the fuel clad temperatures and the capabilities of the free-piston Stirling engine.

APPENDIX A

GPHS MATERIALS PROPERTIES

The physical properties of the GPHS materials which are required for the thermal analysis are given in Tables A.1 through A.8. These values were used in the GPHS thermal model developed by Pat Dunn (Appendix B) and incorporated into the GPHS/FPSE system thermal analysis performed for this project. The values were obtained from John A. Loffreda of the General Electric Company's Astro Space Division.

Table A.1 Fuel Pellet - PuO_2

Temperature (°F)	Thermal Conductivity (BTU/hr-ft-°F)	Emissivity
100	0.242	0.6
572	0.254	0.643
752	0.266	0.659
932	0.315	0.676
1112	0.325	0.692
1292	0.335	0.709
1472	0.545	0.725
1652	0.59	0.742
1832	0.635	0.758
2012	0.681	0.775
2192	0.726	0.791
2500	0.747	0.819
3000	0.78	0.865
3500	0.814	0.911
4000	0.848	0.956
5000	0.915	0.956
20000	0.915	0.956

Table A.3 GIS Sides - FWPF

Temperature (°F)	Thermal Conductivity (BTU/hr-ft-°F)	Emissivity
0	98.8	0.812
500	75.8	0.814
750	67.1	0.816
1000	59.6	0.818
1250	53.3	0.821
1500	48.3	0.824
1750	44.2	0.828
2000	40	0.832
2500	35	0.84
3000	30.8	0.848
4000	27.9	0.865
4800	26.6	0.882
20000	26.6	1

Table A.2 Fuel Clad - DOP-26 Ir

Temperature (°F)	Thermal Conductivity (BTU/hr-ft-°F)	Emissivity
0	85	0.0838
1000	79	0.137
2000	76.5	0.191
3000	65.5	0.245
4000	65	0.298
20000	65	0.62

Table A.4 GIS End Cap (with holes) - FWPF

Temperature (°F)	Thermal Conductivity (BTU/hr-ft-°F)	Emissivity
0	63.8	0.72
500	49.7	0.745
750	44	0.757
1000	38.7	0.769
1250	40.2	0.779
1500	30.9	0.789
1750	28.2	0.8
2000	26.2	0.81
2500	23.3	0.831
3000	22	0.851
4000	20.6	0.886
4800	20	0.912
20000	20	1

Table A.6 Aeroshell - FWFP X,Y Direction

Temperature (°F)	Thermal Conductivity (BTU/hr-ft-°F)	Emissivity
0	98.8	0.812
500	75.8	0.814
750	67.1	0.816
1000	59.6	0.818
1250	53.3	0.821
1500	48.3	0.824
1750	44.2	0.828
2000	40	0.832
2500	35	0.84
3000	30.8	0.848
4000	27.9	0.865
4800	26.6	0.882
20000	26.6	1

Table A.5 Floating Membrane - FWPF

Temperature (°F)	Thermal Conductivity (BTU/hr-ft-°F)	Emissivity
100	49.3	0.72
500	40.2	0.745
750	35.5	0.757
1000	31.2	0.769
1250	27.8	0.779
1500	25	0.789
1750	22.8	0.8
2000	21.1	0.81
2500	18.8	0.831
3000	17.8	0.851
4000	16.7	0.886
7800	16.1	0.912
20000	16.1	1

Table A.7 Aeroshell - FWPF Z Direction

Temperature (°F)	Thermal Conductivity (BTU/hr-ft-°F)	Emissivity
0	77.4	0.642
500	60.3	0.675
750	53.5	0.696
1000	46.9	0.716
1250	41.7	0.734
1500	37.5	0.752
1750	34.2	0.77
2000	31.7	0.788
2500	28.3	0.82
3000	26.7	0.853
4000	25	0.905
4800	24.2	0.943
20000	24.2	1

Table A.8 Insulator Sleeve and Disc - CBCF-3

Temperature (°F)	Thermal Conductivity (BTU/hr-ft-°F)	Emissivity
0	0.03545	0.8
392	0.052	0.8
572	0.061	0.8
752	0.071	0.8
932	0.081	0.8
1112	0.086	0.8
1292	0.091	0.8
1472	0.096	0.8
1652	0.101	0.8
1832	0.107	0.8
2012	0.112	0.8
2192	0.117	0.8
2372	0.122	0.8
2552	0.128	0.8
3000	0.141	0.8
4000	0.171	0.8
10000	0.7	0.8

APPENDIX B

GPHS MODULE THERMAL MODEL

This appendix contains three sections: (I) the SINDA input deck for the GPHS thermal model, (II) a series of diagrams depicting the nodal arrangement of the thermal model, and (III) thermal analysis results showing the temperatures of the GPHS interior nodes for four specific thermal environments. The thermal model and the thermal analyses were prepared specifically for use in this project by the Engineering Directorate of NASA Lewis Research Center.

I. SINDA INPUT DECK FOR GPHS THERMAL MODEL

```
BCD 3THERMAL LPCS
BCD 9 GPHS STEADY STATE THERMAL MODEL
BCD 9
END
BCD 3NODE DATA
REM
REM *******************  AEROSHELL NODES  ******************
REM
GEN  100, 6, 1, 2000., -1.
REM
REM *******************  SIDE "A" NODES  *******************
REM
GEN  600, 6, 1, 2000., -1.      $ FUEL PELLET 1
GEN  625, 6, 1, 2000., -1.      $ FUEL PELLET 2
GEN  400, 5, 1, 2000., -1.      $ IRIDIUM CLADDING 1
GEN  425, 5, 1, 2000., -1.      $ IRIDIUM CLADDING 2
GEN  500, 3, 1, 2000., -1.      $ FLOATING MEMBRANE
GEN  300, 3, 2, 2000., -1.      $ GIS
GEN  325, 3, 2, 2000., -1.      $ GIS
     340,       2000., -1.      $ GIS
GEN  202, 2, 4, 2000., -1.      $ CBCF SLEEVE (EXTERIOR)
GEN  207, 2, 4, 2000., -1.      $      "
GEN  212, 2, 4, 2000., -1.      $      "
GEN  217, 2, 4, 2000., -1.      $      "
GEN  227, 2, 4, 2000., -1.      $      "
GEN  232, 2, 4, 2000., -1.      $      "
GEN  237, 2, 4, 2000., -1.      $      "
GEN  242, 2, 4, 2000., -1.      $      "
GEN  233, 4, 5, 2000., -1.      $      "
GEN  702, 2, 4, 2000., -1.      $ CBCF SLEEVE (INTERIOR)
GEN  707, 2, 4, 2000., -1.      $      "
GEN  712, 2, 4, 2000., -1.      $      "
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 GEN  717, 2, 4, 2000., -1.        $      "
 GEN  727, 2, 4, 2000., -1.        $      "
 GEN  732, 2, 4, 2000., -1.        $      "
 GEN  737, 2, 4, 2000., -1.        $      "
 GEN  742, 2, 4, 2000., -1.        $      "
 GEN  733, 4, 5, 2000., -1.        $      "
 REM
 REM ******************  SIDE "B" NODES  ******************
 REM
 GEN 1600, 6, 1, 2000., -1.        $ FUEL PELLET 3
 GEN 1625, 6, 1, 2000., -1.        $ FUEL PELLET 4
 GEN 1400, 5, 1, 2000., -1.        $ IRIDIUM CLADDING 3
 GEN 1425, 5, 1, 2000., -1.        $ IRIDIUM CLADDING 4
 GEN 1500, 3, 1, 2000., -1.        $ FLOATING MEMBRANE
 GEN 1300, 3, 2, 2000., -1.        $ GIS
 GEN 1325, 3, 2, 2000., -1.        $ GIS
     1340,       2000., -1.        $ GIS
 GEN 1202, 2, 4, 2000., -1.        $ CBCF SLEEVE (EXTERIOR)
 GEN 1207, 2, 4, 2000., -1.        $      "
 GEN 1212, 2, 4, 2000., -1.        $      "
 GEN 1217, 2, 4, 2000., -1.        $      "
 GEN 1227, 2, 4, 2000., -1.        $      "
 GEN 1232, 2, 4, 2000., -1.        $      "
 GEN 1237, 2, 4, 2000., -1.        $      "
 GEN 1242, 2, 4, 2000., -1.        $      "
 GEN 1233, 4, 5, 2000., -1.        $      "
 GEN 1702, 2, 4, 2000., -1.        $ CBCF SLEEVE (INTERIOR)
 GEN 1707, 2, 4, 2000., -1.        $      "
 GEN 1712, 2, 4, 2000., -1.        $      "
 GEN 1717, 2, 4, 2000., -1.        $      "
 GEN 1727, 2, 4, 2000., -1.        $      "
 GEN 1732, 2, 4, 2000., -1.        $      "
 GEN 1737, 2, 4, 2000., -1.        $      "
 GEN 1742, 2, 4, 2000., -1.        $      "
 GEN 1733, 4, 5, 2000., -1.        $      "
 REM
 REM ******************  BOUNDARY NODES  ******************
 REM
    -10000, 1850., 1.              $ RADIATION SINK
 END
 BCD 3CONDUCTOR DATA
 REM
 REM ****************  AEROSHELL CONDUCTION  ****************
 REM
 SIM   101, 2, 1, 100, 0, 104, 1, A7, .01015
 SIM   103, 2, 1, 102, 0, 104, 1, A7, .01015
 DIM   105, 2, 1, 100, 0, 101, 2, A8, .05722, A7, .03982
 DIM   107, 2, 1, 102, 0, 101, 2, A8, .05722, A7, .03982
 DIM   109, 2, 1, 104, 0, 101, 2, A8, .05484, A7, .02996
 DIM   111, 2, 1, 105, 0, 101, 2, A8, .05484, A7, .02996
 REM
 REM *************  SIDE "A" INTERIOR CONDUCTORS  ***********
 REM
 SIV   600,        600,     601,     A1, 1.033       $ PELLET 1
 SIV   601,        601,     605,     A1, 2.221       $    "
 SIV   602,        605,     602,     A1, 6.235       $    "
 SIM   603, 2, 1, 600, 0, 603, 1, A1, .04736         $    "
 SIM   605, 2, 1, 601, 0, 603, 1, A1, .04736         $    "
 SIM   607, 2, 1, 605, 0, 603, 1, A1, .04736         $    "
 SIV   625,        625,     626,     A1, 1.033       $ PELLET 2
 SIV   626,        626,     630,     A1, 2.221       $    "
 SIV   627,        630,     627,     A1, 6.235       $    "
 SIM   628, 2, 1, 625, 0, 628, 1, A1, .04736         $    "
 SIM   630, 2, 1, 626, 0, 628, 1, A1, .04736         $    "
 SIM   632, 2, 1, 630, 0, 628, 1, A1, .04736         $    "
 SIM   400, 2, 1, 400, 4, 401, 2, A2, .002899        $ CLADING 1
 SIM   402, 2, 1, 401, 2, 402, 0, A2, .01301         $    "
 SIM   425, 2, 1, 425, 4, 426, 2, A2, .002899        $ CLADING 2
 SIM   427, 2, 1, 426, 2, 427, 0, A2, .01301         $    "
```

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SIV   500,       500,    501,    A5, .01773     $ FLTNG MEM.
SIV   501,       501,    502,    A5, .08229     $    "
SIM   300, 2, 1, 300,25, 302,25, A4, .04604     $ GIS
SIM   302, 2, 1, 302,25, 304,25, A3, .09564     $  "
SIM   304, 2, 1, 304,25, 340, 0, A3, .08398     $  "
REM                                      $ ** SLEEVE COND **
SIM   200, 4, 1, 202, 5, 702, 5, A6, .6875  $ THRU THICKNESS
SIM   204, 4, 1, 227, 5, 727, 5, A6, .6875  $        "
SIM   208, 4, 1, 206, 5, 706, 5, A6, 1.946  $        "
SIM   212, 4, 1, 231, 5, 731, 5, A6, 1.946  $        "
SIM   216, 4, 1, 233, 5, 733, 5, A6, .6733  $        "
SIM   240, 4, 1, 206, 5, 233, 5, A6, .01040 $ ALONG LENGTH
SIM   248, 4, 1, 231, 5, 233, 5, A6, .01040 $        "
SIM   256, 4, 1, 706, 5, 733, 5, A6, .01040 $        "
SIM   264, 4, 1, 731, 5, 733, 5, A6, .01040 $        "
SIM   268, 3, 1, 202, 5, 207, 5, A6, .002626$ CIRCUM ON ENDS
SIV   271,       217,    202,    A6, .002626$        "
SIM   272, 3, 1, 227, 5, 232, 5, A6, .002626$        "
SIV   275,       242,    227,    A6, .002626$        "
SIM   276, 3, 1, 702, 5, 707, 5, A6, .002626$        "
SIV   279,       717,    702,    A6, .002626$        "
SIM   280, 3, 1, 727, 5, 732, 5, A6, .002626$        "
SIV   283,       742,    727,    A6, .002626$        "
SIM   284, 3, 1, 206, 5, 211, 5, A6, .002858$ CRCM ON LENGTH
SIV   287,       221,    206,    A6, .002858$        "
SIM   288, 3, 1, 231, 5, 236, 5, A6, .002858$        "
SIV   291,       246,    231,    A6, .002858$        "
SIM   700, 3, 1, 706, 5, 711, 5, A6, .002858$        "
SIV   703,       721,    706,    A6, .002858$        "
SIM   704, 3, 1, 731, 5, 736, 5, A6, .002858$        "
SIV   707,       746,    731,    A6, .002858$        "
SIM   708, 3, 1, 233, 5, 238, 5, A6, .000989$        "
SIV   711,       248,    233,    A6, .000989$        "
SIM   712, 3, 1, 733, 5, 738, 5, A6, .000989$        "
SIV   715,       748,    733,    A6, .000989$        "
SIV - 800,       602,    402,    A11, 4.398E-11 $PT 1/CLD 1
SIM - 801, 2, 1, 603, 1, 400, 4, A11, 1.101E-11 $      "
SIV - 825,       627,    427,    A11, 4.398E-11 $PT 2/CLD 2
SIM - 826, 2, 1, 628, 1, 425, 4, A11, 1.101E-11 $      "
SIV - 803,       402,    304,    A12, 5.176E-11 $ CLAD 1/GIS
SIV - 804,       400,    300,    A13, 1.288E-11 $     "
SIV - 828,       427,    329,    A12, 5.176E-11 $ CLAD 2/GIS
SIV - 829,       425,    325,    A13, 1.288E-11 $     "
SIM - 805, 2, 1, 404, 0, 500, 1, A14, 0.644E-11 $ CLAD 1/FM
SIM - 830, 2, 1, 429, 0, 500, 1, A14, 0.644E-11 $ CLAD 2/FM
SIV - 824,       502,    340,    A15, 1.949E-11 $ FM/GIS
SIM - 832, 4, 1, 300, 0, 702, 5, A17, 5.615E-12 $ GIS/SLEEVE
SIM - 836, 4, 1, 325, 0, 727, 5, A17, 5.615E-12 $    "
SIM - 840, 4, 1, 304, 0, 706, 5, A16, 1.936E-11 $    "
SIM - 844, 4, 1, 329, 0, 731, 5, A16, 1.936E-11 $    "
SIM - 848, 4, 1, 340, 0, 733, 5, A16, 6.347E-12 $    "
REM
REM *************  SIDE "B" INTERIOR CONDUCTORS  ***********
REM
SIV  1600,      1600,   1601,    A1, 1.033      $ PELLET 3
SIV  1601,      1601,   1605,    A1, 2.221      $    "
SIV  1602,      1605,   1602,    A1, 6.235      $    "
SIM  1603, 2, 1,1600, 0,1603, 1, A1, .04736     $    "
SIM  1605, 2, 1,1601, 0,1603, 1, A1, .04736     $    "
SIM  1607, 2, 1,1605, 0,1603, 1, A1, .04736     $    "
SIV  1625,      1625,   1626,    A1, 1.033      $ PELLET 4
SIV  1626,      1626,   1630,    A1, 2.221      $    "
SIV  1627,      1630,   1627,    A1, 6.235      $    "
SIM  1628, 2, 1,1625, 0,1628, 1, A1, .04736     $    "
SIM  1630, 2, 1,1626, 0,1628, 1, A1, .04736     $    "
SIM  1632, 2, 1,1630, 0,1628, 1, A1, .04736     $    "
SIM  1400, 2, 1,1400, 4,1401, 2, A2, .002899    $ CLADING 3
SIM  1402, 2, 1,1401, 2,1402, 0, A2, .01301     $    "
SIM  1425, 2, 1,1425, 4,1426, 2, A2, .002899    $ CLADING 4
```

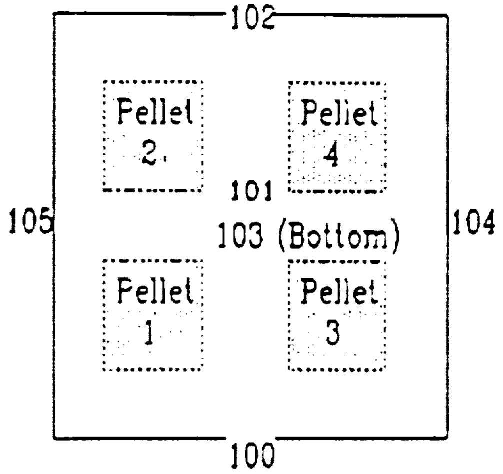
```
SIM  1427, 2, 1,1426, 2,1427, 0, A2, .01301      $    "
SIV  1500,       1500,   1501,    A5, .01773      $ FLTNG MEM.
SIV  1501,       1501,   1502,    A5, .08229      $    "
SIM  1300, 2, 1,1300,25,1302,25, A4, .04604      $ GIS
SIM  1302, 2, 1,1302,25,1304,25, A3, .09564      $  "
SIM  1304, 2, 1,1304,25,1340, 0, A3, .08398      $  "
REM                                         $ ** SLEEVE COND **
SIM  1200, 4, 1,1202, 5,1702, 5, A6, .6875  $ THRU THICKNESS
SIM  1204, 4, 1,1227, 5,1727, 5, A6, .6875  $       "
SIM  1208, 4, 1,1206, 5,1706, 5, A6, 1.946  $       "
SIM  1212, 4, 1,1231, 5,1731, 5, A6, 1.946  $       "
SIM  1216, 4, 1,1233, 5,1733, 5, A6, .6733  $       "
SIM  1240, 4, 1,1206, 5,1233, 5, A6, .01040 $ ALONG LENGTH
SIM  1248, 4, 1,1231, 5,1233, 5, A6, .01040 $       "
SIM  1256, 4, 1,1706, 5,1733, 5, A6, .01040 $       "
SIM  1264, 4, 1,1731, 5,1733, 5, A6, .01040 $       "
SIM  1268, 3, 1,1202, 5,1207, 5, A6, .002626$ CIRCUM ON ENDS
SIV  1271,       1217,   1202,    A6, .002626$      "
SIM  1272, 3, 1,1227, 5,1232, 5, A6, .002626$      "
SIV  1275,       1242,   1227,    A6, .002626$      "
SIM  1276, 3, 1,1702, 5,1707, 5, A6, .002626$      "
SIV  1279,       1717,   1702,    A6, .002626$      "
SIM  1280, 3, 1,1727, 5,1732, 5, A6, .002626$      "
SIV  1283,       1742,   1727,    A6, .002626$      "
SIM  1284, 3, 1,1206, 5,1211, 5, A6, .002858$ CRCM ON LENGTH
SIV  1287,       1221,   1206,    A6, .002858$      "
SIM  1288, 3, 1,1231, 5,1236, 5, A6, .002858$      "
SIV  1291,       1246,   1231,    A6, .002858$      "
SIM  1700, 3, 1,1706, 5,1711, 5, A6, .002858$      "
SIV  1703,       1721,   1706,    A6, .002858$      "
SIM  1704, 3, 1,1731, 5,1736, 5, A6, .002858$      "
SIV  1707,       1746,   1731,    A6, .002858$      "
SIM  1708, 3, 1,1233, 5,1238, 5, A6, .000989$      "
SIV  1711,       1248,   1233,    A6, .000989$      "
SIM  1712, 3, 1,1733, 5,1738, 5, A6, .000989$      "
SIV  1715,       1748,   1733,    A6, .000989$      "
SIV -1800,       1602,   1402,    A11, 4.398E-11 $PT 3/CLD 3
SIM -1801, 2, 1,1603, 1,1400, 4, A11, 1.101E-11 $      "
SIV -1825,       1627,   1427,    A11, 4.398E-11 $PT 4/CLD 4
SIM -1826, 2, 1,1628, 1,1425, 4, A11, 1.101E-11 $      "
SIV -1803,       1402,   1304,    A12, 5.176E-11 $ CLAD 3/GIS
SIV -1804,       1400,   1300,    A13, 1.288E-11 $     "
SIV -1828,       1427,   1329,    A12, 5.176E-11 $ CLAD 4/GIS
SIV -1829,       1425,   1325,    A13, 1.288E-11 $     "
SIM -1805, 2, 1,1404, 0,1500, 1, A14, 0.644E-11 $ CLAD 3/FM
SIM -1830, 2, 1,1429, 0,1500, 1, A14, 0.644E-11 $ CLAD 4/FM
SIV -1824,       1502,   1340,    A15, 1.949E-11 $ FM/GIS
SIM -1832, 4, 1,1300, 0,1702, 5, A17, 5.615E-12 $ GIS/SLEEVE
SIM -1836, 4, 1,1325, 0,1727, 5, A17, 5.615E-12 $    "
SIM -1840, 4, 1,1304, 0,1706, 5, A16, 1.936E-11 $    "
SIM -1844, 4, 1,1329, 0,1731, 5, A16, 1.936E-11 $    "
SIM -1848, 4, 1,1340, 0,1733, 5, A16, 6.347E-12 $    "
REM
REM     *** RADK'S BETWEEN SLEEVES AND AEROSHELL ***
REM
SIM - 901, 2, 1,  206,  10,  101, 2, A18, 2.142E-11 $ CYL/AS
SIM - 903, 2, 1, 1206,  10,  101, 2, A18, 2.142E-11 $   "
SIM - 905, 2, 1,  221, 990,  105,-1, A19, 2.142E-11 $   "
SIM - 907, 2, 1,  231,  10,  101, 2, A18, 2.142E-11 $   "
SIM - 909, 2, 1, 1231,  10,  101, 2, A18, 2.142E-11 $   "
SIM - 911, 2, 1,  246, 990,  105,-1, A19, 2.142E-11 $   "
SIM - 913, 2, 1,  233,  10,  101, 2, A18, 7.022E-12 $   "
SIM - 915, 2, 1, 1233,  10,  101, 2, A18, 7.022E-12 $   "
SIM - 917, 2, 1,  248, 990,  105,-1, A19, 7.022E-12 $   "
SIM - 919, 4, 1,  202,   5,  100, 0, A19, 6.873E-12 $ END
        CAPS/AS
SIM - 923, 4, 1, 1202,   5,  100, 0, A19, 6.873E-12 $   "
SIM - 927, 4, 1,  227,   5,  102, 0, A19, 6.873E-12 $   "
SIM - 931, 4, 1, 1227,   5,  102, 0, A19, 6.873E-12 $   "
```

```
    - 935,       238,       1248,          4.682E-12 $ SLV A
           /SLV B
GEN - 936, 2, 1,  211,   25,1221,27,       1.428E-11 $   "
REM
REM          *** RADK'S TO THE ENVIRONMENT ***
REM
SIV -1000, 100, 10000, A20, 9.518E-11 $ AEROSHELL FRONT
SIV -1001, 102, 10000, A20, 9.518E-11 $ AEROSHELL BACK
SIV -1002, 101, 10000, A21, 1.670E-10 $ AEROSHELL TOP
SIV -1003, 103, 10000, A21, 1.670E-10 $ AEROSHELL BOTTOM
SIV -1004, 104, 10000, A20, 9.125E-11 $ AEROSHELL RIGHT SIDE
SIV -1005, 105, 10000, A20, 9.125E-11 $ AEROSHELL LEFT  SIDE
END
BCD 3CONSTANTS DATA
    1, 62.5  $ POWER DISSIPATION PER PELLET (WATTS)
    NDIM=1000,ARLXCA=.05,DRLXCA=.05,NLOOP=1000
    BALENG=4.26
END
BCD 3ARRAY DATA
REM FUEL PELLET K(BTU/FT-HR-F) VS. T(F)
    1, -1000., .242, 100., .242, 572., .254, 752., .266
       932., .315, 1112., .325, 1292., .335, 1472., .545
       1652., .59, 1832., .635, 2012., .681, 2192., .726
       2500., .747, 3000., .78, 3500., .814, 4000., .848
       5000., .915, 20000., .915, END
REM IRIDIUM CLADING K(BTU/FT-HR-F) VS. T(F)
    2, -1000., 85., 0., 85., 1000., 79., 2000., 76.5
       3000., 65.5, 4000., 65., 20000., 65., END
REM GIS SIDES K(BTU/FT-HR-F) VS. T(F)
    3, -1000., 98.8, 0., 98.8, 500., 75.8, 750., 67.1
       1000., 59.6, 1250., 53.3, 1500., 48.3, 1750., 44.2
       2000., 40., 2500., 35., 3000., 30.8, 4000., 27.9
       4800., 26.6, 20000., 26.6, END
REM GIS END SECTION WITH HOLES K(BTU/FT-HR-F) VS. T(F)
    4, -1000., 63.8, 0., 63.8, 500., 49.7, 750., 44.
       1000., 38.7, 1250., 40.2, 1500., 30.9, 1750., 28.2
       2000., 26.2, 2500., 23.3, 3000., 22., 4000., 20.6
       7800., 20., 20000., 20., END
REM FLOATING MEMBRANE K(BTU/FT-HR-F) VS. T(F)
    5, -1000., 49.3, 100., 49.3, 500., 40.2, 750., 35.5
       1000., 31.2, 1250., 27.8, 1500., 25., 1750., 22.8
       2000., 21.1, 2500., 18.8, 3000., 17.8, 4000., 16.7
       4800., 16.1, 20000., 16.1, END
REM CBCF SLEEVE K(BTU/FT-HR-F) VS. T(F)
    6, -1000., .03545, 0., .03545, 392., .052, 572., .061
       752., .071, 932., .081, 1112., .086, 1292., .091
       1472., .096, 1652., .101, 1832., .107, 2012., .112
       2192., .117, 2372., .122, 2552., .128, 3000., .141
       4000., .171, 10000., .7, END
REM AEROSHELL X,Y DIR K(BTU/FT-HR-F) VS. T(F)
    7, -1000., 98.8, 0., 98.8, 500., 75.8, 750., 67.1
       1000., 59.6, 1250., 53.3, 1500., 48.3, 1750., 44.2
       2000., 40.0, 2500., 35.0, 3000., 30.8, 4000., 27.9
       4800., 26.6, 20000., 26.6, END
REM AEROSHELL Z DIR K(BTU/FT-HR-F) VS. T(F)
    8, -1000., 77.4, 0., 77.4, 500., 60.3, 750., 53.3
       1000., 46.9, 1250., 41.7, 1500., 37.5, 1750., 34.2
       2000., 31.7, 2500., 28.3, 3000., 26.7, 4000., 25.
       4800., 24.2, 20000., 24.2, END
REM "SCRIPT F" VS. T(F), PELLET-TO-CLADDING
    11, -1000., .0794, 0., .0794, 1000., .129, 2000., .181
        3000., .236, 4000., .294, 20000., .603, END
REM "SCRIPT F" VS. T(F), CLADDING-TO-GIS SIDES
    12, -1000., .0822, 0., .0822, 1000., .133, 2000., .184
        3000., .235, 4000., .285, 20000., .620, END
REM "SCRIPT F" VS. T(F), CLADING-TO-GIS ENDS
    13, -1000., .0812, 0., .0812, 1000., .132, 2000., .183
        3000., .235, 4000., .287, 20000., .620, END
REM "SCRIPT F" VS. T(F), CLADING-TO-FLOATING MEMBRANE
```

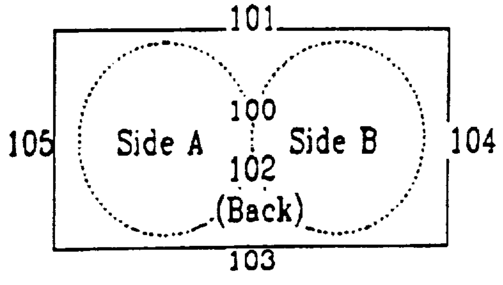
```
            14, -1000., .0812, 0., .0812, 1000., .132, 2000., .183
                3000., .235, 4000., .287, 20000., .620, END
        REM "SCRIPT F" VS. T(F), FLOATING MEMBRANE-TO-GIS
            15, -1000., .617, 0., .617, 500., .637, 750., .647
                1000., .657, 1250., .666, 1500., .669, 1750., .686
                2000., .696, 2500., .717, 3000., .738, 4000., .778
                4800., .813, 20000., 1., END
        REM "SCRIPT F" VS. T(F), GIS SIDES-TO-CBCF SLEEVE
            16, -1000., .675, 0., .675, 500., .676, 750., .678
                1000., .679, 1250., .681, 1500., .683, 1750., .686
                2000., .689, 2500., .694, 3000., .700, 4000., .711
                20000., .8, END
        REM "SCRIPT F" VS. T(F), GIS ENDS-TO-CBCF SLEEVE
            17, -1000., .610, 0., .610, 500., .628, 750., .637
                1000., .645, 1250., .652, 1500., .659, 1750., .667
                2000., .674, 2500., .688, 3000., .702, 4000., .725
                7800., .743, 20000., .8, END
        REM "SCRIPT F" VS. T(F), CBCF SLEEVE-TO-AEROSHELL TOP & BOT
            18, -1000., .553, 0., .553, 500., .578, 750., .593
                1000., .607, 1250., .620, 1500., .633, 1750., .646
                2000., .658, 2500., .680, 3000., .703, 4000., .738
                4800., .763, 20000., .8, END
        REM "SCRIPT F" VS. T(F), CBCF SLEEVE-TO-AEROSHELL SIDES
            19, -1000., .675, 0., .675, 500., .676, 750., .678
                1000., .679, 1250., .681, 1500., .683, 1750., .686
                2000., .689, 2500., .694, 3000., .700, 4000., .711
                4800., .723, 20000., .8, END
        REM EMISSIVITY VS. T(F), AEROSHELL X,Y DIRECTION
            20, -1000., .812, 0., .812, 500., .814, 750., .816
                1000., .818, 1250., .821, 1500., .824, 1750., .828
                2000., .832, 2500., .84 , 3000., .848, 4000., .865
                4800., .882, 20000., 1., END
        REM EMISSIVITY VS. T(F), AEROSHELL Z DIRECTION
            21, -1000., .642, 0., .642, 500., .675, 750., .696
                1000., .716, 1250., .734, 1500., .752, 1750., .77
                2000., .788, 2500., .82 , 3000., .853, 4000., .905
                4800., .943, 20000., 1., END
        END
        BCD 3EXECUTION
            STDSTL
        END
        BCD 3VARIABLES 1
        REM STORE POWER DISSIPATIONS
M       Q600 = XK1 * 3.412 / 3.
M       Q601 = XK1 * 3.412 / 3.
M       Q605 = XK1 * 3.412 / 3.
M       Q625 = XK1 * 3.412 / 3.
M       Q626 = XK1 * 3.412 / 3.
M       Q630 = XK1 * 3.412 / 3.
M       Q1600 = XK1 * 3.412 / 3.
M       Q1601 = XK1 * 3.412 / 3.
M       Q1605 = XK1 * 3.412 / 3.
M       Q1625 = XK1 * 3.412 / 3.
M       Q1626 = XK1 * 3.412 / 3.
M       Q1630 = XK1 * 3.412 / 3.
        END
        BCD 3VARIABLES 2
        END
        BCD 3OUTPUT CALLS
            QIPRNT
            TPRINT
        END
        BCD 3END OF DATA
```

II. GPHS THERMAL MODEL NODAL ARRANGEMENT

Aeroshell Nodal Arrangement
&
General Model Layout



Top View

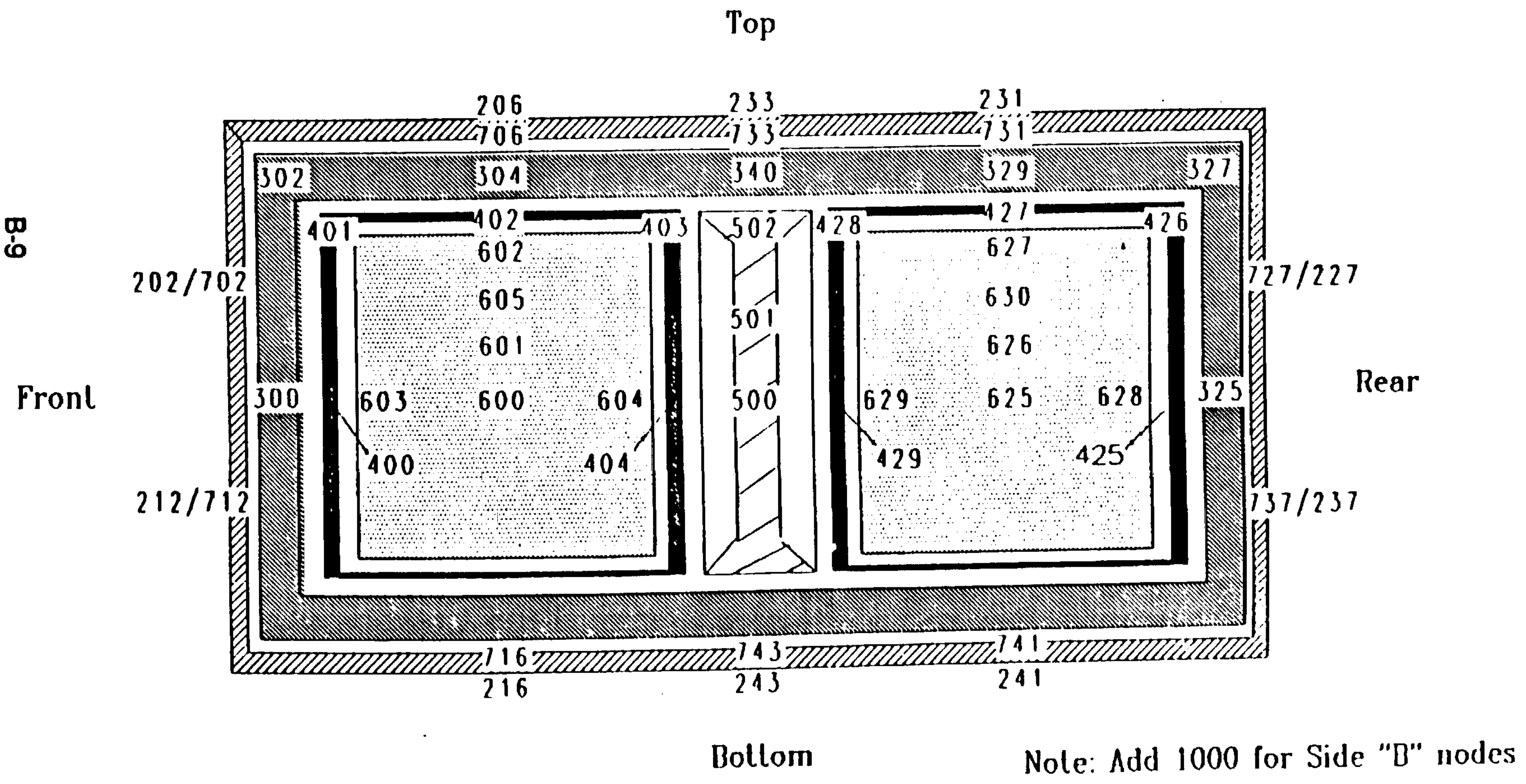


Front View

GPHS Interior

Nodal Arrangement

(Side "A")

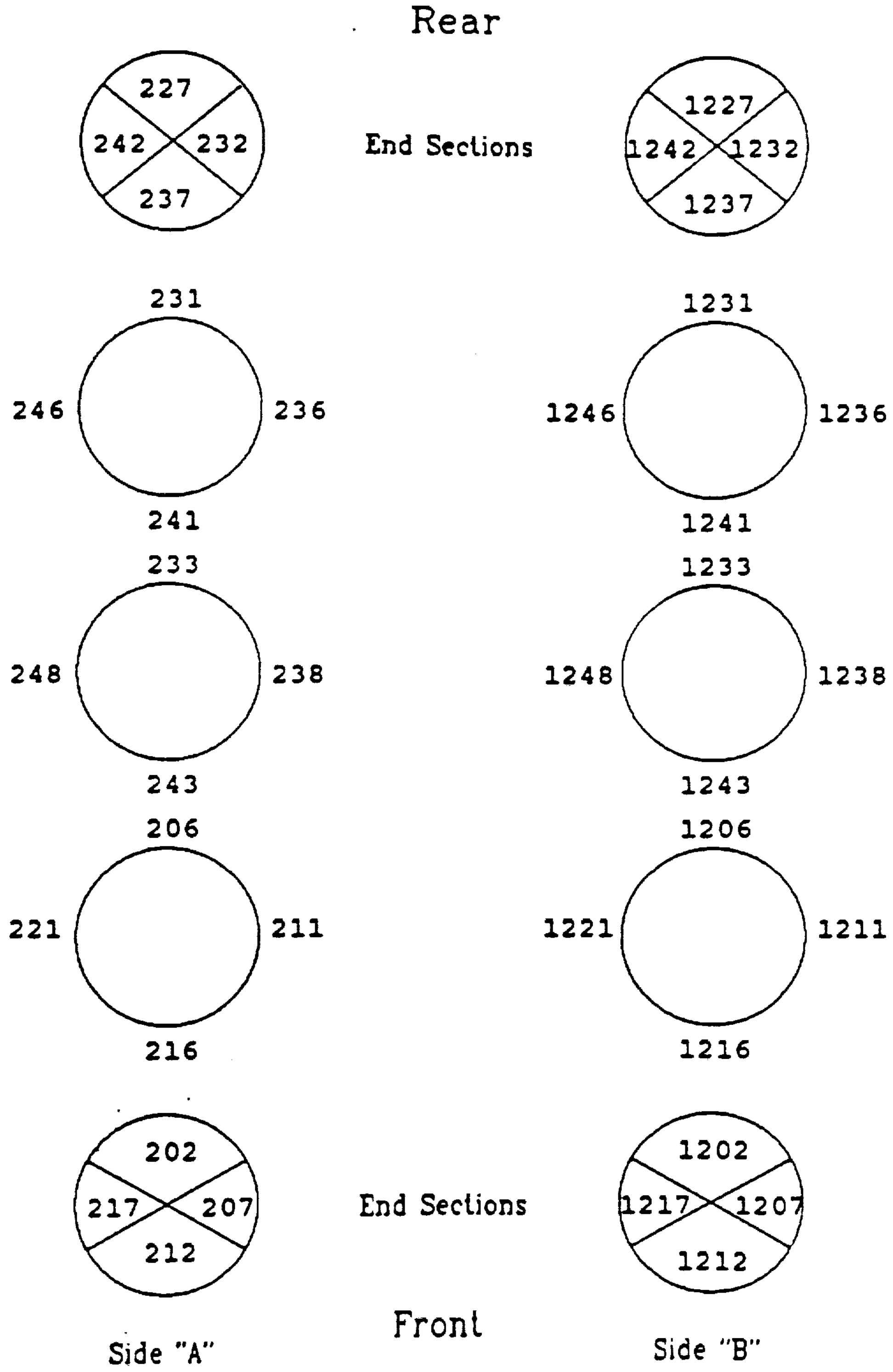


Note: Add 1000 for Side "B" nodes

CBCF Sleeve

Nodal Arrangement

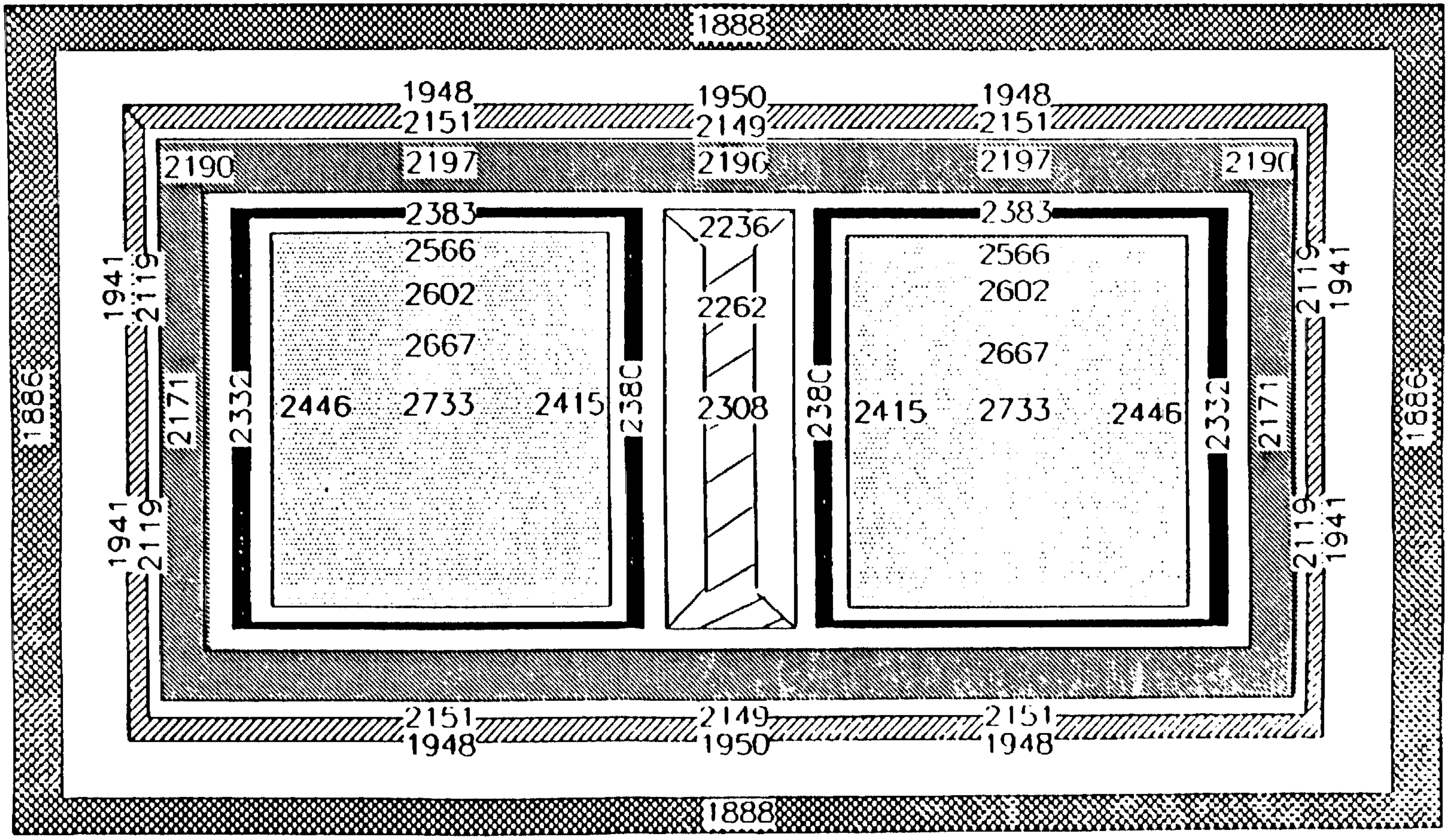
Note: Exterior nodes shown
Interior nodes are 700 series
View Looking from the front



III. GPHS INTERIOR NODAL TEMPERATURES FOR FOUR DIFFERENT THERMAL ENVIRONMENTS

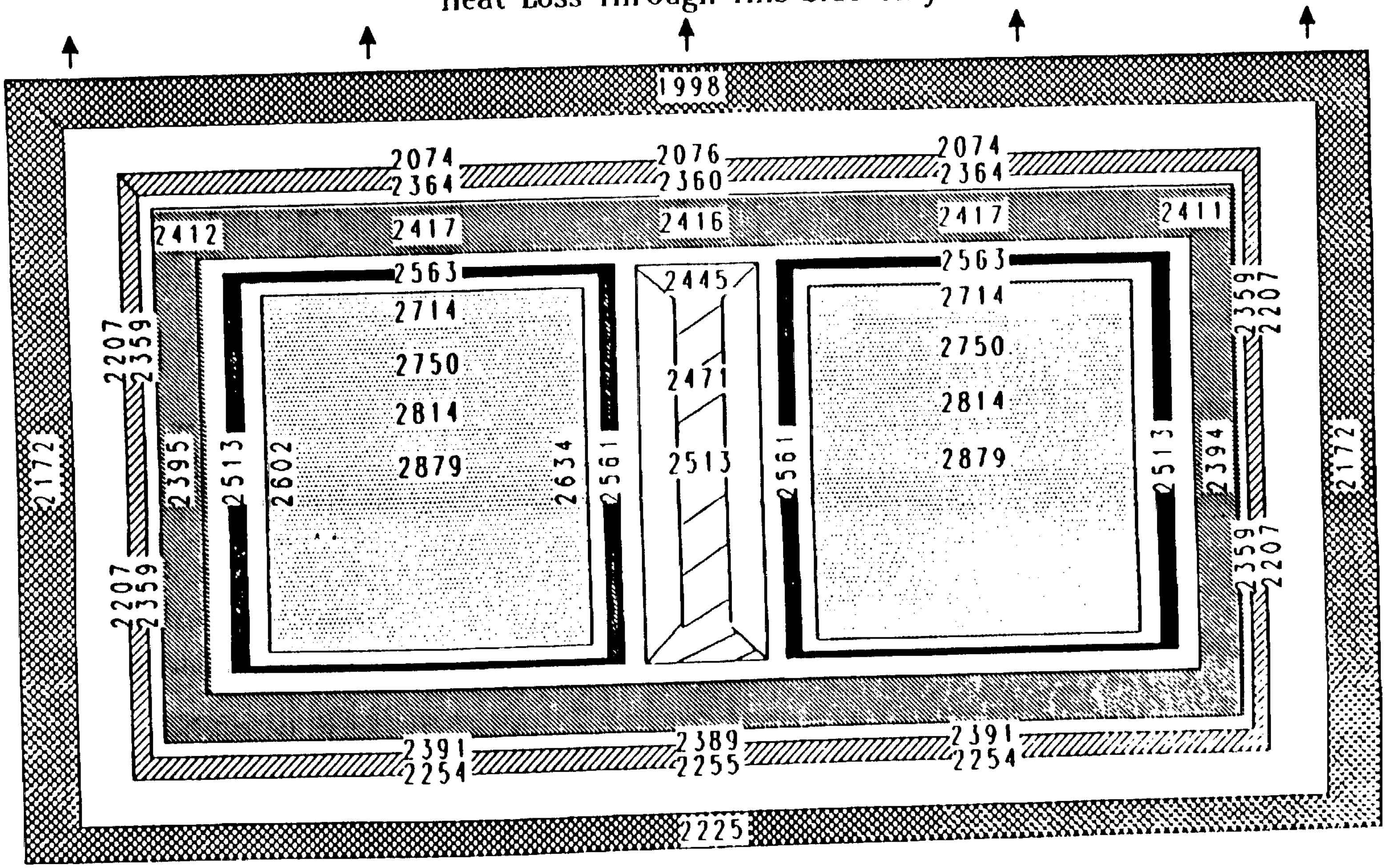
GPHS Temperatures

Comparison case with G.E.
Heat loss on all sides
Environment at 1850 Deg F
Temperatures in Deg F



GPHS Temperatures

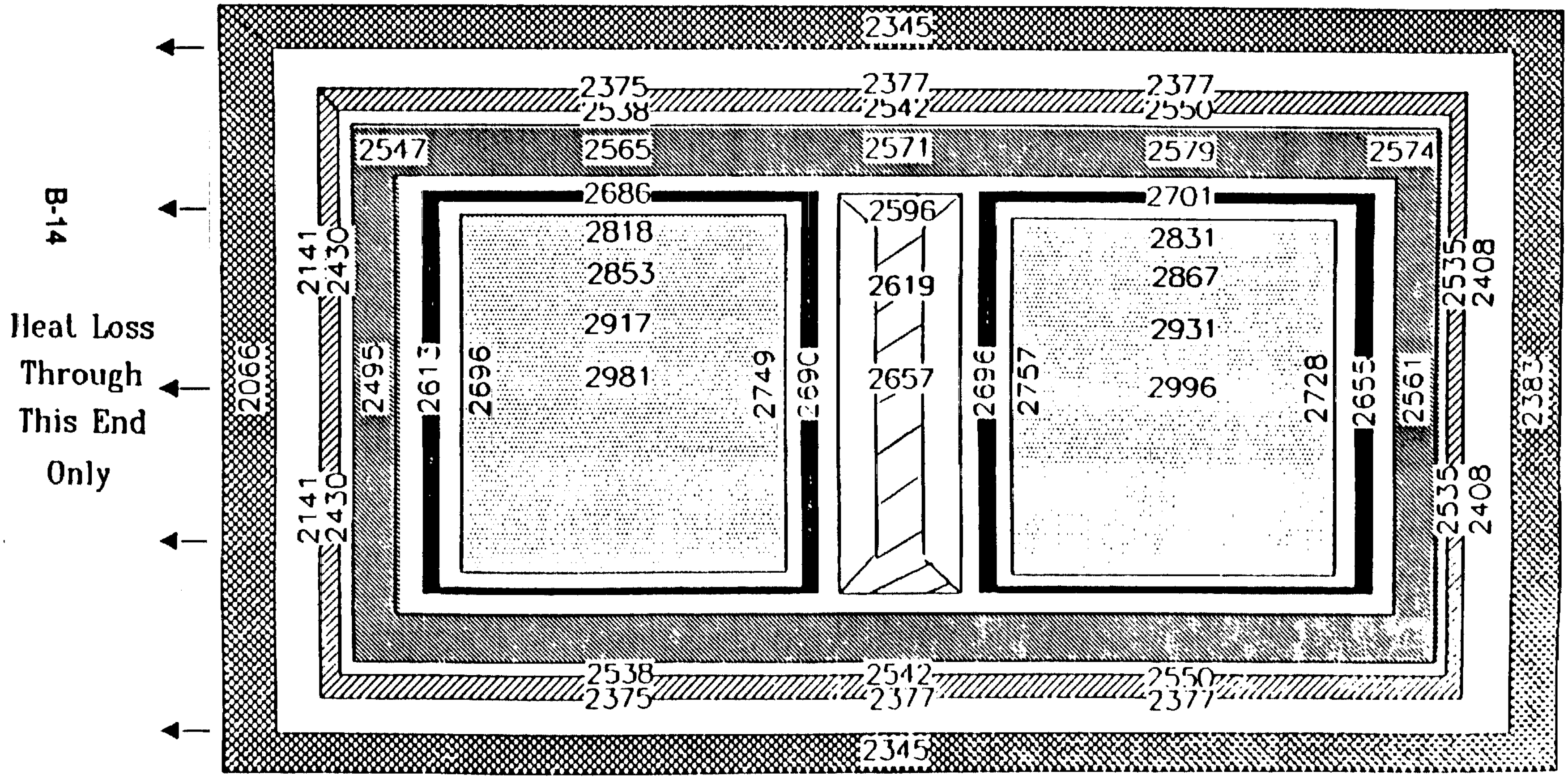
Environment at 1880 Deg F
Temperatures in Deg F



GPHS Temperatures

Environment at 1880 Deg F

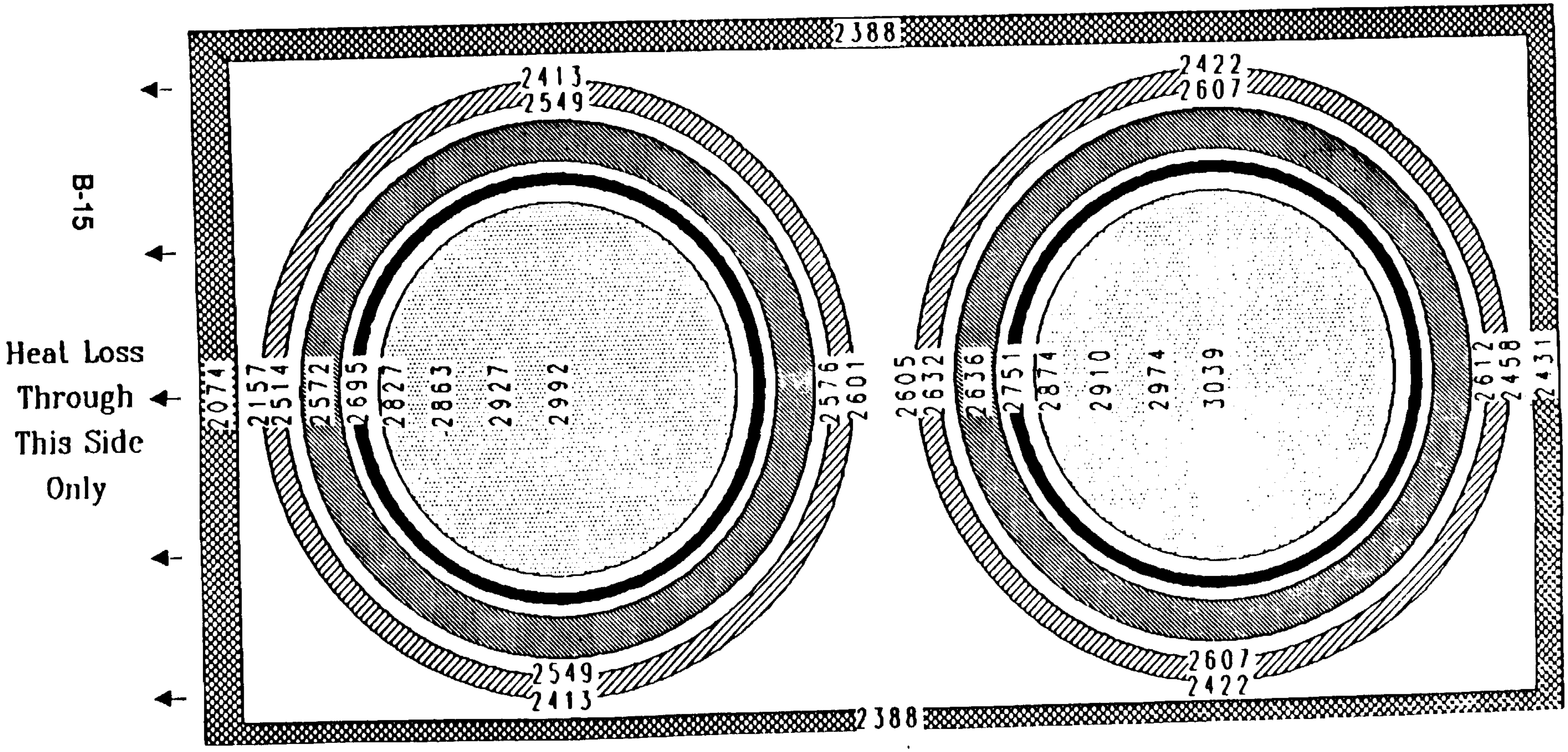
Temperatures in Deg F



GPHS Temperatures

Environment at 1880 Deg F

Temperatures in Deg F



APPENDIX C

TRASYS INPUT FILE FOR THERMAL ANALYSIS OF THE 250 W_e GPHS/FPSE POWER SYSTEM

```
HEADER OPTIONS DATA
TITLE GPHS/FPSE 250We POWER SYSTEM
      MODEL = DOPS
      RSO = RSOUT2
HEADER SURFACE DATA
C
D     0.08333
C
BCS   BSRL     $ HEAT SINK CYLINDER
S     SURFN=10100
      TYPE=CYL, ACTIVE=OUT
      ALPHA=1.0, EMISS=0.8
      SHADE=BOTH, BSHADE=BOTH
      R = 1.0
      ZMIN = 0.0
      ZMAX = 3.0
      AXMIN = 0.0
      AXMAX = 360.0
      NNAX = 1
      NNZ = 1
C
C
BCS   BSHD      $ DISK-SHAPED END CAP TO HEAT SINK
S     SURFN=10200
      TYPE=DISK, ACTIVE=TOP
      ALPHA=1.0, EMISS=0.2
      SHADE=BOTH, BSHADE=BOTH
      Z = 3.0
      RMIN = 0.0
      RMAX = 1.0
      AXMIN = 0.0
      AXMAX = 360.0
      NNAX = 1
      NNR = 1
C
C
BCS   GPHS1       $ GPHS RADIOISOTOPE HEAT SOURCE
S     SURFN = 100
      TYPE = BOX6, ACTIVE = OUT
      ALPHA = 1.0, EMISS = 0.8
      SHADE = BOTH, BSHADE = BOTH
      P1 = 3.826, 2.09, 3.668
C
C
BCS   GPHS2       $ GPHS RADIOISOTOPE HEAT SOURCE
S     SURFN = 2100
      TYPE = BOX6, ACTIVE = OUT
      ALPHA = 1.0, EMISS = 0.8
      SHADE = BOTH, BSHADE = BOTH
      P1 = 3.826, 2.09, 3.668
C
```

```
C
BCS   GPHS3        $ GPHS RADIOISOTOPE HEAT SOURCE
S      SURFN = 4100
       TYPE = BOX6, ACTIVE = OUT
       ALPHA = 1.0, EMISS = 0.8
       SHADE = BOTH, BSHADE = BOTH
       P1 = 3.826, 2.09, 3.668
C
C
BCS   GPHS4        $ GPHS RADIOISOTOPE HEAT SOURCE
S      SURFN = 6100
       TYPE = BOX6, ACTIVE = OUT
       ALPHA = 1.0, EMISS = 0.8
       SHADE = BOTH, BSHADE = BOTH
       P1 = 3.826, 2.09, 3.668
C
C
BCS   WALL         $ CYLINDRICAL INNER SURFACE OF
C                    POWER SYSTEM ENCLOSURE
S      SURFN = 10400
       TYPE = CYL, ACTIVE = IN
       ALPHA = 1.0, EMISS = 0.1
       SHADE = BOTH, BSHADE = BOTH
       R = 4.8
       ZMIN = 0.0
       ZMAX = 4.668
       AXMIN = 0.0
       AXMAX = 360.0
       NNAX = 1
       NNZ = 1
C
C
BCS   BSRT         $ DISK-SHAPED INNER SURFACE ON HEATER
C                    HEAD END OF POWER SYSTEM ENCLOSURE
S      SURFN = 10500
       TYPE=DISK, ACTIVE=TOP
       ALPHA=1.0, EMISS=0.1
       SHADE=BOTH, BSHADE=BOTH
       Z = 0.0
       RMIN = 1.0
       RMAX = 4.8
       AXMIN = 0.0
       AXMAX = 360.0
       NNAX = 1
       NNR = 1
C
C
BCS   TSRT           $ DISK-SHAPED INNER SURFACE AT OPPOSITE
C                      END OF POWER SYSTEM ENCLOSURE
S      SURFN = 10600
       TYPE=DISK, ACTIVE=BOTTOM
       ALPHA=1.0, EMISS=0.1
       SHADE=BOTH, BSHADE=BOTH
       Z = 4.668
       RMIN = 0.0
       RMAX = 4.8
       AXMIN = 0.0
       AXMAX = 360.0
       NNAX = 1
       NNR = 1
C
C
HEADER BCS DATA
C
C              POSITIONING OF GPHS MODULES
C
BCS   BSRL,     0.0, 0.0, 0.0, 0.0, 0.0, 0.0
BCS   BSHD,     0.0, 0.0, 0.0, 0.0, 0.0, 0.0
BCS   GPHS1,     5.126524E-3,  0.230576, 4.16667E-2, 0.0, 0.0, -45.0
```

```
BCS   GPHS2,   -0.230576,  5.126524E-3, 4.16667E-2, 0.0, 0.0,  45.0
BCS   GPHS3,   -5.126524E-3, -0.230576, 4.16667E-2, 0.0, 0.0, 135.0
BCS   GPHS4,    0.230576, -5.126524E-3, 4.16667E-2, 0.0, 0.0,-135.0
BCS   WALL,    0.0, 0.0, 0.0, 0.0, 0.0, 0.0
BCS   BSRT,    0.0, 0.0, 0.0, 0.0, 0.0, 0.0
BCS   TSRT,    0.0, 0.0, 0.0, 0.0, 0.0, 0.0
HEADER OPERATIONS DATA
BUILD DOPS,BSRL,BSHD,GPHS1,GPHS2,GPHS3,GPHS4,WALL,BSRT,TSRT
C
C     CALCULATION OF GEOMETRIC CONFIGURATION FACTORS
L     FFCAL
C
C     GRAY BODY CALCULATIONS
      CALL GBDATA('BOTH',' ','FF')
L     GBCAL
C
C     CALCULATION OF RADIATION CONDUCTORS
      CALL RKDATA(' ',' ',0,0,'NO',0,0,0,'YES',' ')
L     RKCAL
C
END OF DATA
```

APPENDIX D

SINDA INPUT DECK FOR THERMAL ANALYSIS OF THE 250 W_e GPHS/FPSE POWER SYSTEM

```
BCD 3THERMAL LPCS
BCD 9 GPHS/FPSE 250We STEADY STATE THERMAL MODEL
BCD 9
END
REM ***********
BCD 3NODE DATA
REM ***********
REM
REM
REM ********  POWER SYSTEM ENCLOSURE NODES  ********
REM
GEN 10400,   3, 100,  1500., -1.     $ INTERIOR
GEN 10700,   3, 100,   200., -1.     $ EXTERIOR
REM
REM
REM *********  END CAP TO HEAT SINK NODE  **********
REM
    10200,            1500., -1.     $ DISK
REM
REM
REM ***************  BOUNDARY NODES  ***************
REM
    -99999,           -460.,  1.     $ RADIATING TO SPACE
    -10100,           1430.,  1.     $ HEAT SINK CYLINDER
REM
REM
REM ****************  GPHS 1 NODES  ****************
REM
REM
REM     ********  AEROSHELL #1 NODES  ********
REM
GEN  100, 6, 1, 2000., -1.
REM
REM     **********  SIDE "1A" NODES  *********
REM
GEN  600, 6, 1, 2000., -1.       $ FUEL PELLET 1
GEN  625, 6, 1, 2000., -1.       $ FUEL PELLET 2
GEN  400, 5, 1, 2000., -1.       $ IRIDIUM CLADDING 1
GEN  425, 5, 1, 2000., -1.       $ IRIDIUM CLADDING 2
GEN  500, 3, 1, 2000., -1.       $ FLOATING MEMBRANE
GEN  300, 3, 2, 2000., -1.       $ GIS
GEN  325, 3, 2, 2000., -1.       $ GIS
     340,       2000., -1.       $ GIS
GEN  202, 2, 4, 2000., -1.       $ CBCF SLEEVE (EXTERIOR)
GEN  207, 2, 4, 2000., -1.       $      "
GEN  212, 2, 4, 2000., -1.       $      "
GEN  217, 2, 4, 2000., -1.       $      "
GEN  227, 2, 4, 2000., -1.       $      "
GEN  232, 2, 4, 2000., -1.       $      "
GEN  237, 2, 4, 2000., -1.       $      "
```

```
GEN  242, 2, 4, 2000., -1.      $      "
GEN  233, 4, 5, 2000., -1.      $      "
GEN  702, 2, 4, 2000., -1.      $ CBCF SLEEVE (INTERIOR)
GEN  707, 2, 4, 2000., -1.      $      "
GEN  712, 2, 4, 2000., -1.      $      "
GEN  717, 2, 4, 2000., -1.      $      "
GEN  727, 2, 4, 2000., -1.      $      "
GEN  732, 2, 4, 2000., -1.      $      "
GEN  737, 2, 4, 2000., -1.      $      "
GEN  742, 2, 4, 2000., -1.      $      "
GEN  733, 4, 5, 2000., -1.      $      "
REM
REM      **********  SIDE "1B" NODES  *********
REM
GEN 1600, 6, 1, 2000., -1.      $ FUEL PELLET 3
GEN 1625, 6, 1, 2000., -1.      $ FUEL PELLET 4
GEN 1400, 5, 1, 2000., -1.      $ IRIDIUM CLADDING 3
GEN 1425, 5, 1, 2000., -1.      $ IRIDIUM CLADDING 4
GEN 1500, 3, 1, 2000., -1.      $ FLOATING MEMBRANE
GEN 1300, 3, 2, 2000., -1.      $ GIS
GEN 1325, 3, 2, 2000., -1.      $ GIS
    1340,       2000., -1.      $ GIS
GEN 1202, 2, 4, 2000., -1.      $ CBCF SLEEVE (EXTERIOR)
GEN 1207, 2, 4, 2000., -1.      $      "
GEN 1212, 2, 4, 2000., -1.      $      "
GEN 1217, 2, 4, 2000., -1.      $      "
GEN 1227, 2, 4, 2000., -1.      $      "
GEN 1232, 2, 4, 2000., -1.      $      "
GEN 1237, 2, 4, 2000., -1.      $      "
GEN 1242, 2, 4, 2000., -1.      $      "
GEN 1233, 4, 5, 2000., -1.      $      "
GEN 1702, 2, 4, 2000., -1.      $ CBCF SLEEVE (INTERIOR)
GEN 1707, 2, 4, 2000., -1.      $      "
GEN 1712, 2, 4, 2000., -1.      $      "
GEN 1717, 2, 4, 2000., -1.      $      "
GEN 1727, 2, 4, 2000., -1.      $      "
GEN 1732, 2, 4, 2000., -1.      $      "
GEN 1737, 2, 4, 2000., -1.      $      "
GEN 1742, 2, 4, 2000., -1.      $      "
GEN 1733, 4, 5, 2000., -1.      $      "
REM
REM
REM ****************  GPHS 2 NODES  ****************
REM
REM
REM      ********  AEROSHELL #2 NODES  ********
REM
GEN 2100, 6, 1, 2000., -1.
REM
REM      **********  SIDE "2A" NODES  *********
REM
GEN 2600, 6, 1, 2000., -1.      $ FUEL PELLET 1
GEN 2625, 6, 1, 2000., -1.      $ FUEL PELLET 2
GEN 2400, 5, 1, 2000., -1.      $ IRIDIUM CLADDING 1
GEN 2425, 5, 1, 2000., -1.      $ IRIDIUM CLADDING 2
GEN 2500, 3, 1, 2000., -1.      $ FLOATING MEMBRANE
GEN 2300, 3, 2, 2000., -1.      $ GIS
GEN 2325, 3, 2, 2000., -1.      $ GIS
    2340,       2000., -1.      $ GIS
GEN 2202, 2, 4, 2000., -1.      $ CBCF SLEEVE (EXTERIOR)
GEN 2207, 2, 4, 2000., -1.      $      "
GEN 2212, 2, 4, 2000., -1.      $      "
GEN 2217, 2, 4, 2000., -1.      $      "
GEN 2227, 2, 4, 2000., -1.      $      "
GEN 2232, 2, 4, 2000., -1.      $      "
GEN 2237, 2, 4, 2000., -1.      $      "
GEN 2242, 2, 4, 2000., -1.      $      "
GEN 2233, 4, 5, 2000., -1.      $      "
GEN 2702, 2, 4, 2000., -1.      $ CBCF SLEEVE (INTERIOR)
```

```
GEN 2707, 2, 4, 2000., -1.        $      "
GEN 2712, 2, 4, 2000., -1.        $      "
GEN 2717, 2, 4, 2000., -1.        $      "
GEN 2727, 2, 4, 2000., -1.        $      "
GEN 2732, 2, 4, 2000., -1.        $      "
GEN 2737, 2, 4, 2000., -1.        $      "
GEN 2742, 2, 4, 2000., -1.        $      "
GEN 2733, 4, 5, 2000., -1.        $      "
REM
REM      **********  SIDE "2B" NODES  *********
REM
GEN 3600, 6, 1, 2000., -1.        $ FUEL PELLET 3
GEN 3625, 6, 1, 2000., -1.        $ FUEL PELLET 4
GEN 3400, 5, 1, 2000., -1.        $ IRIDIUM CLADDING 3
GEN 3425, 5, 1, 2000., -1.        $ IRIDIUM CLADDING 4
GEN 3500, 3, 1, 2000., -1.        $ FLOATING MEMBRANE
GEN 3300, 3, 2, 2000., -1.        $ GIS
GEN 3325, 3, 2, 2000., -1.        $ GIS
    3340,       2000., -1.        $ GIS
GEN 3202, 2, 4, 2000., -1.        $ CBCF SLEEVE (EXTERIOR)
GEN 3207, 2, 4, 2000., -1.        $      "
GEN 3212, 2, 4, 2000., -1.        $      "
GEN 3217, 2, 4, 2000., -1.        $      "
GEN 3227, 2, 4, 2000., -1.        $      "
GEN 3232, 2, 4, 2000., -1.        $      "
GEN 3237, 2, 4, 2000., -1.        $      "
GEN 3242, 2, 4, 2000., -1.        $      "
GEN 3233, 4, 5, 2000., -1.        $      "
GEN 3702, 2, 4, 2000., -1.        $ CBCF SLEEVE (INTERIOR)
GEN 3707, 2, 4, 2000., -1.        $      "
GEN 3712, 2, 4, 2000., -1.        $      "
GEN 3717, 2, 4, 2000., -1.        $      "
GEN 3727, 2, 4, 2000., -1.        $      "
GEN 3732, 2, 4, 2000., -1.        $      "
GEN 3737, 2, 4, 2000., -1.        $      "
GEN 3742, 2, 4, 2000., -1.        $      "
GEN 3733, 4, 5, 2000., -1.        $      "
REM
REM
REM ****************  GPHS 3 NODES  ****************
REM
REM
REM      ********  AEROSHELL #3 NODES  ********
REM
GEN 4100, 6, 1, 2000., -1.
REM
REM      **********  SIDE "3A" NODES  *********
REM
GEN 4600, 6, 1, 2000., -1.        $ FUEL PELLET 1
GEN 4625, 6, 1, 2000., -1.        $ FUEL PELLET 2
GEN 4400, 5, 1, 2000., -1.        $ IRIDIUM CLADDING 1
GEN 4425, 5, 1, 2000., -1.        $ IRIDIUM CLADDING 2
GEN 4500, 3, 1, 2000., -1.        $ FLOATING MEMBRANE
GEN 4300, 3, 2, 2000., -1.        $ GIS
GEN 4325, 3, 2, 2000., -1.        $ GIS
    4340,       2000., -1.        $ GIS
GEN 4202, 2, 4, 2000., -1.        $ CBCF SLEEVE (EXTERIOR)
GEN 4207, 2, 4, 2000., -1.        $      "
GEN 4212, 2, 4, 2000., -1.        $      "
GEN 4217, 2, 4, 2000., -1.        $      "
GEN 4227, 2, 4, 2000., -1.        $      "
GEN 4232, 2, 4, 2000., -1.        $      "
GEN 4237, 2, 4, 2000., -1.        $      "
GEN 4242, 2, 4, 2000., -1.        $      "
GEN 4233, 4, 5, 2000., -1.        $      "
GEN 4702, 2, 4, 2000., -1.        $ CBCF SLEEVE (INTERIOR)
GEN 4707, 2, 4, 2000., -1.        $      "
GEN 4712, 2, 4, 2000., -1.        $      "
GEN 4717, 2, 4, 2000., -1.        $      "
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GEN 4727, 2, 4, 2000., -1.       $      "
GEN 4732, 2, 4, 2000., -1.       $      "
GEN 4737, 2, 4, 2000., -1.       $      "
GEN 4742, 2, 4, 2000., -1.       $      "
GEN 4733, 4, 5, 2000., -1.       $      "
REM
REM      **********  SIDE "3B" NODES  *********
REM
GEN 5600, 6, 1, 2000., -1.       $ FUEL PELLET 3
GEN 5625, 6, 1, 2000., -1.       $ FUEL PELLET 4
GEN 5400, 5, 1, 2000., -1.       $ IRIDIUM CLADDING 3
GEN 5425, 5, 1, 2000., -1.       $ IRIDIUM CLADDING 4
GEN 5500, 3, 1, 2000., -1.       $ FLOATING MEMBRANE
GEN 5300, 3, 2, 2000., -1.       $ GIS
GEN 5325, 3, 2, 2000., -1.       $ GIS
    5340,       2000., -1.       $ GIS
GEN 5202, 2, 4, 2000., -1.       $ CBCF SLEEVE (EXTERIOR)
GEN 5207, 2, 4, 2000., -1.       $      "
GEN 5212, 2, 4, 2000., -1.       $      "
GEN 5217, 2, 4, 2000., -1.       $      "
GEN 5227, 2, 4, 2000., -1.       $      "
GEN 5232, 2, 4, 2000., -1.       $      "
GEN 5237, 2, 4, 2000., -1.       $      "
GEN 5242, 2, 4, 2000., -1.       $      "
GEN 5233, 4, 5, 2000., -1.       $      "
GEN 5702, 2, 4, 2000., -1.       $ CBCF SLEEVE (INTERIOR)
GEN 5707, 2, 4, 2000., -1.       $      "
GEN 5712, 2, 4, 2000., -1.       $      "
GEN 5717, 2, 4, 2000., -1.       $      "
GEN 5727, 2, 4, 2000., -1.       $      "
GEN 5732, 2, 4, 2000., -1.       $      "
GEN 5737, 2, 4, 2000., -1.       $      "
GEN 5742, 2, 4, 2000., -1.       $      "
GEN 5733, 4, 5, 2000., -1.       $      "
REM
REM
REM ****************  GPHS 4 NODES  ****************
REM
REM
REM      ********  AEROSHELL #4 NODES  ********
REM
GEN 6100, 6, 1, 2000., -1.
REM
REM      **********  SIDE "4A" NODES  *********
REM
GEN 6600, 6, 1, 2000., -1.       $ FUEL PELLET 1
GEN 6625, 6, 1, 2000., -1.       $ FUEL PELLET 2
GEN 6400, 5, 1, 2000., -1.       $ IRIDIUM CLADDING 1
GEN 6425, 5, 1, 2000., -1.       $ IRIDIUM CLADDING 2
GEN 6500, 3, 1, 2000., -1.       $ FLOATING MEMBRANE
GEN 6300, 3, 2, 2000., -1.       $ GIS
GEN 6325, 3, 2, 2000., -1.       $ GIS
    6340,       2000., -1.       $ GIS
GEN 6202, 2, 4, 2000., -1.       $ CBCF SLEEVE (EXTERIOR)
GEN 6207, 2, 4, 2000., -1.       $      "
GEN 6212, 2, 4, 2000., -1.       $      "
GEN 6217, 2, 4, 2000., -1.       $      "
GEN 6227, 2, 4, 2000., -1.       $      "
GEN 6232, 2, 4, 2000., -1.       $      "
GEN 6237, 2, 4, 2000., -1.       $      "
GEN 6242, 2, 4, 2000., -1.       $      "
GEN 6233, 4, 5, 2000., -1.       $      "
GEN 6702, 2, 4, 2000., -1.       $ CBCF SLEEVE (INTERIOR)
GEN 6707, 2, 4, 2000., -1.       $      "
GEN 6712, 2, 4, 2000., -1.       $      "
GEN 6717, 2, 4, 2000., -1.       $      "
GEN 6727, 2, 4, 2000., -1.       $      "
GEN 6732, 2, 4, 2000., -1.       $      "
GEN 6737, 2, 4, 2000., -1.       $      "
```

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GEN 6742, 2, 4, 2000., -1.       $      "
GEN 6733, 4, 5, 2000., -1.       $      "
REM
REM      **********  SIDE "4B" NODES  *********
REM
GEN 7600, 6, 1, 2000., -1.       $ FUEL PELLET 3
GEN 7625, 6, 1, 2000., -1.       $ FUEL PELLET 4
GEN 7400, 5, 1, 2000., -1.       $ IRIDIUM CLADDING 3
GEN 7425, 5, 1, 2000., -1.       $ IRIDIUM CLADDING 4
GEN 7500, 3, 1, 2000., -1.       $ FLOATING MEMBRANE
GEN 7300, 3, 2, 2000., -1.       $ GIS
GEN 7325, 3, 2, 2000., -1.       $ GIS
    7340,       2000., -1.       $ GIS
GEN 7202, 2, 4, 2000., -1.       $ CBCF SLEEVE (EXTERIOR)
GEN 7207, 2, 4, 2000., -1.       $      "
GEN 7212, 2, 4, 2000., -1.       $      "
GEN 7217, 2, 4, 2000., -1.       $      "
GEN 7227, 2, 4, 2000., -1.       $      "
GEN 7232, 2, 4, 2000., -1.       $      "
GEN 7237, 2, 4, 2000., -1.       $      "
GEN 7242, 2, 4, 2000., -1.       $      "
GEN 7233, 4, 5, 2000., -1.       $      "
GEN 7702, 2, 4, 2000., -1.       $ CBCF SLEEVE (INTERIOR)
GEN 7707, 2, 4, 2000., -1.       $      "
GEN 7712, 2, 4, 2000., -1.       $      "
GEN 7717, 2, 4, 2000., -1.       $      "
GEN 7727, 2, 4, 2000., -1.       $      "
GEN 7732, 2, 4, 2000., -1.       $      "
GEN 7737, 2, 4, 2000., -1.       $      "
GEN 7742, 2, 4, 2000., -1.       $      "
GEN 7733, 4, 5, 2000., -1.       $      "
REM
REM
REM
END
REM***************************************************
REM***************************************************
REM
BCD 3CONDUCTOR DATA
REM
REM***************************************************
REM***************************************************
REM
REM
REM *************************************************
REM         CONDUCTANCE BETWEEN INTERIOR AND
REM        EXTERIOR OF POWER SYSTEM ENCLOSURE
REM *************************************************
REM
    -10401, 10400, 10700, 1.0E-25     $ CYLINDER
    -10501, 10500, 10800, 1.0E-25     $ HEAT SINK END
    -10601, 10600, 10900, 1.0E-25     $ OPPOSITE END
REM
REM
REM *************************************************
REM                RADKS TO SPACE
REM *************************************************
REM
    -10701, 10700, 99999, 2.496E-10   $ CYL: STRUCTURE - SPACE
    -10801, 10800, 99999, 1.094E-10   $ BOT: STRUCTURE - SPACE
    -10901, 10900, 99999, 1.131E-10   $ TOP: STRUCTURE - SPACE
REM
REM
REM *************************************************
REM         CONDUCTION DATA FOR HEAT TRANSFER
REM         BETWEEN SIDES OF EACH GPHS BLOCK
REM *************************************************
REM
REM      ******  AEROSHELL 1 CONDUCTION  ******
```

```
REM
SIM  8101, 2, 1, 100, 0, 104,-2, A7, .01015
SIM  8103, 2, 1, 105, 0, 104,-2, A7, .01015
DIM  8105, 2, 1, 100, 0, 101, 2, A8, .05722, A7, .03982
DIM  8107, 2, 1, 105, 0, 101, 2, A8, .05722, A7, .03982
DIM  8109, 2, 1, 104, 0, 101, 2, A8, .05484, A7, .02996
DIM  8111, 2, 1, 102, 0, 101, 2, A8, .05484, A7, .02996
REM
REM
REM      ******  AEROSHELL 2 CONDUCTION  ******
REM
SIM  2101, 2, 1,2100, 0,2104,-2, A7, .01015
SIM  2103, 2, 1,2105, 0,2104,-2, A7, .01015
DIM  2105, 2, 1,2100, 0,2101, 2, A8, .05722, A7, .03982
DIM  2107, 2, 1,2105, 0,2101, 2, A8, .05722, A7, .03982
DIM  2109, 2, 1,2104, 0,2101, 2, A8, .05484, A7, .02996
DIM  2111, 2, 1,2102, 0,2101, 2, A8, .05484, A7, .02996
REM
REM
REM      ******  AEROSHELL 3 CONDUCTION  ******
REM
SIM  4101, 2, 1,4100, 0,4104,-2, A7, .01015
SIM  4103, 2, 1,4105, 0,4104,-2, A7, .01015
DIM  4105, 2, 1,4100, 0,4101, 2, A8, .05722, A7, .03982
DIM  4107, 2, 1,4105, 0,4101, 2, A8, .05722, A7, .03982
DIM  4109, 2, 1,4104, 0,4101, 2, A8, .05484, A7, .02996
DIM  4111, 2, 1,4102, 0,4101, 2, A8, .05484, A7, .02996
REM
REM
REM      ******  AEROSHELL 4 CONDUCTION  ******
REM
SIM  6101, 2, 1,6100, 0,6104,-2, A7, .01015
SIM  6103, 2, 1,6105, 0,6104,-2, A7, .01015
DIM  6105, 2, 1,6100, 0,6101, 2, A8, .05722, A7, .03982
DIM  6107, 2, 1,6105, 0,6101, 2, A8, .05722, A7, .03982
DIM  6109, 2, 1,6104, 0,6101, 2, A8, .05484, A7, .02996
DIM  6111, 2, 1,6102, 0,6101, 2, A8, .05484, A7, .02996
REM
REM ************************************************
REM         CONDUCTANCES BETWEEN INTERIOR
REM             NODES OF GPHS BLOCKS
REM ************************************************
REM
REM   **  GPHS 1, SIDE "A" INTERIOR CONDUCTORS  **
REM
SIV  8600,         600,     601,     A1, 1.033      $ PELLET 1
SIV  8601,         601,     605,     A1, 2.221      $    "
SIV  8602,         605,     602,     A1, 6.235      $    "
SIM  8603, 2, 1, 600, 0, 603, 1, A1, .04736     $    "
SIM  8605, 2, 1, 601, 0, 603, 1, A1, .04736     $    "
SIM  8607, 2, 1, 605, 0, 603, 1, A1, .04736     $    "
SIV  8625,         625,     626,     A1, 1.033      $ PELLET 2
SIV  8626,         626,     630,     A1, 2.221      $    "
SIV  8627,         630,     627,     A1, 6.235      $    "
SIM  8628, 2, 1, 625, 0, 628, 1, A1, .04736     $    "
SIM  8630, 2, 1, 626, 0, 628, 1, A1, .04736     $    "
SIM  8632, 2, 1, 630, 0, 628, 1, A1, .04736     $    "
SIM  8400, 2, 1, 400, 4, 401, 2, A2, .002899    $ CLADING 1
SIM  8402, 2, 1, 401, 2, 402, 0, A2, .01301     $    "
SIM  8425, 2, 1, 425, 4, 426, 2, A2, .002899    $ CLADING 2
SIM  8427, 2, 1, 426, 2, 427, 0, A2, .01301     $    "
SIV  8500,         500,     501,     A5, .01773     $ FLOATING MEM.
SIV  8501,         501,     502,     A5, .08229     $    "
SIM  8300, 2, 1, 300,25, 302,25, A4, .04604     $ GIS
SIM  8302, 2, 1, 302,25, 304,25, A3, .09564     $  "
SIM  8304, 2, 1, 304,25, 340, 0, A3, .08398     $  "
REM                                           $ ** SLEEVE COND **
SIM  8200, 4, 1, 202, 5, 702, 5, A6, .6875  $ THRU THICKNESS
SIM  8204, 4, 1, 227, 5, 727, 5, A6, .6875  $       "
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SIM  8208, 4, 1, 206, 5, 706, 5, A6, 1.946  $       "
SIM  8212, 4, 1, 231, 5, 731, 5, A6, 1.946  $       "
SIM  8216, 4, 1, 233, 5, 733, 5, A6, .6733  $       "
SIM  8240, 4, 1, 206, 5, 233, 5, A6, .01040 $ ALONG LENGTH
SIM  8248, 4, 1, 231, 5, 233, 5, A6, .01040 $       "
SIM  8256, 4, 1, 706, 5, 733, 5, A6, .01040 $       "
SIM  8264, 4, 1, 731, 5, 733, 5, A6, .01040 $       "
SIM  8268, 3, 1, 202, 5, 207, 5, A6, .002626$ CIRCUMF ON ENDS
SIV  8271,       217,     202,     A6, .002626$      "
SIM  8272, 3, 1, 227, 5, 232, 5, A6, .002626$      "
SIV  8275,       242,     227,     A6, .002626$      "
SIM  8276, 3, 1, 702, 5, 707, 5, A6, .002626$      "
SIV  8279,       717,     702,     A6, .002626$      "
SIM  8280, 3, 1, 727, 5, 732, 5, A6, .002626$      "
SIV  8283,       742,     727,     A6, .002626$      "
SIM  8284, 3, 1, 206, 5, 211, 5, A6, .002858$ CIRCUMF ON LENGTH
SIV  8287,       221,     206,     A6, .002858$      "
SIM  8288, 3, 1, 231, 5, 236, 5, A6, .002858$      "
SIV  8291,       246,     231,     A6, .002858$      "
SIM  8700, 3, 1, 706, 5, 711, 5, A6, .002858$      "
SIV  8703,       721,     706,     A6, .002858$      "
SIM  8704, 3, 1, 731, 5, 736, 5, A6, .002858$      "
SIV  8707,       746,     731,     A6, .002858$      "
SIM  8708, 3, 1, 233, 5, 238, 5, A6, .000989$      "
SIV  8711,       248,     233,     A6, .000989$      "
SIM  8712, 3, 1, 733, 5, 738, 5, A6, .000989$      "
SIV  8715,       748,     733,     A6, .000989$      "
SIV -8800,       602,     402,     A11, 4.398E-11 $ PELLET 1/CLAD 1
SIM -8801, 2, 1, 603, 1, 400, 4, A11, 1.101E-11 $        "
SIV -8825,       627,     427,     A11, 4.398E-11 $ PELLET 2/CLAD 2
SIM -8826, 2, 1, 628, 1, 425, 4, A11, 1.101E-11 $        "
SIV -8803,       402,     304,     A12, 5.176E-11 $ CLAD 1/GIS
SIV -8804,       400,     300,     A13, 1.288E-11 $      "
SIV -8828,       427,     329,     A12, 5.176E-11 $ CLAD 2/GIS
SIV -8829,       425,     325,     A13, 1.288E-11 $      "
SIM -8805, 2, 1, 404, 0, 500, 1, A14, 0.644E-11 $ CLAD 1/FM
SIM -8830, 2, 1, 429, 0, 500, 1, A14, 0.644E-11 $ CLAD 2/FM
SIV -8824,       502,     340,     A15, 1.949E-11 $ FM/GIS
SIM -8832, 4, 1, 300, 0, 702, 5, A17, 5.615E-12 $ GIS/SLEEVE
SIM -8836, 4, 1, 325, 0, 727, 5, A17, 5.615E-12 $     "
SIM -8840, 4, 1, 304, 0, 706, 5, A16, 1.936E-11 $     "
SIM -8844, 4, 1, 329, 0, 731, 5, A16, 1.936E-11 $     "
SIM -8848, 4, 1, 340, 0, 733, 5, A16, 6.347E-12 $     "
REM
REM   **  GPHS 1, SIDE "B" INTERIOR CONDUCTORS  **
REM
SIV  1600,       1600,    1601,    A1, 1.033      $ PELLET 3
SIV  1601,       1601,    1605,    A1, 2.221      $    "
SIV  1602,       1605,    1602,    A1, 6.235      $    "
SIM  1603, 2, 1,1600, 0,1603, 1, A1, .04736     $    "
SIM  1605, 2, 1,1601, 0,1603, 1, A1, .04736     $    "
SIM  1607, 2, 1,1605, 0,1603, 1, A1, .04736     $    "
SIV  1625,       1625,    1626,    A1, 1.033      $ PELLET 4
SIV  1626,       1626,    1630,    A1, 2.221      $    "
SIV  1627,       1630,    1627,    A1, 6.235      $    "
SIM  1628, 2, 1,1625, 0,1628, 1, A1, .04736     $    "
SIM  1630, 2, 1,1626, 0,1628, 1, A1, .04736     $    "
SIM  1632, 2, 1,1630, 0,1628, 1, A1, .04736     $    "
SIM  1400, 2, 1,1400, 4,1401, 2, A2, .002899    $ CLADING 3
SIM  1402, 2, 1,1401, 2,1402, 0, A2, .01301     $    "
SIM  1425, 2, 1,1425, 4,1426, 2, A2, .002899    $ CLADING 4
SIM  1427, 2, 1,1426, 2,1427, 0, A2, .01301     $    "
SIV  1500,       1500,    1501,    A5, .01773     $ FLOATING MEM.
SIV  1501,       1501,    1502,    A5, .08229     $    "
SIM  1300, 2, 1,1300,25,1302,25, A4, .04604     $ GIS
SIM  1302, 2, 1,1302,25,1304,25, A3, .09564     $  "
SIM  1304, 2, 1,1304,25,1340, 0, A3, .08398     $  "
REM                                         $ ** SLEEVE COND **
SIM  1200, 4, 1,1202, 5,1702, 5, A6, .6875  $ THRU THICKNESS
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SIM  1204, 4, 1,1227, 5,1727, 5, A6, .6875  $      "
SIM  1208, 4, 1,1206, 5,1706, 5, A6, 1.946  $      "
SIM  1212, 4, 1,1231, 5,1731, 5, A6, 1.946  $      "
SIM  1216, 4, 1,1233, 5,1733, 5, A6, .6733  $      "
SIM  1240, 4, 1,1206, 5,1233, 5, A6, .01040 $ ALONG LENGTH
SIM  1248, 4, 1,1231, 5,1233, 5, A6, .01040 $      "
SIM  1256, 4, 1,1706, 5,1733, 5, A6, .01040 $      "
SIM  1264, 4, 1,1731, 5,1733, 5, A6, .01040 $      "
SIM  1268, 3, 1,1202, 5,1207, 5, A6, .002626$ CIRCUMF ON ENDS
SIV  1271,       1217,   1202,    A6, .002626$      "
SIM  1272, 3, 1,1227, 5,1232, 5, A6, .002626$      "
SIV  1275,       1242,   1227,    A6, .002626$      "
SIM  1276, 3, 1,1702, 5,1707, 5, A6, .002626$      "
SIV  1279,       1717,   1702,    A6, .002626$      "
SIM  1280, 3, 1,1727, 5,1732, 5, A6, .002626$      "
SIV  1283,       1742,   1727,    A6, .002626$      "
SIM  1284, 3, 1,1206, 5,1211, 5, A6, .002858$ CIRCUMF ON LENGTH
SIV  1287,       1221,   1206,    A6, .002858$      "
SIM  1288, 3, 1,1231, 5,1236, 5, A6, .002858$      "
SIV  1291,       1246,   1231,    A6, .002858$      "
SIM  1700, 3, 1,1706, 5,1711, 5, A6, .002858$      "
SIV  1703,       1721,   1706,    A6, .002858$      "
SIM  1704, 3, 1,1731, 5,1736, 5, A6, .002858$      "
SIV  1707,       1746,   1731,    A6, .002858$      "
SIM  1708, 3, 1,1233, 5,1238, 5, A6, .000989$      "
SIV  1711,       1248,   1233,    A6, .000989$      "
SIM  1712, 3, 1,1733, 5,1738, 5, A6, .000989$      "
SIV  1715,       1748,   1733,    A6, .000989$      "
SIV -1800,       1602,   1402,    A11, 4.398E-11 $ PELLET 3/CLAD 3
SIM -1801, 2, 1,1603, 1,1400, 4, A11, 1.101E-11 $      "
SIV -1825,       1627,   1427,    A11, 4.398E-11 $ PELLET 4/CLAD 4
SIM -1826, 2, 1,1628, 1,1425, 4, A11, 1.101E-11 $      "
SIV -1803,       1402,   1304,    A12, 5.176E-11 $ CLAD 3/GIS
SIV -1804,       1400,   1300,    A13, 1.288E-11 $     "
SIV -1828,       1427,   1329,    A12, 5.176E-11 $ CLAD 4/GIS
SIV -1829,       1425,   1325,    A13, 1.288E-11 $     "
SIM -1805, 2, 1,1404, 0,1500, 1, A14, 0.644E-11 $ CLAD 3/FM
SIM -1830, 2, 1,1429, 0,1500, 1, A14, 0.644E-11 $ CLAD 4/FM
SIV -1824,       1502,   1340,    A15, 1.949E-11 $ FM/GIS
SIM -1832, 4, 1,1300, 0,1702, 5, A17, 5.615E-12 $ GIS/SLEEVE
SIM -1836, 4, 1,1325, 0,1727, 5, A17, 5.615E-12 $    "
SIM -1840, 4, 1,1304, 0,1706, 5, A16, 1.936E-11 $    "
SIM -1844, 4, 1,1329, 0,1731, 5, A16, 1.936E-11 $    "
SIM -1848, 4, 1,1340, 0,1733, 5, A16, 6.347E-12 $    "
REM
REM
REM   **  GPHS 2, SIDE "A" INTERIOR CONDUCTORS  **
REM
SIV  2600,       2600,   2601,    A1, 1.033      $ PELLET 1
SIV  2601,       2601,   2605,    A1, 2.221      $    "
SIV  2602,       2605,   2602,    A1, 6.235      $    "
SIM  2603, 2, 1,2600, 0,2603, 1, A1, .04736     $    "
SIM  2605, 2, 1,2601, 0,2603, 1, A1, .04736     $    "
SIM  2607, 2, 1,2605, 0,2603, 1, A1, .04736     $    "
SIV  2625,       2625,   2626,    A1, 1.033      $ PELLET 2
SIV  2626,       2626,   2630,    A1, 2.221      $    "
SIV  2627,       2630,   2627,    A1, 6.235      $    "
SIM  2628, 2, 1,2625, 0,2628, 1, A1, .04736     $    "
SIM  2630, 2, 1,2626, 0,2628, 1, A1, .04736     $    "
SIM  2632, 2, 1,2630, 0,2628, 1, A1, .04736     $    "
SIM  2400, 2, 1,2400, 4,2401, 2, A2, .002899    $ CLADING 1
SIM  2402, 2, 1,2401, 2,2402, 0, A2, .01301     $    "
SIM  2425, 2, 1,2425, 4,2426, 2, A2, .002899    $ CLADING 2
SIM  2427, 2, 1,2426, 2,2427, 0, A2, .01301     $    "
SIV  2500,       2500,   2501,    A5, .01773     $ FLOATING MEM.
SIV  2501,       2501,   2502,    A5, .08229     $    "
SIM  2300, 2, 1,2300,25,2302,25, A4, .04604     $ GIS
SIM  2302, 2, 1,2302,25,2304,25, A3, .09564     $  "
SIM  2304, 2, 1,2304,25,2340, 0, A3, .08398     $  "
```

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REM                                             $ ** SLEEVE COND **
SIM  2200, 4, 1,2202, 5,2702, 5, A6, .6875  $ THRU THICKNESS
SIM  2204, 4, 1,2227, 5,2727, 5, A6, .6875  $      "
SIM  2208, 4, 1,2206, 5,2706, 5, A6, 1.946  $      "
SIM  2212, 4, 1,2231, 5,2731, 5, A6, 1.946  $      "
SIM  2216, 4, 1,2233, 5,2733, 5, A6, .6733  $      "
SIM  2240, 4, 1,2206, 5,2233, 5, A6, .01040 $ ALONG LENGTH
SIM  2248, 4, 1,2231, 5,2233, 5, A6, .01040 $      "
SIM  2256, 4, 1,2706, 5,2733, 5, A6, .01040 $      "
SIM  2264, 4, 1,2731, 5,2733, 5, A6, .01040 $      "
SIM  2268, 3, 1,2202, 5,2207, 5, A6, .002626$ CIRCUMF ON ENDS
SIV  2271,       2217,   2202,    A6, .002626$     "
SIM  2272, 3, 1,2227, 5,2232, 5, A6, .002626$     "
SIV  2275,       2242,   2227,    A6, .002626$     "
SIM  2276, 3, 1,2702, 5,2707, 5, A6, .002626$     "
SIV  2279,       2717,   2702,    A6, .002626$     "
SIM  2280, 3, 1,2727, 5,2732, 5, A6, .002626$     "
SIV  2283,       2742,   2727,    A6, .002626$     "
SIM  2284, 3, 1,2206, 5,2211, 5, A6, .002858$ CIRCUMF ON LENGTH
SIV  2287,       2221,   2206,    A6, .002858$     "
SIM  2288, 3, 1,2231, 5,2236, 5, A6, .002858$     "
SIV  2291,       2246,   2231,    A6, .002858$     "
SIM  2700, 3, 1,2706, 5,2711, 5, A6, .002858$     "
SIV  2703,       2721,   2706,    A6, .002858$     "
SIM  2704, 3, 1,2731, 5,2736, 5, A6, .002858$     "
SIV  2707,       2746,   2731,    A6, .002858$     "
SIM  2708, 3, 1,2233, 5,2238, 5, A6, .000989$     "
SIV  2711,       2248,   2233,    A6, .000989$     "
SIM  2712, 3, 1,2733, 5,2738, 5, A6, .000989$     "
SIV  2715,       2748,   2733,    A6, .000989$     "
SIV -2800,       2602,   2402,    A11, 4.398E-11 $ PELLET 1/CLAD 1
SIM -2801, 2, 1,2603, 1,2400, 4, A11, 1.101E-11 $      "
SIV -2825,       2627,   2427,    A11, 4.398E-11 $ PELLET 2/CLAD 2
SIM -2826, 2, 1,2628, 1,2425, 4, A11, 1.101E-11 $      "
SIV -2803,       2402,   2304,    A12, 5.176E-11 $ CLAD 1/GIS
SIV -2804,       2400,   2300,    A13, 1.288E-11 $    "
SIV -2828,       2427,   2329,    A12, 5.176E-11 $ CLAD 2/GIS
SIV -2829,       2425,   2325,    A13, 1.288E-11 $    "
SIM -2805, 2, 1,2404, 0,2500, 1, A14, 0.644E-11 $ CLAD 1/FM
SIM -2830, 2, 1,2429, 0,2500, 1, A14, 0.644E-11 $ CLAD 2/FM
SIV -2824,       2502,   2340,    A15, 1.949E-11 $ FM/GIS
SIM -2832, 4, 1,2300, 0,2702, 5, A17, 5.615E-12 $ GIS/SLEEVE
SIM -2836, 4, 1,2325, 0,2727, 5, A17, 5.615E-12 $    "
SIM -2840, 4, 1,2304, 0,2706, 5, A16, 1.936E-11 $    "
SIM -2844, 4, 1,2329, 0,2731, 5, A16, 1.936E-11 $    "
SIM -2848, 4, 1,2340, 0,2733, 5, A16, 6.347E-12 $    "
REM
REM   **  GPHS 2, SIDE "B" INTERIOR CONDUCTORS  **
REM
SIV  3600,       3600,   3601,    A1, 1.033      $ PELLET 3
SIV  3601,       3601,   3605,    A1, 2.221      $    "
SIV  3602,       3605,   3602,    A1, 6.235      $    "
SIM  3603, 2, 1,3600, 0,3603, 1, A1, .04736     $    "
SIM  3605, 2, 1,3601, 0,3603, 1, A1, .04736     $    "
SIM  3607, 2, 1,3605, 0,3603, 1, A1, .04736     $    "
SIV  3625,       3625,   3626,    A1, 1.033      $ PELLET 4
SIV  3626,       3626,   3630,    A1, 2.221      $    "
SIV  3627,       3630,   3627,    A1, 6.235      $    "
SIM  3628, 2, 1,3625, 0,3628, 1, A1, .04736     $    "
SIM  3630, 2, 1,3626, 0,3628, 1, A1, .04736     $    "
SIM  3632, 2, 1,3630, 0,3628, 1, A1, .04736     $    "
SIM  3400, 2, 1,3400, 4,3401, 2, A2, .002899    $ CLADING 3
SIM  3402, 2, 1,3401, 2,3402, 0, A2, .01301     $    "
SIM  3425, 2, 1,3425, 4,3426, 2, A2, .002899    $ CLADING 4
SIM  3427, 2, 1,3426, 2,3427, 0, A2, .01301     $    "
SIV  3500,       3500,   3501,    A5, .01773     $ FLOATING MEM.
SIV  3501,       3501,   3502,    A5, .08229     $    "
SIM  3300, 2, 1,3300,25,3302,25, A4, .04604     $ GIS
SIM  3302, 2, 1,3302,25,3304,25, A3, .09564     $  "
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SIM  3304, 2, 1,3304,25,3340, 0, A3, .08398     $ "
REM                                            $ ** SLEEVE COND **
SIM  3200, 4, 1,3202, 5,3702, 5, A6, .6875  $ THRU THICKNESS
SIM  3204, 4, 1,3227, 5,3727, 5, A6, .6875  $       "
SIM  3208, 4, 1,3206, 5,3706, 5, A6, 1.946  $       "
SIM  3212, 4, 1,3231, 5,3731, 5, A6, 1.946  $       "
SIM  3216, 4, 1,3233, 5,3733, 5, A6, .6733  $       "
SIM  3240, 4, 1,3206, 5,3233, 5, A6, .01040 $ ALONG LENGTH
SIM  3248, 4, 1,3231, 5,3233, 5, A6, .01040 $       "
SIM  3256, 4, 1,3706, 5,3733, 5, A6, .01040 $       "
SIM  3264, 4, 1,3731, 5,3733, 5, A6, .01040 $       "
SIM  3268, 3, 1,3202, 5,3207, 5, A6, .002626$ CIRCUMF ON ENDS
SIV  3271,       3217,   3202,    A6, .002626$      "
SIM  3272, 3, 1,3227, 5,3232, 5, A6, .002626$      "
SIV  3275,       3242,   3227,    A6, .002626$      "
SIM  3276, 3, 1,3702, 5,3707, 5, A6, .002626$      "
SIV  3279,       3717,   3702,    A6, .002626$      "
SIM  3280, 3, 1,3727, 5,3732, 5, A6, .002626$      "
SIV  3283,       3742,   3727,    A6, .002626$      "
SIM  3284, 3, 1,3206, 5,3211, 5, A6, .002858$ CIRCUMF ON LENGTH
SIV  3287,       3221,   3206,    A6, .002858$      "
SIM  3288, 3, 1,3231, 5,3236, 5, A6, .002858$      "
SIV  3291,       3246,   3231,    A6, .002858$      "
SIM  3700, 3, 1,3706, 5,3711, 5, A6, .002858$      "
SIV  3703,       3721,   3706,    A6, .002858$      "
SIM  3704, 3, 1,3731, 5,3736, 5, A6, .002858$      "
SIV  3707,       3746,   3731,    A6, .002858$      "
SIM  3708, 3, 1,3233, 5,3238, 5, A6, .000989$      "
SIV  3711,       3248,   3233,    A6, .000989$      "
SIM  3712, 3, 1,3733, 5,3738, 5, A6, .000989$      "
SIV  3715,       3748,   3733,    A6, .000989$      "
SIV -3800,       3602,   3402,    A11, 4.398E-11 $ PELLET 3/CLAD 3
SIM -3801, 2, 1,3603, 1,3400, 4, A11, 1.101E-11 $      "
SIV -3825,       3627,   3427,    A11, 4.398E-11 $ PELLET 4/CLAD 4
SIM -3826, 2, 1,3628, 1,3425, 4, A11, 1.101E-11 $      "
SIV -3803,       3402,   3304,    A12, 5.176E-11 $ CLAD 3/GIS
SIV -3804,       3400,   3300,    A13, 1.288E-11 $    "
SIV -3828,       3427,   3329,    A12, 5.176E-11 $ CLAD 4/GIS
SIV -3829,       3425,   3325,    A13, 1.288E-11 $    "
SIM -3805, 2, 1,3404, 0,3500, 1, A14, 0.644E-11 $ CLAD 3/FM
SIM -3830, 2, 1,3429, 0,3500, 1, A14, 0.644E-11 $ CLAD 4/FM
SIV -3824,       3502,   3340,    A15, 1.949E-11 $ FM/GIS
SIM -3832, 4, 1,3300, 0,3702, 5, A17, 5.615E-12 $ GIS/SLEEVE
SIM -3836, 4, 1,3325, 0,3727, 5, A17, 5.615E-12 $    "
SIM -3840, 4, 1,3304, 0,3706, 5, A16, 1.936E-11 $    "
SIM -3844, 4, 1,3329, 0,3731, 5, A16, 1.936E-11 $    "
SIM -3848, 4, 1,3340, 0,3733, 5, A16, 6.347E-12 $    "
REM
REM
REM   **  GPHS 3, SIDE "A" INTERIOR CONDUCTORS  **
REM
SIV  4600,       4600,   4601,    A1, 1.033       $ PELLET 1
SIV  4601,       4601,   4605,    A1, 2.221       $    "
SIV  4602,       4605,   4602,    A1, 6.235       $    "
SIM  4603, 2, 1,4600, 0,4603, 1, A1, .04736      $    "
SIM  4605, 2, 1,4601, 0,4603, 1, A1, .04736      $    "
SIM  4607, 2, 1,4605, 0,4603, 1, A1, .04736      $    "
SIV  4625,       4625,   4626,    A1, 1.033       $ PELLET 2
SIV  4626,       4626,   4630,    A1, 2.221       $    "
SIV  4627,       4630,   4627,    A1, 6.235       $    "
SIM  4628, 2, 1,4625, 0,4628, 1, A1, .04736      $    "
SIM  4630, 2, 1,4626, 0,4628, 1, A1, .04736      $    "
SIM  4632, 2, 1,4630, 0,4628, 1, A1, .04736      $    "
SIM  4400, 2, 1,4400, 4,4401, 2, A2, .002899     $ CLADING 1
SIM  4402, 2, 1,4401, 2,4402, 0, A2, .01301      $    "
SIM  4425, 2, 1,4425, 4,4426, 2, A2, .002899     $ CLADING 2
SIM  4427, 2, 1,4426, 2,4427, 0, A2, .01301      $    "
SIV  4500,       4500,   4501,    A5, .01773      $ FLOATING MEM.
SIV  4501,       4501,   4502,    A5, .08229      $    "
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SIM  4300, 2, 1,4300,25,4302,25, A4, .04604     $ GIS
SIM  4302, 2, 1,4302,25,4304,25, A3, .09564     $ "
SIM  4304, 2, 1,4304,25,4340, 0, A3, .08398     $ "
REM                                           $ ** SLEEVE COND **
SIM  4200, 4, 1,4202, 5,4702, 5, A6, .6875  $ THRU THICKNESS
SIM  4204, 4, 1,4227, 5,4727, 5, A6, .6875  $        "
SIM  4208, 4, 1,4206, 5,4706, 5, A6, 1.946  $        "
SIM  4212, 4, 1,4231, 5,4731, 5, A6, 1.946  $        "
SIM  4216, 4, 1,4233, 5,4733, 5, A6, .6733  $        "
SIM  4240, 4, 1,4206, 5,4233, 5, A6, .01040 $ ALONG LENGTH
SIM  4248, 4, 1,4231, 5,4233, 5, A6, .01040 $        "
SIM  4256, 4, 1,4706, 5,4733, 5, A6, .01040 $        "
SIM  4264, 4, 1,4731, 5,4733, 5, A6, .01040 $        "
SIM  4268, 3, 1,4202, 5,4207, 5, A6, .002626$ CIRCUMF ON ENDS
SIV  4271,      4217,   4202,    A6, .002626$        "
SIM  4272, 3, 1,4227, 5,4232, 5, A6, .002626$        "
SIV  4275,      4242,   4227,    A6, .002626$        "
SIM  4276, 3, 1,4702, 5,4707, 5, A6, .002626$        "
SIV  4279,      4717,   4702,    A6, .002626$        "
SIM  4280, 3, 1,4727, 5,4732, 5, A6, .002626$        "
SIV  4283,      4742,   4727,    A6, .002626$        "
SIM  4284, 3, 1,4206, 5,4211, 5, A6, .002858$ CIRCUMF ON LENGTH
SIV  4287,      4221,   4206,    A6, .002858$        "
SIM  4288, 3, 1,4231, 5,4236, 5, A6, .002858$        "
SIV  4291,      4246,   4231,    A6, .002858$        "
SIM  4700, 3, 1,4706, 5,4711, 5, A6, .002858$        "
SIV  4703,      4721,   4706,    A6, .002858$        "
SIM  4704, 3, 1,4731, 5,4736, 5, A6, .002858$        "
SIV  4707,      4746,   4731,    A6, .002858$        "
SIM  4708, 3, 1,4233, 5,4238, 5, A6, .000989$        "
SIV  4711,      4248,   4233,    A6, .000989$        "
SIM  4712, 3, 1,4733, 5,4738, 5, A6, .000989$        "
SIV  4715,      4748,   4733,    A6, .000989$        "
SIV -4800,      4602,   4402,    A11, 4.398E-11 $ PELLET 1/CLAD 1
SIM -4801, 2, 1,4603, 1,4400, 4, A11, 1.101E-11 $      "
SIV -4825,      4627,   4427,    A11, 4.398E-11 $ PELLET 2/CLAD 2
SIM -4826, 2, 1,4628, 1,4425, 4, A11, 1.101E-11 $      "
SIV -4803,      4402,   4304,    A12, 5.176E-11 $ CLAD 1/GIS
SIV -4804,      4400,   4300,    A13, 1.288E-11 $     "
SIV -4828,      4427,   4329,    A12, 5.176E-11 $ CLAD 2/GIS
SIV -4829,      4425,   4325,    A13, 1.288E-11 $     "
SIM -4805, 2, 1,4404, 0,4500, 1, A14, 0.644E-11 $ CLAD 1/FM
SIM -4830, 2, 1,4429, 0,4500, 1, A14, 0.644E-11 $ CLAD 2/FM
SIV -4824,      4502,   4340,    A15, 1.949E-11 $ FM/GIS
SIM -4832, 4, 1,4300, 0,4702, 5, A17, 5.615E-12 $ GIS/SLEEVE
SIM -4836, 4, 1,4325, 0,4727, 5, A17, 5.615E-12 $    "
SIM -4840, 4, 1,4304, 0,4706, 5, A16, 1.936E-11 $    "
SIM -4844, 4, 1,4329, 0,4731, 5, A16, 1.936E-11 $    "
SIM -4848, 4, 1,4340, 0,4733, 5, A16, 6.347E-12 $    "
REM
REM   **  GPHS 3, SIDE "B" INTERIOR CONDUCTORS  **
REM
SIV  5600,      5600,   5601,    A1, 1.033      $ PELLET 3
SIV  5601,      5601,   5605,    A1, 2.221      $    "
SIV  5602,      5605,   5602,    A1, 6.235      $    "
SIM  5603, 2, 1,5600, 0,5603, 1, A1, .04736     $    "
SIM  5605, 2, 1,5601, 0,5603, 1, A1, .04736     $    "
SIM  5607, 2, 1,5605, 0,5603, 1, A1, .04736     $    "
SIV  5625,      5625,   5626,    A1, 1.033      $ PELLET 4
SIV  5626,      5626,   5630,    A1, 2.221      $    "
SIV  5627,      5630,   5627,    A1, 6.235      $    "
SIM  5628, 2, 1,5625, 0,5628, 1, A1, .04736     $    "
SIM  5630, 2, 1,5626, 0,5628, 1, A1, .04736     $    "
SIM  5632, 2, 1,5630, 0,5628, 1, A1, .04736     $    "
SIM  5400, 2, 1,5400, 4,5401, 2, A2, .002899    $ CLADING 3
SIM  5402, 2, 1,5401, 2,5402, 0, A2, .01301     $    "
SIM  5425, 2, 1,5425, 4,5426, 2, A2, .002899    $ CLADING 4
SIM  5427, 2, 1,5426, 2,5427, 0, A2, .01301     $    "
SIV  5500,      5500,   5501,    A5, .01773     $ FLOATING MEM.
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SIV  5501,        5501,   5502,    A5, .08229     $    "
SIM  5300, 2, 1,5300,25,5302,25, A4, .04604     $ GIS
SIM  5302, 2, 1,5302,25,5304,25, A3, .09564     $ "
SIM  5304, 2, 1,5304,25,5340, 0, A3, .08398     $ "
REM                                           $ ** SLEEVE COND **
SIM  5200, 4, 1,5202, 5,5702, 5, A6, .6875  $ THRU THICKNESS
SIM  5204, 4, 1,5227, 5,5727, 5, A6, .6875  $      "
SIM  5208, 4, 1,5206, 5,5706, 5, A6, 1.946  $      "
SIM  5212, 4, 1,5231, 5,5731, 5, A6, 1.946  $      "
SIM  5216, 4, 1,5233, 5,5733, 5, A6, .6733  $      "
SIM  5240, 4, 1,5206, 5,5233, 5, A6, .01040 $ ALONG LENGTH
SIM  5248, 4, 1,5231, 5,5233, 5, A6, .01040 $      "
SIM  5256, 4, 1,5706, 5,5733, 5, A6, .01040 $      "
SIM  5264, 4, 1,5731, 5,5733, 5, A6, .01040 $      "
SIM  5268, 3, 1,5202, 5,5207, 5, A6, .002626$ CIRCUMF ON ENDS
SIV  5271,       5217,   5202,     A6, .002626$     "
SIM  5272, 3, 1,5227, 5,5232, 5, A6, .002626$     "
SIV  5275,       5242,   5227,     A6, .002626$     "
SIM  5276, 3, 1,5702, 5,5707, 5, A6, .002626$     "
SIV  5279,       5717,   5702,     A6, .002626$     "
SIM  5280, 3, 1,5727, 5,5732, 5, A6, .002626$     "
SIV  5283,       5742,   5727,     A6, .002626$     "
SIM  5284, 3, 1,5206, 5,5211, 5, A6, .002858$ CIRCUMF ON LENGTH
SIV  5287,       5221,   5206,     A6, .002858$     "
SIM  5288, 3, 1,5231, 5,5236, 5, A6, .002858$     "
SIV  5291,       5246,   5231,     A6, .002858$     "
SIM  5700, 3, 1,5706, 5,5711, 5, A6, .002858$     "
SIV  5703,       5721,   5706,     A6, .002858$     "
SIM  5704, 3, 1,5731, 5,5736, 5, A6, .002858$     "
SIV  5707,       5746,   5731,     A6, .002858$     "
SIM  5708, 3, 1,5233, 5,5238, 5, A6, .000989$     "
SIV  5711,       5248,   5233,     A6, .000989$     "
SIM  5712, 3, 1,5733, 5,5738, 5, A6, .000989$     "
SIV  5715,       5748,   5733,     A6, .000989$     "
SIV -5800,       5602,   5402,     A11, 4.398E-11 $ PELLET 3/CLAD 3
SIM -5801, 2, 1,5603, 1,5400, 4, A11, 1.101E-11 $      "
SIV -5825,       5627,   5427,     A11, 4.398E-11 $ PELLET 4/CLAD 4
SIM -5826, 2, 1,5628, 1,5425, 4, A11, 1.101E-11 $      "
SIV -5803,       5402,   5304,     A12, 5.176E-11 $ CLAD 3/GIS
SIV -5804,       5400,   5300,     A13, 1.288E-11 $     "
SIV -5828,       5427,   5329,     A12, 5.176E-11 $ CLAD 4/GIS
SIV -5829,       5425,   5325,     A13, 1.288E-11 $     "
SIM -5805, 2, 1,5404, 0,5500, 1, A14, 0.644E-11 $ CLAD 3/FM
SIM -5830, 2, 1,5429, 0,5500, 1, A14, 0.644E-11 $ CLAD 4/FM
SIV -5824,       5502,   5340,     A15, 1.949E-11 $ FM/GIS
SIM -5832, 4, 1,5300, 0,5702, 5, A17, 5.615E-12 $ GIS/SLEEVE
SIM -5836, 4, 1,5325, 0,5727, 5, A17, 5.615E-12 $    "
SIM -5840, 4, 1,5304, 0,5706, 5, A16, 1.936E-11 $    "
SIM -5844, 4, 1,5329, 0,5731, 5, A16, 1.936E-11 $    "
SIM -5848, 4, 1,5340, 0,5733, 5, A16, 6.347E-12 $    "
REM
REM
REM   **  GPHS 4, SIDE "A" INTERIOR CONDUCTORS  **
REM
SIV  6600,       6600,   6601,     A1, 1.033      $ PELLET 1
SIV  6601,       6601,   6605,     A1, 2.221      $    "
SIV  6602,       6605,   6602,     A1, 6.235      $    "
SIM  6603, 2, 1,6600, 0,6603, 1, A1, .04736     $    "
SIM  6605, 2, 1,6601, 0,6603, 1, A1, .04736     $    "
SIM  6607, 2, 1,6605, 0,6603, 1, A1, .04736     $    "
SIV  6625,       6625,   6626,     A1, 1.033      $ PELLET 2
SIV  6626,       6626,   6630,     A1, 2.221      $    "
SIV  6627,       6630,   6627,     A1, 6.235      $    "
SIM  6628, 2, 1,6625, 0,6628, 1, A1, .04736     $    "
SIM  6630, 2, 1,6626, 0,6628, 1, A1, .04736     $    "
SIM  6632, 2, 1,6630, 0,6628, 1, A1, .04736     $    "
SIM  6400, 2, 1,6400, 4,6401, 2, A2, .002899    $ CLADING 1
SIM  6402, 2, 1,6401, 2,6402, 0, A2, .01301     $    "
SIM  6425, 2, 1,6425, 4,6426, 2, A2, .002899    $ CLADING 2
```

```
SIM  6427, 2, 1,6426, 2,6427, 0, A2, .01301      $    "
SIV  6500,       6500,   6501,    A5, .01773      $ FLOATING MEM.
SIV  6501,       6501,   6502,    A5, .08229      $    "
SIM  6300, 2, 1,6300,25,6302,25, A4, .04604      $ GIS
SIM  6302, 2, 1,6302,25,6304,25, A3, .09564      $ "
SIM  6304, 2, 1,6304,25,6340, 0, A3, .08398      $ "
REM                                            $ ** SLEEVE COND **
SIM  6200, 4, 1,6202, 5,6702, 5, A6, .6875  $ THRU THICKNESS
SIM  6204, 4, 1,6227, 5,6727, 5, A6, .6875  $       "
SIM  6208, 4, 1,6206, 5,6706, 5, A6, 1.946  $       "
SIM  6212, 4, 1,6231, 5,6731, 5, A6, 1.946  $       "
SIM  6216, 4, 1,6233, 5,6733, 5, A6, .6733  $       "
SIM  6240, 4, 1,6206, 5,6233, 5, A6, .01040 $ ALONG LENGTH
SIM  6248, 4, 1,6231, 5,6233, 5, A6, .01040 $       "
SIM  6256, 4, 1,6706, 5,6733, 5, A6, .01040 $       "
SIM  6264, 4, 1,6731, 5,6733, 5, A6, .01040 $       "
SIM  6268, 3, 1,6202, 5,6207, 5, A6, .002626$ CIRCUMF ON ENDS
SIV  6271,       6217,   6202,    A6, .002626$       "
SIM  6272, 3, 1,6227, 5,6232, 5, A6, .002626$       "
SIV  6275,       6242,   6227,    A6, .002626$       "
SIM  6276, 3, 1,6702, 5,6707, 5, A6, .002626$       "
SIV  6279,       6717,   6702,    A6, .002626$       "
SIM  6280, 3, 1,6727, 5,6732, 5, A6, .002626$       "
SIV  6283,       6742,   6727,    A6, .002626$       "
SIM  6284, 3, 1,6206, 5,6211, 5, A6, .002858$ CIRCUMF ON LENGTH
SIV  6287,       6221,   6206,    A6, .002858$       "
SIM  6288, 3, 1,6231, 5,6236, 5, A6, .002858$       "
SIV  6291,       6246,   6231,    A6, .002858$       "
SIM  6700, 3, 1,6706, 5,6711, 5, A6, .002858$       "
SIV  6703,       6721,   6706,    A6, .002858$       "
SIM  6704, 3, 1,6731, 5,6736, 5, A6, .002858$       "
SIV  6707,       6746,   6731,    A6, .002858$       "
SIM  6708, 3, 1,6233, 5,6238, 5, A6, .000989$       "
SIV  6711,       6248,   6233,    A6, .000989$       "
SIM  6712, 3, 1,6733, 5,6738, 5, A6, .000989$       "
SIV  6715,       6748,   6733,    A6, .000989$       "
SIV -6800,       6602,   6402,    A11, 4.398E-11 $ PELLET 1/CLAD 1
SIM -6801, 2, 1,6603, 1,6400, 4, A11, 1.101E-11 $       "
SIV -6825,       6627,   6427,    A11, 4.398E-11 $ PELLET 2/CLAD 2
SIM -6826, 2, 1,6628, 1,6425, 4, A11, 1.101E-11 $       "
SIV -6803,       6402,   6304,    A12, 5.176E-11 $ CLAD 1/GIS
SIV -6804,       6400,   6300,    A13, 1.288E-11 $      "
SIV -6828,       6427,   6329,    A12, 5.176E-11 $ CLAD 2/GIS
SIV -6829,       6425,   6325,    A13, 1.288E-11 $      "
SIM -6805, 2, 1,6404, 0,6500, 1, A14, 0.644E-11 $ CLAD 1/FM
SIM -6830, 2, 1,6429, 0,6500, 1, A14, 0.644E-11 $ CLAD 2/FM
SIV -6824,       6502,   6340,    A15, 1.949E-11 $ FM/GIS
SIM -6832, 4, 1,6300, 0,6702, 5, A17, 5.615E-12 $ GIS/SLEEVE
SIM -6836, 4, 1,6325, 0,6727, 5, A17, 5.615E-12 $     "
SIM -6840, 4, 1,6304, 0,6706, 5, A16, 1.936E-11 $     "
SIM -6844, 4, 1,6329, 0,6731, 5, A16, 1.936E-11 $     "
SIM -6848, 4, 1,6340, 0,6733, 5, A16, 6.347E-12 $     "
REM
REM   **  GPHS 4, SIDE "B" INTERIOR CONDUCTORS  **
REM
SIV  7600,       7600,   7601,    A1, 1.033       $ PELLET 3
SIV  7601,       7601,   7605,    A1, 2.221       $    "
SIV  7602,       7605,   7602,    A1, 6.235       $    "
SIM  7603, 2, 1,7600, 0,7603, 1, A1, .04736      $    "
SIM  7605, 2, 1,7601, 0,7603, 1, A1, .04736      $    "
SIM  7607, 2, 1,7605, 0,7603, 1, A1, .04736      $    "
SIV  7625,       7625,   7626,    A1, 1.033       $ PELLET 4
SIV  7626,       7626,   7630,    A1, 2.221       $    "
SIV  7627,       7630,   7627,    A1, 6.235       $    "
SIM  7628, 2, 1,7625, 0,7628, 1, A1, .04736      $    "
SIM  7630, 2, 1,7626, 0,7628, 1, A1, .04736      $    "
SIM  7632, 2, 1,7630, 0,7628, 1, A1, .04736      $    "
SIM  7400, 2, 1,7400, 4,7401, 2, A2, .002899     $ CLADING 3
SIM  7402, 2, 1,7401, 2,7402, 0, A2, .01301      $    "
```

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SIM  7425, 2, 1,7425, 4,7426, 2, A2, .002899    $ CLADING 4
SIM  7427, 2, 1,7426, 2,7427, 0, A2, .01301     $    "
SIV  7500,       7500,   7501,     A5, .01773     $ FLOATING MEM.
SIV  7501,       7501,   7502,     A5, .08229     $    "
SIM  7300, 2, 1,7300,25,7302,25, A4, .04604     $ GIS
SIM  7302, 2, 1,7302,25,7304,25, A3, .09564     $  "
SIM  7304, 2, 1,7304,25,7340, 0, A3, .08398     $  "
REM                                            $ ** SLEEVE COND **
SIM  7200, 4, 1,7202, 5,7702, 5, A6, .6875  $ THRU THICKNESS
SIM  7204, 4, 1,7227, 5,7727, 5, A6, .6875  $       "
SIM  7208, 4, 1,7206, 5,7706, 5, A6, 1.946  $       "
SIM  7212, 4, 1,7231, 5,7731, 5, A6, 1.946  $       "
SIM  7216, 4, 1,7233, 5,7733, 5, A6, .6733  $       "
SIM  7240, 4, 1,7206, 5,7233, 5, A6, .01040 $ ALONG LENGTH
SIM  7248, 4, 1,7231, 5,7233, 5, A6, .01040 $       "
SIM  7256, 4, 1,7706, 5,7733, 5, A6, .01040 $       "
SIM  7264, 4, 1,7731, 5,7733, 5, A6, .01040 $       "
SIM  7268, 3, 1,7202, 5,7207, 5, A6, .002626$ CIRCUMF ON ENDS
SIV  7271,       7217,   7202,     A6, .002626$      "
SIM  7272, 3, 1,7227, 5,7232, 5, A6, .002626$      "
SIV  7275,       7242,   7227,     A6, .002626$      "
SIM  7276, 3, 1,7702, 5,7707, 5, A6, .002626$      "
SIV  7279,       7717,   7702,     A6, .002626$      "
SIM  7280, 3, 1,7727, 5,7732, 5, A6, .002626$      "
SIV  7283,       7742,   7727,     A6, .002626$      "
SIM  7284, 3, 1,7206, 5,7211, 5, A6, .002858$ CIRCUMF ON LENGTH
SIV  7287,       7221,   7206,     A6, .002858$      "
SIM  7288, 3, 1,7231, 5,7236, 5, A6, .002858$      "
SIV  7291,       7246,   7231,     A6, .002858$      "
SIM  7700, 3, 1,7706, 5,7711, 5, A6, .002858$      "
SIV  7703,       7721,   7706,     A6, .002858$      "
SIM  7704, 3, 1,7731, 5,7736, 5, A6, .002858$      "
SIV  7707,       7746,   7731,     A6, .002858$      "
SIM  7708, 3, 1,7233, 5,7238, 5, A6, .000989$      "
SIV  7711,       7248,   7233,     A6, .000989$      "
SIM  7712, 3, 1,7733, 5,7738, 5, A6, .000989$      "
SIV  7715,       7748,   7733,     A6, .000989$      "
SIV -7800,       7602,   7402,     A11, 4.398E-11 $ PELLET 3/CLAD 3
SIM -7801, 2, 1,7603, 1,7400, 4, A11, 1.101E-11 $       "
SIV -7825,       7627,   7427,     A11, 4.398E-11 $ PELLET 4/CLAD 4
SIM -7826, 2, 1,7628, 1,7425, 4, A11, 1.101E-11 $       "
SIV -7803,       7402,   7304,     A12, 5.176E-11 $ CLAD 3/GIS
SIV -7804,       7400,   7300,     A13, 1.288E-11 $     "
SIV -7828,       7427,   7329,     A12, 5.176E-11 $ CLAD 4/GIS
SIV -7829,       7425,   7325,     A13, 1.288E-11 $     "
SIM -7805, 2, 1,7404, 0,7500, 1, A14, 0.644E-11 $ CLAD 3/FM
SIM -7830, 2, 1,7429, 0,7500, 1, A14, 0.644E-11 $ CLAD 4/FM
SIV -7824,       7502,   7340,     A15, 1.949E-11 $ FM/GIS
SIM -7832, 4, 1,7300, 0,7702, 5, A17, 5.615E-12 $ GIS/SLEEVE
SIM -7836, 4, 1,7325, 0,7727, 5, A17, 5.615E-12 $    "
SIM -7840, 4, 1,7304, 0,7706, 5, A16, 1.936E-11 $    "
SIM -7844, 4, 1,7329, 0,7731, 5, A16, 1.936E-11 $    "
SIM -7848, 4, 1,7340, 0,7733, 5, A16, 6.347E-12 $    "
REM
REM **************************************************
REM       RADIATION CONDUCTANCES BETWEEN SLEEVES
REM         AND AEROSHELLS INSIDE GPHS BLOCKS
REM **************************************************
REM
REM   **  GPHS 1, RADK'S [SLEEVES <--> AEROSHELL] **
REM
SIM -8901, 2, 1,  206,  10,  101, 2, A18, 2.142E-11 $ CYL/A.S.
SIM -8903, 2, 1, 1206,  10,  101, 2, A18, 2.142E-11 $   "
SIM -8905, 2, 1,  221, 990,  102, 2, A19, 2.142E-11 $   "
SIM -8907, 2, 1,  231,  10,  101, 2, A18, 2.142E-11 $   "
SIM -8909, 2, 1, 1231,  10,  101, 2, A18, 2.142E-11 $   "
SIM -8911, 2, 1,  246, 990,  102, 2, A19, 2.142E-11 $   "
SIM -8913, 2, 1,  233,  10,  101, 2, A18, 7.022E-12 $   "
SIM -8915, 2, 1, 1233,  10,  101, 2, A18, 7.022E-12 $   "
```

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SIM -8917, 2, 1,  248, 990,  102, 2, A19, 7.022E-12 $  "
SIM -8919, 4, 1,  202,   5,  100, 0, A19, 6.873E-12 $ END CAPS/A.S.
SIM -8923, 4, 1, 1202,   5,  100, 0, A19, 6.873E-12 $  "
SIM -8927, 4, 1,  227,   5,  105, 0, A19, 6.873E-12 $  "
SIM -8931, 4, 1, 1227,   5,  105, 0, A19, 6.873E-12 $  "
    -8935,        238,       1248,           4.682E-12 $ SLV A/SLV B
GEN -8936, 2, 1,  211,   25,1221,27,         1.428E-11 $  "
REM
REM   **  GPHS 2, RADK'S [SLEEVES <--> AEROSHELL] **
REM
SIM -2901, 2, 1, 2206,  10, 2101, 2, A18, 2.142E-11 $ CYL/A.S.
SIM -2903, 2, 1, 3206,  10, 2101, 2, A18, 2.142E-11 $  "
SIM -2905, 2, 1, 2221, 990, 2102, 2, A19, 2.142E-11 $  "
SIM -2907, 2, 1, 2231,  10, 2101, 2, A18, 2.142E-11 $  "
SIM -2909, 2, 1, 3231,  10, 2101, 2, A18, 2.142E-11 $  "
SIM -2911, 2, 1, 2246, 990, 2102, 2, A19, 2.142E-11 $  "
SIM -2913, 2, 1, 2233,  10, 2101, 2, A18, 7.022E-12 $  "
SIM -2915, 2, 1, 3233,  10, 2101, 2, A18, 7.022E-12 $  "
SIM -2917, 2, 1, 2248, 990, 2102, 2, A19, 7.022E-12 $  "
SIM -2919, 4, 1, 2202,   5, 2100, 0, A19, 6.873E-12 $ END CAPS/A.S.
SIM -2923, 4, 1, 3202,   5, 2100, 0, A19, 6.873E-12 $  "
SIM -2927, 4, 1, 2227,   5, 2105, 0, A19, 6.873E-12 $  "
SIM -2931, 4, 1, 3227,   5, 2105, 0, A19, 6.873E-12 $  "
    -2935,       2238,       3248,           4.682E-12 $ SLV A/SLV B
GEN -2936, 2, 1, 2211,   25,3221,27,         1.428E-11 $  "
REM
REM   **  GPHS 3, RADK'S [SLEEVES <--> AEROSHELL] **
REM
SIM -4901, 2, 1, 4206,  10, 4101, 2, A18, 2.142E-11 $ CYL/A.S.
SIM -4903, 2, 1, 5206,  10, 4101, 2, A18, 2.142E-11 $  "
SIM -4905, 2, 1, 4221, 990, 4102, 2, A19, 2.142E-11 $  "
SIM -4907, 2, 1, 4231,  10, 4101, 2, A18, 2.142E-11 $  "
SIM -4909, 2, 1, 5231,  10, 4101, 2, A18, 2.142E-11 $  "
SIM -4911, 2, 1, 4246, 990, 4102, 2, A19, 2.142E-11 $  "
SIM -4913, 2, 1, 4233,  10, 4101, 2, A18, 7.022E-12 $  "
SIM -4915, 2, 1, 5233,  10, 4101, 2, A18, 7.022E-12 $  "
SIM -4917, 2, 1, 4248, 990, 4102, 2, A19, 7.022E-12 $  "
SIM -4919, 4, 1, 4202,   5, 4100, 0, A19, 6.873E-12 $ END CAPS/A.S.
SIM -4923, 4, 1, 5202,   5, 4100, 0, A19, 6.873E-12 $  "
SIM -4927, 4, 1, 4227,   5, 4105, 0, A19, 6.873E-12 $  "
SIM -4931, 4, 1, 5227,   5, 4105, 0, A19, 6.873E-12 $  "
    -4935,       4238,       5248,           4.682E-12 $ SLV A/SLV B
GEN -4936, 2, 1, 4211,   25,5221,27,         1.428E-11 $  "
REM
REM   **  GPHS 4, RADK'S [SLEEVES <--> AEROSHELL] **
REM
SIM -6901, 2, 1, 6206,  10, 6101, 2, A18, 2.142E-11 $ CYL/A.S.
SIM -6903, 2, 1, 7206,  10, 6101, 2, A18, 2.142E-11 $  "
SIM -6905, 2, 1, 6221, 990, 6102, 2, A19, 2.142E-11 $  "
SIM -6907, 2, 1, 6231,  10, 6101, 2, A18, 2.142E-11 $  "
SIM -6909, 2, 1, 7231,  10, 6101, 2, A18, 2.142E-11 $  "
SIM -6911, 2, 1, 6246, 990, 6102, 2, A19, 2.142E-11 $  "
SIM -6913, 2, 1, 6233,  10, 6101, 2, A18, 7.022E-12 $  "
SIM -6915, 2, 1, 7233,  10, 6101, 2, A18, 7.022E-12 $  "
SIM -6917, 2, 1, 6248, 990, 6102, 2, A19, 7.022E-12 $  "
SIM -6919, 4, 1, 6202,   5, 6100, 0, A19, 6.873E-12 $ END CAPS/A.S.
SIM -6923, 4, 1, 7202,   5, 6100, 0, A19, 6.873E-12 $  "
SIM -6927, 4, 1, 6227,   5, 6105, 0, A19, 6.873E-12 $  "
SIM -6931, 4, 1, 7227,   5, 6105, 0, A19, 6.873E-12 $  "
    -6935,       6238,       7248,           4.682E-12 $ SLV A/SLV B
GEN -6936, 2, 1, 6211,   25,7221,27,         1.428E-11 $  "
REM
REM
REM **************************************************
REM               RADKS FROM TRASYS
REM **************************************************
REM
    -       1,  10100,  10200, 1.44871E-13$
    -       2,  10100,    100, 8.78349E-13$
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-     3,  10100,    101, 2.92091E-11$
-     4,  10100,    102, 9.46276E-13$
-     5,  10100,    103, 1.70504E-12$
-     6,  10100,    104, 9.79457E-13$
-     7,  10100,    105, 3.87351E-12$
-     8,  10100,   2100, 8.78348E-13$
-     9,  10100,   2101, 2.92048E-11$
-    10,  10100,   2102, 9.24256E-13$
-    11,  10100,   2103, 1.72961E-12$
-    12,  10100,   2104, 9.54927E-13$
-    13,  10100,   2105, 4.19903E-12$
-    14,  10100,   4100, 8.78348E-13$
-    15,  10100,   4101, 2.92049E-11$
-    16,  10100,   4102, 9.54944E-13$
-    17,  10100,   4103, 1.72960E-12$
-    18,  10100,   4104, 9.24261E-13$
-    19,  10100,   4105, 4.19903E-12$
-    20,  10100,   6100, 8.78348E-13$
-    21,  10100,   6101, 2.92090E-11$
-    22,  10100,   6102, 9.79479E-13$
-    23,  10100,   6103, 1.70498E-12$
-    24,  10100,   6104, 9.46260E-13$
-    25,  10100,   6105, 3.87351E-12$
-    26,  10100,  10400, 2.37619E-12$
-    27,  10100,  10500, 4.89943E-12$
-    28,  10100,  10600, 1.15739E-12$
-    29,  10200,    100, 4.99907E-13$
-    30,  10200,    101, 5.91492E-13$
-    31,  10200,    102, 8.60044E-14$
-    32,  10200,    103, 1.27886E-13$
-    33,  10200,    104, 9.21329E-14$
-    34,  10200,    105, 3.96286E-14$
-    35,  10200,   2100, 4.99907E-13$
-    36,  10200,   2101, 5.84488E-13$
-    37,  10200,   2102, 8.77847E-14$
-    38,  10200,   2103, 1.43460E-13$
-    39,  10200,   2104, 8.66905E-14$
-    40,  10200,   2105, 3.96937E-14$
-    41,  10200,   4100, 4.99907E-13$
-    42,  10200,   4101, 5.84488E-13$
-    43,  10200,   4102, 8.66906E-14$
-    44,  10200,   4103, 1.43460E-13$
-    45,  10200,   4104, 8.77848E-14$
-    46,  10200,   4105, 3.96937E-14$
-    47,  10200,   6100, 4.99907E-13$
-    48,  10200,   6101, 5.91492E-13$
-    49,  10200,   6102, 9.21349E-14$
-    50,  10200,   6103, 1.27881E-13$
-    51,  10200,   6104, 8.60044E-14$
-    52,  10200,   6105, 3.96287E-14$
-    53,  10200,  10400, 1.88480E-13$
-    54,  10200,  10500, 5.01245E-14$
-    55,  10200,  10600, 6.58720E-13$
-    56,    100,    101, 2.62294E-12$
-    57,    100,    102, 1.07898E-12$
-    58,    100,    103, 1.60315E-12$
-    59,    100,    104, 1.15642E-12$
-    60,    100,    105, 4.44002E-13$
-    61,    100,   2100, 6.33911E-12$
-    62,    100,   2101, 2.53408E-12$
-    63,    100,   2102, 1.10186E-12$
-    64,    100,   2103, 1.80075E-12$
-    65,    100,   2104, 1.08759E-12$
-    66,    100,   2105, 4.44396E-13$
-    67,    100,   4100, 6.33911E-12$
-    68,    100,   4101, 2.53408E-12$
-    69,    100,   4102, 1.08759E-12$
-    70,    100,   4103, 1.80074E-12$
-    71,    100,   4104, 1.10187E-12$
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-      74,     100,    6101, 2.62294E-12$
-      75,     100,    6102, 1.15644E-12$
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-      77,     100,    6104, 1.07898E-12$
-      78,     100,    6105, 4.44002E-13$
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-     103,     101,    6105, 1.94296E-12$
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-     106,     101,   10600, 3.45621E-12$
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-     108,     102,     104, 1.77331E-12$
-     109,     102,     105, 1.22987E-12$
-     110,     102,    2100, 1.07898E-12$
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-     112,     102,    2102, 1.62716E-12$
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-     114,     102,    2104, 1.71745E-12$
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-     133,     103,    2100, 1.60315E-12$
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-     135,     103,    2102, 4.03306E-12$
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-     179,     105,    2103, 2.09902E-12$
-     180,     105,    2104, 1.24027E-12$
-     181,     105,    2105, 6.57195E-12$
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-     194,     105,   10400, 2.85167E-12$
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-     196,     105,   10600, 5.85054E-13$
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-     199,    2100,    2103, 1.80075E-12$
-     200,    2100,    2104, 1.08759E-12$
-     201,    2100,    2105, 4.44396E-13$
-     202,    2100,    4100, 6.33910E-12$
-     203,    2100,    4101, 2.53408E-12$
-     204,    2100,    4102, 1.08759E-12$
-     205,    2100,    4103, 1.80074E-12$
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-    232,   2101,   6105, 1.93978E-12$
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-    235,   2101,  10600, 3.33911E-12$
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    -     399,    6104,    10500, 1.55561E-12$
    -     400,    6104,    10600, 1.42176E-12$
    -     401,    6105,    10400, 2.85167E-12$
    -     402,    6105,    10500, 8.31038E-12$
    -     403,    6105,    10600, 5.85054E-13$
    -     404,   10400,    10500, 3.60696E-12$
    -     405,   10400,    10600, 3.11619E-12$
    -     406,   10500,    10600, 7.40009E-13$
REM
REM
END
REM ****************
BCD 3CONSTANTS DATA
REM ****************
REM
    1, 62.5  $ POWER DISSIPATION PER PELLET (WATTS)
    NDIM=5000,ARLXCA=.05,DRLXCA=.05,NLOOP=1000
    BALENG=4.26
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END
REM ************
BCD 3ARRAY DATA
REM ************
REM
REM      **  FUEL PELLET K(BTU/FT-HR-F) VS. T(F)  **
    1, -1000., .242, 100., .242, 572., .254, 752., .266
       932., .315, 1112., .325, 1292., .335, 1472., .545
       1652., .59, 1832., .635, 2012., .681, 2192., .726
       2500., .747, 3000., .78, 3500., .814, 4000., .848
       5000., .915, 20000., .915, END
REM    **  IRIDIUM CLADING K(BTU/FT-HR-F) VS. T(F)  **
    2, -1000., 85., 0., 85., 1000., 79., 2000., 76.5
       3000., 65.5, 4000., 65., 20000., 65., END
REM       **  GIS SIDES K(BTU/FT-HR-F) VS. T(F)  **
    3, -1000., 98.8, 0., 98.8, 500., 75.8, 750., 67.1
       1000., 59.6, 1250., 53.3, 1500., 48.3, 1750., 44.2
       2000., 40., 2500., 35., 3000., 30.8, 4000., 27.9
       4800., 26.6, 20000., 26.6, END
REM  * GIS END SECTION W/ HOLES K(BTU/FT-HR-F) VS. T(F) *
    4, -1000., 63.8, 0., 63.8, 500., 49.7, 750., 44.
       1000., 38.7, 1250., 40.2, 1500., 30.9, 1750., 28.2
       2000., 26.2, 2500., 23.3, 3000., 22., 4000., 20.6
       7800., 20., 20000., 20., END
REM    **  FLOATING MEMBRANE K(BTU/FT-HR-F) VS. T(F)  **
    5, -1000., 49.3, 100., 49.3, 500., 40.2, 750., 35.5
       1000., 31.2, 1250., 27.8, 1500., 25., 1750., 22.8
       2000., 21.1, 2500., 18.8, 3000., 17.8, 4000., 16.7
       4800., 16.1, 20000., 16.1, END
REM       **  CBCF SLEEVE K(BTU/FT-HR-F) VS. T(F)  **
    6, -1000., .03545, 0., .03545, 392., .052, 572., .061
       752., .071, 932., .081, 1112., .086, 1292., .091
       1472., .096, 1652., .101, 1832., .107, 2012., .112
       2192., .117, 2372., .122, 2552., .128, 3000., .141
       4000., .171, 10000., .7, END
REM    **  AEROSHELL X,Y DIR K(BTU/FT-HR-F) VS. T(F)  **
    7, -1000., 98.8, 0., 98.8, 500., 75.8, 750., 67.1
       1000., 59.6, 1250., 53.3, 1500., 48.3, 1750., 44.2
       2000., 40.0, 2500., 35.0, 3000., 30.8, 4000., 27.9
       4800., 26.6, 20000., 26.6, END
REM      **  AEROSHELL Z DIR K(BTU/FT-HR-F) VS. T(F)  **
    8, -1000., 77.4, 0., 77.4, 500., 60.3, 750., 53.3
       1000., 46.9, 1250., 41.7, 1500., 37.5, 1750., 34.2
       2000., 31.7, 2500., 28.3, 3000., 26.7, 4000., 25.
       4800., 24.2, 20000., 24.2, END
REM      **  "SCRIPT F" VS. T(F), PELLET-TO-CLADDING  **
    11, -1000., .0794, 0., .0794, 1000., .129, 2000., .181
        3000., .236, 4000., .294, 20000., .603, END
REM   **  "SCRIPT F" VS. T(F), CLADDING-TO-GIS SIDES  **
    12, -1000., .0822, 0., .0822, 1000., .133, 2000., .184
        3000., .235, 4000., .285, 20000., .620, END
REM    **  "SCRIPT F" VS. T(F), CLADING-TO-GIS ENDS  **
    13, -1000., .0812, 0., .0812, 1000., .132, 2000., .183
        3000., .235, 4000., .287, 20000., .620, END
REM  * "SCRIPT F" VS. T(F), CLADING-TO-FLOATING MEMBRANE *
    14, -1000., .0812, 0., .0812, 1000., .132, 2000., .183
        3000., .235, 4000., .287, 20000., .620, END
REM   ** "SCRIPT F" VS. T(F), FLOATING MEMBRANE-TO-GIS **
    15, -1000., .617, 0., .617, 500., .637, 750., .647
        1000., .657, 1250., .666, 1500., .669, 1750., .686
        2000., .696, 2500., .717, 3000., .738, 4000., .778
        4800., .813, 20000., 1., END
REM  **  "SCRIPT F" VS. T(F), GIS SIDES-TO-CBCF SLEEVE  **
    16, -1000., .675, 0., .675, 500., .676, 750., .678
        1000., .679, 1250., .681, 1500., .683, 1750., .686
        2000., .689, 2500., .694, 3000., .700, 4000., .711
        20000., .8, END
REM  **  "SCRIPT F" VS. T(F), GIS ENDS-TO-CBCF SLEEVE  **
    17, -1000., .610, 0., .610, 500., .628, 750., .637
```

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                 1000., .645, 1250., .652, 1500., .659, 1750., .667
                 2000., .674, 2500., .688, 3000., .702, 4000., .725
                 7800., .743, 20000., .8, END
         REM  *"SCRIPT F" VS. T(F), CBCF SLEEVE-TO-AEROSHELL TOP & BOTTOM*
             18, -1000., .553, 0., .553, 500., .578, 750., .593
                 1000., .607, 1250., .620, 1500., .633, 1750., .646
                 2000., .658, 2500., .680, 3000., .703, 4000., .738
                 4800., .763, 20000., .8, END
         REM  * "SCRIPT F" VS. T(F), CBCF SLEEVE-TO-AEROSHELL SIDES *
             19, -1000., .675, 0., .675, 500., .676, 750., .678
                 1000., .679, 1250., .681, 1500., .683, 1750., .686
                 2000., .689, 2500., .694, 3000., .700, 4000., .711
                 4800., .723, 20000., .8, END
         REM  **  EMISSIVITY VS. T(F), AEROSHELL X,Y DIRECTION  **
             20, -1000., .812, 0., .812, 500., .814, 750., .816
                 1000., .818, 1250., .821, 1500., .824, 1750., .828
                 2000., .832, 2500., .84 , 3000., .848, 4000., .865
                 4800., .882, 20000., 1., END
         REM  **  EMISSIVITY VS. T(F), AEROSHELL Z DIRECTION  **
             21, -1000., .642, 0., .642, 500., .675, 750., .696
                 1000., .716, 1250., .734, 1500., .752, 1750., .77
                 2000., .788, 2500., .82 , 3000., .853, 4000., .905
                 4800., .943, 20000., 1., END
         END
         REM
         REM ************
         BCD 3EXECUTION
         REM ************
             STDSTL
         END
         REM **************
         BCD 3VARIABLES 1
         REM **************
         REM
         REM STORE POWER DISSIPATIONS
M        Q600 = XK1 * 3.412 / 3.
M        Q601 = XK1 * 3.412 / 3.
M        Q605 = XK1 * 3.412 / 3.
M        Q625 = XK1 * 3.412 / 3.
M        Q626 = XK1 * 3.412 / 3.
M        Q630 = XK1 * 3.412 / 3.
M        Q1600 = XK1 * 3.412 / 3.
M        Q1601 = XK1 * 3.412 / 3.
M        Q1605 = XK1 * 3.412 / 3.
M        Q1625 = XK1 * 3.412 / 3.
M        Q1626 = XK1 * 3.412 / 3.
M        Q1630 = XK1 * 3.412 / 3.
M        Q2600 = XK1 * 3.412 / 3.
M        Q2601 = XK1 * 3.412 / 3.
M        Q2605 = XK1 * 3.412 / 3.
M        Q2625 = XK1 * 3.412 / 3.
M        Q2626 = XK1 * 3.412 / 3.
M        Q2630 = XK1 * 3.412 / 3.
M        Q3600 = XK1 * 3.412 / 3.
M        Q3601 = XK1 * 3.412 / 3.
M        Q3605 = XK1 * 3.412 / 3.
M        Q3625 = XK1 * 3.412 / 3.
M        Q3626 = XK1 * 3.412 / 3.
M        Q3630 = XK1 * 3.412 / 3.
M        Q4600 = XK1 * 3.412 / 3.
M        Q4601 = XK1 * 3.412 / 3.
M        Q4605 = XK1 * 3.412 / 3.
M        Q4625 = XK1 * 3.412 / 3.
M        Q4626 = XK1 * 3.412 / 3.
M        Q4630 = XK1 * 3.412 / 3.
M        Q5600 = XK1 * 3.412 / 3.
M        Q5601 = XK1 * 3.412 / 3.
M        Q5605 = XK1 * 3.412 / 3.
M        Q5625 = XK1 * 3.412 / 3.
```

```
M       Q5626 = XK1 * 3.412 / 3.
M       Q5630 = XK1 * 3.412 / 3.
M       Q6600 = XK1 * 3.412 / 3.
M       Q6601 = XK1 * 3.412 / 3.
M       Q6605 = XK1 * 3.412 / 3.
M       Q6625 = XK1 * 3.412 / 3.
M       Q6626 = XK1 * 3.412 / 3.
M       Q6630 = XK1 * 3.412 / 3.
M       Q7600 = XK1 * 3.412 / 3.
M       Q7601 = XK1 * 3.412 / 3.
M       Q7605 = XK1 * 3.412 / 3.
M       Q7625 = XK1 * 3.412 / 3.
M       Q7626 = XK1 * 3.412 / 3.
M       Q7630 = XK1 * 3.412 / 3.
        END
        REM **************
        BCD 3VARIABLES 2
        REM **************
        END
        REM ***************
        BCD 3OUTPUT CALLS
        REM ***************
            QIPRNT
            TPRINT
        END
        BCD 3END OF DATA
```

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16. Abstract

Thermal analyses were performed for two distinct configurations of a proposed space nuclear power system which combines the U.S. Department of Energy's (DOE) General Purpose Heat Source (GPHS) modules with state-of-the-art Free-Piston Stirling Engines (FPSE). The two configurations correspond to systems with power levels of 250 W_e and 500 W_e. The 250 W_e GPHS/FPSE power system utilizes four GPHS modules and one FPSE, and the 500 W_e contains eight GPHS modules and two FPSEs. The configurations of the systems and the bases for selecting the configurations are described. Brief introductory sections are included to describe the GPHS modules and free-piston Stirling engines.

The primary focus of the thermal analyses is on the temperature of the iridium fuel clad within the GPHS modules. A design goal temperature of 1573 K has been selected as upper limit for the fuel clad during normal operating conditions. The basis for selecting this temperature limit is discussed in detail.

Results obtained from thermal analysis of the 250 W_e GPHS/FPSE power system indicate fuel clad temperatures which slightly exceed the design goal temperature of 1573 K. The results are considered favorable due to the numerous conservative assumptions used in developing the thermal model and performing the thermal analysis. To demonstrate the effects of the conservatism, a brief sensitivity analysis is performed in which a few of the key system parameters are varied to determine their effect on the fuel clad temperatures. It is concluded that thermal analysis of a more detailed thermal model would be expected to yield fuel clad temperatures below the design goal temperature limit of 1573 K.

17. Key Words (Suggested by Author(s))
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