172
11/22/78

LA-7546-SR

Status Report

DR 759

MASTER

General-Purpose Heat Source Development

Phase II—Conceptual Designs

University of California

LOS ALAMOS SCIENTIFIC LABORATORY

Post Office Box 1663 Los Alamos, New Mexico 87545

LA-7546-SR
Status Report

UC-23

Issued: November 19

General-Purpose Heat Source Development

Phase II—Conceptual Designs

E. C. Snow
R. W. Zocher
I. M. Grinborg*
L. E. Hulbert*

NOTICE

This report was prepared as an account of work sponsored by the United States Government. Neither the United States nor the United States Department of Energy, nor any of their employees, nor any of their contractors, subcontractors, or any other person, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe upon privately owned rights.

*Battelle Columbus Laboratories, 505 King Avenue, Columbus, OH 43201.

CONTENTS

ABSTRACT	1
1.0. INTRODUCTION	2
2.0. CONCEPTUAL DESIGNS SELECTIONS	2
2.1. Basic Geometry	2
2.2. Seven Conceptual Designs	4
3.0 CONCEPTUAL DESIGNS ANALYSES	8
3.1. Reentry Thermal and Ablation	8
3.2. Reentry Thermal Stress	14
3.3. Other Analyses	15
4.0. SUMMARY	19

GENERAL-PURPOSE HEAT SOURCE DEVELOPMENT PHASE II--CONCEPTUAL DESIGNS

by

E. C. Snow, R. W. Zocher,
I. M. Grinberg, and L. E. Hulbert

ABSTRACT

Basic geometric module shapes and fuel arrays were studied to determine how well they could be expected to meet the General Purpose Heat Source (GPHS) design requirements. Seven conceptual designs were selected, detailed drawings produced, and these seven concepts analyzed. Three of these design concepts were selected as GPHS Trial Designs to be reanalyzed in more detail and tested. The geometric studies leading to the selection of the seven Conceptual Designs, the analyses of these designs, and the selection of the three Trial Designs will be discussed in this report.

1.0. INTRODUCTION

In the past, there have been a number of space and terrestrial applications of radioisotope fueled heat sources.² For most of these applications, the heat source and the conversion system required to produce electrical power were designed for a specific mission or series of missions. The only method available to these power systems to change the total electrical power output was to add integral numbers of complete conversion systems, which often results in weight and volume penalties. As each of these designs evolved, considerable time and money was spent on the development and qualification of each different heat source. The rationale for the development of a General Purpose Heat Source (GPHS) is that a great deal of time and money can be saved, as well as systems weight and volume, if a modular heat source can be developed and qualified that will meet the needs of conversion systems that exist now and those that are being developed.

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

Modular. A modular heat source will have the flexibility to be compatible with the various static and dynamic conversion systems. If the module is relatively small, it will also have the versatility of affording small

incremental changes in total electrical power without severe weight and volume penalties.

High-Power Density. The power density of the GPHS modules is to be at least 75 thermal watts per pound. Maximum power density of the modules should result in an overall reduction in size and weight of the conversion systems.

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

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

In order that the GPHS meet the needs of the various dynamic and static conversion systems and display the desired safety attributes, studies were performed to determine the GPHS design requirements. The results of those studies were given in the Phase I Report¹ for this development project.

This report covers the studies of the basic geometry considerations for the GPHS Conceptual Designs. The analyses of these designs, as well as the selection of those to be considered as GPHS Trial Designs, is also covered in this report.

2.0. CONCEPTUAL DESIGN SELECTIONS

2.1. Basic Geometry

When considering the basic geometry for a modular heat source like the GPHS, one looks for simple geometric shapes that can be easily used as heat source building blocks. The simpler the shape, such as a cube, the less the restrictions on how these basic building blocks can be used in a heat-source array. One must also consider that, in general, the simpler the shape, the easier it is to fabricate and test.

The simplest shape that comes to mind for building blocks is a cube, as mentioned before. However, because of the aerodynamic characteristics of a cube, a more desirable shape would be a half of a cube, as shown in Fig. 2-1. Also shown are several possible arrays in which this block shape can be stacked to form a heat source. Of course, there are any number of geometric shapes with rectangular cross sections that can also be stacked in a multiple of heat-source arrays. Some of these were considered in the GPHS Conceptual Designs and are described later. In order to maximize the versatility of the module geometry, shapes with octagonal, circular, triangular, etc. cross sections were avoided. The decision was made to avoid such shapes unless it was found that the goals of the project could not be met with the simpler rectangular geometries.

The next consideration in the basic geometry of the modular heat source is how to arrange the fuel within the module. The most effective way, from a thermal power density point of view, would be to have a single fuel body the same shape as the module, thereby occupying the maximum space within the module. Such a fuel body design is shown in Fig. 2-2a, with an indication of the protection members that would be required. Unfortunately, such a shape is not a practical one to fabricate from the PuO_2 fuel to be used in the GPHS, because of thermal stress problems within the body associated with the nonsymmetric shape. It is also difficult to conceive of a clad member in this shape that would maintain its integrity during a terminal velocity impact event.

Fig. 2-1.
Basic stacking arrays for a "half-cube"
geometry.

amount of protective materials required will be determined by tests and analyses. The fuel inventory is governed by the desire to be able to change the electrical output of the Radioisotopic Thermoelectric Generator (RTG) by increments as small as 25 watts (electrical). However, if the modules are too small, the numbers required for any given heat source increases and the heat-source power density decreases. Very large numbers of very small modules also create more handling and other safety problems. These considerations suggest that the thermal inventory per module should be in the 250 to 300 watts range.

In considering the basic fuel pellet size, there are also opposing influences. Internal thermal stress problems indicate that the maximum size of the fuel pellets should be kept below 100 watts. On the other hand, if the fuel pellets are too small, there are problems associated with handling and encapsulation. There are also weight penalties associated with the increased clad material required for the larger number of fuel bodies. These considerations lead to a range of fuel pellet size between 20 and 75 thermal watts. The physical dimensions of the fuel pellets are dictated by the restriction on the density. Experiments designed to evaluate the transport of helium through the fuel body pore space indicate that the maximum density should be between 84 and 86% of theoretical.

A much more stable shape for the PuO_2 fuel form would be a sphere, as shown in Fig. 2-2b. However, due to the poor packing efficiency associated with spherical shapes within a rectangular box, this arrangement would produce the lowest thermal power density. A workable compromise between these two extremes is the case of cylindrical fuel pellets. Two such cases are shown in Figs. 2-2c and 2-2d.

If one considers the relative power density associated with the three geometries shown in Figs. 2-2b, c, and d, one comes up with the numbers given in Table II-1. The highest power density is produced with the geometry employing four $L/D = 1$ pellets as shown in Fig. 2-2c. The lowest power density is achieved with the spherical fuel pellets. Therefore, all but one of the Conceptual Designs considered have cylindrical shaped fuel pellets. In the one exception, spherical fuel pellets were used for comparative purposes and to insure a back-up design in the event that the forming of the cylindrical shapes from the cladding materials presented a problem.

The size of the basic GPHS module is dictated by the fuel inventory and the safety protection required. The

Fig. 2-2.
Fuel loading concepts for a "half-cube" geometry

With the above basic geometry considerations and restrictions in mind, the next section will describe and justify the selection of the seven Conceptual Designs. The methods of analyses and results for these seven designs will be described and discussed in the following sections.

2.2. Seven Conceptual Designs

Conceptual Design number one (CD1), shown in Fig. 2-3, is a "half-cube" geometry with the fuel in four 62.5 watt pellets, for a total module inventory of 250 watts. The fuel pellets are cylindrical in shape, with an $L/D = 1$. To allow maximum packing density of fuel, the fuel pellets are loaded from both faces of the module. The spanner holes in the closure caps may or may not be required for proper assembly. The rounded corners are not required, but are a means of saving weight. The corner radiusing is done from the center of the module so that by adding small pieces of graphite to the sides, the cross-section of the module could be adjusted to fit a cylindrical heat source cavity.

The "half-cube" geometry is an obvious choice, because of its stacking versatility. It also has a relatively low ballistic coefficient, resulting in reasonably good reentry characteristics and low terminal velocities. By good reentry characteristics, reference is made to the ablation, heating, and thermal

TABLE II-1

GPHS GEOMETRICAL POWER RATIOS AT TWO MODULE POWER LEVELS

<u>250 W Module:</u>	<u>Capsules/Module</u>	<u>Power Density Ratio*</u>
Sphere	4	1.00
Cylinder (L/D = 1)	4	1.22
Cylinder (L/D = 3)	3	1.17
Cylinder (L/D = 1)	9	1.09
<u>300 W Module:</u>		
Sphere	4	1.07
Cylinder (L/D = 1)	4	1.39
Cylinder (L/D = 3)	3	1.34

* All power density ratios are relative to the 250 W module with spherical fuel pellets.

stress response of the geometric shape during the reentry event. This design, with its four L/D = 1 fuel pellets, also has the highest thermal power density, as discussed in the previous section.

Conceptual Design number two (CD2), shown in Fig. 2-4, is also of the "half-cube" geometry. However, this concept has the fuel loaded in nine fuel pellets,

Fig. 2-3.
Design concept CD1

Fig. 2-4.
Design concept CD2.

three pellets in each of the three post-impact containment capsules. Each capsule contains 83.3 watts, for a total module inventory of 250 watts. Closures for loading the fueled capsules are made on two of the small faces of the module. As in CD1, the corners of the reentry member are rounded to save weight.

This design has the same aerodynamic characteristics as CD1, and should have the same reentry response and low-terminal velocity. One possible advantage of CD2 over CD1 is that there are no closures on the large face where most of the reentry ablation is expected to take place. It is yet to be determined by ablation testing whether or not closures on this surface cause significant problems. This design concept would also require only three capsules and, therefore, only three welds and three vents. This could result in a saving of weight and a lowering of the probability of problems due to vent failure. However, if one vent per capsule would not handle the generation rate of the fuel inside, six vents would be required and this advantage would be reversed. Even with these possible weight advantages of CD2, it has a slightly lower volume thermal power density than CD1.

Conceptual Design number three (CD3), shown in Fig. 2-5, has the shape of a long, thin parallelepiped with four 62.5 watt fuel pellets down the centerline. The fuel pellets are cylindrical in shape with an $L/D = 1$ and are oriented so that their cylindrical axis is parallel to the long dimension of the reentry body. Loading of the four fuel pellets would be accomplished through a closure on one end of the module.

This module geometry should have a slightly higher ballistic coefficient than CD1 and 2, resulting in slightly higher velocities. However, it is expected that this body would fly in an attitude with the long axis perpendicular to the velocity and rotate about that centerline axis. This should result in uniform ablation and heating, which may minimize the thickness of thermal and ablation protection required. This design could be used in a very small cross-section heat source configuration, about one half that of CD1 and 2. However, if this module was to be stacked in a heat source array like that shown in Figs. 2-1 b or c, the increment of thermal power would be 1000 and 500 watts, respectively.

Conceptual Design number four (CD4), shown in Fig. 2-6, is a simple cube with one cylindrical 62.5 watt fuel pellet inside. This concept is simply a GPHS 62.5 watt fuel pellet with an impact and reentry member around it.

CD-3	
TOTAL POWER	250 W
WIDTH	4.80 cm (1.89 in.)
HEIGHT	14.60 cm (5.75 in.)
VOLUME	336.4 cm ³ (20.5 in. ³)
POWER DENSITY	0.74 W/cm ³ (12.2 W/in. ³)

CD-4	
TOTAL POWER	62.5 W
WIDTH	4.80 cm (1.89 in.)
HEIGHT	5.00 cm (1.97 in.)
VOLUME	115.2 cm ³ (7.0 in. ³)
POWER DENSITY	0.54 W/cm ³ (8.93 W/in. ³)

Fig. 2-5.
Design Concept CD3.

Fig. 2-6.
Design Concept CD4.

CD4 is obviously the simplest of the seven Conceptual Designs. It would undoubtedly be the easiest to fabricate and test and the most versatile for stacking arrays. However, its ballistic coefficient would be somewhat higher than the other design concepts, resulting in a slightly poorer reentry response and higher terminal impact velocity. It would also require at least four times as many pieces to be loaded into the RTG to form a heat source, which, in most cases, is undesirable. Though this design geometry is not expected to be used in the GPHS, it is being carried through the Conceptual Designs analyses as a basic geometry to be used for comparison.

Conceptual Design number five (CD5), shown in Fig. 2-7, is a "half-cube" geometry very similar to CD2. The main difference is that in this design geometry the fuel is loaded in nine individually clad 27.8 watt cylindrical pellets. As in CD2, the fuel pellets would be loaded from the small faces of the module.

This geometry will have the same reentry response as CD2, which should be relatively good. However, these small individually clad fuel pellets should respond to impact much better than the long cigar-shaped capsules used in CD2.

Conceptual Design number six (CD6), shown in Fig. 2-8, is a rectangular shaped module design containing eight 62.5 watt cylindrical fuel pellets. This design concept is very much like CD1 with eight fuel pellets in the reentry body instead of four. As in CD1, the fuel pellets will be loaded from both sides of the module through threaded closures in the large faces of the reentry member.

This geometry has the lowest ballistic coefficient, which should result in a slightly better reentry response than CD1, but a slightly higher impact velocity because of the higher density. This concept does result in a higher thermal power density per module, but each module contains a total thermal inventory of 500 watts, thereby decreasing the power level increment versatility. Probably the main disadvantage of this geometry is that the module dimensions are too large to allow full-scale testing in all of the possible accident environments.

Conceptual Design number seven (CD7), shown in Fig. 2-9, is almost identical to CD1 in the outside shape of the reentry member. The basic difference between the two concepts is that CD7 employs four spherical 62.5 watt fuel pellets instead of the cylindrical ones used in CD1.

Fig. 2-7.
Design concept CD5.

Fig. 2-8.
Design concept CD6.

Fig. 2-9.
Design concept CD7.

This module geometry will have somewhat the same reentry response and impact velocity as CD1, but the thermal power density is significantly lower. The only reason that this concept was selected in addition to CD1 was that, at that time, the development work on forming cylindrical shapes out of iridium clad was not complete. This concept was, therefore, intended only as a back-up to CD1, in the event of clad forming problems.

3.0 CONCEPTUAL DESIGNS ANALYSES

3.1 Reentry Thermal and Ablation

The reentry thermal and ablation calculations for the seven Conceptual Designs (CD1-CD7) were done by Battelle Columbus Laboratories (BCL). Details

of those calculations, including assumptions, methods of analyses, and results have been published in a BCL July-September 1977 quarterly report.³ Only a summary of their work and the more important results will be presented here.

The BCL reentry calculations started with the normal operating conditions, proceeded through the reentry events and terminated at the time of earth impact. Calculations were done for both an orbital decay or low-angle reentry and a prompt or high-angle reentry. For the orbital decay reentry, the initial reentry angle γ , was assumed to be -5.3 degrees at 122 000 m (400 000 ft) with an initial velocity of 11 000 m/s (36 000 ft/s). Breakup of the RTG and the release of the GPHS modules was assumed to occur at approximately the same altitude used by General Electric (GE) for the MHW-LES 8/9,⁴ or about 83 000 m (270 000 ft). This is the reentry mode that results in the most ablation and highest clad temperatures and was the trajectory used for the thermal and ablation analyses of the GPHS Conceptual Designs. Thermal and ablation analyses were also done for the prompt reentry case, but primarily as input to the thermal stress analyses. The conditions assumed for the prompt reentry case will be discussed in the next section.

Since the analyses done on the Conceptual Designs were intended to be used as a method of screening the seven designs and materials that might be used, these calculations were performed using a two-dimensional, finite difference thermal model. It is intended that the more detailed and costly three-dimensional codes will be used at a later date when the field of designs and candidate materials has been considerably narrowed. A typical two-dimensional thermal network used by BCL is shown in Fig. 3-1. This thermal model is for CD1 and is symmetric about the z axis. This model is not detailed enough to handle some of the fine points of the designs, such as threaded closures, spanner holes, etc., but it should give reasonable ablation and clad temperature results for design and materials screening purposes.

To determine the initial conditions of the heat source modules just prior to a reentry event, a steady-state calculation for normal operating conditions was done for each of the seven designs. For these calculations, the hot shoe temperature was assumed to be 900°C and all of the gaps between the various components

Fig. 3-1.
Typical thermal network used for thermal and ablation analyses of CDI by BCL.³

Fig. 3-2.
Typical operating temperature profile for CDI by BCL.³

were assumed to be filled with helium. A typical steady-state temperature profile for CDI is given in Fig. 3-2.

With this temperature profile as a starting point, the temperature profile through the module, as well as the ablation of the reentry member was determined as a function of time from the point of the module's release from the RTG. This calculation was continued until the time at which the module was determined to have impacted the earth's surface. The two curves in Fig. 3-3 show the maximum and minimum clad temperature histories of CDI for a low-angle reentry event. From these curves, one can get the peak clad temperature during reentry and minimum clad temperature at impact, and establish the probable clad performance during such

Fig. 3-3.
Typical maximum, minimum clad temperature histories for CDI by BCL.³

an event. One looks for a design geometry in which the peak clad temperature remains well below the failure temperature and is above the clad embrittlement temperature at the point of earth impact.

At the same time the temperature histories for the clad were being determined, the loss of material from the surface of the reentry member, due to ablation, was also being evaluated. The curves in Fig. 3-4 show the maximum recession of the ablation or reentry member of CD1 for four different ablation materials. This information is of importance in selecting the proper material for the reentry member and designing the member thickness to optimize performance and safety. With the results of the total recession and recession profile for the design modules, the drag coefficients and subsequent terminal velocities could also be determined for the seven GPHS Conceptual Designs. In this case, one looks for a design that will have the minimum terminal velocity, thus minimizing the severity of the impact event to follow.

Drawings of the seven GPHS Conceptual Designs analyzed by BCL are given in Figs. 3-5 through 3-11. The results of these thermal and ablation calculations are summarized in Tables III-1, 2, and 3. Table III-1 shows the peak clad temperature for the seven Conceptual Designs for four different ablation materials in the reentry member. Table III-2 shows the minimum clad temperature at impact for the seven designs and four reentry member materials. Table III-3 shows the total maximum recession of the reentry member for all seven designs and four reentry member materials. Also included in Table III-3 is the terminal or impact velocity of each design being considered.

Fig. 3-4.

Typical total maximum ablation for four reentry materials in CD1 by BCL.³

Fig. 3-5.

Assembly drawing for CD1. All dimensions in mm and (in.).

Fig. 3-6.

Assembly drawing for CD2. All dimensions in mm and (in.).

Fig. 3-7.

Assembly drawing for CD3. All dimensions in mm and (in.).

Fig. 3-8.

Assembly drawing for CD4. All dimensions in mm and (in.).

Fig. 3-9.

Assembly drawing for CD5. All dimensions in mm and (in.).

TABLE III-1

PEAK CLAD TEMPERATURES DURING A LOW ANGLE REENTRY ENVIRONMENT. (°C)

Design No. Reentry Member	CD1	CD2	CD3	CD4	CD5	CD6	CD7
994-2	2118	1993	1999	2141	1961	2028	2031
Pyrocarb 903	2060	1965	1995	-	1933	1998	-
AVCO 3D Mod 3A	2147	2024	1986	2205	1993	2073	2065
POCO AXF 5Q	2086	1966	1966	2138	1936	2013	2005

TABLE III-2

CLAD IMPACT TEMPERATURES FOLLOWING A LOW-ANGLE REENTRY EVENT. (°C)

Design No. Reentry Member	<u>CD1</u>	<u>CD2</u>	<u>CD3</u>	<u>CD4</u>	<u>CD5</u>	<u>CD6</u>	<u>CD7</u>
994-2	617	692	615	454	691	752	706
Pyrocarb 903	626	732	626	-	729	762	-
AVCO 3D Mod 3A	588	676	584	431	671	728	683
POCO AXF 5Q	614	695	613	518	691	747	708

TABLE III-3

MAXIMUM RECESSION AND IMPACT VELOCITY FOR A LOW-ANGLE REENTRY

Design No. Reentry Member	<u>CD1</u>	<u>CD2</u>	<u>CD3</u>	<u>CD4</u>	<u>CD5</u>	<u>CD6</u>	<u>CD7</u>
994-2	2.8 mm (0.11 in.)	2.5 mm (0.10 in.)	2.0 mm (0.08 in.)	3.0 mm (0.12 in.)	2.3 mm (0.09 in.)	2.5 mm (0.10 in.)	2.8 mm (0.11 in.)
Pyrocarb 903	2.5 mm (0.10 in.)	2.3 mm (0.09 in.)	2.0 mm (0.08 in.)	-	2.3 mm (0.09 in.)	2.3 mm (0.09 in.)	-
AVCO 3D Mod 3A	2.8 mm (0.11 in.)	2.5 mm (0.10 in.)	1.8 mm (0.07 in.)	3.0 mm (0.12 in.)	2.3 mm (0.09 in.)	2.3 mm (0.09 in.)	2.5 mm (0.10 in.)
POCO AXF 5Q	2.5 mm (0.10 in.)	2.5 mm (0.10 in.)	2.0 mm (0.08 in.)	3.3 mm (0.13 in.)	2.3 mm (0.09 in.)	2.5 mm (0.10 in.)	2.8 mm (0.11 in.)
Impact velocity	55.2 m/s (181 ft/s)	53.0 m/s (174 ft/s)	54.6 m/s (179 ft/s)	58.5 m/s (192 ft/s)	50.9 m/s (167 ft/s)	56.1 m/s (184 ft/s)	55.5 m/s (182 ft/s)

The resulting temperatures as given in Tables III-1 and 2 indicate that the peak clad temperatures are too high for the Pt-3008 clad material and impact temperatures are too low for the iridium clad material for all seven of the Conceptual Designs. However, the results do show some trends as to preference in design geometry. These results also show that these temperatures are not very dependent on the material used for the reentry member. The total reentry member ablation is within reason for all of the designs and materials. All of the impact velocities are relatively low, which helps the low temperature clad embrittlement problem that might be encountered with iridium alloy clad materials.

3.2. Reentry Thermal Stress

As was mentioned in the previous section, the thermal and ablation calculations were also done for the prompt or high angle reentry case. However, these were done only as input to the thermal stress analyses. On the other hand, thermal stress analyses were not done for the orbital decay or low angle reentry case, since the main problems with thermal stress will be encountered in the case of highest heating rates and subsequent high thermal gradients. Such was the case for the high angle reentry event.

For the prompt reentry event, the angle of attack of the module entering the earth's atmosphere was assumed to be -89.9° at an altitude of 122 000 m (400 000 ft). The initial velocity of the RTG at the altitude was assumed to be 11 000 m/s (36 000 ft/s), with RTG breakup and GPHS module release at an altitude of about 61 000 m (200 000 ft). This breakup altitude was sufficiently high to provide the peak aerodynamic heating rates experienced on this trajectory.

The temperature profile histories that were used as input to the thermal stress analyses were done on the same thermal network model as used in the two-dimensional thermal analyses for the low angle reentry. A typical thermal network was shown in Fig. 3-1 for CD1. The same network, for the reentry member only, is shown in Fig. 3-12 and was the network used in the two-dimensional finite element thermal stress code DOASIS.³ In later discussions of the results, the numbers in the elements of this network will be helpful in locating those areas where the thermal stress was a maximum. A typical temperature profile for the leading face of CD1 is shown in Fig. 3-13 in a three-dimensional representation. Since this temperature profile varies throughout the reentry event, there are a very large number of such profiles required to define the temperature profile history.

The results of these thermal stress analyses give, as a function of time, such information as thermal stress within each network element, displacement of the elements, etc., and allow one to determine if the reentry member design is likely to fail due to tensile stress during such a reentry event. The maximum total displacement of the thermal stress network for CD1 is

Fig. 3-12.
Finite element mesh for CD1 used by BCL.³

Fig. 3-13.
Typical temperature distribution³
along leading face of CD1 by BCL.

element 159, the only element number in this figure.

A summary of the thermal stress results for CD1 is given in Table III-4, for the four reentry member materials considered. Similar results for mechanical strain are given in Table III-5. Tables of results for the other six designs are given in Appendix G of the BCL July-September 1977 quarterly report.³ To evaluate the effect of the variation in design geometry on the maximum tensile stresses encountered, the ratio of maximum tensile stress to yield stress has been plotted for each of the seven designs. These plots, for two reentry member materials, are

Fig. 3-14.
Typical reentry member displacement³
plot for CD1 by BCL.

shown in Fig. 3-14. One should note that the displacement at the outer edge is larger than at the center of the member, resulting in bending along the exterior of the reentry member. This bending results in tensile stresses along the inner surfaces, with concentrations of stress near the inner corners in the area of elements 159 and 160. The stress associated with this displacement, for the upper half of the network where the stresses are highest, is shown in a three-dimensional representation given in Fig. 3-15. In this figure, points to the left of the thermal grid represent compression and points to the right represent tension. One can see that the maximum tensile stress occurs in

given in Fig. 3-16. The curves show some dependence on design changes within the seven GPHS Conceptual Designs, but not enough to have a strong influence on design screening and selections. The curves do show that a reentry member of the 3D carbon carbon composites, such as the AVCO 3D Mod 3A, should be adequate to handle the stresses encountered during a prompt reentry event. Three-dimensional thermal stress analyses will be very helpful in determining the detailed effects of stress concentrations in areas such as the threads and other sharply discontinuous surface variations within the reentry member. However, these costly and time consuming analyses will not be done until the number of design geometries has been reduced.

3.3 Other Analyses

The analyses, other than reentry, that were done for the seven GPHS Conceptual Designs were primarily related to performance. Considerations

Fig. 3-15.
Typical radial stress (σ_r) for CD1 by
BCL.³

were given to analytical safety analyses, but the state of the art in most areas of analytical safety analyses is not sufficiently advanced to yield very useful results. The two safety areas of most concern are the solid propellant fire environment and the post reentry impact. Currently, there aren't any good models for the solid propellant fire environment, and since all seven of the designs have essentially the same amount of exterior protection, solid propellant fire analyses would add little to the design screening and selections. The survivability of the modules in the other launch abort environments, such as blast overpressure, fragments, or low velocity impacts, is more dependent on material than design and will be determined in subsequent testing.

An earth impact of something as complex as a GPHS module, is somewhat beyond the state of the art for analytical impact analyses. One can only draw on experience of past impact testing and look for features within each design that might decrease the probability of impact survival. For instance, all but design CD4 have the possibility of a multiple capsule impact, that is one or more capsules impacting the lead capsule and adding to its total deformation. Designs CD 2, 3, 5 and 6 could experience three or four capsules impacting in an additive manner. In design CD2, an impact that occurs with the velocity vector not aligned

TABLE III-4

SUMMARY OF THERMAL STRESS RESULTS FOR CONCEPTUAL DESIGN NO. 1

Material	Temp. (°F)	Tensile Stress Results				Compressive Stress Results		
		Max. Stress (Ksi)	(Location)	Stress/Yield (%)	Stress/ Ultimate (%)	Temp. (°F)	Max. Stress (Ksi)	(Location)
994-2	4143.2	3.61	159	102.3	56.2	5564.8	2.27	211
AXF5Q	3788.4	9.81	159	-	93.4	5603.8	7.97	212
Pyrocarb 903	2480.1	12.22	159	-	122.2	5620.0	13.69	215
3-d Mod 3a	3953.2	2.61	159	45.8*	29.5	5632.4	1.97	211

* Based on compressive yield stress

TABLE III-5

MECHANICAL STRAIN RESULTS FOR CONCEPTUAL DESIGN NO. 1

Material	Temp (°F)	Max. Strain (mechanical)		Strain/Strain-to-Failure
		$\left(\frac{\text{in.}}{\text{in.}} \times 10^{-3}\right)$	(Location)	
994-2	4357.8	3.72	161	0.76
ANF5Q	3788.4	9.31	159	0.63
Pyrocarb 903	2732.4	2.72	169	1.21*
3-d Mod 3a	3953.2	2.96	159	0.32

*Based on $\epsilon_{\text{failure}} = \frac{\sigma_{\text{ult.}}}{E}$

with the fuel capsule cylindrical axis or perpendicular to it, could result in the fuel pellets sliding relative to one another, creating a punch-through failure mode. Though specific impact calculations were not performed on these Conceptual Designs, considerations, like those mentioned here, were taken into account when screening the seven design geometries.

There are two measures to be used for the performance capability of the GPHS Conceptual Designs modules, the mass power density and the volume power density. Since the materials for the various module components, other than the

Fig. 3-16.

Ratio of maximum tensile stress to yield stress for two reentry member materials vs conceptual design number.³

fuel, have not been defined at this time, the mass power density was not used. The volume power density was calculated for each of the seven design concepts shown in the figures in Section 3.1 above. The dimensions and volume power density for these designs are summarized in Table III-6. The goal of the GPHS project is a module with a volume power density of at least 0.46 W/cm³ (7.5 W/in.³). The results given in Table III-6 would suggest that any of the seven geometries would achieve this goal. However, one must recognize that additional protection that will be required to correct the reentry temperature problems and that may be required to survive the impact, fragments, and blast overpressure types of environments, will most likely decrease these power densities. One should also realize that the mass power density criteria of 165.3 W/kg (75 W/lb) will be even more difficult to meet.

TABLE III-6
VOLUME POWER DENSITY FOR THE SEVEN GPHS CONCEPTUAL DESIGNS

Design	Length cm (in.)	Width cm (in.)	Height cm (in.)	Volume cm ³ (in. ³)	Total Power (W)	Power Density W/cm ³ (W/in. ³)
CD1	9.59 (3.78)	9.59 (3.78)	5.16 (2.03)	474.56 (29.01)	250	0.53 (8.62)
CD2	11.14 (4.38)	8.53 (3.36)	4.40 (1.73)	418.11 (25.46)	250	0.60 (9.82)
CD3	5.07 (2.00)	5.07 (2.00)	17.84 (7.02)	458.58 (28.08)	250	0.55 (8.90)
CD4	5.32 (2.09)	5.32 (2.09)	4.76 (1.87)	134.72 (8.17)	62.5	0.46 (7.65)
CD5	10.86 (4.27)	10.86 (4.27)	4.50 (1.77)	530.73 (32.27)	250	0.47 (7.75)
CD6	9.38 (3.69)	17.99 (7.08)	5.17 (2.03)	872.42 (53.03)	500	0.57 (9.43)
CD7	9.88 (3.89)	9.88 (3.89)	5.59 (2.20)	545.66 (33.29)	250	0.46 (7.51)

Also considered in the evaluation and screening of the seven GPHS Conceptual Designs was the fabricability of the various module components. For instance, at the time this evaluation was being performed, the feasibility of fabricating a cylindrical capsule of iridium alloy had not been demonstrated. This could have become an especially significant problem in CD2, where cylindrical capsules with a $L/D = 3.0$ must be produced. Of equal concern is the fabrication of the proposed fuel geometries. In general, the larger the fuel pellet, the more difficult it is to fabricate in a homogeneous, crack-free form. This has been a significant reason for limiting the size of the fuel bodies to less than 75W thermal watts.

Cost of fabrication and materials was also considered in these analyses, but it was concluded that cost differences between the seven geometries would be of minor importance in relation to the percentage of cost that is associated with the fuel itself. However, cost can be directly related to the time required to fabricate parts, and in this context it was considered in the screening of these designs.

The discussions of how the analyses were considered in the evaluation of each of the seven GPHS Conceptual Designs will be covered in more detail in the next section. In that section, the specific reasoning for accepting or rejecting each design from future consideration and testing will be discussed.

4.0 SUMMARY

To summarize the screening and selections of those Conceptual Designs to be tested, it will be easier to discuss those design geometries that were rejected first and give the arguments as to why they will not be considered further. The first rejected design was CD2. This design geometry has a lot to offer, such as high-power density, low-impact velocity, reasonable ablation, and better than average reentry temperatures. The main reason for rejecting this concept is related to the safety performance that would be anticipated for this design at impact. The long cylindrical shape of the fuel capsule, $L/D = 3.0$, is subject to severe deformation during an "off-angle" impact. In addition, the three fuel pellets could break up in such a manner as to provide two large pieces of fuel sliding relative to each other, resulting in the possibility of severe punch-through failures. The three fuel pellets are interlocked with each other, but in a shear loading situation, this interlocking portion of the pellet would be the most likely point of fuel fracture. The long cylindrical capsule will also have a higher probability of suffering damage in a bending mode than the smaller capsules used for the individually clad fuel pellets. Such bending stress could result from either "off-angle" impacts or blast overpressure. The longer capsules would also be more difficult to fabricate, as would be the fuel pellets with the interlocking end geometries.

CD3 also has a lot to offer, such as reasonable impact velocity, reentry temperature, etc. The main reason for rejecting this design geometry was that it has too small a cross section to be used without stacking the modules in groups of four, as shown in Fig. 3-7. In this stacking configuration, the power increment becomes 1000 W thermal, which is much larger than preferred for a modular concept such as GPHS. The length of this module geometry would also make it difficult, if not impossible, to do fueled impact testing for all orientations.

CD4, which was included only for its data base value, has high reentry peak temperatures, low impact temperatures, high impact velocity, largest ablation, and a relatively low power density. In loading the heat source modules into an RTG, this design would require the handling of four times as many modules as most of the other designs. With these results in mind, the reasons for the rejection of CD4 should be obvious.

CD6 was also rejected. The main reasons relate to the size, in that the 500 W thermal increment is larger than desirable and the dimensions are such that this module concept cannot be tested in a full fueled impact in all orientations. This module can also be very nearly duplicated by two CD1 modules, and does not have nearly the stacking versatility.

With the elimination of these four design concepts, we are left with the three, CD1, CD5, and CD7, that were to be considered for more detailed analyses and testing. As was mentioned earlier, CD7 had been and was still being carried as a back-up geometry using the spherical fuel capsule, in the event that difficulty in forming the cylindrical capsules from the iridium alloy was encountered. Considering its reentry peak and impact temperatures, and the relatively low volume power density, it would be very difficult to add the required thermal protection and still maintain the required 0.46 W/cm^3 (7.5 W/in.^3). The mass power density would also undoubtedly suffer a similar fate.

The smaller fuel capsule assemblies used in CD5 show promise of being safer in an impact situation than the larger capsules used in the other design concepts. The peak reentry clad temperature is nearer that required for survival of the Pt-3008 clad than it is for the other designs, thus requiring less in the way of thermal corrective measures. Though the power density is not as

high as one would hope for, it can be improved by going to a 300 watt nine-capsule module, without significantly degrading the module versatility. The impact temperature is also higher than for some of the other design concepts, therefore making the use of iridium alloy clad more acceptable.

CD1 was chosen because it is probably the easiest to fabricate and test, and should display an acceptable safety index and good versatility. With only four capsules and fuel pellets to fabricate and load, the costs associated with the production of this module should be relatively low. The module simplicity and symmetry will also minimize the numbers of test orientations required to characterize the module response to abort environments. The impact velocity and ablation are relatively low and with the current power density of this geometry, corrections for the reentry thermal behavior should not drive the performance below the required criteria.

In summary, Conceptual Designs CD2, 3, 4, and 6 were dropped from future considerations for reasons given above. The design concepts selected to be carried into the Trial Designs phase of the GPHS project were CD1, 5 and 7. With the successful formation of cylindrical fuel capsules from iridium alloys, CD7 has been subsequently removed from further consideration, leaving CD1 and 5. These two geometries will be improved and reanalyzed before they are tested in any full-up configuration. At the same time, components of each geometry will be tested and evaluated as to their potential for use in the GPHS modular heat source concept. It is planned that the results of the testing and analyses on these two GPHS Trial Designs will allow for a reasonable selection of the design geometry that will become the prototype for the GPHS module.

REFERENCES

1. E. C. Snow and R. W. Zocher, "General Purpose Heat Source Development, Phase I--Design Requirements," Los Alamos Scientific Laboratory report LA-7385-SR (September 1978).
2. W. E. Osmeyer (TES) and R. T. Carpenter (ERDA), "Mission Applications for the Low Cost, High-Performance Generator (LCHPG)," presented at the ANS Annual Meeting in Toronto, Canada, June 1976.
3. E. L. Foster, Jr., Compiler, "Heat Source Component Development Program Quarterly Report for July-September 1977," Battelle Columbus Laboratories report BMI-X-685 (October 1977).
4. "Multihundred Watt Radioisotope Thermoelectric Generator Program, Final Safety Analysis Report, Volume II, Accident Model Document for LES 8/9," General Electric, March 1975.