Heat Source Component Development Program

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MASTER

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FOREWORD

This is the fifth of a series of reports describing the results of several analytical and experimental programs being conducted at Battelle-Columbus Laboratories to develop components for advanced radio-isotope heat source applications . The heat sources will for the most part be used in advanced static and dynamic power conversion systems. These reports replace the informal monthly technical letter reports previously prepared and are being utilized so that more cohesive presentations of results can be achieved . In addition, a series of summary management monthly reports was initiated in July of 1976, to permit DOE assessment of contractual progress. Previous reports are identified as BMI-X-672 October 1976, BMI-X-676 January, 1977, BMI-X-679 April 1977, BMI-X-683 July 1977, and BMI-X-685 October 1977 .

The activities covered in this new series of reports are conducted under Contract No .W-7405-eng-92, Task 94. The specific efforts in progress during the period covered by this report were in support of the General Purpose Heat Source (GPHS) Development Program that is being led by the Los Alamos Scientific Laboratory (LASL). These specific efforts were concerned with: Analyses of Trial Designs with emphasis on Modifications of Reentry Heating and Thermal Stress Analytical Models, GPHS Reentry Simulation Testing with emphasis on aerodynamic stability, aerodynamic heating, and ablation, and Helium Vent Development with emphasis on fabrication and qualification testing of platinum and iridium nonselective vents .

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ANALYSIS OF GPHS TRIAL DESIGN
(I. M. Grinberg - Task Leader)

The General Purpose Heat Source (GPHS) is being developed by Los Alamos Scientific Laboratory (LASL) for the Department of Energy (DOE) Division of Nuclear Research and Application (DNRA). The first mission scheduled for the GPHS is the NASA Out-of-Ecliptic Flight in January, 1983.

LASL has formulated a program to design and qualify a heat source having certain attributes*, and has generated Trial GPHS Designs, for analysis, testing, and evaluation. Following the analysis and evaluation of the trial designs and materials, a prototype design will be selected. Proof tests of the prototype design will be conducted to insure GPHS technology readiness and compliance with the applicable safety specifications.

During the last quarterly reporting period, activities within this task's efforts were directed toward:

- Conducting performance analyses and evaluations of the thermal, ablation, and thermal stress response of the GPHS module conceptual designs (designs preceeding the trial designs)
- Collecting and compiling property and performance availability, fabricability and cost data on graphite and carbon/carbon composite candidate materials
- Experimentally measuring the diffusion controlled combustion characteristics of graphite and carbon/carbon candidate materials.

Summary

During the current reporting period, (October-December, 1977, January-February, 1978), activities in this task were conducted as follows:

- Documentation of results of the reentry thermal, ablation, and thermal stress analyses of the conceptual designs.

*"General Purpose Heat Source Program Plan", prepared for ERDA, DNRA, by LASL, CMB-5-C-77-873; Rev. 2, 31 March 1977.

- Identification and completion of modifications to the thermal and ablation models used to determine the performance response of the heat source modules during reentry.
- Initiation of modifications to the thermal stress model used to determine the performance response of heat source modules during reentry.
- Completion and documentation of the surface chemistry experiments.
- Initiation and completion of activities in support of LASL to define test plans for the trial design phase of the GPHS development program.
- Participation in the GPHS design review meeting held at DOE/Germantown, Maryland, December 19-20, 1977.
- Initiation of the thermal analysis of Trial Design 1.1.

Work This PeriodReentry Analysis

(I. M. Grinberg)

During this reporting period, technical activities were devoted to modifying the thermal, ablation, and thermal stress models which are used to determine the response of heat source modules during reentry. In addition, limited thermal analyses were conducted for Trial Design 1.1. The results of these activities are described below.

Thermal and Ablation Analysis

(G. R. Whitacre)

Model Modifications

(G. R. Whitacre)

The BCL Reentry Thermal Analysis computer code was used for the reentry thermal and ablation analyses of the GPHS Conceptual Designs^{*}. Following the completion of that study it was agreed that certain improvements should be made to the analytical tools so that additional effects could be considered in the analysis of the Trial Designs. Some of the effects that were considered are discussed elsewhere in this report. In this section, the actual modifications that have been made to the computer code are described.

In the previous analysis, the back or leeward face was assumed to be an adiabatic surface. In many reentry analyses this is a valid assumption and no provision was contained in the code to apply heating (or cooling) to this surface. For GPHS modules, this heat transfer may be significant in the stable mode of reentry and must be included when the tumbling mode of reentry is considered. Therefore, the code was modified to include heat transfer on the back face.

Because data on the heat transfer distribution on the leeward face of GPHS-shaped modules are not available, an average convective heat-transfer correlation or heating factor was applied to the entire back face. The effect of a varying surface temperature was included for both convective

* Battelle's Quarterly Report on "Heat Source Component Development Program," for July-September, 1977, (issued October, 1977), BMI-X-685.

heating and heat loss from the back face by reradiation. For hypersonic and supersonic flow, the base heating correlation described elsewhere in this report was programmed directly into the heat transfer subroutine. For subsonic flow, a heat transfer factor expressed as a ratio of the stagnation point heat-transfer rate is used.

Preliminary results of reentry analyses performed during this reporting period for the GPHS trial designs indicate that the convective heating effect on the leeward face is negligible at high Mach numbers. As the Mach number decreases toward unity during reentry, the convective heat transfer to the back face is no longer negligible. However, at low, supersonic Mach numbers, the heat loss from the back face by reradiation tends to balance the convective heating; thus, the previously used assumption of an adiabatic surface is quite good in this Mach number regime. For subsonic flow and/or cooling conditions, the leeward heat transfer will be significant. It should be noted that the thermal code allows heating and cooling to occur at different locations at the same time on any of the external faces depending on the surface temperature (value of wall enthalpy relative to the gas recovery enthalpy).

The subsonic heat transfer and pressure distributions may be quite different from the supersonic heat transfer and pressure distributions on the forward, leeward, and sidefaces of the heat source module. In the analysis of the GPHS conceptual designs, one set of heating and pressure factors was used for the entire reentry. The factors used were applicable to supersonic flow and were expressed as a function of surface position and were normalized by the stagnation point values. The code has now been modified so that different distributions may be supplied for subsonic and supersonic flow. However, difficulty has been experienced in obtaining pertinent heat transfer and pressure distribution data from the literature for the GPHS module shape. Gas cap radiation was changed so that a constant view factor is used for the windward face and a second view factor (usually zero) is used for the side and leeward faces.

The results of the surface chemistry experiments^{*} were incorporated into the code in a preliminary manner. In previous analyses it was necessary to assume that a fixed ratio of CO to CO₂ was formed at the module wall-gas boundary layer interface during the entire diffusion-controlled

^{*}See pp 108-122 of previous Quarterly Report, BMI-X-685.

oxidation regime. Generally, the conservative assumption was used that all CO was formed at the module wall. Based on the experimental work, the code was modified so that a switch from CO to CO₂ formation occurs at a specified wall temperature. Above this temperature (1100 C), CO formation is used with a diffusion mass loss constant of 0.00635 lb/ft^{3/2} sec atm^{1/2}, a heat of combustion of 3950 Btu/lb and a gas blocking coefficient of 0.66 for laminar flow. The blocking coefficient is used to reduce the incoming convective heating by an amount equal to $B \dot{M} (\Delta H)$, where

B = the blocking coefficient

$\dot{M}$ = mass loss rate

ΔH = the enthalpy difference across the boundary layer.

Below the switching temperature, which can be varied according to reentry member material characteristics, CO₂ formation is used; the value of the mass loss constant is reduced by a factor of two, the value of the heat of combustion is increased to 14,100 Btu/lb, and the value of the blocking coefficient becomes 0.59. This approach approximates the double plateau of graphite oxidation obtained experimentally.

In the graphite sublimation regime, the Scala mass loss and heat transfer reduction correlations are used in the analysis.* In the kinetically-controlled oxidation regime, experimentally determined activation energies and collision frequencies are used to calculate the mass loss rate, and CO₂ combustion is assumed unless the switching temperature is very low. A smooth transition regime is provided between the diffusion- and kinetic-controlled oxidation regimes.

Substantial improvements were incorporated into the method used to analyze the effect gaps have on heat transfer in the GPHS modules. Some of these changes required code modifications while others are only changes to the input.

In the previous conceptual design analysis, it was assumed that all of the gaps within the heat source module were filled with He in the continuum regime. A constant thermal conductivity typical of an

* See pp 74-93 of previous Quarterly Report, BMI-X-685

average temperature was used and all of the gap dimensions were maintained at their nominal values during reentry. Radiation across a gap from one material to another is added to the gas conduction. The following improvements in modeling the effect gaps have on heat transfer within the GPHS module have been incorporated into the heat transfer analysis: (1) The conductivity of the gas in the gap - This is a strong function of temperature increasing nearly linearly with temperature. In the continuum regime there is very little dependence of the gas thermal conductivity on pressure. However, at pressures approaching those of the free molecular regime, there is a rapid decrease in the gas conductivity. This decrease is approximated in the code by specifying a cut-off altitude above which it is assumed that heat transfer by gas conduction does not occur and radiation is the only heat transfer mechanism across the gaps. By equating the mean free path of air based on external static pressure to the typical gap width of 0.005 in., a cut-off altitude of 127 Kft was determined. For the gaps outside the metal containment member, the assumption of "vacuum gaps" is made above the cut-off altitude; at lower altitudes in the continuum regime, the assumption of "air gaps" is made with the thermal conductivity varying with temperature. (2) The gap between the fuel and the metal containment member is treated so as to maintain a helium pressure inside the clad - In previous analyses, using flow characteristics of the GE vent, it was assumed that the vent kept the helium pressure within the continuum range. This assumption will also be used for the trial design analysis. However, if significantly higher permeability vents are used, the gas pressure between the fuel and metal containment member will be lower, and the internal gap may become effectively a vacuum gap. (3) The gaps consider deceleration of the module during reentry - It is quite probable in stable reentry that this deceleration force will completely close the gaps forward of the fuel in the flight direction and also supply enough pressure to essentially eliminate any contact resistance. An option was added to the code to eliminate specified gaps during reentry even though they existed during the steady state operation.

Details of the model modifications pertaining to heat transfer to the leeward surface of the heat source module and to boundary layer transition and wall roughness follow.

Base Heating and Cooling
(A. A. Boiarski)

At supersonic and hypersonic flight, a reentering heat source module experiences most of the aerodynamic heating on the windward surface at and near the forward stagnation point with a negligible amount of heat transfer occurring on the aft surface near the rear stagnation zone. At low supersonic speeds the leeward or base heating can be sufficiently high to warrant its inclusion in the total energy input to the body. Also, some leeward cooling will occur at low flight Mach numbers. In previous GPHS heating analyses, the base heating and cooling was assumed to be negligible. This assumption was formerly justified by examination of free-flight data for cone-cylinder vehicles^{*}. For this case, the base heating was turbulent in nature and was found to be only 0.5 percent of the stagnation heating value for sharp cones traveling at hypersonic speeds (i.e., $M_{\infty} \approx 14$) and Reynolds numbers based on the vehicle diameter of $Re_{\infty, d} = 1.2 \times 10^4$. It was also noted that base heating did increase with nose bluntness to an estimated 1.5 percent for a hemisphere-cylinder shaped vehicle. For reentry configurations exhibiting a large degree of bluntness, e.g., Apollo Command Module, free-flight measurements have shown that the base heating is approximately 2.5 percent of the stagnation point rate for $M_{\infty} \approx 27$ and a $Re_{\infty, d} = 1.4 \times 10^4$.^{**}

For the GPHS modules at peak aerodynamic heating conditions, the Mach number is approximately 30 and the Reynolds number is of the order of $10^4 - 10^5$. Hence, it was concluded that base heating could be neglected during the peak heating. However, for lower flight speeds, the base heating will increase relative to the windward heating rates and could become important. Base cooling may also play an important role for the GPHS module configuration.

^{*} Lockman, W. K., AIAA Journal, 5, p 1898, 1967.

^{**} Lockman, W. K., J. of Spacecraft and Rockets, 7, p 93, 1970.

The mechanism whereby heat is transferred to the base of a GPHS-type module for face-on entry at hypersonic speeds (i.e., $M_\infty > 3$) is shown in Figure 1. Air at ambient conditions ahead of the module is processed by the strong bow shock wave such that the gas pressure and temperature are significantly increased. This high temperature environment results in windward surface heating due to energy transfer from the hot gas to the module surfaces. However, a significant portion of the heat remains in the gas. This high temperature gas then expands around the body continually increasing in velocity, through the sonic line (i.e., $M = 1$) into a supersonic expansion region until it reaches the aft corner of the module (i.e., point C). At this point the Mach number, M_C , is supersonic ($M_C < 6$), and the gas temperature and pressure have decreased somewhat due to the flow expansion. Although the majority of the flow enthalpy finds its way through a complex flow structure into the vehicle wake, a small quantity of heat, Q , flows through the shear layer, into the recirculation zone and base boundary layer and finally enters the wall. The wall temperature, T_w , governs the direction and magnitude of the wall heat transfer rate, $\dot{q}_w$. The initial stagnation conditions (i.e., P_o , T_o) and the state of the flow at the corner nearest the base (i.e., conditions at point C), also play a significant role in determining the base heating or cooling rate.

Theoretical methods have been developed to calculate the base heat transfer rate for turbulent flow conditions for a variety of vehicle shapes. However, the GPHS module design is not a conventional aerodynamic reentry shape so no specific theory or even experimental data are available. To overcome this difficulty, an empirical correlation method developed by Page and Dixon* was used in the present analysis. This correlation compares favorably to experimental data** for various vehicle shapes as shown in Figure 2.

A curve fit to this correlation was developed whereby the base heating rate for $T_w < T_o$ can be written as

* Page, R. H., and Dixon, R. J., "Base Heat Transfer in a Turbulent Separated Flow", Proceedings of the 5th Inter. Conf. on Space Tech. and Science", 1963, AGNE Pub. Corp., Tokyo, Japan, pp 295-308.

** Fletcher, L. S., "Base Heat Transfer in an Axisymmetric Supersonic Flow", AIAA Journal, 8, 1970.

FIGURE 1. DIAGRAM OF GPHS BASE HEATING MECHANISM

FIGURE 2. CORRELATION USED TO CALCULATE BAS HEAT TRANSFER TO GPHS MODULE IN HYPERSONIC FLOW REGIME

$$\dot{q}_w = 144 P_o \sqrt{T_o} 10^{(AX^2 + BX + C)}, \text{ BTU/ft}^2\text{-sec} \quad , \quad (1)$$

where

$$\begin{aligned} \chi &= (T_w/T_o) \\ A &= 0.076 M_c^2 - 0.633 M_c - 0.34 \\ B &= -0.053 M_c^2 + 0.498 M_c - 0.84 \\ C &= 0.041 M_c^2 - 1.008 M_c - 1.87. \end{aligned}$$

In Equation (1), P_o is in psia and T_o in $^{\circ}\text{R}$. For the case where $T_w > T_o$ (i.e., leeward cooling), the parameter χ in Equation (1) is changed to $\chi = T_o/T_w$.

The calculation of base heat transfer can proceed provided that an estimate can be made of the flow Mach number, M_c , at the leeward corner of the heat source module as a function of free-flight Mach number. The value was obtained using normal-shock-expressions* to estimate the stagnation pressure ratio, P_o/P_1 , on the windward side of the body. It was then assumed that the flow expanded to a corner surface pressure, P_c of 3 times the ambient pressure, P_1 . This value of surface pressure ratio, $P_c/P_1 = 3$, was obtained from data and theory for an end-on cylinder in hypersonic flow**. The corner Mach number was then computed using the ratio of corner pressure to stagnation pressure, P_c/P_o , and the isentropic tables given in NACA Report 1135*. Results of these shock-plus-expansion calculations are shown in Figure 3. Also shown in Figure 3 is a curve fit to the above calculations, where

$$\begin{aligned} M_c = 0.7486 + 0.3218 M_{\infty} - 9.457 \times 10^{-3} M_{\infty}^2 \\ + 1.060 \times 10^{-4} M_{\infty}^3 \quad . \end{aligned} \quad (2)$$

* NACA Report No. 1135, 1953.

** Chernyi, G. G., Introduction to Hypersonic Flow, p 217, Academic Press, New York (1961).

FIGURE 3. GPHS MODULE LEEWARD CORNER MACH NUMBER AS A FUNCTION OF FLIGHT VEHICLE MACH NUMBER

For tumbling reentry of the heat source module, Equation (2) is applied to the leeward face in a time-average manner. For end-on entry, the corner Mach number would be somewhat lower since $P_{q_c} \approx P_1^*$, but the method of analysis would be identical given a new relation for M_c as a function of the free-stream Mach number.

Due to the lack of any experimental information on leeward heat transfer coefficients for GPHS module shapes in the transonic flight regime, the above correlation developed by Page and Dixon was used down to a Mach number of unity. Although this extrapolation is beyond the defined limit of application of the correlation, GPHS modules spend only a small portion of the reentry time at these flight conditions. Therefore, possible errors in the temperature calculations and reentry member mass loss resulting from this extrapolation are expected to be minor and have little effect on the overall results.

At subsonic Mach numbers, cooling will occur on the leeward face of the GPHS module. Because no data could be found for subsonic heat transfer coefficients on the leeward surface of GPHS-shaped modules, the heat-transfer coefficient was estimated using data for other body shapes. A value of 0.8 of the windward face stagnation point heat transfer was used over the entire leeward face based on cylinder data at $Re \approx 10^{5**}$.

*Chernyi, G. G., Introduction to Hypersonic Flow, p 217, Academic Press, New York (1961).

**Kreith, F., Principles of Heat Transfer, p 374, International Textbook Company, Scranton, (1958).

Boundary Layer Transition and Wall Roughness
(A. A. Boiarski)

The type of boundary layer (i.e., laminar or turbulent) which exists over the surface of the GPHS module will affect the heat transfer rate to that surface. Furthermore, the surface of some carbon-carbon materials can be rough due to the presence of the weaved fiber structure. This wall roughness can hasten laminar-to-turbulent boundary layer transition as well as augment the heat transfer rate itself. Usually, this heat transfer augmentation is considered operative only for a turbulent boundary layer case. There is some evidence that similar augmentation occurs for laminar boundary layers, but flight conditions for the present GPHS reentry conditions indicate that augmentation does not occur in the laminar regime.

For the turbulent boundary layer case, a correlation was developed to relate the Stanton number for a rough wall, St_r , to that of a smooth wall, St_s , using the parameters K_r^* where,

$$K_r = St_r / St_s \quad , \quad (3)$$

K_r can be computed using the following:

$$\begin{aligned} X < 10, K_r &= 1.0 \text{ (i.e., no augmentation)} \\ 10 < X < 10^4, K_r &= 1 + 2/3 (\log X - 1) \\ 10^4 \leq X, K_r &= 3.0 \end{aligned} \quad (4)$$

where

$$X = Re_k \sqrt{St_s} (T_e/T_w)^{1.3} \quad . \quad (5)$$

In Equation (5), Re_k is the Reynolds number based on the nominal roughness height, k . T_e and T_w are the boundary layer edge and wall temperature values, respectively. The data used to obtain Equation (4) was derived from sphere-cone models at $M_\infty = 5$, roughness heights from 0.5 to 80 mils, and $0.4 \leq \frac{T_w}{T_e} \leq 0.6$.

* Wool, M. R., Aerotherm Report 75-159, Aerotherm Division/Acurex Corp., June, 1975.

The question then arises as to whether or not the boundary layer on a GPHS module is laminar or turbulent in nature. To determine this with certainty requires a calculation of the laminar-to-turbulent transition point, an area of fluid mechanics that remains difficult to treat theoretically, or the conduct of experiments on GPHS-shaped modules.

A correlation has been developed for sphere-cone models as follows:*

$$[Re_{\theta} (\frac{k}{\phi\theta})^{0.7}] < 225, \text{ laminar boundary layer,}$$

$$[Re_{\theta} (\frac{k}{\phi\theta})^{0.7}] \geq 225, \text{ turbulent boundary layer} \quad (6)$$

where

$$\phi = (\frac{\beta}{10}) + (1 + \frac{\beta}{4}) \frac{T_w}{T_e}.$$

In Equation (6), Re_{θ} is the Reynolds number based on the boundary layer momentum thickness θ . Surface roughness height, k , and the effects of mass transfer and wall temperature are also accounted for through the parameters β and T_w/T_e , respectively. To evaluate Equation (6) properly, a separate computer program would need to be run in order to calculate the momentum thickness and corresponding Re_{θ} as a function of distance from the windward stagnation point on the GPHS module throughout reentry. In the interest of maximizing the use of the available resources, values of θ and Re_{θ} available from flat plate solutions were used instead. For the shallow angle trajectory ($\gamma = -5.3$ degrees), it was found that transition would not occur. For the steep angle trajectory ($\gamma = -89.9$ degrees), it was found that $[Re_{\theta} (\frac{k}{\phi\theta})^{0.7}] \approx 400$ using peak Reynolds number flight conditions, $\phi = 1$, and a nominal wall roughness value of $k = 0.002$ in. Hence, a more accurate analysis is required to determine the likelihood of laminar-to-turbulent transition for the GPHS module configuration. It is our judgment that boundary layer separation would occur before transition to turbulent flow could take place. This judgment is based on the fact that more sophisticated calculations by JHU/APL indicate a low probability of transition on the MHW cylinder configuration during reentry.** The GPHS modules will

* Ibid.

** Private Communication, J. C. Hagan of the Johns Hopkins University Applied Physics Laboratory.

encounter lower flight velocities and more favorable leeward pressure gradients which should ensure that a laminar boundary layer would persist throughout before separation. In summary, the GPHS aerodynamic heating is presently assumed to be governed by laminar flow equations and roughness will not cause transition or heat transfer augmentation.

Thermal Analysis of Trial Design 1.1

Trial Design 1.1 is revision of Conceptual Design 1 in which the pyrolytic graphite insulation has been extended around the corners of the impact member. This extension is an attempt to reduce the heat transfer into the clad and thereby reduce the peak clad temperature caused by reentry heating. The additional insulation should also increase the clad temperature at impact by decreasing the cooling during the latter portion of the trajectory.

Figure 4 is an assembly drawing of Trial Design 1.1 as provided by LASL. The module is a right square cylinder having a nominal broadface dimension of 92.7 mm (3.65 in.) and a nominal height of 53.5 mm (2.11 in.). The corners of the module are chamfered and the edges are rounded. It is a 250 W(t) module containing four (4) 62.5 W(t) $\text{Pu}^{238}\text{O}_2$ fuel pellets. Each fuel pellet is inserted from a broadface of the module, two from one face and two from the opposite face. Specific details relating to the fuel, metal cladding, reentry member and impact member are very similar to Conceptual Design 1, and are described in detail in the previous quarterly report*.

Figure 5 shows the thermal model used for TD 1.1. The approach used is the same as was employed in the conceptual design thermal analyses. An axisymmetric, two-dimensional thermal network is used with the model broadface circular area matching the actual broadface area of the TD 1.1 module. A cross section through the fuel pellet centerline was taken as the cross section to be used in the model with all dimensions preserved in the longitudinal or z direction. In this manner the axisymmetric model diameter represents a value which is numerically between the actual across-flat dimension and the across-corner dimension of the heat source module. The adjustment to match the model diameter was taken near the model centerline and distances in the r direction match the actual cross section of the module

* BMI-X-685.

FIGURE 4. ASSEMBLY DRAWING OF GPHS TRIAL DESIGN TD 1.1

FIGURE 5. THERMAL MODEL OF TRIAL DESIGN TD 1.1

at all other locations. The adequacy of this two dimensional approximation will be checked by direct comparison with analyses performed using a three dimensional model for one trial design later during this phase of the project.

Gaps are provided at various material interfaces per drawings Nos. 26Y-79580-1, -2, and -3 supplied by LASL. A gap of 0.010 in. is provided between the metal containment clad and the fuel for steady-state operation and is assumed to be filled with helium. It is assumed that during reentry the deceleration of the module forces the fuel forward such that the fuel and metal clad are in contact along the forward fuel face. Based on the TD 1.1 detail drawings, a gap of 0.005 in. is placed between the clad and the impact member and a gap of 0.0085 in. is used between the clad and pyrographite. As previously discussed, these gaps transfer heat by radiation only when the mean free path of the gas is greater than the gap dimension. When the external pressure increases during reentry so that the mean free path is less than the gap dimension, continuum gas conduction with air in the gaps is added to the gap radiation. Because of deceleration during reentry, it is assumed that contact is made between the forward clad face and the pyrographite, effectively eliminating the gap. The nodes labeled "clad" in Figure 5 actually include the 0.025-in.-thick clad material and the gaps on either side of the clad. The effective density and conductivity are calculated for this combined node which permits a larger stable time step in the explicit solution of the heat conduction equation. Gaps of 0.005 in. are provided between the impact member and the reentry member. These gaps are assumed to be vacuum gaps at low pressure and air in a continuum at the appropriate pressure. A thin (0.005-in.-thick) Grafoil compliance pad is placed between the impact member and the pyrographite. Because of this pad and the assembly procedure, no gaps are provided between the impact member and pyrographite where the Grafoil is located.

Contact resistance is modeled at the thread region of the retainer plug. A 30 percent contact area is assumed based on details of possible thread designs provided by LASL. Heat transfer through the remainder of the threaded region is assumed to be by radiation and by gas conduction when appropriate. The modeling of the pyrographite is somewhat approximate due to restrictions in the model. In the flat portion, see Figure 4,

the low thermal conductivity direction of the material is taken to be in the z direction. In the first nodes of the curved portion of the pyrographite adjoining the flat, the low k direction is taken as the model r direction. In the remaining curved portion nodes, the low k direction is the model z direction and this part of the pyrographite will probably not be too effective in blocking heat. The cut-out in the model of the outer pyrographite is also a result of model restrictions but should have an insignificant effect on the thermal results.

Because the thermal model is axisymmetric, the fuel is placed in a torus rather than four distinct pellets. This results in a larger volume of fuel in the model than actually exists in the module. Therefore, the density and volumetric heat generation of the fuel are reduced in the model so that the actual fuel weight and heat generation of the module are exactly matched in the model.

Figure 6 shows the steady-state temperature profile for space operation of TD 1.1 with a 900 C hot junction temperature. The operating temperatures are much higher than the previous results for Conceptual Design 1. The assumption of "vacuum gaps" is being used in the trial design analyses whereas the assumption of helium-filled gaps was used in the conceptual design analysis. The peak fuel temperature has increased to 1243 C from 1046 C and the peak clad temperature to 1176 C from 985 C.

The reentry thermal and ablation analysis for TD 1.1 will be conducted during the next quarter. The effect of the tumbling mode of reentry in addition to the broadside stable mode will be determined. Two modified Trial Designs (1.2 and 1.3) will also be modeled and analyzed. Analyses for Trial Design 2.1-2.3 will also be conducted. This design has 9 fuel pellets for a total of 300 W(t) and is similar to Conceptual Design No. 5 but has additional pyrographitic for thermal protection. It has also been changed to have the fuel pellets inserted from the broad faces rather than the edge.

Based on the information provided by LASL, reentry response analyses of TD 1.1-1.3 and TD 2.1-2.3 will be performed for two reentry member materials, 994 bulk graphite and FMI 223 carbon-carbon made from HM-3000 fiber. Sufficient thermophysical and mechanical properties of the bulk graphite are available and on hand for the reentry analysis. However, most of the thermophysical and mechanical properties for the 223 carbon/carbon

FIGURE 6. STEADY STATE TEMPERATURE PROFILE FOR TRIAL DESIGN TD 1.1
WITH GRAPHITE 994-2 REENTRY MEMBER

material made from HM-3000 fibers are needed as are the thermophysical properties for the preferred impact member, Pyrocarb 848. Contacts have been reestablished at WPAFB/AFML, SoRI, and Hitco in order to determine the availability of properties for these two materials. Based on the available information, it appears that it will be necessary to make engineering estimates of the material properties using available property data from other "similar" materials.

As previously indicated in this section, reentry analyses of the trial design modules are being performed for reentry of the individual modules. An assessment has been made of the analysis requirements for reentry of stacked modules assuming the modules do not break apart sufficiently soon following generator breakup. Three reentry modes were considered as follows:

- for reentry of the stacked modules in an "end-on" configuration (unlikely configuration), the two-dimensional modeling techniques in current use can be used to determine the thermal, ablation, and thermal stress response.
- for reentry of the stacked modules in a "side-on spinning" mode, the techniques and methods in current use can be used to determine the thermal, ablation, and thermal stress response
- for reentry of the stacked modules in a "side-on stable" mode, three-dimensional modeling techniques are needed to determine the thermal and thermal stress response.

At this time in the project, it is recommended that analyses for reentry of stacked modules be deferred pending the outcome of aerodynamic stability tests being planned by LASL for conduct at NASA AMES during Spring, 1978. It is hoped that these tests will not only determine the stability orientation of individual modules, if any, but will also identify the tendency of stacked modules to separate following generator breakup or assume a stable reentry orientation.

Consideration was also given to conducting analyses to determine the reentry response of individual heat source modules entering in the "edge-on" mode. For this reentry configuration, three-dimensional techniques are required for the thermal and thermal stress response. It is recommended that conduct of such analyses be deferred pending the outcome of the aerodynamic stability tests to be conducted at NASA-Ames. If required, these analyses can be performed during the May-July, 1978, period without adverse impact to the project progress.

Finite Element Analysis of GPHS Reentry Member
(L. E. Hulbert)

Plans for the initial stress analysis of the trial designs call for a two-dimensional plane strain model of the reentry member through its minimum subsection as was done for the conceptual designs. On receipt of the prints for Trial Design 1 (TD 1.1) it was found that the minimum web thickness is planned to be about 0.050 in. or less. It is not clear at this point whether such a thin web serves any useful purpose. However, one aspect of the design of TD 1.1 is that there is a much larger variation in the relative distance between adjacent cavities in TD 1.1 than in CD 1. An evaluation of the effect of this variation on the stresses in the reentry member would require a three-dimensional analysis.

It is currently planned to use Battelle's program AXISOL in the plane strain analysis of TD 1.1-1.3. This program has the capability to allow a double line of nodes to open under tension to simulate the action of the closure threads. Since there were tensile stresses on the inside of the reentry member of the conceptual designs, it is expected that the threads will separate in this region. Two analyses will be made. In one, the threads will be allowed to separate. In the second analysis, the threads will be kept pinned. In this way, an attempt will be made to bound the thread stresses. However, once again, a realistic analysis of the stresses requires a three-dimensional analysis.

Three variations of Trial Design 1 were received. These variations (designated TD 1.1, 1.2, 1.3) differ in the amount of

pyrolytic graphite included for thermal insulation of the metal clad. Although the overall size of the reentry member in each variation is different, the basic thickness of the web sections and the internal fillet radii of the fuel cavity corners is the same in the three designs. A study of the designs showed that by starting with a finite model of TD 1.3, it would be possible to obtain models of TD 1.1 and 1.2 by deleting or shrinking elements.

This editing process will be carried out by using Battelle's STAGING system which was used in developing the various graphical displays of the conceptual design models presented in the Quarterly Progress Report for August-September, 1977. The display and edit system of STAGING will be used to make these changes interactively.

A finite element model of TD 1.3 was generated from the print supplied by LASL using Battelle's digitizer system. Figure 7 shows this model which was plotted with the STAGING system. It is noted that, in contrast to the conceptual designs, this model has included a number of triangular elements to model the cavity corners smoothly so that a better determination can be made of the stress concentrations.

Since this model differs considerably from the finite difference model being used to obtain reentry temperatures, an interpolation scheme is needed to obtain finite element nodal temperatures from the finite difference results. An interpolation procedure was developed and checked out late in 1977 in another program at Battelle. This procedure will be checked out to make sure it works for the trial designs and then applied to obtain the necessary temperatures.

Three-Dimensional Stress Analysis of Trial Designs (L. E. Hulbert)

The initial steps of the plane strain analysis of the trial designs is described in the previous section. This approach follows that which was used in the analysis of the conceptual designs carried out in 1977. However, the objective of the conceptual design stress analysis was to compare the relative stresses between different designs. It was recognized that a number of approximations were made that could significantly

FIGURE 7. FINITE ELEMENT DESIGN OF GPHS MODULE
TRIAL DESIGN 1.3

affect the magnitude of the stresses. It was assumed without verification that these effects would not change the relative ranking of the different designs.

The objective of the current stress analysis will be to obtain reasonable predictions or estimates of the absolute magnitudes of the stresses in the trial designs. These are necessary to be able to decide whether the designs will withstand reentry thermal stresses. Thus, it is believed that closer attention should be given to the complicated three-dimensionality of the stresses in the trial design reentry member.

Significant three-dimensional effects are believed to occur in two ways: (a) in the variation in the thickness of the web between the four cavities as seen in the top view of TD 1.3 in Figure 8 and (b) in the effect of hoop stresses (i.e., out of plane tensile stresses) on the relative deformations of the closure threads and the threads in the closure hole of the reentry member. A study of the two orthographic views of TD 1.3 shown in Figure 8 shows some very thin areas between one threaded hole and the adjacent fuel cavity which has its plug on the opposite side of the reentry member. It is very possible that a crack could be started in this section that would propagate through the tensile stress region to shear off the middle column between the four holes. This fracture might then allow a sufficient bow to the reentry member surface to open one or both of the closures. Since the plane strain analysis model does not account for the stress normal to the plane B - B (Figure 8), no estimate can be made for the probability of this type of failure without a three-dimensional analysis.

A three-dimensional model of the reentry member would include one quarter of the full reentry member block. This quarter is shown by dotted lines in the top view of Figure 8. It is noted that the model encompasses half of one cavity with a closure on top and half of one cavity with the closure on the bottom of the reentry member. Edges of this quadrant are symmetry planes. It is estimated that an adequate model of this design could be made with about 1200 elements and 2000 nodes with 6000 degrees of freedom. A similar three-dimensional model of TD 2 would require between 1.5 and 2 times the number of nodes and elements because of its greater complexity.

FIGURE 8. DETAIL DRAWING OF TRIAL DESIGN TD1.3

GPHS Reentry Simulation Testing
(R. G. Luce)

This section summarizes the work performed by Battelle in support of LASL to develop a Test Program Plan for the Trial Design Phase of the GPHS Project. Battelle's role in providing test planning support to LASL consisted of

- Reviewing critical design features of importance to the thermal response of heat source modules
- Identifying GPHS module design features that may require testing to define their ablation response
- Defining the types of testing required
- Identifying facilities suitable for testing and obtaining preliminary estimates of test cost and facility availability.

It is intended that this effort and the information presented herein will serve as a guideline for the selection of tests that should be conducted in support of the trial design trade-off analyses and materials selection.

At the initiation of this planning support activity, discussions were held with LASL personnel to help focus the Battelle effort to those areas of immediate concern which would complement those efforts underway at LASL.

It was agreed that Battelle should concentrate on three major areas of testing: (1) aerodynamic stability, (2) aerodynamic heating, and (3) ablation. Key design features associated with the trial designs that will require testing are identified. The type of testing and test conditions are also discussed.

Reentry Environment

The environment experienced by the GPHS module during reentry is discussed below. To determine the approximate reentry trajectories for the heat source modules, it was assumed that the module would reenter aerodynamically stable either broadface or edge-on (see Figure 9) at two entry angles of -89.9° (steep entry) and -5.3° (shallow entry). The combination of these two module attitudes and reentry angles result in aerodynamic estimates which

FIGURE 9. DEFINITION OF REENTRY ATTITUDES OF GPHS MODULE

are representative of the range of flight conditions associated with a reentering GPHS module.

Partial results of the trajectory analysis are given in Figures 10 and 11 for the steep and shallow entry angles, respectively. In these figures, the module stagnation point heating rate and pressure, Reynolds number, and velocity are presented as a function of altitude. The values of the stagnation point heating rate are for a 1-in. radius hemisphere. The heating rate was related to a hemispherical geometry because many facilities have calibration data for this configuration. For the steep angle trajectory, Figure 10, it can be seen that the peak aerodynamic heating and pressure levels occur at hypersonic speeds for both module attitudes. The maximum Reynolds number occurs at approximately 90 Kft and 75 Kft for the broadface and edge-on attitudes, respectively. At peak Reynolds number, the module speed is above a Mach number of 10 for both module attitudes. As the module goes through the supersonic and transonic flight regimes, it will encounter unsteady aerodynamic loads that could result in unsteady aerodynamic loads and unsteady motion of the module. This unsteady motion (such as tumbling) will affect the trajectory and therefore the resulting flight conditions.

Figure 11 shows the flight conditions for the shallow-angle GPHS module entry for broadface and edge-on stable attitudes. A major portion of the aerodynamic heating occurs above an altitude of 150 Kft and peak heating occurs at approximately 220 Kft for both module attitudes. There is a difference in the module stagnation pressure profiles for the broadface and edge-on entries. The module stagnation pressure for the broadface entry reaches an initial maximum value of approximately 0.1 atm at 200 Kft and remains at this pressure level down to an altitude of approximately 150 Kft. The module stagnation pressure for the edge-on entry reaches an initial maximum value at approximately 125 Kft. At peak heating, the stagnation pressure is approximately 0.14 atm, which is 40 percent higher than the stagnation pressure at peak heating for the broadface entry.

Presented in Table 1 are values of the flight conditions and environmental parameters at which ablation and aerodynamic stability ground tests should be conducted. These values are based on the analysis of flight conditions as discussed above.

FIGURE 10. TRAJECTORY RESULTS FOR STEEP REENTRY ANGLE

FIGURE 11. TRAJECTORY RESULTS FOR SHALLOW REENTRY

TABLE 1. GPHS REENTRY FLIGHT CONDITIONS FOR STEEP AND SHALLOW REENTRIES

Type of Test	M_∞	Re/ℓ $10^6/\text{Ft}$	$\dot{q}\sqrt{R},$ $\frac{\text{Btu in}^{1/2}}{\text{Ft}^2\text{-Sec}}$	$P_{\text{stag}},$ atm
Ablation	>5	~ 1.5	1000-5000	6-10
Stability	>5	0.2-0.75	N/A	0.5-2.0
<u>Shallow Entry</u>				
Ablation	>5	0.025-0.075	1000-1400	0.1-0.15
Stability	>5	≤ 0.025	N/A	≤ 0.02

The aerodynamic heating rate ($\dot{q}\sqrt{R}$) values presented in Table 1 correspond to the heating on a 1-in. radius hemispherical shape. The module stagnation pressure for the aerodynamic stability test is lower than that for the ablation test. This is because the stability of the module should be determined at an altitude higher than that corresponding to peak convective heating.

Aerodynamic Testing

In order to verify GPHS design concepts, it will be necessary to conduct either full-scale flight tests or simulated tests in ground-based facilities. Historically, it has been possible to perform selective simulation tests in ground-based facilities to provide the aerodynamic data necessary to verify and/or compare the aerodynamic performance of various designs. With respect to the GPHS designs being considered, three types of aerodynamic testing should be considered. They are: aerodynamic stability, aerodynamic heating, and ablation. The amount of testing required will depend on the data that is available for the particular GPHS geometries and materials being considered. Preliminary results of the trajectory analyses such as those presented in the previous

section are useful in order to determine the flow regimes of importance and to determine the simulated test conditions. Details of the aerodynamic tests recommended in support of the GPHS module design and development activities are discussed further in this section.

Aerodynamic Stability. The aerodynamic stability and unstable modes of motion of the GPHS module in the various flight regimes (hypersonic, supersonic, and subsonic speeds) should be known in order to perform appropriate thermal and structural analyses. The stability of a module as it reenters the earth's atmosphere will have an effect on the module's heating, ablation, and terminal velocity.

Based on the preliminary results of the trajectory analysis of broadface and edge-on module attitudes, it appears that a major portion of the aerodynamic heating occurs at module speeds in the hypersonic regime. Therefore, it is necessary to characterize the hypersonic aerodynamic stability of the module. Since the individual GPHS modules are closely packaged in a single container, the individual module attitudes will be strongly influenced by the other modules during container breakup and module separation. Two important questions associated with module separation must be answered: (1) How much time is required for the modules to separate completely (no flow interactions), and (2) after separation, do the modules establish a stable attitude?

It is important that the modules separate and disperse a distance sufficiently large to eliminate shock and flow-field interactions. If the required flight time to disperse the modules is relatively long, the modules will enter the high heating rate portion of the trajectory in a close pattern. This is undesirable since a module could experience high heating rates due to shock wave interactions with other modules and result in excessive reentry member ablation and possible failure. Therefore, it is also desirable that the modules disperse rapidly. After the modules separate, module stability and/or motion will be a function of the aerodynamic forces and moments, the module geometry and mass, and moments of inertia characteristics.

Tests should be performed to determine the hypersonic stability of the modules. Stability tests can be performed in either hypersonic wind tunnels, ballistic ranges, and/or actual full-scale tests (without

fuel). Full-scale testing is desirable, but would be quite expensive and difficult to perform with respect to obtaining the desired data. Existing hypersonic wind tunnel facilities and ballistic ranges can be used to simulate module trajectory conditions in order to determine the stability of the module. Based on the types of tests and information that is required from the tests, it is recommended that ballistic facilities be used to obtain the required hypersonic stability data.

Ballistic tests should be performed on clustered GPHS modules and on individual modules. Results from the clustered module tests for the module attitudes and angular rates should be used to select test conditions for the individual module tests.

The initial orientation of the clustered modules should be varied over a range of angles resulting from the most probable generator breakup configuration. Initial orientation angles of the module package should be selected from the results of system breakup analysis or a number of possible cluster orientations should be used if it is not feasible to conduct such an analysis. It is anticipated that the results from the cluster tests will determine the following:

- Time required for module dispersion
- Motion of individual modules after dispersion
- If there are any stable module attitudes.

If it is possible to determine the aerodynamic stability of the individual modules from the cluster test results, the additional individual module tests can be eliminated.

In order to perform subscale model tests in a ballistic range facility, it is important that the appropriate model flight dynamic conditions be simulated so the test results can be applied to full-scale flight conditions. The test Reynolds number and Mach number should be selected to ensure that the aerodynamic coefficients (C_D , C_L , and C_M) are representative of full-scale values in the flow regime of interest. The actual body dynamics can be viewed and (1) translational motion (essentially horizontal during ballistic test) and (2) angular motion.

For horizontal flight, the rate of change of velocity is given by

$$m\dot{V} = -C_D \frac{\rho V^2}{2} S \quad , \quad (7)$$

where

- V = the velocity in ft/sec
- m = the mass in slugs
- C_D = the drag coefficient
- ρ = the air density in slugs per cubic foot
- S = the reference area in ft^2 .

A nondimensional time unit, τ , can be used such that

$$\tau = \frac{2V_o}{\ell} t \quad , \quad (8)$$

where

- ℓ = a characteristic length, in ft
- t = time, in seconds
- V_o = a reference flight speed.

Then

$$\frac{d}{dt} = \frac{2V_o}{\ell} \frac{d}{d\tau} \quad . \quad (9)$$

When V is near V_o , Equation (7) becomes

$$\frac{d}{d\tau} (V) = - \frac{C_D \rho V_o S}{4m} \ell \quad . \quad (10)$$

Now, if we introduce a dimensionless velocity variable,

$$u = \frac{\Delta V}{V_o} \quad ,$$

$$\Delta V = V_o u \quad ,$$

and

$$\frac{d}{d\tau} (V) = V_o \frac{d}{d\tau} (u) \quad .$$

Substituting into (10)

$$\frac{du}{d\tau} = - C_D \frac{\rho S \ell}{4m} , \quad (11)$$

where both sides of Equation (11) are dimensionless.

For rotational motion about a principal axis of the body, the equation is of the form:

$$I_y \ddot{\theta} = C_{m\theta} \frac{\rho V_o^2 S \ell}{2} \left(\frac{\dot{\theta} \ell}{2V} \right) + C_{m\theta} \frac{\rho V_o^2 S \ell \theta}{2} , \quad (12)$$

where

I_y = the moment of inertia about the axis of rotation, in slug-ft²,

C_m = the moment coefficient, and

$$C_{m\theta} = \frac{\partial C_m}{\partial \left(\frac{\dot{\theta} \ell}{2V} \right)} ,$$

$$C_{m\theta} = \frac{\partial C_m}{\partial \theta} , \text{ by the conventional definitions.}$$

Again, using the definition of τ ,

$$\dot{\theta} = \frac{2V_o}{\ell} \frac{d\theta}{d\tau}$$

$$\ddot{\theta} = \frac{4V_o^2}{\ell^2} \frac{d^2\theta}{d\tau^2}$$

So

$$I_y = \frac{4V_o^2}{\ell^2} \frac{d^2\theta}{d\tau^2} = C_{m\theta} \frac{\rho V_o^2}{2} S \ell \frac{d\theta}{d\tau} + C_{m\theta} \frac{\rho V_o^2 S \ell}{2} \theta ,$$

or

$$\frac{d^2\theta}{d\tau^2} = [C_{m\dot{\theta}} \frac{\rho S \ell^3}{8I_y}] \frac{d\theta}{d\tau} + C_{m\theta} [\frac{\rho S \ell^3}{8I_y}] \theta \quad (13)$$

The above analysis indicates that in order to have dynamic similarity (translational and angular module motions), the parameters $\frac{\rho S \ell}{m}$ and $\frac{\rho S \ell^3}{I_y}$ (in Equations (11) and (13), respectively) should be appropriately scaled in accordance with the aerodynamic forces and moments. It is difficult to determine the actual angular motion of the module, even for a simple analysis of the one degree of freedom results indicated by Equation (13), because the aerodynamic coefficient $C_{m\theta}$ and $C_{m\dot{\theta}}$ are unknown quantities and are functions of θ . This leads to an additional problem related to the time duration of the tests.

If the module should have an oscillating damped or divergent motion, the period of oscillation may be sufficiently long in comparison to the time duration of the test. This would make it difficult, if not impossible, to determine if the module is dynamically stable. It is recommended that details related to interpretation of test results be discussed with personnel responsible for conducting the dynamic stability tests since they should have standard techniques that can be used to analyze such test results.

Specific activities which should be conducted in support of the aerodynamic stability tests, in addition those normally performed by the test facility, are:

- select test matrix
 - orientation and release
 - test conditions
 - single and stacked tests
- design test models
- prepare test documentation
- test participation
- analyze/interpret test results.

Aerodynamic Heating.

Hypersonic Flow. In order to perform an accurate thermal analysis for a GPHS module, it is necessary that a complete description of the three-dimensional aerodynamic heating be specified. Facilities are available which can produce environments which closely simulate the flight conditions anticipated for the GPHS module during reentry. Included in this category are wind tunnel, shock tunnel, rocket exhaust, and high-speed test track facilities. Each of these facilities normally have operating envelopes which correspond to portions of the GPHS module flight regimes of interest.

The results of a preliminary trajectory analysis for the GPHS (TD 1.1) indicates that a major portion of the heating occurs at module speeds in the hypersonic regime (above a Mach number of 5). The most appropriate type of facility for determining the aerodynamic heating rates and spatial heating distributions at high Mach numbers is a hypersonic wind tunnel. Detailed information on the heat transfer distribution around a body can be obtained using full-scale wind tunnel models with the appropriate instrumentation.

It is believed that at this stage of the GPHS project, the reentry thermal analysis can be performed with sufficient accuracy using the available heat transfer and pressure data such that additional aerodynamic heating tests need not be conducted. Although there are inconsistencies in some of the available data which should be resolved during the GPHS project prior to the final design selection, current project resources can be more effectively directed by obtaining vital information relating to the module aerodynamic stability and module/material ablation characteristics.

The test matrix associated with aerodynamic heating tests should include the following:

- (1) Heat transfer coefficient data for various module attitudes (defined from stability tests)
- (2) Base heating
- (3) Surface roughness effects
- (4) Module geometry detail tests (closures, gaps, and fabrication tolerances.

Subsonic Flow. Data on the heat transfer and pressure distribution on GPHS module shapes are needed at subsonic speeds where cooling of the module occurs. This information is needed in order to accurately determine the metal containment (clad) temperature at impact. Such tests can be conducted using full-scale models in transonic/subsonic wind tunnel facilities. Data on windward, side, and leeward module surfaces should be obtained; no applicable data could be found in the literature.

Tests to determine the subsonic heat transfer and pressure levels and distributions on GPHS module shapes can be deferred until the prototype phase of the GPHS project. The need for these tests and the amount of testing required can be determined through the conduct of reentry sensitivity analyses during the current project phase. In this manner, the effect of uncertainties and variations in the aerothermal boundary conditions on clad temperature at impact can be determined.

Specific activities which should be conducted in support of the subsonic aerodynamic heating tests, in addition to those normally performed by the test facility, are:

- select test matrix
 - test conditions
 - orientation of models
- design calorimeter models
- select test facilities
- prepare test documentation
- test participation
- analyze/interpret test results.

Ablation Tests. Presented below is an outline of suggested GPHS ablation tests and a list of facilities suitable for conducting such tests.

Test Considerations. Ablation tests should be conducted during the trial design phase of the GPHS project in order to obtain basic characterization data on the candidate reentry member materials and determine ablation characteristics due to the interaction of the aerothermal environment with specific GPHS module design features. Tests to generate the basic characterization information would determine the effects of material surface

roughness on mass loss at simulated reentry conditions and of three-dimensional material fabrication features on mass loss.

Significant amounts of ablation data have been generated for many bulk graphite and carbon/carbon material systems. The majority of this data has been obtained in the development and application of thermal protection materials to reentry vehicle systems. The GPHS module stagnation heating rates and pressures associated with steep and shallow trajectories are not as severe as the heating and pressures experienced by missile nose cones during reentry. It is anticipated that only a limited amount of the existing ablation data can be directly applied to this project, and therefore it is recommended that the plan include tests to characterize the candidate materials being considered for the GPHS module reentry member.

Information is also needed from ablation tests to determine the ablation characteristics resulting from the interaction of the aerothermal environment with various module design details. It is anticipated that the results of these tests will establish local ablation rates in the vicinity of closures, gaps, surface discontinuities due to fabrication tolerances, and module corners and edges. One module design features of particular importance in this regard is the fuel retainer plug design. It is anticipated that enhanced ablation will occur at this location because of the local surface discontinuity that exists.

The conditions at which the ablation tests should be conducted are given in Table 1. The conditions of importance for the basic material ablation tests are the module stagnation point heating rate ($\dot{q} \sqrt{R}$) and module stagnation pressure (P_{stag}). Values for both steep and shallow reentry angles are presented in Table 1, and ablation tests should be conducted at conditions consistent with both entry angles. The Mach number does not have to be simulated in the basic materials characterization tests. Standard models (hemisphere-cylinder and/or sphere-cone configurations) can be used to obtain material ablation data.

Configuration detail ablation tests require the use of models similar in geometry and size to the GPHS modules and a more accurate simulation of the flow field. Either full-scale or subscale sectional model tests can be conducted to obtain the desired information. If possible, full-scale models of the system being investigated should be used. If this is not

feasible, e.g., facility size limitations or high costs, then sub-scale and/or sectional models can be used.

Sub-scale or sectional ablation models must be designed to ensure that the prototype details are properly configured. For example, it is important that local surface and geometric details be properly designed into the test models. The test environment for the module configuration detail tests should be selected on the basis of the test model design and the actual flight conditions (specified in Table 1). Although some of the actual test conditions may be different from those indicated in Table 1 because of the particular test model being used, the simulated test environment should be consistent with the flight stagnation heating rates and pressures.

Specific activities which should be conducted in support of the ablation tests, in addition to those normally performed by the test facility, are:

- select test matrix
 - test conditions
 - geometric features
 - threads
 - corners
 - gaps
 - materials orientation
- design test models
- design calorimeter models
- select instrumentation
- select test facilities
- prepare test documentation
- analyze/interpret test results.

Ablation Test Facilities. Several test facilities were contacted to determine facility availability, operating envelope, and test costs relative to the conduct of GPHS module ablation tests. The results of the facility survey are presented in Table 2. Due to project time constraints, it was not possible to contact all of the facilities that can conduct the ablation tests. A pre-test document containing the test requirements and requesting test support should be prepared and submitted to all appropriate facilities.

TABLE 2. TEST FACILITY INFORMATION

Facility	Availability	Cost Run	Additional Cost	Models Run	Maximum Power, MW	Maximum Heater Pressure, atm	Nozzle Size: Range of Exit Diameters, in.
NASA Langley	bad	none	none		30	20	--
NASA Ames	fair	none	none		20	1-50	3-42
WPAFB 50 MW	fair	\$2833	\$3358(occup)	5	50	100	
McDonnell-Douglas	good	(1)	none	3-5-7	2-12	200	1.25-8.0
ARO, Inc.	good	\$4000	none	7	12-20	10-100	0.85-3.0
Martin Marietta	good	(1)	--	5	6	30	0.6-10
GE-RES D	fair	(1)	--	2	3	12	0.6-5.0

(1) Detailed test requirements are needed before
cost estimate can be given.

Detailed cost estimates could not be obtained from the various facilities because a detailed test plan is not yet available. Two of the facilities gave cost estimates on a per run basis, assuming that the tests were of a routine nature. These cost estimates are probably accurate relative to the materials characterization tests but are not representative of the cost associated with configuration detail testing due to the expected need for additional facility support.

The availability of the facilities was rated as "bad", "fair", and "good". "Bad" availability implies that there is less than a 10 percent possibility of obtaining a test window during the 1978 calendar year. "Fair" implies that there is a 50 percent possibility of obtaining test time in the facility this year, and "good" implies a greater than 90 percent possibility of obtaining suitable facility availability.

All of the facilities listed in Table 2 can achieve the reentry environments required for the ablation tests (see Table 1) and, have nozzles of sufficient size to accommodate the specimen sizes needed to obtain valid material characterization. It is anticipated that for the module configuration ablation tests, larger exit diameter nozzles (~8 to 10 inches) will be required to accommodate the test models. For these tests, the facility heater operating stagnation pressure will have to be relatively high (> 50 atm) in order to achieve the desired test model pressures. The higher heater stagnation pressure is required because of the larger nozzle area expansion ratios needed to achieve a gas stream of sufficient size to accommodate the model size.

Schedule

The GPHS Project Schedule was reviewed to determine when the various aerodynamic test results would be required to meet milestone target dates.

The results of the hypersonic stability test should be obtained prior to May, 1978, in order to factor them into the aerothermal reentry analysis of the trial designs. Therefore, the aerodynamic stability tests should begin no later than March, 1978.

Ablation testing of the candidate reentry member materials should be completed by June, 1978, in order to impact the reentry analysis of the trial designs and the reentry member material selection.

The ablation tests for various GPHS design features such as closures, gaps, corner, and edge ablation should be performed sufficiently early to impact the selection of the prototype design. These test results should be obtained sufficiently early to be factored into the aerothermal reentry analysis of the trial designs.

A lead time of approximately 4 to 6 months should be factored into the project schedule for preparing pre-test documents, selecting and fabricating models, and selecting appropriate facilities for the ablation tests.

HELIUM VENT DEVELOPMENT
(C. A. Alexander and M. P. Rausch)

Introduction

The objective of this task is to develop and fabricate helium vent systems capable of long-term unobstructed helium passage while constraining particulate release and egress or ingress of other gases. In this development parametric studies are being made of the meaningful variables determined by analytical examination of previous efforts, theoretical vent modeling, and basic vapor transport relationships that have been developed at BCL in earlier studies.

Summary

Four Pt 3008 and three Dop-26 vents have been fabricated and shipped to LASL for diffusion testing.

Work This Period

Work this period was directed toward the fabrication of platinum and iridium nonselective vents. Pt-3008 as well as Dop-26 vents were prepared in a planar configuration and shipped to LASL for diffusion studies. The fabrication procedures for the platinum vents were as follows. The vents were prepared by electrical discharge machining (EDM) technique from 0.025 in. thick Pt-3008 to a diameter of 0.071 in.. The labyrinth pattern and central exit orifice (0.049 in. diameter) were machined by the same technique (EDM) and the pattern was recessed in the vent to a depth 0.002 in. to assure proper alignment of the cover plate. Pt-3008 cover plates, 0.375 in. diameter and 0.005 in. thick, were EDM machined to include the eight tapered orifices.

The vent pieces were cleaned ultrasonically in a cold, then hot Alconox[®] bath. They were then rinsed in ethyl alcohol, soaked in a 50/50 nitric acid/water solution, and finally rinsed in deionized water. The vents were filled with a 50 w/o platinum/thoria cermet, fired in vacuum at 1200 C for 15 minutes; then were refilled and refired under the same conditions.

Concurrently with the work, a graphite (POCO) die was machined to accommodate vents of these dimensions and, prior to vent bonding, was degassed in the hot press facility for two hours at 1600 C. Each vent was then assembled in the graphite die and diffusion bonded in the hot press at 1200 C for one hour under a nitrogen atmosphere. A final cleanup of the fabricated vents was performed prior to shipment. This included a low temperature heat treatment for 30 minutes in 0.5 atm of hydrogen; and was followed by a two hour bakeout at 900 C under the same hydrogen pressure.

The initial fabrication procedures for the iridium vents were the same as those used in preparing the Pt 3008 vents. The vents were EDM machined from 0.025 in. thick Dop-26 iridium to 0.071 in. in diameter. The labyrinth pattern, recessed 0.002 in. into the vent for cover plate alignment, and 0.040 in. diameter central helium access duct were then EDM machined. Cover plates, 0.375 in. in diameter and 0.005 in. thick, were also EDM machined to include the eight tapered orifices.

The vent pieces were cleaned ultrasonically in a cold, then hot Alconox[®] bath. They were then rinsed in ethyl alcohol, soaked in aqua regia, and final rinsed in deionized water. The vents were filled with a 50 w/o iridium/thoria cermet, fired in vacuum at 1450 C for 15 minutes; then were refilled and refired under the same conditions. Each vent was then assembled in the graphite die and diffusion bonded in the hot press at 1450 C for 15 minutes under a nitrogen atmosphere. Prior to shipment, residual carbon (from the hot pressing stage) was removed from the vent surfaces with an overnight low temperature asher treatment.

The vent flow characteristics were evaluated for each vent. The throughput of three platinum vents, designated BCL-PPN-3L through 5L, was 3×10^{-3} cc-atm/sec. A fourth vent BCL-PPN-1L, whose conductance was slightly greater than twice that of the other platinum vents, was also shipped. The measured throughput of the three iridium vents, designated BCL-IPN-3L through 5L; was 10^{-6} , 4×10^{-3} , and 3×10^{-3} cc-atm/sec, respectively. It is felt that vent BCL-IPN-3L, whose characteristics approach that of a selective vent in throughput, may offer performance suitable for terrestrial applications.

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