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Overview of Technical Challenges of Re-Entry Analysis of Radioisotope Heat Sources

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The analytical and experimental effort conducted by the Applied Physics Laboratory of the Johns Hopkins University for the U.S. Department of Energy in predicting the re-entry ablation and thermostructural response of heat sources is described. The environment addressed is that posed by accidental entries of heat sources from an earth-gravity-assist trajectory, such as that of the Galileo mission. Also described are the analytical tools and limitations of the analytical methods used for thermal and thermostructural analysis and of the experimental databases used for material thermal and mechanical properties in the analyses for these environments. These limitations are translated into challenges for improving re-entry predictions, for testing materials at very high temperatures, and for ablation tests at very high heating rates and pressures. Safety assessment for a mission is not addressed here.

Nomenclature

B'	= mass transfer parameter
C_A, C_N, C_Y	= axial, normal, and yaw force coefficients
C_l, C_m, C_n	= rolling, pitching, and yawing moment coefficients
C_{lp}, C_{mq}, C_{nr}	= roll, pitch, and yaw damping coefficients
E	= Young's modulus
g_x	= axial acceleration
$\dot{m}$	= rate of mass transfer
$\dot{m}_D$	= $\dot{m}$ at the diffusion-limited regime
p, q, r	= roll, pitch, and yaw rate
P_t'	= stagnation pressure
V	= velocity
α_R	= resultant angle of attack
ϕ, θ, β	= aerodynamic roll, pitch, and yaw angles, $\beta = -\psi$
γ	= re-entry angle

I. Introduction

THE United States requires that each space mission involving a nuclear power source be analyzed to assess the potential risk of the mission to the world's population and environment. The U.S. Department of Energy (DOE), Office of Special Applications, provides safety analyses and tests to assess this risk. The Johns Hopkins University Applied Physics Laboratory (JHU/APL) is tasked by DOE to evaluate the thermal and thermostructural response of radioisotope heat sources under accidental Earth re-entry conditions. An example of these heat sources is the General Purpose Heat Source (GPHS) (Fig. 1), which is used to provide power to the Galileo and Ulysses spacecrafts and which will be used to provide power to the Cassini spacecraft.

Analysis of the re-entry response of radioisotope heat sources that are used to power or provide heat to spacecraft with missions to the outer planets, and that use Earth flybys for gravity assist, presents formidable analytical and experimental challenges. The analysis is difficult for the following reasons: 1) the re-entry speeds, and consequently energies, generate stagnation heating rates that are at present beyond those obtainable in test facilities with air as the medium and with reasonably sized test sections; 2) the stagnation temperatures are in the high sublimation regime, where the characterization of the thermochemistry both for air and for the re-entry material is limited; and 3) the heat source can spend much of its heat pulse in rarefied flow, where the characterization of the aerothermodynamic and aerodynamic parameters of interest for motion and heating is also limited.

Many other important aspects of these missions require analyses that include re-entry mechanics, aerothermodynamics, and thermostructural disciplines. This overview, however, addresses specifically the analytical and experimental evaluation of the re-entry response of heat sources that may accidentally enter the Earth's atmosphere from an earth-gravity-assist (EGA) trajectory. This paper presents an overview of the technical issues addressed by the staff of the Aerospace Nuclear Safety Program (ANSP) of JHU/APL for re-entry of heat sources used by the DOE Office of Special Applications.

It is not the purpose of this paper to present results of predicted ablation responses of heat sources, nor to provide a safety assessment for re-entry of the heat sources. The predictions derived for the various missions are incorporated in the DOE Safety Analyses Reports for those missions and are part of the overall safety evaluation. The process involves several levels of scrutiny and several agencies, including the DOE, the Department of Defense, and NASA.[1]

II. Configuration

The re-entry configurations of recent interest are 1) heat sources for radioisotope thermoelectric generators (RTGs) used in spacecraft for interplanetary missions and 2) heat sources used to heat spacecraft components on the same missions. Specifically, a stack of 18 GPHSs (Fig. 1) is used in the RTG (Fig. 2), which is designed and manufactured by Martin Marietta Astro Space (formerly General

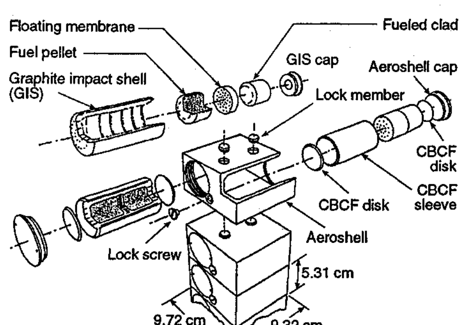

Fig. 1 General Purpose Heat Source (GPHS).

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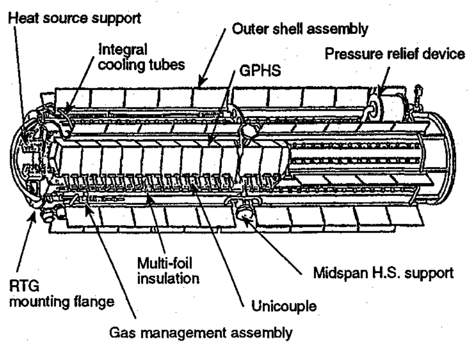

Fig. 2 GPHS radioisotope thermoelectric generator (RTG).

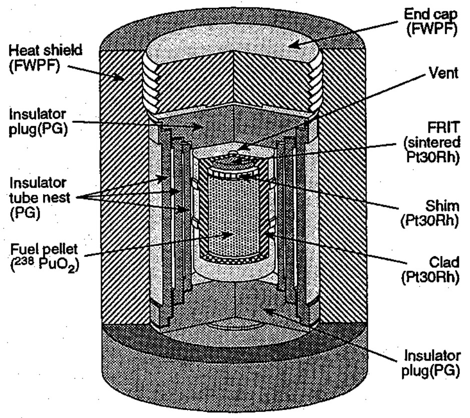

Fig. 3 Lightweight radioisotope heater unit.

Electric/Astro Space). Two of these RTGs were used in the Galileo spacecraft, and one in the Ulysses spacecraft. The GPHS consists of an aeroshell (in the shape of a parallelepiped) made of AVCO carbon-carbon composite fine-weave pierced fabric (FWPF) material. The aeroshell contains two FWPF cylindrical containers, each containing two plutonium dioxide ($^{238}PuO_2$) pellets enclosed in iridium clads. Each GPHS module provides a nominal 245 W (thermal [t]) of power. The heater units, designated light-weight radioisotope heater units (LWRHU), measure 1 × 1 in. and are cylindrical containers also made of FWPF enclosing $^{238}PuO_2$ in platinum-rhodium (PtRh) clads and providing 1 W (t) of power (Fig. 3).

III. Analytical Tools

The main objective of the analytical evaluation of the re-entry response of the heat sources is to determine the extent of ablation and the thermostructural response. Two thermostructural codes were used by the ANSP staff of JHU/APL to evaluate the thermostructural response of the GPHS and LWRHU modules for the Galileo mission. One is the finite-element MacNeal Schwendler Corporation (MSC) NASA structural-analysis (NASTRAN) code,[2] version 65, used for three-dimensional (3-D) analysis. At the time of this analysis, the MSC/NASTRAN code modeled only linear stress-strain material properties, which is conservative. Improved versions of NASTRAN may be able to model nonlinear materials with temperature-dependent properties. John A. Ecker and Yale Chang address these analyses in Ref. 3. The other thermostructural code is the Stress Analysis of Axisymmetric Solids (SASS III) code used for axisymmetric and 2-D analysis of the LWRHU in its end-on and side-on orientation.[4] The input of temperature to the thermostructural code for GPHS and LWRHU is derived from the 3-D analysis and axisymmetric re-entry thermal analysis codes of JHU/APL. The 3-D thermal analysis code is designated Reentry Thermal Analysis Program (RETAP). The axisymmetric option of a JHU/APL code (designated SHTP-E) was used for the end-on analysis.[5] For onedimensional analysis, the JHU/APL version of the Aerotherm Charring Material Thermal Response and Ablation Program (CMA) code is used.[6] The aerothermodynamic methods in these thermal analysis codes are summarized by D. W. Conn in Ref. 7. Some of the correlations used are discussed in Refs. 8 and 9. The trajectory parameters (specifically, stagnation heating) that are input to the thermal analysis codes are derived from a three-degree-of-freedom (DOF) re-entry trajectory code.[10] The correlation used for stagnation heating in this code is described in Ref. 11. The configurational flight attitude for GPHS is derived from re-entry motion studies using a 6-DOF simulation that allows for 360-deg rotation in the aerodynamic resultant angle of attack and roll attitude and for simplified ablation effects.[12]

IV. Re-Entry Environment

A. Flyby Trajectory: Initial Conditions

A typical flyby trajectory is the Galileo trajectory devised by the Jet Propulsion Laboratory (JPL) for its mission to Jupiter (Fig. 4). In its Earth flybys, Galileo's approach to the Earth in an accidental re-entry had a possible re-entry speed of approximately 46,800 ft/s. (For re-entry to occur, however, several sequential system failures would have had to occur; thus, the probability of Galileo re-entering during the flyby was very low.) The possible re-entry speed represents the nominal speed derived by JPL from estimated breakup boundaries for the spacecraft and RTG. These boundary conditions, as put together by JHU/APL for the nominal velocity (from the JPL estimates), are given in Fig. 5. These were used as the initial conditions for the re-entry analysis.

B. Re-Entry Attitude: Aerodynamics, Motion

The re-entry attitude is part of the re-entry environment in that the heating rate and its distribution are dependent on the configurational aerodynamic attitude as well as the configurational shape. The attitude, of course, depends on the aerodynamics. Because the GPHS is a low-aspect-ratio parallelepiped and is free falling, its entry motion can be fully rotational (in aerodynamic angles). The re-entry motion simulation used at JHU/APL is a 6-DOF simulation that allows for full rotation in the resultant angle of attack and in the aerodynamic roll attitude (Fig. 6), thus accounting for motion in the three orthogonal axes. The aerodynamic data sets likewise have been generated (mostly experimentally for an unablated body) to represent full rotational motion, but are only available at hypersonic and low subsonic speeds.[13,14] (The subsonic aerodynamics are used throughout the subsonic range in motion studies to determine the most likely impact attitudes at terminal velocity. The hypersonic aerodynamics are used throughout the supersonic range.) Limited data on plates and cylinders have been used to estimate the aerody-

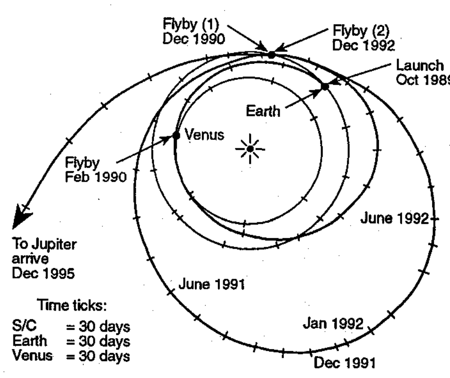

Fig. 4 Galileo Venus-Earth-Earth gravity assist (VEEGA).

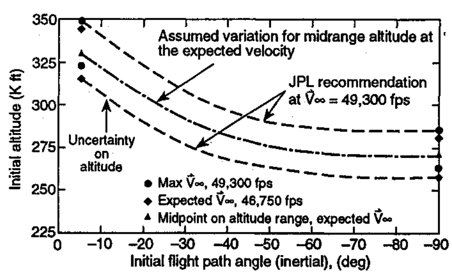

Fig. 5 Predicted release conditions for GPHS module re-entries; Galileo VEEGA mission profile.

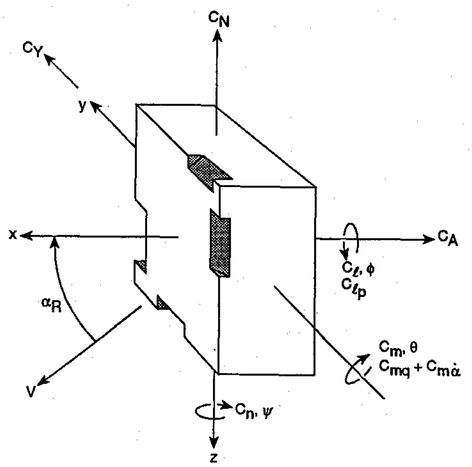

Fig. 6 Model-fixed axis system.

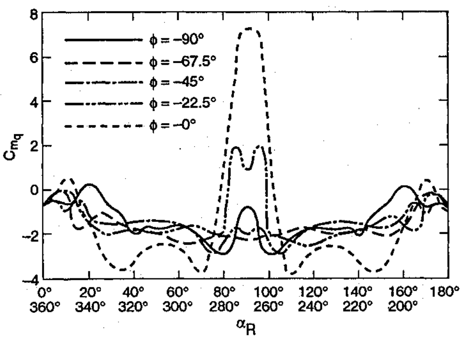

Fig. 7 Pitch damping coefficient of the GPHS module, $M = 0.1$.

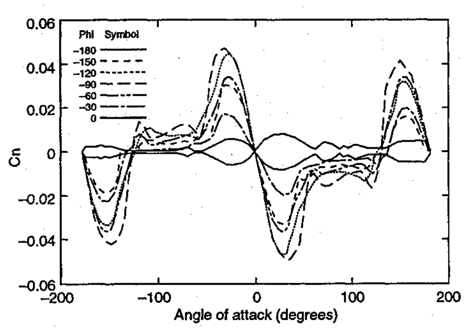

Fig. 8 Yaw moment coefficient of the GPHS module, $M = 10$.

namics for the free-molecule region; the bridging is assumed linear with a Knudsen-number function. Because of the GPHS shape and the full range in rotation, the aerodynamic coefficients can be highly nonlinear (e.g., Figs. 7 and 8). Ablation effects on hypersonic static stability have also been determined experimentally for various stages of broad-face ablation using shapes derived from arc-jet tests reported by Lutz and Chan.[15] These effects (e.g., Fig. 9) have also been incorporated in the motion simulation as a function of altitude range for the heat pulse. Statistical investigations using the 6-DOF re-entry motion program and the limited aerodynamic data available are conducted to provide the most likely average re-entry GPHS attitude during the heat pulse.[16,17] Some examples of the motion from the 6-DOF simulation are given for the resultant angle of attack in Fig. 10 for a shallow entry and in Fig. 11 for a steep entry. These types of results are used to idealize an attitude that is used in thermal and ablation analysis and in thermostructural analysis.

C. Aerothermodynamics: Heating

Using the nominal initial conditions of Fig. 5, predictions of stagnation heating and decelerations, as partially indicated in Fig. 12, are obtained for steep and shallow entries ($\gamma = -90$ and -7 deg) of GPHS in an orientation broadside to the wind. The heating rate

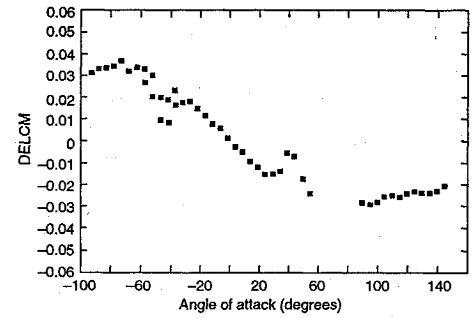

Fig. 9 Incremental values of pitching moment coefficient due to windward face ablation; $M = 10$, $\phi = 0$ deg.

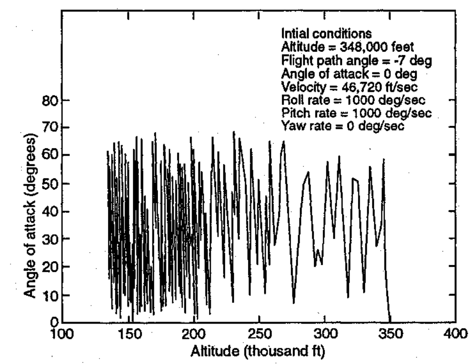

Fig. 10 Effect of combined pitch and roll rate, VEEGA shallow GPHS re-entry, ablating body.

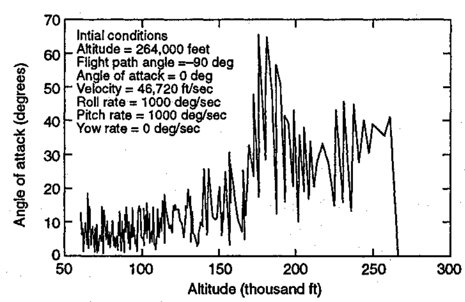

Fig. 11 Effect of combined pitch and roll rate, VEEGA steep GPHS re-entry, ablating body.

for the most shallow EGA re-entry is about one order of magnitude greater than for the orbital decay re-entry. For the steep re-entry, it is more than three orders of magnitude greater. Also, shock-layer radiation heating is very important for the EGA re-entries. For the steep entry, radiation heating is almost four times the magnitude of convective heating. The heat pulse for steep entry is very short—about 5 s. The change in altitude during this period is 150,000 ft.

Another comparison of the re-entry environment experienced by the heat sources when entering from an EGA trajectory is shown in Fig. 13. It is shown here that steep entries as well as shallow entries reside in a flow region extending from continuum flow to a flow region where the air is rarefied, dissociated, and ionized. This region is more severe than that experienced by the shuttle, or expected for Aero-Assisted Orbital Transfer Vehicle (AOTV) experiments as depicted by Chapman.[18]

The predicted temperatures for the three re-entry conditions discussed above are compared in Fig. 14. For the EGA entries, the extreme temperatures, heating rates, and decelerations are at the upper limits of the present analytic and experimental capabilities for assessing the re-entry response of these heat sources.

V. Limitations in Re-Entry Analysis of FWPF Materials and Modules

A consequence of the high energies associated with the high velocities during EGA accidental entries is that this EGA environment

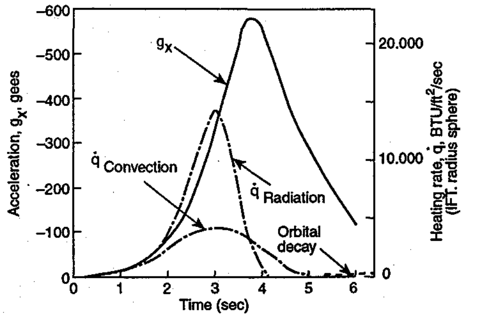

Fig. 12 Steep entry of GPHS. Initial velocity = 46,720 ft/s, altitude = 270,000 ft.

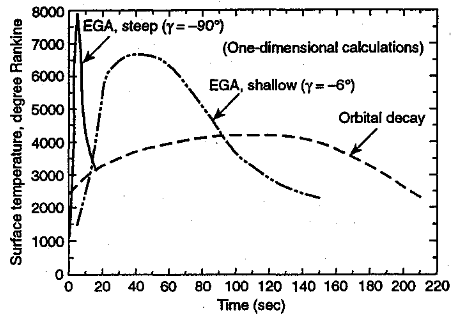

Fig. 14 Comparison of surface temperature of EGA and orbital-decay entries.

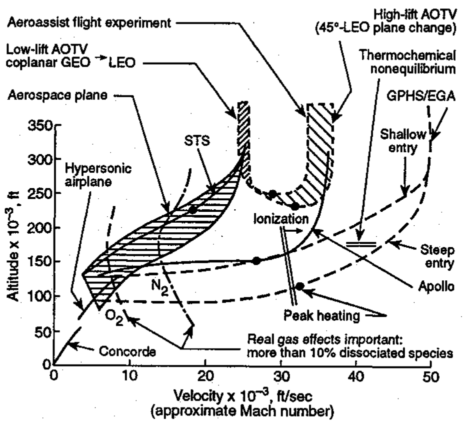

Fig. 13 Comparison of GPHS/EGA flight environment with other hypersonic flight environments. AOTV = Aero-assisted Orbital Transfer Vehicle. (Adapted from Ref. 18.)

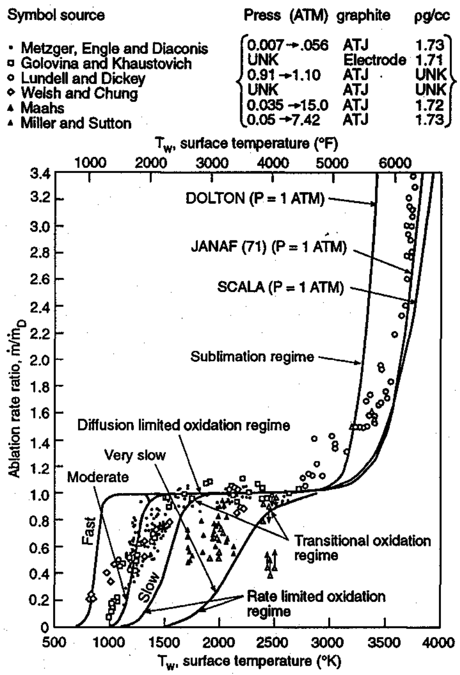

Fig. 15 Thermochemical ablation regimes for graphite.

is at the limit of the current computational and experimental tools, especially at steep entries. The flow field ranges from free-molecule to continuum with dissociation and ionization. As noted previously, radiation heating can exceed convective heating, and the coupling of the two is difficult to characterize. The ablation processes and the interaction of the ablation products with heat transfer are also uncertain. The thermal and thermostructural models are based on limited test data at these high temperatures for the FWPF material, and experiments at these high temperatures are difficult to conduct. Because of these limitations and uncertainties, the re-entry response predictions have been on the conservative side. The challenge, and the objective of the present effort, is to improve the predictions by reducing uncertainties. Some examples of the analytic and experimental challenges follow.

A. Aerodynamic Shape: Effect on Motion and Thermal and Thermostructural Analysis

As discussed in Sec. IV.B, the results of 6-DOF motion simulations are employed to derive idealized attitudes for use in thermal and thermostructural analyses. Aerodynamic data used in these simulations are available only for unablated configurations and for configurations representing broad-face ablation. It is difficult to obtain ablation data that simulate a tumbling (or fully rotating) configuration; as found in motion studies,[16,17] this configuration is a possible attitude during the heat pulse in an EGA-type entry. The thermal and thermostructural codes used so far do not provide for a moving boundary that results from ablation, but it is planned to incorporate this feature into the codes.

B. Thermal Analysis and Experimentation

An example of an issue in thermal modeling is depicted in Fig. 15, which shows the mass-loss ratio for graphite materials as a function of temperature. The region of interest for the EGA entries is the sublimation region, where recession is a very strong function of temperature. The test data shown on these correlations are for solid graphites and include mechanical recession. Test data for FWPF in the region of concern are very limited.

The acquisition of test data on recession at these high sublimation temperatures and at the high stagnation heating rates and pressures of interest is difficult. Test facilities that provide the desired conditions, especially for a full-scale GPHS test module, are scarce; it is difficult to measure temperatures and recession accurately enough to develop a sublimation model. Table 1 presents a comparison of the stagnation heating rates obtainable in the NASA/ARC 20-MW and 60-MW arc-jet facilities with the predicted values for an orbital decay entry, an EGA shallow entry, and an EGA steep entry. The values are given for a 1 ft-radius sphere. The present facilities fall short of providing the predicted heating rates by several orders of magnitude. Also, only the convective component is obtained with the present arc-jet test facilities. Temperatures in the region of interest are obtainable with the 60-MW NASA facility, but the accompanying stagnation pressures are one order of magnitude lower than desired to simulate the steep entry. To achieve the heating rates in a test section compatible for testing the full-scale GPHS module requires a high-enthalpy facility. For coupon testing, higher heating rates could be achieved by using smaller nozzles in the present facilities.

Data on thermal properties of FWPF are also limited at the high temperatures. Thermal conductivity and thermal expansion data are not available above 5000°F. Heating distribution data sufficient to verify or develop the thermal models needed to represent the most probable re-entry orientations are also limited. This task, however, is one for state-of-the-art technology.

Table 1 Achievable test conditions in NASA/ARC arc-jet facilities vs predicted heating rates ($\dot{q}$, Btu/ft^2 · s) and stagnation pressures (P'_t, atm), 1-ft-radius sphere

Predicted	Test
Orbital decay, 20 MW	
$\dot{q}_{av} = 47$	$\dot{q} = 62$
$\dot{q}_{max} = 80$	
$P'_{t\,av} = 0.0563$ atm	$P'_t = 0.06$
EGA,[a] 60 MW	
Shallow entry, $\gamma \leq \lvert 20°\rvert$	
$\dot{q}_{av} = 700$–3300	$\dot{q} \approx 600$
$P'_t = 0.5$–1.0	$P'_t \approx 1.0$
Steep entry	
$\dot{q}_{av} \approx 12,000$	
$P'_t = 10.3$	

[a] Earth gravity assist.

A review of ablation in the three regimes is given in Ref. 8. Analytically, in the rate-limited regime, JHU/APL uses the moderate rate. The method proposed by Hunter et al.[19] is preferred, primarily because it is based on nonequilibrium chemistry. This method has been incorporated by Chan in JHU/APL's one-dimensional ablation code.[6] Ablation in this regime is small compared with ablation during sublimation. The diffusion-limited regime is representative of the type of ablation encountered in an orbital-decay re-entry. This constancy in mass transfer rate was used in deriving average test conditions for the 20-MW arc-jet test in the simulation of GPHS in an orbital-decay entry as described by Lutz and Chan.[15]

At the very high temperatures in the sublimation regime, the parameters needed to calculate mass transfer vary so rapidly that convergence of the heat balance equation becomes difficult. A discussion of the aerothermodynamic methodology used in JHU/APL's heat and mass transfer computations in this and other regions is given by Perini.[8,9] Figures 16 and 17 present another demonstration of the severity of the environment that stresses the analytic solution. The relationship between heat and mass transfer used in JHU/APL's codes is mainly the Putz-Bartlett correlation. The mass transfer parameter B', which is very sensitive to temperature at the EGA temperatures (Fig. 17), is generated with the Aerotherm EST computer code using the JANNAF thermochemical data.[20] At EGA steep entries, the values of B' are of the order of 1000, and thus convective heat transfer approaches zero very soon at entry for steep entries; that is, heat transfer is radiatively dominated. Accounting for these rapid changes in some heat and mass transfer parameters, the vanishing of others, the coupling of convective and radiative heat transfer, and blockage effects resulting from ablation at these EGA environments is a computational challenge that D. W. Conn et al. at JHU/APL are still addressing in the JHU/APL Aerospace Nuclear Safety Program.

C. Thermostructural Analysis and Experimentation

For the thermostructural analysis, the challenges are also both analytical and experimental. The material properties for FWPF (and

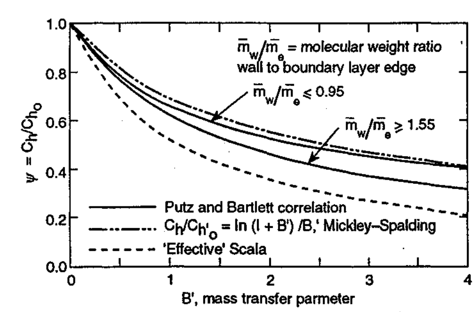

Fig. 16 Blowing and nonblowing heat transfer ratio ψ as a function of B'.

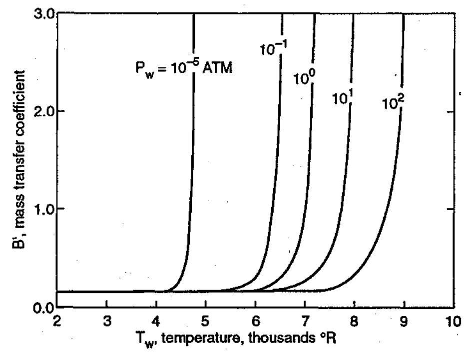

Fig. 17 Mass transfer parameter B' for carbon and air based on 1971 JANNAF thermochemical data.

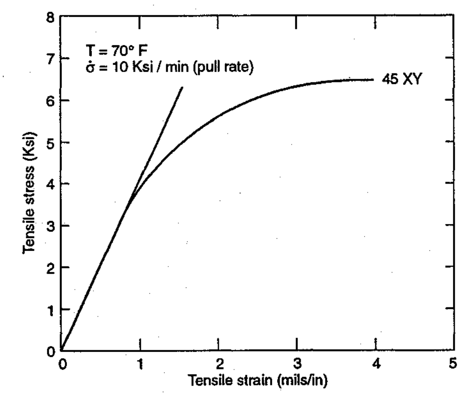

Fig. 18 Tensile stress-strain behavior of billets of fine-weave pierced fabric.

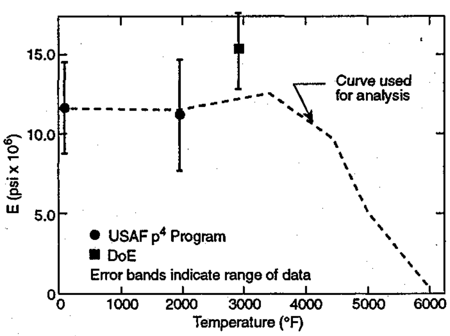

Fig. 19 Tensile elastic modulus vs temperature.

solid graphites) are highly nonlinear and temperature-dependent in their stress-strain relations (e.g., Fig. 18). Here again, mechanical properties for FWPF are lacking in the high-temperature region, and extrapolations have thus been necessary above 3000°F for tensile strength and 5500°F for compressive strength (Fig. 19). (Because the material is 3-D weave, it is anisotropic and tensile, and its compressive strengths are different.)

Until recently, the Southern Research Institute (SoRI) data were the only test data available on mechanical properties of FWPF. Data recently obtained by Los Alamos National Laboratory (LANL) show higher strength for FWPF than the SoRI data (Fig. 20); tensile-strength data have been obtained by LANL to 5000°F. To match the predicted temperatures, test data are required to temperatures of about 7000°F.

An ultimate-bending-strength test of a FWPF specimen in the NASA 60-MW arc-jet tunnel at temperatures around 7000°F is possible but not simple. JHU/APL has developed preliminary plans for DOE for such a test as well as for the others already mentioned.

In addition to a limited database, the analyses thus far have been linear in stress-strain, which may be too conservative; that is, the thermoplastic region has not been simulated. The recent versions

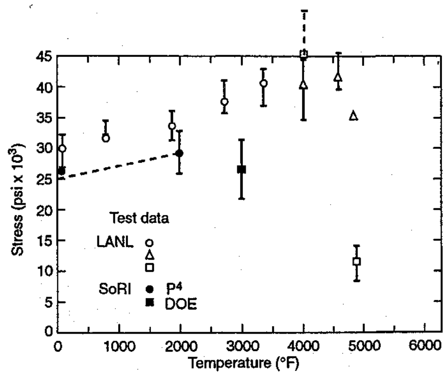

Fig. 20 Tensile strength vs temperature.

of NASTRAN (66 and 67) have advertised the ability to handle nonlinear materials with temperature-dependent properties. With the ultimate goal of coupling the thermal and mechanical loads, JHU/APL is currently evaluating this code, as reported by Chang and Ecker.[3]

VI. Computational Fluid Dynamics in Thermal Analysis

In the absence of experimental data to verify our thermal models at the high temperatures of interest, we are pursuing the use of computational fluid dynamics (CFD) codes to check out our assumptions, specifically on radiation and convection heating, and to complement our calculations with our engineering codes. The codes used at JHU/APL for re-entry thermal analysis are engineering codes. The 3-D Reentry Thermal Analysis Program solves the heat balance equation for temperature distribution and surface recession along the trajectory. It uses correlations for thermochemistry and thermal properties of materials, for heat transfer and mass transfer as a function of temperature, for heating distribution for various shapes, etc., all correlations being limited at the higher temperatures of interest. Assumptions are also made on shock-layer radiation effects and blockage, on bridging of continuum and free molecule heating, on chemistry rates (equilibrium chemistry), and on the boundary-layer state (laminar, attached). The thermal models also assume, based on limited motion studies, some steady-state (nonoscillating) orientation (the motion studies themselves are based on limited aerodynamic test data).

Pending experimental verification of the currently assumed thermal correlations or development of new ones, CFD computations especially for radiation and convection heating and the coupling of the two would be useful. Currently JHU/APL is installing a NASA Navier-Stokes (NS) code, designated Stagnation Streamline Navier Stokes code, with the goal of calculating shock-layer radiation and convection heating for the condition of interest in an EGA entry environment. In addition to the NS codes, NASA has developed CFD codes based on kinetic theory and with Monte Carlo solution that could provide an insight into the validity of our assumptions.

VII. Conclusions

Analysis of the thermal, ablation, and thermostructural response of heat sources that may accidentally enter the Earth's atmosphere from EGA trajectories present a computational and experimental challenge. Some areas where improvements can be made in the predictive tools for re-entry thermal and thermostructural analysis of heat sources in an EGA environment have been identified. Experimental technology and facilities could also be improved for the acquisition of ablation data, temperature measurements, and measurements of mechanical and thermal properties of materials at the high temperatures and high heating rates associated with EGA entries of heat sources. The future outlook for space exploration programs using radioisotope power systems[21] gives impetus to continue seeking advances in computational and experimental technology as well as materials technology to support analysis of the re-entry response of these systems.

Acknowledgments

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References

[1]Bennett, G. L., "Overview of the U.S. Flight Safety Process for Space Nuclear Power," *Nuclear Safety Technical Progress Review*, Vol. 22. No. 4, 1981, pp. 423–434.

[2]Anon., *MSC/NASTRAN Version 65, User's Manual*, Vols. I and II, The MacNeal-Schwendler Corporation, Los Angeles, 1985.

[3]Chang, Y., and Ecker, J. A., "Thermoplastic Analysis of General-Purpose Heat Source Modules," AIAA Paper 93-0380, Jan. 1993.

[4]Grose, J. G., and Jones, R. M., "Finite-Element Stress Analysis of Axisymmetric and Plane Solids with Different Orthotropic, Temperature-Dependent Material Properties in Tension and Compression," Aerospace Rep. TR-0059 (S6816-53)-1, Los Angeles, CA, June 1971.

[5]Randall, J. D., "SHTP-E, A Computer Implementation of the Finite-Difference Embedding Method of Ablation Analysis," Rept. CP 067 (DOE/ASMP 3060-16), Johns Hopkins Univ., Laurel, MD, May 1978.

[6]Chan, C. C., "Modifications to the Aerotherm Charring Material Thermal Response and Ablation Program (CMA) for Carbon Ablation Analysis," Rept. TG-1373, Johns Hopkins Univ., Laurel, MD, March 1989.

[7]Anon., "Re-entry Response of the Light Weight Radioisotope Heater Unit Resulting from a Venus-Earth-Earth Gravity Assist Maneuver Accident," Rept. ANSP-M-19 (DOE/OSA/32087-19), Johns Hopkins Univ., Laurel, MD, Oct. 1988.

[8]Perini, L. L., "Review of Graphite Ablation Theory and Experimental Data," Rept. ANSP-M-1, Johns Hopkins Univ., Laurel, MD, Dec. 1971.

[9]Perini, L. L., "Heat and Mass Transfer Correlation Equations for Subliming Graphite in High-Speed Flow," Rept. ANSP-M-11 (AEC/SNS 3060-D11), Johns Hopkins Univ., Laurel, MD, Aug. 1974.

[10]Perini, L. L., "Users Manual for the 3DOF Trajectory Computer Program," Rept. ANSP-M-6, Johns Hopkins Univ., Laurel, MD, Sept. 1973.

[11]Perini, L. L., "Compilation and Correlation of Experimental, Hypersonic, Stagnation Point Convective Heating Rates," Rept. ANSP-M-4, Johns Hopkins Univ., Laurel, MD, July 1972.

[12]Sharbaugh, R. C., "Users Manual for Aerospace Nuclear Safety Program Six-Degree-of-Freedom Re-entry Simulation (TMAGRA 6C)," Rept. ANSP-M-20 (DOE/OSA/32140-20), Johns Hopkins Univ., Laurel, MD, Feb. 1990.

[13]Lucero, E. F., and Barnett, J. C., "Construction of the Aerodynamics of the GPHS Module for Full Rotational Motion at Subsonic Speeds," Rept. ANSP-M-18, Johns Hopkins Univ., Laurel, MD, Sept. 1986.

[14]Lucero, E. F., Hagan, J. C., and Beyers, M. E., "Subsonic Aerodynamics of Rectangular Parallelepiped Shapes of Fineness Ratio of One-Half," *Journal of Spacecraft and Rockets*, Vol. 24, No. 4, 1987, pp. 311–318; see also AIAA Paper 86-0399.

[15]Lutz, S. A., and Chan, C. C., "Ablation Response Testing of Aerospace Power Supplies," AIAA Paper 93-0381, Jan. 1993.

[16]Lucero, E. F., and Sharbaugh, R. C., "GPHS Motion Studies for Heat Pulse Intervals of Reentries from Gravity Assist Trajectories," Rept. ANSP-M-21 (DOE/NE 32140-21), Johns Hopkins Univ., Laurel, MD, March 1990.

[17]Sharbaugh, R. C., "Follow-up Investigation of GPHS Motion During Heat Pulse Intervals of Reentries from Gravity Assist Trajectories," ANSP-M-22 (DOE/NE 32140-22), Johns Hopkins Univ., Laurel, MD, March 1992.

[18]Chapman, G. T., "An Overview of Hypersonic Aerodynamics," *Communications in Applied Numerical Methods*, Vol. 4, Wiley, New York, 1988, pp. 319–325.

[19]Hunter, L. W., Perini, L. L., Conn, D. W., and Brenza, P. T., "Calculation of Carbon Ablation on a Re-Entry Body during Supersonic/Subsonic Flight," *Journal of Spacecraft and Rockets*, Vol. 23, No. 5, 1986, pp. 487–491.

[20]Perini, L. L., "Curve Fits of JANNAF Thermochemical Data," Rept. ANSP-M-5, Johns Hopkins Univ., Laurel, MD, Sept. 1972.

[21]Lange, R. G., "Radioisotope Power Systems for the Exploration of Space," Ninth Symposium on Space Nuclear Power Systems, Paper 3, Plenary Session IV, Univ. of New Mexico, Albuquerque, NM, Jan. 1992.