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**Preliminary Reentry Safety Assessment
of the General Purpose Heat Source Module
for the Cassini Mission**

**Johns Hopkins University ■ Applied Physics Laboratory
Johns Hopkins Road, Laurel, Maryland 20707
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**Preliminary Reentry Safety Assessment
of the General Purpose Heat Source Module
for the Cassini Mission**

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ABSTRACT

As tasked by the U. S. Department of Energy/Office of Special Applications, and in support of the Environmental Impact Statement for the Cassini mission, The Johns Hopkins University/Applied Physics Laboratory (JHU/APL) has conducted preliminary one-dimensional ablation and thermal analyses of the General Purpose Heat Source (GPHS). The predicted earth entry conditions provided by the Jet Propulsion Laboratory (JPL) for a Cassini Venus-Venus-Earth-Jupiter Gravity Assist (VVEJGA) trajectory were used as initial conditions.

The results of this study which constitute the initial reentry analysis assessment leading to the Cassini Updated Safety Analysis Report (USAR) consist principally of:

- (1) determination of capture angle,
- (2) stagnation heating rates for reentry angles, gamma, of capture angle (approximately -6 degrees), -30, -50, and -90 degrees,
- (3) results of ablation and thermal response for GPHS at two orientations,
- (4) a general discussion of the assumptions, methodology, and limitations used in the analysis, and
- (5) implications from the results regarding fuel release during reentry flight derived from an assignment of a failure criterion resulting from uncertainties in the analysis.

The Galileo analyses for accidents in the phases ranging from launch to parking orbit (Phase 4), as presented in the Galileo Final Safety Analysis Report (FSAR), are assumed to apply to Cassini through the equivalent Cassini Phase 6. The results of the Galileo Phase 4 analyses are also included in this report. From

these results, it is expected that an initially undamaged GPHS module will survive all Cassini Phase 6 reentry conditions.

For accidental entries of the GPHS from a Cassini VVEJGA trajectory, these initial results indicate that:

- (1) The capture angle at the release conditions provided by JPL is -5.9° for a broadface normal orientation and -6° for a tumbling module.
- (2) The predicted maximum combined convective and radiative stagnation reference heating rate is about six times the value predicted for the Galileo VEEGA entry conditions. Heating is radiatively dominated for moderate to steep reentries. Radiative heating rates are based on the radiation transport model, RAD/EQUIL, using a conservative estimate for shock layer thickness. Less conservative approaches will also be examined in a continuing effort.
- (3) Burnthrough is predicted for the broadface normal orientation at all reentry angles.

The clad temperature for a broadface entry at burnthrough is maximum for $\gamma = -5.9^\circ$ and is 3128°R . The clad melt failure criterion is a value of 4410°R which represents iridium's melt point minus 500°R to account for uncertainties in the analysis.

The burnthrough altitudes for the broadface case range from 118K feet for $\gamma = -90^\circ$ entries to 200K feet at capture angle. Upon aeroshell burnthrough, the carbon bonded carbon fiber (CBCF) insulation will be immediately removed based on observations from full-scale GPHS arc jet tests. This sequence will very likely lead to clad melt failures and possibly partial melting of the fuel. High altitude fuel release may result if there is sufficient residual energy in the heat pulse to also burn through the Graphite Impact Shell (GIS). The GPHS aeroshell burnthrough occurs at approximately the peak value of the heat pulse. The GPHS velocity at burnthrough ranges from approximately 45,000 ft/s to 50,000 ft/s. When allowance is made for uncertainties in the analysis, the initiating velocity and heat load for a sequential analysis will be significantly higher. From sequential one-dimensional studies conducted for the Galileo entry conditions, and from the present analysis, the GIS will likely experience ablation failures if released at these velocity-altitude conditions particularly at entry angles shallower than about -20° and for an end-on free-flight orientation.

- (4) For the tumbling orientation, burnthrough is not predicted but the uncertainties in the analyses need to be weighed prior to drawing final conclusions. The recession ranges from 0.09 inches to 0.12 inches. The peak clad temperature for this orientation ranges from 2960°R to 3640°R.

The results given here are initial results from effort that will continue with the goal of providing a reentry safety assessment for GPHS/Cassini as part of the Cassini USAR scheduled for late 1995. The next planned efforts include calculations of ablation for the broadface normal orientation using a less conservative approach for radiation heating, and conducting a one-dimensional thermal and ablation analysis for the GIS assembly using the GPHS aeroshell failure conditions as initial conditions. Following these analyses, it is planned to conduct a three-dimensional GPHS module thermal analyses for the broadface normal and tumbling orientations followed by a thermostructural analysis of the aeroshell. Beyond this, it is the goal to obtain measurements of heating rate distribution data as a function of pitch and roll orientation to permit refinement of the broadface and tumbling analyses and analysis at other angles of attack indicated to be probable by six degree of freedom motion analysis. These data will be used to construct and/or refine thermal models for these cases which will be used to conduct three-dimensional thermal and thermostructural analyses.

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SUMMARY AND CONCLUSIONS

A preliminary Earth reentry safety assessment of a single, free-flight General Purpose Heat Source (GPHS) module has been conducted to determine the reentry response and related safety implications for an initially fully configured, undamaged module. This assessment separates the mission into reentry environments resulting from hypothesized accident scenarios occurring (a) up through spacecraft deployment and transplanetary injection from parking orbit (i.e., Phase 4 and earlier phases, as defined in the Galileo Mission Profile), and (b) during the Earth gravity assist (EGA) segment of Cassini's Venus-Venus-Earth-Jupiter Gravity Assist (VVEJGA) trajectory maneuvers. Specifics regarding accident scenarios and related occurrence probabilities are not the subject of this report. Furthermore, the reentry domain being addressed does not encompass terminal impact behavior of the fuel containment assembly.

In assessing GPHS reentry safety for Phase 6 and earlier phases of the Cassini mission, a review was conducted of the earlier Galileo reentry analyses based on a Centaur upper stage launch configuration. This information has been reported in the Galileo Final Safety Analysis Report. Based on this review, it has been assumed that the initial spacecraft reentry map (i.e., initial velocities and flight path angles) determined for Galileo will be representative of Cassini's initial conditions. The results of the Galileo GPHS reentry case studies selected from the initial reentry map are included in this report. Based on these results and mission similarities, it is expected that an initially undamaged GPHS module will survive all reentry environments up through Phase 6 of the Cassini mission.

However, the Galileo results for EGA instigated reentries could not be extended to the Cassini mission due to Cassini's significantly greater Earth flyby velocities. Accordingly, JHU/APL has conducted preliminary one-dimensional (1-D) ablation and thermal analyses of the GPHS module to assess clad thermal and aeroshell ablation failure modes for this class of reentries. Time constraints on this study did not permit multidimensional analyses which more accurately define reentry thermal response and is a requisite in assessing the aeroshell's thermostructural (i.e., thermal stress) failure mode. This study is the initial reentry assessment leading to the Cassini Update Safety Analysis Report (USAR) and its preliminary nature is indicated by the listed assumptions and conditions and future enhancements suggested in this report. This 1-D study consists principally of:

- (1) assigning initial GPHS reentry conditions based on the Cassini spacecraft breakup analysis by the Jet Propulsion Laboratory (JPL),

- (2) determination of the GPHS's capture flight path angle, γ , for both 'broadface normal' and 'tumbling' flight orientations,
- (3) determination of stagnation heating rates for γ conditions of capture angle, -30° , -50° and -90° at a common velocity of 63,550 fps and for both flight orientations,
- (4) ablation and thermal response calculations for the above reentry conditions and orientations, and
- (5) qualification, interpretation and finally, nuclear safety 'implications' of the results.

The numerical results for Cassini EGA reentries indicate that:

- (1) The capture angle corresponding to a broadface normal flight orientation is -5.9° and slightly higher at -6° for a tumbling motion.
- (2) Cassini's combined convective and radiative heating rates in the peak heating region of the reentry heat pulses for moderate to steep reentries (of -30° , -50° and -90°) are about six times the predicted values for corresponding Galileo EGA reentry angles and corresponding methodology in deriving radiative heating. The Cassini thermal environments for these three reentry cases are quite comparable and radiatively dominated while the shallow (capture) reentry case provides the critical ablation/thermal environment for GPHS and is convectively dominated.
- (3) Burnthrough of the GPHS aeroshell (approximately a 0.20 inch wall thickness) is predicted for all reentry cases for the broadface normal orientation. Clad temperature has responded to about 3130°R at the time of burnthrough for the shallow reentry case but remains close to initial assigned reentry conditions for the moderate to steep reentry cases.
- (4) Reentry altitude conditions at the time of broadface normal burnthrough ranged from 118K feet for the steep reentry case to 200K feet for the shallow case with module velocities concentrated in a band of 45K to 50K feet per second. If allowance is made for a

75% failure criterion, the velocity and altitude conditions that would be used in a sequential analysis are increased.

- (5) In contrast to the broadface normal results, these early analyses indicate aeroshell survival for tumbling modules at all examined reentry conditions. Aeroshell recession predictions ranged from 0.09 to 0.12 inches while peak clad temperatures varied from 3640 °R for the critical shallow reentry to 2960 °R at the steeper angles.

The time constraints of this study did not permit (a) the continuation of sequential reentry analyses for the GPHS beyond the first level of failure (i.e., aeroshell burnthrough) nor (b) the pursuit of uncertainty analyses, particularly regarding radiative heating, in assessing the end states of the module's fuel. Consequently, any judgments regarding fuel end states are necessarily qualitative at this time and subject to change as subsequent analyses are refined and extended to higher levels of failures in targeting Cassini's USAR.

Based on the premise of sufficient thermal energy during reentry and, at this time, discounting the possibility of aeroshell thermostructural failures, the expected failure sequence of a GPHS module is as follows. Upon ablation failure of the aeroshell, the underlying and highly porous carbon bonded carbon fiber (CBCF) insulation sleeves will be immediately removed as indicated by full-scale GPHS module arc jet tests conducted at the NASA/ARC facilities. The loss of the CBCF thermal insulation will result in melt failures of the fuel clad and possibly partial melting of the fuel while still encased in the graphite impact shells (GIS). The study assumes the state of the GIS assemblies over the duration of the residual heat pulse may either remain captured within the aeroshell remnants (at least for the initially broadface normal orientation) or released as free-flight bodies but not both in sequence. If subsequent ablation failure of the GIS ensues during the remaining heat pulse, atmospheric release of fuel will result with a fraction of the release acquiring a vapor end state. Survival of the GIS during flight could result in ground fuel release at impact.

In making qualitative judgments regarding GPHS failure sequences, it is convenient to relate the interpretation of this study's four specific reentry cases to partitioned zones of the initial GPHS reentry map. Zone A is representative of shallow reentry behavior, zone D is representative of steep reentry behavior, and zones B and C are representative of intermediate or moderate angle reentries. In this qualitative analysis, the failure criterion for clad melt was assigned a temperature of 4410 °R (i.e., iridium's approximate melting point minus 500 °R), while the aeroshell ablation failure criterion was defined to be approximately 75

percent of the wall thickness. These selected failure criteria reflect uncertainty in environmental, thermal, and ablation modeling as well as the superimposed effect of mechanical loading acting on the ablating aeroshell.

The conclusions from this qualitative assessment are restricted to just the likelihood of atmospheric fuel release. They must be viewed as tentative pending further analyses.

These conclusions indicate that atmospheric release and vaporization of fuel for shallow reentries (i.e., zone A) is a plausible scenario for all flight orientations with the greatest likelihood associated with broadface normal entry whether the GIS is released or remains captured. It is also likely that a fuel vapor end state can occur in zones B, C and D for a stable captured GIS state that sustains high levels of radiative heating. Additionally, it appears likely that these zones could experience fuel release and possible vaporization for a free-flight reentry state in an end-on orientation due to the "crush-up" perforations located in the GIS end regions. However, fuel vaporization in these zones becomes much less likely for tumbling conditions regardless of the GIS state. The mass fraction of vaporized fuel cannot be estimated quantitatively at this time since it is dependent upon (a) the timing of the GPHS failure sequence along with (b) the size and shape of the released fuel particles/fragments. However, an estimate of the altitude threshold for fuel vaporization is provided by equating this threshold principally to the terminus of the fully configured GPHS reentry heat pulse for the various zones. An added uncertainty band is included to qualitatively account for the disassembly of the GPHS into smaller reentry bodies of higher ballistic coefficient. These higher ballistic coefficient bodies (e.g., the GIS assembly, fuel fragments, etc.) will result in heat pulse penetration to lower altitudes. The threshold indicates that the zone with the highest likelihood for fuel vaporization, zone A (shallow entries), will also occur at the highest altitude.

It is planned to extend the GPHS reentry computations to sequential analysis of the remaining GPHS components. This will be followed by three-dimensional GPHS module thermal analyses and subsequent aeroshell thermostructural analyses for the steep to moderate reentry zones. Longer range plans include acquisition of heating rate distribution data as a function of pitch and roll orientation to permit refinement of the broadface normal and tumbling analyses as well as analyses at other probable angles of attack indicated by six degree of freedom motion studies.

I. INTRODUCTION

This report discusses the results of one-dimensional (1-D) ablation and thermal analyses of the General Purpose Heat Source (GPHS) resulting from hypothesized accident scenarios for the Cassini mission leading to earth reentries. Specifics regarding such accident scenarios and related occurrence probabilities are not the subject of this report. This discussion is restricted to the reentry response and related safety implications for a single, fully configured module. The reentry domain being addressed does not encompass terminal impact behavior of the fuel containment assembly. The preliminary nature of this study further excludes any attempt to translate module response results into specific source terms or particle size distribution on either a per module or total fuel inventory basis. Finally, a fully configured module at initial reentry infers that conjectured Centaur explosion scenarios occurring during the mission's parking orbit or deployment operations will not yield sufficient overpressure to either damage or partially disassemble the GPHS prior to reentry. If the converse is subsequently demonstrated, then the nuclear safety implications related to module reentries will take on a broader interpretation than intended and provided by this report.

The bases for this qualitative assessment are twofold. First, the GPHS module reentry evaluation conducted in support of the Galileo mission's Final Safety Analysis Report (Reference 1) is, to a large extent, applicable for most of the Cassini mission's phases. However, due to differences in the gravity assist maneuvers conducted for the Galileo mission and planned for the Cassini mission, reentries evolving from accidents during the Earth flyby phase will be significantly different and more severe for Cassini. To that extent, a second basis becomes an abbreviated GPHS module reentry analysis which, while preliminary in nature, can provide insight regarding the likelihood of GPHS ablation or thermal failure events. This preliminary study is the precursor to a series of more refined thermal and thermostructural reentry analyses to be conducted in preparation for the Cassini mission's Updated Safety Analysis Report (USAR) scheduled for the fourth quarter of Fiscal Year (FY) 1995.

The remainder of this report is (a) directed toward briefly demonstrating the applicability of the GPHS/Galileo reentry analyses for Cassini reentries initiated during the spacecraft deployment and injection phase of the mission and, at somewhat greater length, (b) discussing the Cassini's earth gravity assist (EGA) reentry analyses that are currently in progress. In particular, these analyses will be discussed in terms of their framework, limitations and results. From these results, GPHS reentry nuclear safety implications are drawn and

qualified for the Cassini mission. Finally, the necessary analytical and experimental requirements to refine the estimates of EGA reentry environments and GPHS response behavior are presented in brief. These requirements will facilitate translation of the Cassini reentry safety assessment from its current qualitative framework to one more quantitative in nature.

II. GENERAL PURPOSE HEAT SOURCE FAILURE MODES

Reentry safety analyses are concerned with the determination of the design's various thermal and structural response modes relative to component failure modes during reentry flight. Traditionally, such analyses do not include impact response behavior and failure modes but do define terminal impact conditions including velocity, orientation and component temperatures.

An assembly view of the current GPHS design is shown in Figure 1. The reentry failure modes associated with this design are ablation failure of the aeroshell, thermostructural failure (i.e., thermal and mechanical stresses) of the aeroshell and melt failure of the fuel clad. Occurrence of either of the two aeroshell failure modes leads to a sequential reentry analysis in which these same failure modes are now evaluated for the graphite impact shell (GIS). The GIS components may be either captured within the ablated aeroshell or in free flight. This infers that the intervening CBCF members rapidly disintegrate upon direct exposure to the reentry environment. This behavior was observed from full scale GPHS 'test-to-failure' arc-jet ablation investigations (Reference 2). Occurrence of an aeroshell reentry failure leads sequentially to the examination of a clad failure.

Clad melt failures represent a containment breach leading to possibilities of atmospheric or terminal impact source terms depending upon the stage of sequential breakup of the GPHS assembly. Accordingly, due to a GIS failure, an exposed clad melt during flight will result in fuel release to the atmosphere in which some mass fraction of the release may acquire a vaporized end state. The vaporized mass fraction will be dependent upon size and configuration of the fuel fragments/particles and time of release within the reentry heat pulse.

III. COMPARATIVE REENTRY ENVIRONMENTS BETWEEN THE GALILEO AND CASSINI MISSIONS

As hypothesized for the Galileo mission using a Centaur upper stage (Reference 1), similar accident scenarios can be formulated for the Cassini spacecraft which ultimately, upon breakup of the reentering spacecraft and Radioisotope Thermoelectric Generators (RTGs), will lead to the release, dispersion and reentry of individual GPHS modules. While the Cassini mission's

profile will differ from Galileo, particularly regarding gravity assist maneuvers, the Galileo's categorization of a mission into various operational phases should remain the same for Cassini. Consequently, Cassini reentries of 'consequence' become limited to (a) the Centaur upper stage deployment to achieve escape velocity (Phase 6) and (b) the single Earth flyby occurring during the gravity assist maneuvering segment of interplanetary flight.

It is anticipated that the initial reentry map projected for the Cassini spacecraft for Phase 6 and earlier phases will not be significantly altered from the Galileo map developed for a Centaur upper stage shown in Figure 2. Several flight conditions on this map were selected by the Reentry Subpanel of the Interagency Nuclear Safety Review Panel (INSRP) for detailed evaluation and are representative of either critical design or high probability reentry environments. These initial reentry conditions are provided in Table I and provide the basis for assessing Phase 6 Cassini reentries.

The EGA reentry environments for a GPHS module are significantly different between the Galileo and Cassini missions. The initial GPHS reentry flight conditions (RTG release conditions) are compared in Figure 3 for the Galileo and Cassini missions based on NASA-Jet Propulsion Laboratory's (JPL) spacecraft and RTG reentry breakup studies (References 3-5). The differences in the gravity assist maneuvers between missions result in significantly higher reentry energies for Cassini as evidenced by the higher velocities. Such large differences in initial reentry conditions prohibit the use of GPHS/Galileo analyses conducted for the Venus Earth Earth Gravity Assist (VEEGA) reentry environments (Reference 1) as a guidepost for assessing GPHS/Cassini EGA response behavior. Separate, autonomous analyses are necessary for the Cassini EGA reentries.

IV. GPHS SIX DEGREE OF FREEDOM (6DOF) MOTION ANALYSES

The GPHS module's fixed axis system considered in 6DOF reentry motion analyses is shown in Figure 4. The resultant angle of attack, α_R , is the angle subtended by the body's positive x axis and the (relative wind) velocity vector. Early motion studies by both the General Electric Company (GE) and the Applied Physics Laboratory (APL) (References 1 and 6) have indicated that a GPHS module's reentry motion is both (a) complex and (b) sensitive to initial angular displacements and rates. To facilitate reentry thermal analyses, such complex, time dependent motions must become idealized to one of fixed orientation(s). An example would be an oscillatory motion about some angle of

attack position in the GPHS module's pitch plane which becomes idealized as a steady trim condition at that angle of attack.

Early and limited APL and GE 6DOF motion studies suggested three 'idealized' reentry orientations for the GPHS module during hypersonic reentry: tumbling (i.e., full rotation about the pitch and/or yaw axis) and broadface to the wind at $\alpha_R = 0^\circ$ and 60° . The $\alpha_R = 0^\circ$ orientation will be referred to as 'broadface normal'. These idealizations served as representative orientations for early design and evaluation analyses for Phase 4 reentries with particular emphases on the broadface normal and tumbling cases. Extensive 6DOF motion studies were later conducted at APL (References 7 and 8) with improved motion descriptions to determine probable orientations for Galileo's EGA (i.e., VEEGA) reentry conditions. The simulations included the aerodynamic effects of an ablated aeroshell. Parametric studies examined the effects (for VEEGA reentry heat pulse intervals) of initial rotational rates, flight path angles and angles of attack on GPHS motion and orientation (Reference 8). The resulting 'idealized' orientations along with their frequency of occurrence are summarized in Table II. The prevalent orientations are broadface normal (i.e., $\alpha_R = 0^\circ$) $\alpha_R = 30^\circ$, $\alpha_R = 75^\circ$, $\alpha_R = 90^\circ$, and tumbling with the most probable orientation being broadface normal. All orientations are accompanied by a roll rate. The superimposed spinning motion about the roll axis (X axis, Figure 4) is an important element of consideration in EGA reentry analyses since, in most cases, it acts to reduce heat loads to the GPHS surfaces relative to a non-rotating orientation. However, roll axis spin requires that module heating rate distributions be defined as a function of roll angle. For the more probable broadface normal orientation, the spinning effect will have a negligible alleviating effect and may even act to augment broadface convective heating distributions due to centrifugal and coriolis effects on flow field velocities. Of the probable orientations listed in Table II, the broadface normal orientation will likely provide the most severe thermal environment, particularly regarding shock layer radiation. Pending additional motion studies, the Table II orientations are assumed applicable for the Cassini EGA reentries.

V. GPHS/CASSINI PHASE 6 (PARKING ORBIT DEPLOYMENT/INJECTION) REENTRY SAFETY ASSESSMENT

The results of GE's GPHS/Galileo Phase 4 reentry thermal analyses are assumed to apply to the Cassini mission as well in Phase 6. These results are presented in Table III in terms of maximum aeroshell recession and thermal response of the iridium clad member. The clad response is tabulated for reentry peak temperatures and impact temperatures at various altitudes. These analyses

were conducted for tumbling and $\alpha_R = 0^\circ$ for Galileo Phase 4 and at 60° angle of attack orientation for Phase 3 (on-orbit) and considered both early and late GPHS release estimates contained in JPL's breakup studies for the Phase 4 selected reentry cases (Reference 9). Table III indicates that comfortable margins of safety exist with regard to aeroshell ablation and clad melt failure modes for these accident scenarios. The clad's failure criterion is considered to be iridium's melting point temperature at approximately 4910°R . The Galileo FSAR also provided aeroshell thermostructural results for the Phase 4 steep reentry case (i.e., Case 1, Table I) in a broadface normal orientation. While there existed some uncertainty regarding high temperature strength properties for the aeroshell material, Fine Weave Pierce Fabric™ (FWPF), the report concluded that the aeroshell would not experience thermostructural (i.e., thermal stress) failures for this design critical environment.

Galileo Phase 4 reentry studies were also conducted at APL during various development phases of the GPHS with (a) primary focus on the critical broadface normal reentry orientation and (b) a more limited effort toward the tumbling and angle of attack orientations. Case studies in the broadface normal orientation included the shallow, superorbital reentry environment which is design critical regarding thermal response behavior. The conclusions from these studies supported the FSAR results. Additionally, GPHS ablation design margins were experimentally validated for the high probability orbital decay environment by means of full scale arc jet testing in the broadface normal orientation (Reference 2). Finally, based on an independent assessment of the FSAR information, the INSRP Reentry Subpanel's final report for the Galileo mission (Reference 10) was in concurrence with the FSAR conclusion that an initially undamaged GPHS will survive all Phase 4 reentries. This is graphically illustrated in Figure 5 showing the Subpanel's Failure/Abort Sequence Tree (FAST) for Phase 4 accidents.

The GPHS/Cassini design is the same as that derived for the GPHS/Galileo configuration. Therefore, given the same GPHS reentry design and with the expectation that Cassini's initial reentry map for Phase 6 accidents will be similar to Galileo with a Centaur upper stage (since Cassini is also employing a Centaur), the only changes from the Galileo reentry analyses will likely be (a) slight variations in GPHS release conditions due to differences in spacecraft configurations and (b) the possible introduction of different reentry angle of attack orientations based on APL's latest 6DOF motion studies (re: Part III). Neither change is expected to significantly amplify thermal environments for the Cassini Phase 6 reentries so long as the angle of attack reentries are accompanied with a spinning motion about the roll axis. Consequently, at this

time and given the similarities to Galileo, it is expected that an initially undamaged GPHS module will survive all Cassini Phase 6 reentry conditions.

VI. RESULTS OF PRELIMINARY CASSINI EGA REENTRY SAFETY ASSESSMENT

A. GPHS EGA Reentry Trajectories and Environments

Based on the initial GPHS/Cassini EGA reentry map provided by JPL (Reference 5) and illustrated previously in Figure 3, the flight conditions presented in Table IV were selected for 1-D reentry thermal analyses commencing with three degree of freedom (3DOF) trajectory analyses. The minimum flight path angle (γ) case was selected as the module's capture angle for broadface normal and tumbling flight orientations. The results of this capture study are summarized in Table V. The thermal and ablation response results from the reentry analyses are interpreted as representative of zonal behavior for the EGA reentry zones illustrated in Figure 6 as a function of initial flight path angle. Zones A and D are representative of GPHS response behavior for (a) shallow reentries critical in total heat load and (b) steep reentries critical in impulsive heating. The intermediate Zones B and C provide an indication of transition behavior between these two design critical environments.

The APL 3DOF trajectory code (Reference 11) was implemented to generate the flight data required as input for the reentry thermal evaluations. Typically, such data include 'reference' shock layer radiative heating rates and convective heating rates (in both the continuum and free molecule flow regimes) and post-shock total enthalpy and pressure conditions. The two GPHS flight orientations, broadface normal and tumbling, were selected for thermal analyses because (a) they are adaptable to preliminary, engineering 1-D thermal analyses and (b) will permit an assessment of the GPHS's response to large differences in EGA reentry thermal environments. By contrast, the module's intermediate angles of attack (with roll) orientations can not be investigated at this time due to (a) the absence of radiative heating rate data and (b) limited convective heating rate data (Reference 12) as a function of pitch, yaw and roll.

Figure 7 compares the approximate flight corridors for the Cassini and Galileo EGA reentries in an altitude-velocity coordinate frame and further illustrates the relative severity of the Cassini reentry conditions. Another measure of their relative severity is the comparisons of reference convective (Detra, Kemp, and Riddell, Reference 13) and radiative (Callis, Reference 14)

heating rates presented in Table VI. This table indicates that Cassini thermal environments are radiatively dominated at moderate to steep flight path angles.

B. Thermal/Ablation Analysis

1. Framework of the Reentry Thermal/Ablation Analyses

The framework for the Cassini EGA reentry safety assessment for the EIS is one-dimensional ablation and thermal analyses using the Charring Material Thermal Response and Ablation Program (i.e., Aerotherm's CMA code, Reference 15) modified at APL for reentry analyses (R-CMA). This assessment is regarded as preliminary and provides an initial examination of the module's thermal and ablation response behavior for the Cassini reentries. Subsequent analyses providing refinements in environment definition and response modeling are planned to meet the Cassini USAR target date in 1995. These analyses will also likely include further refinements in the zonal partitioning of the GPHS reentry map displayed in Figure 6.

This initial study was not expanded to multi-dimensional thermal analyses necessary in assessing the module aeroshell's thermostructural response primarily because of the time constraint imposed on this study. Over the longer time frame governed by Cassini's USAR, the objectives are to improve definition of (a) the EGA reentry environments (particularly shock layer radiation) and (b) FWPF strength properties at elevated temperatures. These are important requisites in obtaining quality predictions of the aeroshell's thermostructural behavior.

Sequential reentry analyses chained by failure events to the GPHS aeroshell have not been addressed. To illustrate how a single failure event can propagate into a multi-branched sequence of analyses, suppose a GPHS module has reentered at a defined orientation and initial reentry flight condition (from a set of possibilities) and experiences an ablation failure during the entry's heat pulse. The internal GIS assemblies are then either released as autonomous, free flight reentry bodies or remain captured within the ablated aeroshell. In either case, multiple orientations become possible that require individual trajectory and reentry response analyses for the GIS assembly. In like manner, resulting GIS failures for one or more of these orientations lead to the same inquiries regarding the fuel containment assembly and so on down to individual fuel particles. Again, due to imposed time constraints, discussions are limited to only the first level of failure events for the fully configured GPHS module. Accordingly, fuel release deductions can only be made qualitatively at this time.

2. Assumptions and Conditions:

Table VII briefly outlines the assumptions and conditions of the reentry analyses and provides References, where possible, for additional description on engineering models and methodologies. Also, a comprehensive outline of reentry methodologies considered at APL is provided in the final report of the Light Weight Radioisotope Heater Unit (LWRHU) analyses conducted for the Galileo/VEEGA Final Safety Analysis (Reference 16).

Two important conditions of the reentry analyses requiring particular discussion relates to an underlying premise of the R-CMA code. The code's surface energy boundary condition has been formulated on the basis of boundary layer theory in that mass transfer (via the mass transfer coefficient) at the ablating surface is functionally related to the boundary layer's convective heat transfer at the surface. The GPHS aeroshell's surface mass transfer rates for Cassini's high energy EGA reentries can be large enough to separate (i.e., 'blow off') the boundary layer from the aeroshell surface which results in zero convective heating and thereby violates a basic premise of the code. By using the Mickley-Spalding correlation to relate mass transfer to convective heating (i.e., the so-called 'blowing effect', Table VII), the reentry analyses were designed to meet R-CMA's attached boundary layer constraint. However, in the severe reentry heat pulse regions, use of this correlation results in very low mass transfer coefficients (due to non-zero but low convective heating coefficients) which may influence prediction of aeroshell ablation rates. A second condition relating to the surface energy boundary (and hence, to the above condition) is the occurrence of aeroshell ablation in the steep sublimation region for carbon, a region highly sensitive to surface temperature. A differential change in surface temperature (which is an end product of the surface energy balance) can significantly change carbon sublimation rates and thereby influence ablation design margins for the GPHS aeroshell. These conditions will be the subject of future investigations. While future resolution of these conditions is not likely to change conclusions drawn from the current broadface normal analyses, it may alter current tumbling observations.

3. Results of One-Dimensional Ablation and Thermal Analyses

(a) General

One-dimensional reentry thermal analyses were conducted to derive the thermal response of a GPHS module, aeroshell recession and the

temperature history of temperature sensitive components based on reentry trajectories that span the range of the module's release conditions for an inadvertent return of the Cassini spacecraft during the planned VVEJGA Earth flyby. The analyses were conducted by using one-dimensional thermal models and the R-CMA code. Results were derived for tumbling and broadface stable orientations of the module. These limited and preliminary results were derived to meet the EIS schedule for Cassini; more detailed reentry thermal analyses will be conducted for the USAR scheduled for late 1995.

Using the results from these analyses, an assessment of failure is made by assigning an aeroshell ablation failure criterion of 75% of the wall thickness due to uncertainties in the analysis. This assessment is discussed in the following section. The results presented in this section provide for completeness ablation and temperature conditions predicted both with and without this failure criterion.

The reentry trajectories that were selected for analysis were based on the early release conditions of Reference 5 and flight path angles, gammas, of -90, -50, and -30 degrees and the capture angle which is -5.9 and -6.0 degrees, respectively, for a broadside and a tumbling module. Input parameters that are needed for the reentry thermal analyses along the trajectory were obtained using an APL three degree of freedom code that provided both the kinematic parameters and reference heating rates. The shock layer radiation heating rates that were used in this analysis were input directly to the CMA code and were derived using the methodology of Reference 18. This methodology is an improvement from that previously used (References 14 and 17). Perfect gas correlations were used in deriving the effective radius needed to determine radiative heating. The input parameters to the CMA, as a function of altitude consisted of convective and radiative reference heating rates, $\dot{q}_c$ and $\dot{q}_r$, stagnation pressure across a normal shock, $\hat{P}_{t_0}$, and velocity, V . An example of the heating rates, (for a one foot radius sphere) is given for the broadface normal orientation, $\alpha_R = 0^\circ$, in Figure 8.

(b) Description of One-Dimensional Thermal Models

The one-dimensional thermal models were configured as follows. For the reentry cases when the GPHS module is broadface normal, the thermal model represents one-dimensional heat flow completely through the module in a region near the center of a fuel pellet. As such, the model begins at the windward surface of the aeroshell, passes through the following components: aeroshell, CBCF insulator, GIS, clad, fuel, clad, GIS, CBCF, and aeroshell, and

ends at the opposite surface of the aeroshell. The model is representative of most of the module geometry exception for the region where the floating membrane is located.

The one-dimensional thermal model for analysis of a tumbling module is one-half of the above thermal model (i.e., it begins at the surface of the aeroshell and ends at the center of the fuel pellet). The typical procedure for reentry thermal analysis of a tumbling configuration is to uniformly distribute the reentry trajectory heating rates over the total surface area. With this approach and because of the geometrical symmetry of the module's design, the thermal model represents most of the heat flow paths between the outer surface of the aeroshell and the center of a fuel pellet.

The amount of heat generated by the fuel is based on the volume of fuel that is included in the thermal model for the broadside stable orientation, and on the total heat generated by the fuel divided by the total surface area of the module for the thermal model which is used to analyze the tumbling orientation.

The R-CMA code was used to conduct the analyses. The Lawrence Livermore thermo-chemistry data (References 29 and 30) were used to determine equilibrium carbon sublimation rates .

(c) Results for the Broadface Normal Orientation

The results derived for the broadface normal reentry of the module are given in Tables VIII and IX. These tables also list the specific release conditions that were used in the analyses. The primary result is that burnthrough of the aeroshell is predicted for all reentry cases with the broadface normal orientation. Burnthrough is defined as 0.193" of aeroshell recession. The thickness of the broadside section of the aeroshell varies: the minimum thickness is 0.190" in the region of the cavities used for stacking the modules, and at the center of area of the broadside the thickness is about 0.23". The velocity and altitude conditions at the time of aeroshell burnthrough are given in Table VIII for the four reentry cases that were investigated. These results show that the velocity of the module ranges from about 45,500 to 50,000 fps and the altitude ranges from about 118K to 200K feet when aeroshell burnthrough occurs for the broadface normal orientation.

The corresponding trajectory conditions for the assigned 75% failure criterion are (as noted in Table VIII) slightly higher in velocity and altitude. For a postulated GIS release, these constitute the approximate release (i.e., initial)

conditions for a GIS reentry thermal analyses. More accurate release conditions for a GIS will be derived by using a detailed thermal model which accounts for the variation in aeroshell thickness and the increase in convective heating rates with distance from the stagnation point. Note however, that the GIS's may not be released but remain captured in the aeroshell. This configuration requires additional consideration.

The point in the heat pulse when aeroshell burnthrough takes place is shown in Figures 8.a and 8.b. This event occurs about 55% to 75% through the convective heat pulse and 70% to 80% through the radiative heat pulse. Based on the magnitude of velocity and heating rates at the probable time of release for a GIS, and the remaining portion of the heat pulse that still has to be traversed by the GIS, and based on sequential GPHS reentry thermal analyses conducted for Galileo, it is likely that the aeroshell of the GIS will also burn through specifically at reentry angles more shallow than -20° and particularly for end-on orientations.

The temperature of the clad at the time of aeroshell burnthrough is given for the above four reentry cases in Table IX. The initial temperature for the clad is 2820°R . The aeroshell burnthrough occurs before the surface heating rates have an influence on the internal components except for the capture angle reentry case. For this case, the clad temperature is 3128°R . The melt temperature of the iridium clad is 4910°R . (The assigned failure criterion is 4410°R .) The temperatures given for the clad in Table IX are only approximate. Three-dimensional thermal models are required to derive accurate temperature histories for the components of the module.

(d) Results for the Tumbling Orientation

The results of the CMA analyses for a tumbling GPHS orientation are summarized in Table X. Burnthrough of the aeroshell is not predicted; aeroshell recession ranges from about 0.09" to 0.12".

Aeroshell recession is given for two cases in Table X. All conditions in the analysis were the same for both cases except for approximate factors used to convert the shock layer radiation heating rates to a tumbling flight orientation. As part of this conversion, the radius effect on radiative heating in transforming heating rates for a GPHS effective spherical radius of 0.85 to the reference broadface stable effective radius of 1.00 foot was approximated by a radius power law with exponent 'n'. The two cases essentially examined the limits on radius effect with the first case assuming a square root law ($n=1/2$) and the

second case a linear variation ($n=1$). Table X indicates the radius transformation had a minor effect on aeroshell ablation.

While burnthrough of the aeroshell is not predicted for a tumbling module (even when allowing for a 75% ablation failure criterion), aeroshell failures remain a possibility depending upon the results of aeroshell thermal stress analyses.

The peak temperature for the clad during the reentry is also given in Table X. The maximum value of 3641°R occurs with the capture angle (6.0 degrees) reentry. This clad temperature is well below the melt temperature for iridium (4910°R) or the melt failure criterion of 4410°R .

VII. ENHANCEMENTS FOR REENTRY ANALYSES

Table XI provides a comprehensive list of activities in both the experimental and analytical sectors of reentry technology that will improve the extent and quality of the safety assessment for GPHS/Cassini EGA reentries. In so far as possible, these activities should be planned and incorporated into GPHS reentry analyses to meet the Cassini USAR target date (i.e., the end of fiscal year 1995).

If the extent of the reentry safety evaluation is to include angle of attack orientations other than broadface normal and tumbling, it is imperative that GPHS heating distributions for both the radiative and convective modes be adequately defined. Without such definition, any response analyses conducted for these cases will have a high degree of uncertainty.

VIII. REENTRY SAFETY IMPLICATIONS FOR GPHS/CASSINI EGA REENTRIES

A. EGA Reentry Response for the GPHS Module

Several implications can be drawn qualitatively from the abbreviated results of Section VI. Figures 9.a and 9.b recast the preliminary reentry results in terms of percent (%) of governing failure criterion for the EGA reentry zones defined previously in Figure 6. As discussed earlier, zones A and D are representative of reentry behavior for shallow and steep reentries respectively while the intermediate zones can be classified as 'moderate, low (B)' and 'moderate, high (C)'. In this reentry safety assessment the failure criteria are defined as 75% aeroshell wall thickness for ablation and 4410°R for clad melt (i.e.,

iridium's melting point minus 500°R). The failure criteria recognizes uncertainties in the analyses. Furthermore, the reduced wall thickness criterion for ablation allows for the possibility of premature failure due to mechanical loading on the ablating aeroshell.

Aside from answering the basic question of survival or failure for the two GPHS reentry orientations, a striking feature portrayed by these figures is the similarity in GPHS response behavior for zones B, C, and D. The clad's thermal response for these three zones indicate little rise from prescribed initial temperatures (i.e., steady state operational temperatures) at time of failure for broadface normal reentries. The thermal response remains mild even for the tumbling cases which experience the full reentry heat pulse. This response characteristic during hypersonic reentry indicates a spiked heat pulse for flight conditions ranging widely from 'steep to moderate, low' flight path angles (re: Figure 8.a). The implication from this similarity is that any failure event occurring in one of these zones is likely to occur in all three.

Zone A's thermal environment is clearly a departure from the other zones and represents the critical thermal/ablation corridor for this study. This becomes more clearly evident in Figure 10 which characterizes, by zone, the approximate heat pulse expenditure for both the convective and radiative modes to initiate aeroshell ablation failures for the broadface normal reentry cases. These expenditures are expressed in terms of % of the total GPHS model convective and radiative heat loads (re: Figure 8). Reentry zones B, C, and D are radiatively dominated and show large expenditures to initiate failure. In contrast, zone A is convectively dominated and provides a significantly larger heat load (for this mode) to initiate failures. The convective heat load expenditure in zone A is noticeably smaller than the other zones. This figure also provides the residual energy (ΔQ , BTU ft⁻²) and remaining time interval (Δt , seconds) available in the bimodal heat pulse to further heat the module's internal components. In summary, zone A has a significantly greater heat pulse residual than the other zones and is more likely to produce sequential failure in the GPHS components.

B. Relative Environment of Free Flight and Captured GIS

Given an aeroshell ablation failure and presuming sufficient residual energy in the reentry to initiate a clad melt event, the disposition of the GIS becomes an important consideration regarding the likelihood of atmospheric fuel release. GIS disposition includes both its configurational state and orientation subsequent to an aeroshell failure. Its state may be defined as being either captured in the aeroshell remnants or released as a free-flight body while

orientation can be broadly categorized as either stable at some angle of attack for a free GIS or captured in a stable or tumbling GPHS orientation.

In Figure 11, an example of the relative heating between zones is given for a hypothetical case of a free-flight GIS in a side-on stable configuration. The same flight trajectory as the broadface normal GPHS is assumed. This permits an approximate zonal comparison of the residual convective and radiative energy (i.e., ΔQ s) between the reference heating models and the side-on GIS. In this comparison, the residuals are normalized by $\Delta Q_{\text{ref,zone A}}$. Due to the reduced size of the GIS assembly, Zone A becomes even more critical because of the significant amplification in convective heating while the environments for zones B, C, and D become diminished by reductions in the radiative mode. Additionally, the crush-up perforations of the GIS makes it particularly vulnerable to ablation failure for an end-on flight orientation.

If the GIS should remain in the captured configuration, zone A will still provide the critical thermal environment. However, the environments for zones B, C, and D will now become more severe than indicated for the corresponding free-flight conditions for the GIS. If the captured assembly should remain in the broadface normal attitude, local convective heating will likely become amplified relative to reference levels due to shock and local flow interference effects. Radiative heating in these zones will remain comparable to the initial (i.e., fully configured) GPHS levels due to similarity in geometry and resulting shock layer thicknesses. The implication from these observations is that a further understanding of the aerodynamics, aerothermodynamics, and dynamic loading of the captured GIS configuration is required to fully assess GPHS reentry safety.

C. Estimated Likelihood of GPHS Fuel Release for EGA Zones

Based on the results of this study and the implications distilled from them, an estimate has been made of the likelihood of GPHS ablation and melt failure events along with subsequent atmospheric release and vaporization of fuel, Table XII. Since the present analyses are restricted to the first level of a failure sequence, the table ratings are provided strictly in qualitative terms and are arguably subjective in nature. However, they do provide insight to those reentry zones or conditions requiring future attention.

The sequence of events in Table XII is the expected failure sequence to occur during an EGA reentry for a GPHS module in a broadface normal orientation. Implicit in this sequence is the immediate loss of the underlying CBCF thermal insulation upon ablation failure of the aeroshell. Where two

ratings are provided, the likelihood is thought to fall somewhere between the two but biased toward the initial rating. Due to fairly comparable environments, zones B, C and D are all rated the same for a given event and condition. These zonal ratings will undoubtedly become differentiated as (a) future thermal and ablation analyses become more refined and (b) thermostructural response results are incorporated into the scorecard.

The scorecard indicates that atmospheric release and vaporization of fuel for EGA reentries in zone A is plausible with the greatest likelihood associated with stable flight orientations independent of the GIS state. Fuel release and vaporization may also be likely in zones B, C, and D for a stable, captured GIS sustaining high radiation levels or for a free-flight GIS in an end-on flight orientation. However, for remaining configurations, fuel release and vaporization likelihood becomes much less in these zones.

D. Fuel Vaporization

By deferring the possibility of atmospheric releases initiated by aeroshell thermostructural failures, this study indicates the likelihood of fuel vaporization is greatest for zone A. However, the mass fraction of the vaporized fuel cannot be estimated at this time since it is dependent upon (1) the timing of the GPHS failure sequence along with (2) the size and shape of the released fuel particles/fragments. However, Figure 12 does provide an estimate of the altitude threshold for atmospheric vaporization by equating this threshold principally to the terminus of the GPHS reentry heat pulse for the various zones. The added uncertainty band is included to account for the effect of higher ballistic bodies (e.g., a free-flight GIS) as the module undergoes reentry breakup. Higher ballistic coefficient bodies will result in heat pulse penetration to lower altitudes. The threshold indicates that the zone with the highest likelihood for fuel vaporization (zone A) will also occur at the highest altitudes.

IX. CONCLUDING OBSERVATIONS

At this time, little can be stated for the intermediate α_R orientations for a reentering GPHS module (re: Table II). Of the two orientations considered in this study, the $\alpha_R=30^\circ$ configuration will likely lean toward the response behavior recorded for the broadface normal ($\alpha_R=0^\circ$) configuration while the 75° and 90° configurations will respond more like a tumbling module. However, definition of bimodal heating distributions are required for these configurations (as emphasized in Table VIII) in order to perform meaningful response analyses.

In continuing future studies, higher resolution in reentry zone A will be obtained for the broadface normal GPHS module. Currently, this entire zone is being biased on the basis of a minimum flight path trajectory which produces a critical convective heating environment. Future studies may well indicate that some partitions of this zone will not be as likely to produce atmospheric releases as indicated in Table XII.

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Table I

**Reentry Cases for Detailed Evaluation
Through Phase 4 Operations of the Galileo Mission**

Case No.	Galileo
1.	Superorbital, Steep Angle ¹
2.	Superorbital, Gamma Min ²
3.	Orbit Decay ³
4.	Powered ⁴

¹ $V_e = 36000$ fps, $\gamma_e = 39^\circ$
Cruise Configuration
Trimmed Attitude

² $V_e = 36000$ fps
 $\gamma_e = \text{min. for RTC (i.e., capture on first pass)}$
Cruise Configuration
Trimmed Attitude

³ $V_e = 25,700$ fps
 $\gamma_e = 0.2^\circ$
Cruise Configuration
Trimmed/Spinning Attitude

⁴ $V = 21,000$ fps, $\gamma = 10.5^\circ$
27,000 lbs propellants remaining
Spacecraft Stowed

From Reference 1 Table I-4

Table II

**GPHS Idealized Flight Orientations and Frequency
of Occurrence During the Heat Pulse Intervals of Galileo EGA Reentries**

α Average						
αR	0	30	75	90	Tumbling	All
Number of Occurrences	39	13	20	12	10	94
Percent	41.5	13.8	21.3	12.8	10.6	100.0

- Tumbling which usually occurs during the first half of heat pulse is added as additional cases when it occurs. Thus the total number is greater than the 84 cases studied.
- All orientations attendant with spin about x-axis (i.e., roll)
- Data obtained from Reference 8
- Refer to Figure 4 for axis system

Table III

GPHS Thermal and Ablation Response for Galileo Phase 4 Reentries¹

A. Tumbling Orientation

Reentry Type	Initial Temp (°C)		Peak Temp (°C)		Impact Temperature (°C)				Sea Level		Maximum Recession (MILS) %	
	Max	Min	Max	Min	10000 ft Max	10000 ft Min	5000 ft Max	5000 ft Min	Max	Min		
Superorbital, γ_{max}												
Early	1296	1289	1356	1358	1229	1191	1182	1144	1133	1095	27.2	14.7
Late	1296	1289	1363	1356	1226	1188	1179	1141	1132	1094	27.1	14.6
Superorbital, γ_{min}^2												
					3						4	
Early	1296	1289	1579	1573	981	950	947	917	914	883	33.2	17.9
Late	1296	1289	1579	1573	981	950	949	918	914	884	33.2	17.9
Orbital Decay												
Early	1296	1289	1370	1364	1047	1013	1009	975	970	936	19.7	10.6
Late	1298	1289	1420	1413	1068	1032	1028	992	988	953	20.0	10.8
Powered												
Early	1212	1204	1241	1233	1011	979	976	946	939	909	8.1	4.4
Late	1212	1204	1230	1222	1001	969	966	935	931	900	5.9	3.2

B. Broadface Normal Angle of Attack = 0°

Superorbital, γ_{max}												
Early	1296	1289	1352	1316	1172	1134	1126	1088	1077	1040	56.0	30.3
Late	1296	1289	1351	1314	1169	1132	1124	1086	1076	1039	57.0	30.8

C. Angle of Attack = 60°

Orbital Decay												
Early	1296	1289	1404	1394	1067	1031	1028	993	986	952	40.0	21.6
Late	1296	1289	1444	1433	1085	1048	1044	1008	1002	967	41.0	22.2

Notes: 1. Data taken from Reference 1

2. This reentry resulted in a single skip-out of the GPHS modules with an orbit duration above 400 kft long enough for the modules to stabilize in temperature with the space vacuum sink. The resulting temperature of the fueled clads at the final entry was around 1010°C.
3. The peak clad temperature during the final entry was 1233°C max. and 1228°C min.
4. This value includes 15.3 mils ablation resulting from the initial pass through the atmosphere prior to the skip.

Table IV

GPHS Initial Flight Conditions for Cassini EGA Reentries

Broadface Normal			Tumbling		
Velocity Ft/sec	Altitude Kft	Gamma Deg	Velocity Ft/sec	Altitude Kft	Gamma Deg
63,550	323	-5.9 ¹	63,550	323	6.0 ¹
63,550	263	-30.0	63,550	263	-30.0
63,550	250	-50.0	63,550	250	-50.0
63,550	236	-90.0	63,550	236	-90.0

- Notes:
1. designates capture angle leading to direct earth reentry.
 2. Initial conditions equate to early GPHS release with zero wind condition, Reference 5.

Table V

**TDOF Trajectory Results for Determination of GPHS Capture Angles
for Cassini's EGA Release Conditions**

Release Conditions		TDOF Results	
Gamma (deg)	Altitude (Kft)	GPHS Module Orientation	
		Broadface Normal	Tumbling
-5.3	327.6	Escape Orbit	Escape Orbit
-5.4	326.8	Escape Orbit	Escape Orbit
-5.5	326.0	Reenters on 2nd Skip	Escape Orbit
-5.6	325.2	Reenters on 2nd Skip	Reenters on 2nd Skip
-5.7	324.4	Major Skip in Atmosphere	Reenters on 2nd Skip
-5.8	323.6	Minor Skip in Atmosphere	Major Skip in Atmosphere
-5.9 ⁵	323.0	Direct Earth Reentry	Minor Skip in Atmosphere
-6.0 ⁶	323.0	Direct Earth Reentry	Direct Earth Reentry

- Note:
1. Early release conditions from Reference 5
 2. Inertial values.
 3. Gamma - flight path angle.
 4. Release velocity - 63,550 ft/sec
 5. designated capture angle, broadface normal
 6. designated capture angle, tumbling.

Table VI

**Comparison of Peak Heating Rates
for Broadface Normal GPHS for Galileo
and Cassini EGA Reentries**

Gamma	$\dot{Q}$, Convection		$\dot{Q}$, Radiation		
	VEEGA	VVEJGA	VEEGA	VVEJGA ⁴	VVEJGA ⁵
-90	3,973	10,373	14,628	95,340	60,816
-50	3,229	8,668	8,878	64,785	41,399
-30	2,506	6,745	4,650	37,885	23,197
-10	1,358	3,650	960	8,995	-
-5.9	-	2,289	-	-	1,906

Notes:

1. Reference condition: laminar, stagnation heating, 1 ft. radius sphere
2. Q in BTU/ft²-s
3. Convection model: Detra, Kemp, and Riddell (Reference 13)
4. Radiation model: Callis (Reference 14) using Olstad's 8 step absorption model (Reference 17).
5. Present analysis uses Sutton and Hartung's method, Reference 18. See also Figure 8 and discussion of Section VI.B.3(a).

Table VII

**Assumptions and Conditions of the GPHS Preliminary
Thermal and Ablation Analyses for Cassini EGA Reentries**

I. Stagnation Aerothermodynamic Environments

A. Shock Layer Radiation Heating Rates (Reference 18)

- flow field code: Radiating Inviscid Flow Stagnation Point (RIFSP)
 - radiation transport model: RAD/EQUIL (equilibrium flow)
 - axisymmetric flow (i.e., spherical nose geometry)
- GPHS equivalent spherical radius
 - equivalent adiabatic shock standoff distances
 - normal flat plate δ_{sh} (Reference 19)
 - sphere δ_{sh} (Reference 20)
- tumbling factor (referenced to broadface normal orientation)
 - $0.2 \leq F_{rad,tumb} \leq 0.3$ based on simplistic cosine power laws

B. Convective Heating Rates (reentry hypersonic heat pulse)

- reference heating rate (a non-ablating spherical body with 1 foot radius in laminar, stagnation flow)
 - continuum: Detra, Kemp and Riddell (Reference 13)
 - free molecule: free stream energy flux (Reference 21)
- transformation to broadface normal orientation (Reference 22)
 - no heating effect due to roll axis spinning
- tumbling factor (referenced to broadface normal orientation)
 - continuum: (References 23-25)
 - free molecule: cosine law (Reference 21)

Table VII (cont)

**Assumptions and Conditions of the GPHS Preliminary
Thermal and Ablation Analyses for Cassini EGA Reentries**

II. Thermal/Ablation Response

A. Thermal Response

- CMA code, modified for reentry analyses (Reference 15)
- thermal model:
 - broadface normal: one-dimensional model of GPHS cross-section from aeroshell windward broadface surface to leeward broadface surface including internal components
 - tumbling: one-dimensional model of GPHS cross-section from aeroshell broadface surface to centerline of fuel capsule
 - fuel source terms
 - interfaces: vacuumed gaps
- thermal properties: General Electric (Reference 26)
- aeroshell density: $114.7 \text{ lb}_m \text{ ft}^{-3}$

B. Ablation Response

- CMA code, modified for reentry analyses (Reference 15)
- thermochemical carbon ablation models
 - kinetic oxidation (Reference 27)
 - diffusion oxidation (Reference 28)
 - sublimation, equilibrium (Reference 29, 30)
- no mechanical ablation mechanisms

Table VII (cont)

**Assumptions and Conditions of the GPHS Preliminary
Thermal and Ablation Analyses for Cassini EGA Reentries**

III. Coupling Effects

A. Environment

- no shock layer radiation/convection coupling
 - no partitioning of total shock layer total energy
 - shock layer radiation cooling
 - no effect on convective heating

B. Response

- no ablation induced roughness effects
 - boundary layer transition
 - augmented convective heating
- mass transfer (i.e., blowing) effects
 - convective heating blockage: Mickley-Spalding (Reference 31)
 - radiative heating blockage: General Electric (Reference 32)
 - no separated boundary layer due to massive blowing
- no shape change effects
 - ballistic coefficient (i.e., trajectory)
 - aerothermodynamics

Table VIII

**Trajectory Parameters at the Time of Aeroshell Burnthrough
of a Broadface Normal GPHS Module
(Cassini VVEJGA Earth Flyby Module Release Conditions)**

Release Conditions ¹			Conditions at Aeroshell Burnthrough ³		
Velocity (Ft/Sec)	Altitude (Kft)	Gamma Deg	Traj Time (Seconds)	Velocity (Ft/Sec)	Altitude (Kft)
63,550	323	-5.9 ²	30.1	50,025	200.4
63,550	263	-30.0	4.5	45,486	130.4
63,550	250	-50.0	2.8	46,654	121.6
63,550	236	-90.0	2.0	48,424	117.7

Notes:

1. Early Release Conditions of Reference 5
2. Capture Angle
3. Corresponding conditions at 75% ablation of wall thickness are:

γ	Traj Time	Velocity	Altitude
-5.9	26.5	54000	208
-30	4.0	51000	142
-50	2.6	50000	129
-90	1.8	52000	124

Table IX

**Peak Clad Temperature for a Broadface Normal GPHS Module
(Cassini VVEJGA Earth Flyby Module Release Conditions)**

Release Conditions ¹			Trajectory Time Aeroshell Burnthrough (Seconds)	T, clad Peak (°R)
Velocity (Ft/Sec)	Altitude (Kft)	Gamma Deg		
63,550	323	-5.9 ²	30.1	3128
63,550	263	-30.0	4.5	2837
63,550	250	-50.0	2.8	2830
63,550	236	-90.0	2.0	2827

Notes:

1. Early Release Conditions of Reference 5
2. Capture Angle

Table X

**Aeroshell Ablation (R, aero) and Peak Clad Temperature (T,cd,pk)
for a Tumbling GPHS Module
(Cassini VVEJGA Earth Flyby Module Release Conditions)**

Release Conditions			Case No. 1		Case No. 2	
Velocity (Ft/Sec)	Altitude (Kft)	Gamma Deg	R,aero (in)	T,cd,pk (°R)	R,aero (in)	T,cd,pk (°R)
63,550	323	-6.0 ⁴	0.0897	3640	0.0924	3641
63,550	263	-30.0	0.1013	3002	0.1128	2993
63,550	250	-50.0	0.1106	2965	0.1223	2956
63,550	236	-90.0	0.0937	2965	0.0985	2962

Notes:

1. Early Release Conditions of Reference 5
2. Case 1: Radiative heating dependency on (effective) spherical nose radii:
 $(R_{n,2}/R_{n,1})^{n=1/2}$, i.e., square root law.
3. Case 2: $R_{n,2}/R_{n,1}^{n=1}$ i.e., linear law
4. Capture Angle

Table XI

Future Enhancements for Cassini EGA Reentry Analyses

I. Experimental:

A. Convective Heating:

- full scale convective heating distribution tests at pitch and roll combinations
 - specifically address α_R reentry orientations (re: Table II)
 - improve resolution of tumbling heating factors
 - observations of flow field structure

B. Ablation Response:

- coupon testing at high enthalpy, moderate pressure conditions
 - acquire sublimation data for FWPFTM material
 - observe mechanical effects, weave orientation, induced surface roughness, etc.
- full scale GPHS testing-to-failure at $\alpha_R > 0$
 - observe breakup sequence at $\alpha_R > 0$ orientations

C. High Temperature Material Properties:

- FWPFTM (aeroshell) strength properties for thermostructural analyses
- CBCF (insulation) thermal conductivity properties for thermal analyses
 - vacuumed state
 - air infiltrated state, varying pressures

Table XI (cont)
**Future Enhancements
for
Cassini EGA Reentry Analyses**

II. Analytical

- A. Shock Layer Radiative Heating (CFD)**
- equilibrium radiative heating distributions
 - limited flight conditions, select orientations ($\alpha_R > 0$)
 - equilibrium radiative heating distribution, reference ($\alpha_R = 0$) orientation
 - select flight conditions
 - observe flow structure
 - validate engineering approach vis a vis $R_{eff, sph}$
 - nonequilibrium radiative heating distribution
 - reference orientation
 - limited flight conditions
- B. Convective Heating (CFD)**
- convective heating distribution, reference orientation
 - select flight conditions
 - validate engineering methods (e.g., stag heating)
 - real gas scaling of convective heating test data
 - real gas effects on shock stand-off distances
 - convective heating distributions,
 - limited flight conditions, limited orientations ($\alpha_R > 0$)
 - real gas scaling
- C. Combined Radiative/Convective Heating (CFD)**
- coupling effect on convective heating (re: Pt III,A of Table VII)
 - equilibrium radiation model

Table XI (cont)

Future Enhancements for Cassini EGA Reentry Analyses

- D. **Surface Energy Boundary Conditions**
 - alternate surface energy balance algorithms
 - separated boundary layer conditions
 - melt conditions
 - codes: RETAP and RETAP-E (multi-dimensional), R-CMA (1-D)

- E. **Ablation Response**
 - incorporate nonequilibrium vaporization modeling
 - Langmuir-Knudsen, Knudsen layer vaporization models
 - carbon (FWPF), fuel

 - investigate melt modeling
 - melt hydrodynamics
 - melt removal mechanisms
 - emphasis on carbon, fuel.

- F. **Thermostructural**
 - expansion of material property database to temperatures higher than 5500°F
 - couple inertial and thermal loads
 - simulation of non-linear, temperature-dependent material properties
 - analysis with latest LANL mechanical properties
 - continuous accounting of cumulative damage of material with time
 - simulation of different orthogonal stresses

Table XII
Likelihood^(a) of GPHS Fuel Vaporization on a Zonal Basis for Cassini EGA Reentries

A. GPHS Stable^(b) Flight Orientation

Sequence of Events	Zone A	Stable	Tumbling	
		B, C, D	A	B, C, D
1. Aeroshell (c) ablation failure	HL	HL/L	-	-
2. Fuel clad (d) melt failure				
Free GIS state	HL	L/UL	HL/L	UL/L
Captured GIS State	HL	L/HL	HL/L	L/UL
3. GIS Ablation Failure	Implies atmospheric fuel release/vaporization			
Free GIS	HL(e)	L	L	UL/HUL
	HL/L	UL	L	UL/HUL
Captured GIS	HL/L	L/UL	L	UL

B. GPHS Tumbling Flight Orientation

Sequence of Events	Zone A	Stable	Tumbling	
		B, C, D	A	B, C, D
1. Aeroshell ablation failure	-	-	UL/HUL	UL
2. Fuel clad melt failure				
Free GIS state	L	UL	UL	HUL/UL
Captured GIS state	L	UL/L	L/UL	UL/HUL
3. GIS Ablation Failure				
Free GIS	UL/L	UL	UL/HUL	HUL
	UL	HUL	UL/HUL	HUL
Captured GIS	UL	UL/HUL	UL	HUL/UL

Notes:

- (a) Likelihoods represents subjective judgements based on first level failure analyses (ie., aeroshell ablation failures) using failure criteria of Figures 9 (a), and 9 (b).
- (b) Stable orientation represented by broadface normal ($\alpha_R = 0^\circ$) case.
- (c) An aeroshell ablation failure implies removal of the underlying CBCF thermal insulation.
- (d) Fuel clad melt may be accompanied by a partial melting of fuel pellet.
- (e) This row represents an end-on stable flight orientation in which ablation failures may be abetted by the 'crush up' perforations located in the end regions of the GIS.

Codes:

HL Highly likely L Likely HUL Highly unlikely UL Unlikely

DIAGRAM OF GPHS ASSEMBLY (CUTAWAY)

INITIAL REENTRY MAP OF GALILEO SPACECRAFT WITH A CENTAUR UPPER STAGE (FROM REFERENCE 1)

* APPROXIMATE CONDITIONS,
REENTRY CASE STUDIES (re TABLE 1)

COMPARISON OF INITIAL GPHS FLIGHT CONDITIONS FOR GALILEO AND CASSINI EGA REENTRIES

INITIAL REENTRY ALTITUDE , K ft

GPHS BODY-FIXED AXIS SYSTEM

(FROM REFERENCE 7)

FIGURE 4

GALILEO MISSION'S PHASE 4 FAILURE/ABORT SEQUENCE TREE

(FROM REFERENCE 10)

ZONAL EVALUATION OF GPHS RESPONSE FOR CASSINI EGA REENTRIES

FIGURE 6

GPHS APPROXIMATE FLIGHT CORRIDORS FOR GALILEO AND CASSINI EGA REENTRIES

- NOTES:
1. *, MAXIMUM HEATING RATES
 2. BROADFACE NORMAL ORIENTATION
 3. CORRIDOR FOR DIRECT REENTRIES
 4. γ , FLIGHT PATH ANGLE

FIGURE 7

REENTRY HEATING RATES TO A BROADFACE NORMAL GPHS (CASSINI - VVEJGA RELEASE CONDITIONS)

REENTRY HEATING RATES TO A BROADFACE NORMAL GPHS (CASSINI - VVEJGA RELEASE CONDITIONS)

GPFS AEROSHELL ABLATION RESPONSE ON A ZONAL BASIS FOR CASSINI EGA REENTRIES; BROADFACE NORMAL AND TUMBLING REENTRY ORIENTATIONS

NOTES:
 --- LOCATIONS OF REENTRY ANALYSIS
 --- EARLY GPFS RELEASE CONDITIONS (re: FIGURE 3)
 --- BROADFACE NORMAL CASES: STAGNATION RECESSION

FIGURE 9a

GPFS CLAD THERMAL RESPONSE ON A ZONAL BASIS FOR CASSINI EGA REENTRIES; BROADFACE NORMAL AND TUMBLING REENTRY ORIENTATIONS

re: FIGURE 9(a)
* AT TIME OF ABLATION FAILURE
(75% WALL THICKNESS)
na (NOT APPLICABLE)
INITIAL CLAD TEMPERATURE
- 60% OF FAILURE CRITERION

NOTES:

FIGURE 9b

BASIS FOR GPHS AEROSHELL FAILURES; BROADFACE NORMAL ORIENTATION (FAILURE CRITERION: 75% WALL THICKNESS)

HEAT PULSE DEFINITIONS

CONVECTIVE: $\int_0^t \dot{q}_c dt$ WHERE t IS FLIGHT TIME, $M = \text{MACH NO.}$

RADIATIVE: $\int_0^t \dot{q}_r dt$

NOTES:

- re: FIGURE 9 (a)
- GPHS STAGNATION HEATING RATES
- ΔQ RESIDUAL HEAT LOAD, BTU ft^{-2}
- At RESIDUAL HEAT PULSE TIME BASE, SECONDS

FIGURE 10

THE EFFECT OF A FREE FLIGHT GIS ASSEMBLY ON THE RESIDUAL,
CONVECTIVE AND RADIATIVE HEAT LOAD OF CASSINI EGA REENTRIES
ON A ZONAL BASIS; SIDE-ON REENTRY ORIENTATION

INITIAL GPS FLIGHT PATH ANGLE , DEGREES

LIKELY ALTITUDE REGION FOR GPHS FUEL VAPORIZATION DURING CASSINI EGA REENTRIES; INITIAL BROADFACE NORMAL ORIENTATION

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The R-CMA (or CMA) code mentioned in Section VI, Part B and in Tables VII and XXI is Aerotherm Corporation's CMA code (Reference 15) with minor modifications to permit reentry analyses for radioisotope heat sources such as the GPHS. While the 'R' prefix has been added to distinguish it from other versions of the CMA code at JHU/APL, it remains substantively Aerotherm's CMA code. The Aerotherm CMA code represents a significant milestone in the development of computational ablation analyses and continues to serve as the industry standard well into the third decade of its existence.

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