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Aerospace Nuclear Safety Program

GPHS Motion Studies for Heat Pulse Intervals of Reentries from Gravity-Assist Trajectories

Johns Hopkins University Applied Physics Laboratory

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GPHS Motion Studies for Heat Pulse Intervals
of Reentries from Gravity Assist Trajectories

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SUMMARY

Motion studies of the General Purpose Heat Source Module, GPHS, were conducted in the heat pulse interval associated with entries from earth gravity assist trajectories. The APL six-degree-of-freedom reentry program designated TMAGRA6C was used. The objectives of the studies were to (1) determine the effect of ablation on GPHS motion, and (2) determine whether the GPHS module entering the earth's atmosphere from an earth-gravity-assist trajectory has a preferred orientation during the heat pulse phase of reentry.

The results are given in summary form in Figures 107 through 110 for easy visualization of the initial conditions investigated and to provide a quick-look of the resulting motion. Detail of the motion is also given for the parameters of interest for each case studied. Selected values of initial pitch rate, roll rate, and combinations of these within the range 0° to $1000^\circ/\text{sec}$ were investigated for initial reentry angles of -7° (shallow) and -90° (steep) and initial angles of attack of 0° (broadface to the wind) and 90° (see List of Figures on page 5).

Although the studies are not exhaustive, a sufficient number of reentry conditions (initial altitude, reentry angle, angle of attack, rotational motion) have been investigated to deduce certain trends. The results also provide information on additional reentry conditions that need to be investigated. The present results show four GPHS orientations that predominate - all with some pitch oscillations and rolling motion. These are: angles of attack, α_R of 0° , 30° , 90° and tumbling. It should be assumed that all these orientations are equally probable because only combinations of two initial reentry angles, γ_0 , and two values of α_{R0} have been investigated. Further the probability for any given initial rate on orientation is not known.

TABLE OF CONTENTS

LIST OF TABLES	4
LIST OF FIGURES	5
SYMBOLS AND NOMENCLATURE	6
BACKGROUND	7
OBJECTIVES	7
DISCUSSION	7
A. Initial Conditions	7
B. Geometry	8
C. General Trajectory Parameters	8
D. Evaluation of Computations	8
RESULTS	10
A. General	10
B. Effect of Ablation	11
C. Effect of Pitch Rate	12
D. Effect of Roll Rate	12
E. Effect of Combined Initial Pitch and Roll Rates	13
F. Reacting Forces from Accelerations	14
CONCLUSIONS AND RECOMMENDATIONS	15
REFERENCES	16

LIST OF TABLES

1. GPHS reentry conditions analyzed by G. E. (used in this study).
2. Approximate end of Convective Heat Pulse.

LIST OF FIGURES

<u>General Description</u>	<u>Figure No.</u>
Altitude - Gamma Inputs	1-2
Geometry	3-5
Trajectory Parameters for VEEGA Entry	6-11
Comparison of APL and G.E. results, Baseline Configuration	
for VEEGA reentry conditions	12-22
for Orbital and Superorbital entry	23-38
Effect of Ablation	39-46
Effect of Initial Pitch Rate	47-66
Effect of Initial Roll Rate	67-84
Effect of Combined Pitch and Roll Rate	85-106
Graphical Synopsis of Results	107-110

SYMBOLS AND NOMENCLATURE

C_m	pitching moment coefficient, $C_m = \frac{\text{Pitching moment (in-lbs)}}{\bar{q}SL}$	
H	altitude	ft
H5	approximate altitude at end of heat pulse	ft
L	reference length, 3.826 inches	
p	roll rate	deg/s
q	pitch rate	deg/s
$\bar{q}$	dynamic pressure	lbs/ft ²
r	yaw rate	deg/s
S	reference area, 0.0975 ft ²	
t5	approximate time at end of heat pulse	secs
V	velocity	ft/s
$\alpha_R (\alpha)$	resultant angle-of-attack; angle between x axis of GPHS and velocity vector (see Figure 5)	deg
γ	flight path angle measured negatively from the local horizontal to the velocity vector (γ_0 is initial flight path or reentry angle)	deg

Subscripts

o initial conditions

BACKGROUND

The impetus for this investigation was the concern of the DoE aerospace nuclear safety community (including JHU/APL) that the assumption of broadface trim attitude for the GPHS module in thermal analyses may not be generally valid. Specifically, it was surmised that ablation would tend to destabilize the GPHS module and thus preclude any persistence of broadface trim during the heat pulse. At DoE's request in September 1988, JHU/APL formulated a hypersonic aerodynamic test program (Reference 1) to determine the effect of ablation on aerodynamic stability and drag. Specifically, broadface ablation was investigated (References 2 and 3) because broadface geometries of ablated configurations were available for duplication from ablation tests conducted in the 20MW arc jet facility of NASA/Ames (Reference 4).

The effort culminating in the motion studies presented in this memorandum involved several other major tasks including: (1) the development of a 6DOF Reentry Program that accepts the effects of ablation as a function of reentry angle (or heat pulse altitude interval), Reference 5, and (2) the development of a six-component aerodynamic data set, generated from the hypersonic aerodynamic test results on ablation effects (Reference 3). The results presented herein were generated with this 6DOF Reentry Program described in References 5 and 6.

OBJECTIVES

It is the objective of this study to investigate, using the JHU/APL 6DOF Reentry Program, the effects of ablation on reentry motion of the GPHS module and the effect of initial pitch and roll rate of an ablating module.

DISCUSSION

A. Initial Conditions

The 6DOF Reentry Program was developed to allow for varying aerodynamic characteristics and mass properties thus permitting investigation of the effects of ablation, References 5 and 6. This was done by programming a linear variation with an altitude parameter, H_5 , of the aerodynamic coefficients, C_x , and mass properties, Reference 5. The parameter H_5 is the altitude at the end of the heat pulse given in Figure 1. The value of H_5 is primarily dependent on γ_0 and only weakly dependent on the initial altitude H_0 . The initial altitude is taken from the breakup altitude - γ_0 charts for various entry velocities, V_0 , as generated by JPL. The most likely entry velocity of 46720 ft/s was selected for the JHU/APL thermal studies. For this value of V_0 , D. W. Conn developed, Reference 7, from the JPL results the $H_0 - \gamma_0$ charts of Figure 2 - which were used in the thermal studies for LWRHU and GPHS and are used here for consistency. To recap, for these studies, the initial velocity for all cases is 46720 ft/s; the $H_0 - \gamma_0$ relation is given in Figure 2; and, the aerodynamic coefficients and mass properties are linearized between H_0 and H_5 (Figure 1) for ablation effects according to Reference 5.

Comparison will be made with the General Electric 6DOF simulations, but it should be noted that GE/AS used $V_0 = 49000$ ft/s instead of 46720 ft/s in their analyses.

B. Geometry

The initial geometry is, of course, the baseline configuration, Figure 3. The aerodynamics of the ablated body were taken from test configurations patterned after a GPHS module intentionally ablated completely on the broadface, Reference 4, as shown in Figure 4. No ablation data are available for other orientations thus the ablation effects are crude approximations.

Figure 5 shows the body axis system used in the simulation.

C. General Trajectory Parameters

For reference, altitude and Mach number histories are given for the VEEGA trajectories in Figures 6 and 7 for $\gamma_0 = -7^\circ$ and in Figures 8 and 9 for $\gamma_0 = -90^\circ$. For a given angle of attack, the effect of initial rates on these parameters and on deceleration is minimal. The deceleration history is given in Figure 10 and the dynamic pressure history is given in Figure 11 for reference. Note that the rise in dynamic pressure is significant following breakup conditions until about 100K feet have been traversed. This corresponds to an altitude of approximately 240K feet for $\gamma_0 = -7^\circ$ and 180K feet for $\gamma_0 = -90^\circ$. This dynamic pressure profile reflects itself in the aerodynamic forces as will be noted later in the behavior of angle of attack and roll rate. Note that $g_{\max}$ is ≈ 560 g's for $\gamma_0 = -90^\circ$ and $\alpha_0 = 0$.

D. Evaluation of Computations

1. General

The workability of the newly developed 6DOF reentry computer program, TMAGRA6C, used in these studies was evaluated by comparing results from check runs against other 6DOF programs. Specifically, results from check runs with the baseline configuration were compared against those from the APL base program TMAGRA6B for non-ablating configurations and with the results from the 6DOF Reentry program of General Electric/Reentry Systems. The results from the non-ablating TMAGRA6C program agreed well with those from the APL TMAGRA6B program. There was also good agreement with G.E.'s result in a sufficient number of cases to warrant confidence in the JHU/APL TMAGRA6C workability and validity. Whereas G.E.'s hypersonic data set is essentially the same as APL's, the codes may have important internal differences. It is also not clear whether yaw damping is included in G.E.'s simulation. Also, we do not have adequate identification for the G.E. test cases. With these qualifications, the following comparisons which demonstrate the general agreement among programs are documented herein for completeness.

2. Comparison with APL TMAGRA6B Program and with G.E. Program

The two principal parameters of interest in these simulations (and therefore in these comparisons) are angle of attack and roll rate. The angle of attack history provides useful information for thermal analysis on the expected module attitude.

a. $\gamma_0 = -7^\circ$; $\alpha_0 = 0$

The results of the α - history for $\gamma_0 = -7^\circ$, $\alpha_0 = 0$, are given in Figures 12 and 13 from the APL "new" (-C) and "old" (-B) programs and in Figure 14 from the G.E. program. Note that the G. E. initial conditions for γ and V are slightly different from the APL values. The heat pulse for $\gamma_0 = -7^\circ$ and $V_0 = 46720$ ft/s extends from $H_0 = 348K$ ft to $160K$ ft (Figure 1) - approximately 100 seconds. Note from Figures 12 and 13 that $\alpha = \alpha_0 = 0$ for about the first 20 secs (H at 20 sec $\approx 270K$ ft) then oscillates about 10° . In the G.E. simulation however, Figure 14, the GPHS flips to $\alpha = 90^\circ \pm 50^\circ$ at $t \approx 35$ s. The roll rate from the APL -C and -B Programs is less than $400^\circ/s$, Figures 15 and 16. The G.E. results show a much higher roll rate ($2500^\circ/s$), Figure 17, which builds up beginning at $t = 20$ secs. with an accompanying increase in α . The effect of this large roll rate on α_R was thus investigated with the APL simulation. The results are discussed later.

b. $\gamma_0 = -90^\circ$; $\alpha_0 = 0$

For steep entry, $\alpha_0 = 0$ persists to the end of the heat pulse ($t \approx 4.5$ s, $H \approx 90$ K ft), Figures 18 and 19; the G.E. results, Figure 20, show the same results. The roll rate remains less than $\approx 200^\circ/s$.

c. $\gamma_0 = -90^\circ$; $\alpha_0 = 90^\circ$

The APL results for α_R , Figure 21, show a rapid rotation to a constant value of $\alpha_R \approx 5^\circ$. The G.E. results, Figure 22, also show a rapid rotation to about 35° in α_R within the first second but tumbling instead of damping follows this.

d. Orbital and Super Orbital Entries

G.E. reported on motion studies for three GPHS entry conditions involving orbital and super orbital entry, Reference 8. These conditions are given in Table 1. These conditions were run using the APL 6DOF simulation with the baseline configuration for comparison. The Mach number and altitude histories are given in Figures 23 and 24 for the super-orbital trajectory (Case 1) and in Figures 25 and 26 for the orbital decay trajectories. The APL and G.E. results for angle of attack and roll rate are given in Figures 27 to 38.

The approximate end of the convective heat pulse for the orbital, super-orbital, and VEEGA entries are given in Table 2 as deduced from APL and G.E. results. Note that the altitude and times at the "end" of this interval

correspond approximately to the Mach 5 condition. This was also noted in the LWRHU reentry analysis, Reference 9. The Mach 5 altitude-time conditions for a $\gamma = -50^\circ$ entry are also given in Table 2 for reference.

For Case 1, super-orbital case, both the APL and G.E. angle of attack, α_R , histories show damping from $\alpha_R = 24^\circ$ to $\alpha_R \leq 5^\circ$ by the end of the heat pulse altitude, H5 (Figures 27 and 29); the G.E. roll rate increases to $10000^\circ/\text{s}$ in this interval (Figure 30) whereas the APL results show a minor increase $\pm 400^\circ/\text{s}$ (Figure 28).

For the orbital decay entry, both APL and G.E. show that when $\alpha_0 = 0$, case 2, α remains small for most of the heat pulse interval and roll rate remains small, Figures 31-34. When $\alpha_0 = 90^\circ$, case 3, both APL and G.E. show α remaining at near 90° and the roll rate becoming large (Figures 35-38).

In general, the results from the APL reentry programs and the APL and G.E. results are in good qualitative and/or quantitative agreement.

RESULTS

A. General

The results of the 6DOF motion studies for selected VEEGA trajectory reentries are presented in Figures 39 to 106. The histories of the resultant angle-of-attack, α_R , and roll rate, p , are the primary orientation parameters addressed.

An attempt is made in Figures 107 to 110 to summarize the history of angle-of-attack and roll rate for the four initial orientations investigated, viz:

$$\begin{aligned}\gamma_0 &= -7^\circ, \alpha_{R_0} = 0^\circ; \\ \gamma_0 &= -7^\circ, \alpha_{R_0} = 90^\circ; \\ \gamma_0 &= -90^\circ, \alpha_{R_0} = 0^\circ; \text{ and,} \\ \gamma_0 &= -90^\circ; \alpha_{R_0} = 90^\circ.\end{aligned}$$

This very cursory summary gives (along with initial conditions) rough averages of the varying angle-of-attack along with approximate deviations. Where averages do not characterize the history over the entire heat pulse interval, the charts of Figures 107-110 give the approximate state for the first period prior to the rise in dynamic pressure and the state of the second period.

From these summaries and within the limits of the study, specifically in scope, the following deduction is made:

Four idealized attitudes seem to predominate, and pending additional studies, these are recommended for thermal and thermo-structural modelling and analysis, viz:

- a. $\alpha_R = 0^\circ$ (broadside stable),
- b. $\alpha_R = 30^\circ$,
- c. $\alpha_R = 90^\circ$,
- and d. tumbling.

The histories of the motion shown in Figures 39 to 106 are necessary to qualify the summary. Therefore a more detailed discussion of these histories is given in the remainder of this section for completeness.

B. Effect of Ablation

The present APL 6DOF Reentry program TMAGRA6C was configured to allow computations for both the unablated and ablating body, Reference 6. This is done by setting the altitude parameters $H_5 > H_0$ in the former case and $H_5 < H_0$ in the latter case.

The effect of windward face ablation on the trajectory parameters and entry motion of the GPHS module was found to be small. Some examples of these results are given in this section. The effect on deceleration is demonstrated in Figures 39 and 40 to be insignificant.

1. $p_0 = q_0 = r_0 = 0$

For zero initial motion, when $\alpha_{R0} = 0$, the angle of attack remains at or near zero for both baseline and ablating bodies at $\gamma_0 = -7^\circ$ and -90° . When $\alpha_{R0} = 90^\circ$, α damps out continuously to $\alpha \approx 5^\circ$ at H_5 . The roll rate is less than $2000^\circ/\text{s}$. The values $p_0 = q_0 = r_0 = 0$ are considered to be unlikely conditions following spacecraft breakup.

2. $p_0 = q_0 = 1000^\circ/\text{s}; \alpha_0 = 0^\circ$

A more likely set of initial conditions is one that has initial motion in at least two planes. For the initial conditions indicated, the GPHS generally oscillates about $\alpha \approx 30^\circ$ for both baseline and ablating body at $\gamma_0 = -7^\circ$ and -90° , Figures 41 and 42. For the ablating body at $\gamma = -90^\circ$, however, α damps out to $\alpha \approx 5^\circ$ beginning with the rise in dynamic pressure. At $\gamma_0 = -90^\circ$, the roll rate decreases from a maximum of $5000^\circ/\text{s}$ to $2000^\circ/\text{s}$ mostly as a result of the decrease in α , Figures 43 and 44. At $\gamma_0 = -7^\circ$, the roll rate actually increases due to ablation, compare Figures 45 and 46. This is in consonance with the aerodynamic effects discussed in Reference 3 wherein an induced rolling moment coefficient, C_l actually occurred in the region of $\alpha_R \geq 30^\circ$ for the ablated body when the roll angle was 90° .

In either case, however, the roll rate is small as far as inertial loads are concerned (but not as far as cross coupling with α_R as will be seen later).

The remainder of this presentation treats only the ablating body.

C. Effects of Pitch Rate; $p_0 = r_0 = 0$ (Figures 47-66)

1. $\gamma_0 = -7^\circ$, $\alpha_{R0} = 0$

For small initial pitch rates, $q \leq 100^\circ/\text{s}$, the GPHS generally assumes an average angle of attack of less than about 30° , Figures 47 and 49. The roll rate increases with increase in initial pitch rate, Figures 48, 50, 52, so that at a modest initial pitch rate of $250^\circ/\text{s}$ the roll rate assumes a value of approximately $20000^\circ/\text{s}$ by the end of the heat pulse, Figure 52. This results in the GPHS "trimming" side-on ($\alpha_R = 90^\circ \pm 30^\circ$), Figure 51, during the latter half of the heat pulse and tumbling before that. An increase in pitch rate to $1000^\circ/\text{s}$ results in tumbling for most of the heat pulse, Figure 54.

2. $\gamma_0 = -7^\circ$; $\alpha_0 = 90^\circ$

When $\alpha_0 = 90^\circ$ in shallow entry, $\gamma_0 = -7^\circ$, the angle of attack damps out quickly to a small value when $p_0 = q_0 = r_0 = 0$ - averaging to $\alpha_R \leq 10^\circ$, Figure 55. But with a small initial pitching motion of $400^\circ/\text{s}$, Figure 56, the GPHS again tumbles for the first half of the heat pulse and assumes an attitude of $\alpha_R \approx 80^\circ \pm 30^\circ$ thereafter.

3. $\gamma_0 = -90^\circ$; $\alpha_{R0} = 0^\circ$

For steep reentry, small values of α_R (less than $\alpha_R \approx 15^\circ$) persist throughout the heat pulse when the initial pitching rate is $\leq 400^\circ/\text{s}$, Figures 57 to 60. Even at larger pitch rates of $700^\circ/\text{s}$, α_R damps out gradually to $\alpha_R \approx 5^\circ$ at the end of the heat pulse following an initial rapid increase to 90° , Figure 61. When initial pitch rate is increased to $1000^\circ/\text{s}$, Figure 62, the GPHS initially tumbles followed by a gradual damping; but the average α_R during the heat pulse is large.

The roll rate in all of these cases is less than $2000^\circ/\text{s}$.

4. $\gamma_0 = -90^\circ$, $\alpha_{R0} = 90^\circ$

When $\alpha_{R0} = 90^\circ$ for a steep reentry, and initial rates are zero, α_R dampens out gradually to $\alpha_R \approx 5^\circ$, Figure 63. The history of α_R is similar to that obtained when $\alpha_{R0} = 0$ and $q_0 = 700^\circ/\text{s}$; compare with Figure 61. If $q_0 = 700^\circ/\text{s}$ for the present case, Figure 65, α_R again damps out to $\alpha_R \approx 10^\circ \pm 5^\circ$ although the average value of α_R is $\approx 30^\circ$. Even when $q_0 = 1000^\circ/\text{s}$, Figure 66, α_R damps out to a small value following the rise in dynamic pressure.

The maximum roll rate is less than about $3000^\circ/\text{s}$ for all these cases.

D. Effect of Roll Rate (Figures 67-84)

1. $\gamma_0 = -7^\circ$, $\alpha_{R0} = 0^\circ$

For initial roll rates equal to or less than $400^\circ/\text{s}$, α_R remains small ($\alpha_R < 10^\circ$) when $\alpha_{R0} = 0$, Figures 67 through 69. For an intermediate roll rate of

700°/s, α_R increases to $\approx 70^\circ \pm 40^\circ$ (Figure 70) and the roll rate reverses and reaches $\approx -4000^\circ/\text{s}$ by $H = 145\text{K ft.}$ When $p_o = 1000^\circ/\text{s}$, α_R builds up continuously reaching about $80^\circ \pm 25$ near the end of the heat pulse, Figure 71. The roll rate for initial values of 0° and 400° remain under $500^\circ/\text{s}$ but for $p_o = 1000^\circ$, it builds up to $17000^\circ/\text{s}$ by the end of the heat pulse, Figure 72.

A large value of initial roll rate of $2500^\circ/\text{s}$ was also investigated (for the baseline GPHS) because the G.E. case for $\gamma_o = -7^\circ$, $\alpha_{Ro} = 0$ showed disagreement with the APL results in the α - history, see D.2.a under DISCUSSION Section. The G.E. results also showed a large roll rate whereas the APL results did not. When $p_o = 2500^\circ/\text{s}$, the angle of attack and its envelope build up quickly to approximately $35^\circ \pm 35^\circ$, Figure 73, and the roll rate builds up, Figure 74, as was the case for $p_o = 1000^\circ/\text{s}$, Figure 72. It is not inconsistent that differences in the α -H history exist for the G.E. case and the two APL cases since the value of $\alpha \sim [1 - (p/\omega)^2]^{-1/2}$ where $\omega = [(\partial C_m / \partial \alpha) q S L / I_y]^{1/2}$. Thus ω is configuration dependent (including angle of attack) as well as altitude - Mach number dependent.

$$2. \gamma_o = -7^\circ, \alpha_{Ro} = 90^\circ$$

The angle of attack history for zero roll rate was presented in Figure 55. It showed that α damps out quickly to small values. When $p_o = 400^\circ/\text{s}$, α remains at an average value near $\alpha_o = 90^\circ$ throughout the heat pulse, Figure 75.

$$3. \gamma_o = -90^\circ, \alpha_o = 0$$

For the steep entry, when $\alpha_o = 0$ this attitude persists for $p_o = 0$ and $1000^\circ/\text{s}$ when there is no initial pitching motion, Figures 76 and 77.

$$4. \gamma_o = -90^\circ, \alpha_o = 90^\circ$$

When $\alpha_{Ro} = 90^\circ$, there is gradual damping during the heat pulse to $\alpha_R \approx 5^\circ$ when $p_o \leq 250^\circ/\text{s}$, Figures 78, 79, and 80. When $p_o \geq 400^\circ/\text{s}$, α_R persists at angles near α_{Ro} , i.e. 90° , and roll rate increases, Figures 82 through 84. At initial roll rates of $1000^\circ/\text{s}$, the roll rate reaches $25000^\circ/\text{s}$ by the end of the heat pulse ($h = 90000 \text{ ft.}$), Figure 84, and continues. At the end of this run the Mach number was still high ($M \approx 7$) and the roll rate had increased to $p = 55000^\circ/\text{s}$.

E. Effect of Combined Initial Pitch and Roll Rates (Figures 85-106)

For simplicity, assessment of the combined pitch and roll rates was made using the same initial values for both rates. The general result derived from combinations ranging from $p_o = q_o = 0$ to $p_o = q_o = 1000^\circ/\text{s}$ is that the angle of attack during the heat pulse ranges from 5° to 30° when the initial value of angle of attack is zero and when $p_o = q_o > 0$. When $\alpha_{Ro} = 90^\circ$, the GPHS generally persists with the narrow side to the wind when $p_o = q_o \geq 500^\circ/\text{s}$.

1. $\gamma_0 = -7^\circ$, $\alpha_{R0} = 0^\circ$

The results for these initial conditions are given in Figures 85 through 89. For $p_0 = q_0 = 0$, α_R goes to approximately $\alpha_R = 5^\circ \pm 5^\circ$, Figure 85. When $p_0 = q_0 = 400^\circ/\text{s}$ (≈ 1 cycle/sec), Figure 86, $\alpha_R = 30^\circ \pm 30^\circ$, except for a momentary large excursion in α beginning at the start of dynamic pressure buildup. The roll rate reversed at approximately this time. The roll rate again reverses during this excursion in α then increases rapidly reaching $8500^\circ/\text{s}$ by the end of the heat pulse, Figure 87. At $p_0 = q_0 = 1000^\circ/\text{s}$, $\alpha_R = 30^\circ \pm 30^\circ$ and roll rate increases to $8500^\circ/\text{s}$ as before, Figures 88 and 89.

2. $\gamma_0 = -7^\circ$, $\alpha_{R0} = 90^\circ$ (Figures 90 through 95)

When $p_0 = q_0 = 0^\circ$, the angle of attack damps out quickly to a small value, $\alpha_R \leq 10^\circ$ average, Figure 90. When $p_0 = q_0 = 100^\circ/\text{s}$ and $500^\circ/\text{s}$, Figures 91 and 94, $\alpha_R = \alpha_{R0} = 90^\circ$ for the first half of the heat pulse then assumes a value of $30^\circ \pm 30^\circ$ for the latter half of the heat pulse. The characteristics of both the α history and roll rate history for these cases are the same as was discussed for $\gamma_0 = -7^\circ$, $\alpha_0 = 0$ and $p_0 = q_0 = 400^\circ/\text{s}$ (Figures 86 and 87). When $p_0 = q_0 = 250^\circ/\text{s}$ (Figure 92) or $1000^\circ/\text{s}$ (Figure 95), α remains near $\alpha_0 = 90^\circ$ with approximately $\pm 30^\circ$ excursions.

3. $\gamma_0 = -90^\circ$, $\alpha_{R0} = 0^\circ$

When $\gamma_0 = -90^\circ$, α_R ranges between 0° at $p_0 = q_0 = 0$ to an average of $\approx 15^\circ$ at $p_0 = q_0 = 1000^\circ/\text{s}$, Figures 96 to 100.

4. $\gamma_0 = 90^\circ$, $\alpha_{R0} = 90^\circ$ (Figures 101 through 106)

When $p_0 = q_0 = 0$ and $250^\circ/\text{s}$, α_R damps out gradually to $\alpha_R \approx 5^\circ \pm 5^\circ$ averaging about 20° . The character of the α history at $p_0 = q_0 = 250^\circ/\text{s}$ for steep entry differs considerably from that at shallow entry where α remained near $\alpha_0 = 90^\circ$ (see Figure 92). At $p_0 = q_0 = 500^\circ/\text{s}$, α_R remains at $\alpha \approx 90^\circ$ with accompanying large roll rates, Figures 103 through 106.

F. Reacting Forces from Accelerations

In the steep entry, the deceleration of the GPHS reaches 560 g's , Figure 10. The load associated with this deceleration is $F_x = (3.19)(560) = 1786 \text{ lbs.}$ and the unit load is 127 lbs/in^2 . John Ecker has previously examined the significance of this on the thermostructural integrity of GPHS. Briefly, he has found that by itself the load would not cause failure but the tensile and compressive margin of safety decreases when the deceleration load is combined with the thermal load.

The forces resulting from the large roll rates achieved for various reentry conditions as discussed herein were also examined. Of specific interest are the forces on the GPHS caps that contain the GIS's. In the 20MW and 60MW tests,

the GPHS shape that results after complete front face ablation had the GIS caps intact and thus contained the GIS's. Several of the reentry cases examined herein achieved roll rates of about 20000°/s during the heat pulse. This translates to approximately a lateral force of 30 pounds on the GIS cap. (For FWPF, this translates into 1.15 lb force per gram weight). Since roll rate was still increasing in some of these cases, forces larger than 30 lbs should be assumed in examining the structural integrity of the caps. For the case discussed in Section D.4 a roll rate of 55000°/s was obtained in the hypersonic range (albeit beyond the heat pulse). This represents a load on the GIS cap of 188 pounds.

CONCLUSIONS AND RECOMMENDATIONS

1. The most probable average GPHS reentry angles of attack indicated by the present analyses are $\alpha_R = 0^\circ$ (broadside to the wind), $\alpha_R = 30^\circ$, $\alpha_R = 90^\circ$ and tumbling. Sufficient analyses have not been conducted to quote a statistical distribution for these orientations. They should be tentatively considered equally likely.
2. Large roll rates are achieved under certain assumed initial pitch and/or roll rates which translate into lateral accelerations of over 30 g's at the GIS caps. Both the realism of the assumptions for initial conditions and the structural integrity of the GPHS components under this type of loading needs to be assessed.
3. Both additional reentry simulations and information on probabilities on the initial rates at spacecraft breakup are needed to refine the results of the present study. JPL should provide their estimate of the most likely rates of the GPHS at initial reentry conditions.
4. The present analyses addressed only the extremes in reentry angle and angle of attack, i.e. 0° and $|90^\circ|$. Simulations will be conducted pending JPL's input using intermediate values of reentry angle and angle of attack.
5. These analyses are based on estimated damping characteristics at hypersonic speeds. A more accurate determination of the reentry attitude could be obtained if test data on the hypersonic damping would be obtained. The effort and cost to conduct such a program, reduce the test data, and formulate data sets for a 6DOF reentry motion investigation is not trivial. We will pursue such a program if the sponsor, DoE, so desires. In the meantime, the present simulation will be modified to permit a facile change in the magnitude and direction of damping. This will permit parametric investigations of the effect of damping on motion.

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Table 1

GPHS Re-entry Conditions (G.E. Analyses)

		1	2	3
Altitude	(Kft)	264	292	292
Velocity	(ft/sec)	36111	24073	24073
Path Angle	(deg)	-38.78	-0.338	-0.338
Roll rate, p	(deg/sec)	0	0	0
Pitch rate, q	(deg/sec)	130	0	0
Yaw rate, r	(deg/sec)	0	0	0
Total Angle of Attack	(deg)	24	0	90

Table 2

Approximate End of Convective Heat Pulse

Initial Conditions			Approximate Time and Altitude at End of Heat Pulse		
γ_o	V_o	H_o	t5	H5	
deg	Kft/sec	Kft	secs	Kft	
VEEGA					
-7	46.7	348	55	160*	APL
-5.5	45.7	312	80	130	G.E.
-50	46.7	280	9	97	APL
-90	46.7	264	4.2	90	APL
-90	49.3	263	6	70	G.E.
ORBITAL DECAY					
-0.79	25.1	270	210	113	APL
-0.34	24.1	292	250	110	G.E.
SUPERORBITAL ENTRY					
-38.8	36.1	264	10	90	G.E.

* 145 feet used to interpolate for aero coefficients in present simulations. The difference in incremental drag and motion is negligible.

Fig. 1 Altitude H5 representing End of Heat Pulse — Input to 6 DOF TMAGRA6C

Fig. 2 Variation of initial altitude versus flight path angle for the maximum and expected initial velocities for discrete GPHS module reentries; Galileo-VEEGA mission profile.

Fig. 3 Sketch of GPHS module.

Figure 4a

GPHS models for $M = 10$ aerodynamic tests.

Figure 4b Comparison of Cast Model and FWPF Ablated Module

Fig. 5 Model-fixed axis system.

Fig.6 Altitude History,VEEGA Shallow GPHS Reentry,Unablated Body

Fig.7 Mach Number History,VEEGA Shallow GPHS Reentry,Unablated Body

Fig.8 Altitude History,VEEGA Shallow GPHS Reentry,Unablated Body

Fig.9 Altitude History,VEEGA Shallow GPHS Reentry,Unabladed Body

Fig.10 Acceleration Along Flight Path

$$\gamma = -90^\circ$$

$$\gamma = -7^\circ$$

Fig.11 Dynamic Pressure History

Fig.12 VEEGA Shallow GPHS Reentry, Unablated Body (APL TMAGRA6C)

Fig. 13 APL TMAGRA6B Simulation: $H_0 = 348K$ ft;
 $V_0 = 46720$ fps; $\gamma_0 = -7^\circ$; $\alpha_0 = 0^\circ$

Fig. 14 G.E. Simulation: $H_0 = 312K$ ft;
 $V_0 = 45700$ fps; $\gamma_0 = -5.5^\circ$; $\alpha_0 = 0^\circ$

RUN07

Fig.15 VEEGA Shallow GPHS Reentry, Unabladed Body (APL TMAGRA6C)

Fig. 16 APL TMAGRA6B Simulation: $H_0 = 348K$ ft;
 $V_0 = 46720$ fps; $\gamma_0 = -7^\circ$; $\alpha_0 = 0^\circ$

Fig. 17 G.E. Simulation: $H_0 = 312K$ ft;
 $V_0 = 45700$ fps; $\gamma_0 = -5.5^\circ$, $\alpha_0 = 0^\circ$

RUN07

Fig.18 VEEGA Steep GPHS Reentry, Unabladed Body (APL TMAGRA6C)

Fig. 19 APL TMAGRA6B Simulation: $H_0 = 264K$ ft;
 $V_0 = 46720$ fps; $\gamma_0 = -90^\circ$; $\alpha_0 = 0^\circ$

FLIGHT
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Fig. 20 G.E. Simulation: $H_0 = 263K$ ft;
 $V_0 = 49300$ fps; $\gamma_0 = -90^\circ$; $\alpha_0 = 0^\circ$

Fig.21 VEEGA Steep GPHS Reentry, Ablating Body (APL TMAGRA6C)

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A5

Fig. 22 G.E. Simulation: $H_0 = 263K$ ft;

$V = 10300$ fpm; $\gamma = 00.0^\circ - 00^\circ$

Fig. 23 APL Simulation of G.E. Case 1, Super-Orbital Entry,
 $H_0 = 264K$ ft; $V_0 = 36100$ fps ; $\gamma_0 = -38.8^\circ$; $\alpha_0 = 24^\circ$

Fig. 24 APL Simulation of G.E. Case 1, Super-Orbital Entry,
 $H_0 = 264K$ ft; $V_0 = 36100$ fps; $\gamma_0 = -38.8^\circ$; $\alpha_0 = 24^\circ$

Fig. 25 APL Simulation of G.E. Case 2, Orbital Decay,
 $H_0 = 292K \text{ ft}$; $V_0 = 24100 \text{ fps}$; $\gamma_0 = -0.34^\circ$; $\alpha_0 = 24.1^\circ$

Fig. 26 APL Simulation of G.E. Case 2, Orbital Decay,
 $H_0 = 292K \text{ ft}$; $V_0 = 24100 \text{ fps}$; $\gamma_0 = -0.34^\circ$; $\alpha_0 = 24.1^\circ$

Fig. 27 APL Simulation of G.E. Case 1

Fig. 28 APL Simulation of G.E. Case 1

R50

Steep Re-entry, $\delta = 24^\circ$
NASA(Hypersonic)/APL(Subsonic) Aerodynamics
GE Inertia's
Shifted Model 5 CI

Fig. 29 G.E. Simulation of Case 1

RSO

1
Sleep Re-entry, $\delta = 24^\circ$
NASA(Hypersonic)/APL(Subsonic) Aerodynamics
GE Inertia's
Shifted Model 5 C1

Fig. 31 APL Simulation of G.E. Case 2

Fig. 32 APL Simulation of G.E. Case 2

R50

Orbital Decay Re-entry, $\delta = 0^\circ$
NASA(Hypersonic)/APL(Subsonic) Aerodynamics
GE Inertia's
Shifted Model 5 C1

Fig. 33 G.E. Simulation of Case 2

R50

Orbital Decay Re-entry, $\delta = 0^\circ$
NASA(Hypersonic)/APL(Subsonic) Aerodynamics
GE Inertia's
Shifted Model 5 C1

Fig. 35 APL Simulation of G.E. Case 3, Orbital Decay,
 $H_0 = 292K \text{ ft}$; $V_0 = 24100 \text{ fps}$; $\gamma_0 = -0.34^\circ$; $\alpha_0 = 90.0^\circ$

Fig. 36 APL Simulation of G.E. Case 3

R50

Orbital Decay Re-entry, $\delta = 90^\circ$
NASA(Hypersonic)/APL(Subsonic) Aerodynamics
GE Inertia's
Shifted Model 6 Cl

Fig. 37 G.E. Simulation of Case 3

RSO

Orbital Decay Re-entry, $\delta = 90^\circ$
NASA(Hypersonic)/APL(Subsonic) Aerodynamics
GE Inertia's
Shifted Model 6 Cl

Fig. 38 G.E. Simulation of Case 3

Fig. 39 Effect of Broadface Ablation on Acceleration, $\gamma_0 = -7^\circ$

Fig. 40 Effect of Broadface Ablation on Acceleration, $\gamma_0 = -90^\circ$

Fig. 41 Effect of Ablation on Angle of Attack History

Baseline Model

Initial Conditions
 Altitude = 348000 Feet
 Flight Path Angle = -7 Deg
 Angle of Attack = 0 Deg
 Velocity = 46720 Ft/Sec
 Roll Rate = 1000 Deg/Sec
 Pitch Rate = 1000 Deg/Sec
 Yaw Rate = 0 Deg/Sec

Ablating Model

Initial Conditions
 Altitude = 348000 Feet
 Flight Path Angle = -7 Deg
 Angle of Attack = 0 Deg
 Velocity = 46720 Ft/Sec
 Roll Rate = 1000 Deg/Sec
 Pitch Rate = 1000 Deg/Sec
 Yaw Rate = 0 Deg/Sec

Fig. 42 Effect of Ablation on Angle of Attack History

Baseline Model

Ablating Model

Fig. 43 VEEGA Steep GPHS Reentry, Unablated Body

Fig. 44 VEEGA Steep GPHS Reentry, Ablating Body

Fig. 45 VEEGA Shallow GPHS Reentry, Unablated Body

Fig. 46 VEEGA Shallow GPHS Reentry, Ablating Body

Fig. 47 Effect of Pitch Rate, VEEGA Shallow GPHS Reentry, Ablating Body

Fig. 4B Effect of Pitch Rate VEEGA Shallow GPHS Reentry, Ablating Body

Fig. 49 Effect of Pitch Rate, VEEGA Shallow GPHS Reentry, Ablating Body

Fig. 50 Effect of Pitch Rate, VEEGA Shallow GPHS Reentry, Ablating Body

Fig. 51 Effect of Pitch Rate, VEEGA Steep GPHS Reentry, Ablating Body

Fig. 52 Effect of Pitch Rate, VEEGA Steep GPHS Reentry, Ablating Body

Fig. 53 Effect of Pitch Rate, VEEGA Steep GPHS Reentry, Ablating Body

Fig. 54 Effect of Pitch Rate, VEEGA Steep GPHS Reentry, Ablating Body

Fig. 55 Effect of Pitch Rate, VEEGA Shallow GPHS Reentry, Ablating Body

Fig. 56 Effect of Pitch Rate, VEEGA Shallow GPHS Reentry, Ablating Body

Fig. 57 Effect of Pitch Rate, VEEGA Steep GPHS Reentry, Ablating Body

Fig. 5B Effect of Pitch Rate, VEEGA Steep GPHS Reentry, Ablating Body

Fig. 59 Effect of Pitch Rate, VEEGA Steep GPHS Reentry, Ablating Body

Fig. 60 Effect of Pitch Rate, VEEGA Steep GPHS Reentry, Ablating Body

Fig. 61 Effect of Pitch Rate, VEEGA Steep GPHS Reentry, Ablating Body

Fig. 62 Effect of Pitch Rate, VEEGA Steep GPHS Reentry, Ablating Body

Fig. 63 Effect of Pitch Rate, VEEGA Steep GPHS Reentry, Ablating Body

Fig. 64 Effect of Pitch Rate, VEEGA Steep GPHS Reentry, Ablating Body

Fig. 65 Effect of Pitch Rate, VEEGA Steep GPHS Reentry, Ablating Body

Fig. 66 Effect of Pitch Rate, VEEGA Steep GPHS Reentry, Ablating Body

Fig. 67 Effect of Roll Rate, VEEGA Shallow GPHS Reentry, Ablating Body

Fig. 6B Effect of Roll Rate, VEEGA Shallow GPHS Reentry, Ablating Body

Fig. 69 Effect of Roll Rate, VEEGA Shallow GPHS Reentry, Ablating Body

Fig. 70 Effect of Roll Rate, VEEGA Shallow GPHS Reentry, Ablating Body

Fig. 71 Effect of Roll Rate, VEEGA Shallow GPHS Reentry, Ablating Body

Fig. 72 Effect of Roll Rate, VEEGA Shallow GPHS Reentry, Ablating Body

Fig. 73 Effect of Roll Rate, VEEGA Steep GPHS Reentry, Ablating Body

Fig. 74 Effect of Roll Rate, VEEGA Steep GPHS Reentry, Ablating Body

Fig. 75 Effect of Roll Rate, VEEGA Shallow GPHS Reentry, Ablating Body

Fig. 76 Effect of Roll Rate, VEEGA Steep GPHS Reentry, Ablating Body

Fig. 77 Effect of Roll Rate, VEEGA Steep GPHS Reentry, Ablating Body

Fig. 7B Effect of Roll Rate, VEEGA Steep GPHS Reentry, Ablating Body

Fig. 79 Effect of Roll Rate, VEEGA Steep GPHS Reentry, Ablating Body

Fig. 80 Effect of Roll Rate, VEEGA Steep GPHS Reentry, Ablating Body

Fig. B1 Effect of Roll Rate, VEEGA Steep GPHS Reentry, Ablating Body

Fig. B2 Effect of Roll Rate, VEEGA Steep GPHS Reentry, Ablating Body

Fig. 83 Effect of Roll Rate, VEEGA Steep GPHS Reentry, Ablating Body

Fig. B4 Effect of Roll Rate, VEEGA Steep GPHS Reentry, Ablating Body

Fig. B5 Effect of Combined Pitch and Roll Rate,
VEEGA Shallow GPHS Reentry, Ablating Body

Fig. 86 Effect of Combined Pitch and Roll Rate,
VEEGA Steep GPHS Reentry, Ablating Body

Fig. B7 Effect of Combined Pitch and Roll Rate,
VEEGA Steep GPHS Reentry, Ablating Body

Fig. 88 Effect of Combined Pitch and Roll Rate,
VEEGA Shallow GPHS Reentry, Ablating Body

Fig. 89 Effect of Combined Pitch and Roll Rate,
VEEGA Shallow GPHS Reentry, Ablating Body

Fig. 90 Effect of Combined Pitch and Roll Rate,
VEEGA Shallow GPHS Reentry, Ablating Body

Fig. 91 Effect of Combined Pitch and Roll Rate,
VEEGA Shallow GPHS Reentry, Ablating Body

Fig. 92 Effect of Combined Pitch and Roll Rate,
VEEGA Shallow GPHS Reentry, Ablating Body

Initial Conditions
Altitude = 348000 Feet
Flight Path Angle = -7 Deg
Angle of Attack = 90 Deg
Velocity = 46720 Ft/Sec
Roll Rate = 250 Deg/Sec
Pitch Rate = 250 Deg/Sec
Yaw Rate = 0 Deg/Sec

Fig. 93 Effect of Combined Pitch and Roll Rate,
VEEGA Shallow GPHS Reentry, Ablating Body

Fig. 94 Effect of Combined Pitch and Roll Rate,
VEEGA Shallow GPHS Reentry, Ablating Body

Fig. 95 Effect of Combined Pitch and Roll Rate,
VEEGA Shallow GPHS Reentry, Ablating Body

Initial Conditions
Altitude = 348000 Feet
Flight Path Angle = -7 Deg
Angle of Attack = 90 Deg
Velocity = 46720 Ft/Sec
Roll Rate = 1000 Deg/Sec
Pitch Rate = 1000 Deg/Sec
Yaw Rate = 0 Deg/Sec

Fig. 96 Effect of Combined Pitch and Roll Rate,
VEEGA Steep GPHS Reentry, Ablating Body

Fig. 97 Effect of Combined Pitch and Roll Rate,
VEEGA Steep GPHS Reentry, Ablating Body

Fig. 9B Effect of Combined Pitch and Roll Rate,
VEEGA Steep GPHS Reentry, Ablating Body

Fig. 99 Effect of Combined Pitch and Roll Rate,
VEEGA Steep GPHS Reentry, Ablating Body

Fig. 100 Effect of Combined Pitch and Roll Rate,
VEEGA Steep GPHS Reentry, Ablating Body

Fig. 101 Effect of Combined Pitch and Roll Rate,
VEEGA Steep GPHS Reentry, Ablating Body

Fig. 102 Effect of Combined Pitch and Roll Rate,
VEEGA Steep GPHS Reentry, Ablating Body

Fig. 103 Effect of Combined Pitch and Roll Rate,
VEEGA Steep GPHS Reentry, Ablating Body

Fig. 104 Effect of Combined Pitch and Roll Rate,
VEEGA Steep GPHS Reentry, Ablating Body

Fig. 105 Effect of Combined Pitch and Roll Rate,
VEEGA Steep GPHS Reentry, Ablating Body

Fig. 106 Effect of Combined Pitch and Roll Rate,
VEEGA Steep GPHS Reentry, Ablating Body

Figure 107. Synopsis of α_R History and $p_{\max}$ (α/p) During the GPHS Heat Pulse

$$\gamma_0 = -7^\circ; \quad \alpha_{R_0} = 0^\circ$$

$p_0 \backslash q_0$	0	100	250	400	500	700	1000
0	^m $6^\circ \pm 6$	^a $40^\circ \pm 30^\circ$ 3800 °/s	^t $90^\circ \pm 30^\circ$ 19000 °/s	^t $90^\circ \pm 30^\circ$ 18000 °/s			^t 16000 °/s
100							
250	^m $10^\circ \pm 10^\circ$						
400	^m $8^\circ \pm 8^\circ$			^a $30^\circ \pm 30^\circ$ 8500 °/s			
500							
700	^m $80^\circ \pm 50^\circ$						
1000	^m $80^\circ \pm 30^\circ$ 17000 °/s						^a $30^\circ \pm 30^\circ$ 8500 °/s

a = Average

m = Maximum amplitude in first half of trajectory, $\alpha_R = \alpha_{R_0}$

t = Tumbling

Heat Pulse: 348 Kft to 145 Kft. (200K interval); $\bar{q}_{\max}$ at H = 170K ft.

Figure 108. Synopsis of α_R History and $p_{\max}$ (α/p) During the GPHS Heat Pulse

$$\gamma_0 = -7^\circ; \quad \alpha_{R_0} = 90^\circ$$

$p_0 \backslash q_0$	0	100	250	400	500	700	1000
0	^a $10^\circ \pm 10$			^t $80^\circ \pm 30^\circ$ 20000 °/s			
100		^m $30^\circ \pm 30^\circ$ 8000 °/s					
250			$80^\circ \pm 30^\circ$ 20000 °/s				
400	^m $80^\circ \pm 30^\circ$ 20000 °/s						
500					^m $30^\circ \pm 30^\circ$ 5000 °/s		
700							
1000							^m $90^\circ \pm 30^\circ$ 20000 °/s

a = Average

m = Maximum amplitude in first half of trajectory, $\alpha_R = \alpha_{R_0}$

t = Tumbling

Figure 109. Synopsis of α_R History and $p_{\max}$ (α/p) During the GPHS Heat Pulse

$$\gamma_0 = -90^\circ; \quad \alpha_{R_0} = 0^\circ$$

$p_0 \backslash q_0$	0	100	250	400	500	700	1000
0		^a $5^\circ \pm 5^\circ$	^a $9^\circ \pm 6^\circ$	^a $11^\circ \pm 5^\circ$		^a $25^\circ \pm 10^\circ$	^a $55^\circ \pm 20^\circ$
100		^a $5^\circ \pm 5^\circ$					
250							
400				^a $11^\circ \pm 5^\circ$			
500					^a $11^\circ \pm 11^\circ$		
700							
1000							^a $25^\circ \pm 10^\circ$

a = Average

Heat Pulse: 264 Kft to 90 Kft. (174 Kft interval); $\bar{q}_{\max}$ at H = 100K ft.

Figure 110. Synopsis of α_R History and p_{max} (α/p) During the GPHS Heat Pulse

$$\gamma_O = -90^\circ; \alpha_{R_O} = 90^\circ$$

$p_O \backslash q_O$	0	100	250	400	500	700	1000
0	^a $20^\circ \pm 10^\circ$			^a $25^\circ \pm 20^\circ$		^a $30^\circ \pm 20^\circ$	^a $35^\circ \pm 20^\circ$
100	^a $15^\circ \pm 5^\circ$						
250	^a $25^\circ \pm 5^\circ$		^a $20^\circ \pm 5^\circ$				
400	^m $80^\circ \pm 80^\circ$ 7000°/s						
500					$85^\circ \pm 40^\circ$ 20000 °/s		
700							
1000	$88^\circ \pm 10^\circ$ 25000 °/s						$90^\circ \pm 20^\circ$ 20000 °/s

a = Average

m = Maximum amplitude in first half of trajectory, $\alpha_R = \alpha_{R_O}$