JHU/APL
ANSP-M-24
DoE/NE/32170-24
December 1996

Enclosure (1) to: TL-97-033

RECEIVED
MAY 08 1998
OSTI

United States Department of Energy
19901 Germantown Road
Germantown, Md 20874-1290

Aerospace Nuclear Safety Program

REENTRY RESPONSE OF THE
LIGHTWEIGHT RADIOISOTOPE HEATER
UNIT RESULTING FROM A CASSINI
VENUS-VENUS-EARTH-JUPITER
GRAVITY ASSIST MANEUVER ACCIDENT

MASTER

DISTRIBUTION OF THIS DOCUMENT IS UNLIMITED *ph*

THE JOHNS HOPKINS UNIVERSITY - APPLIED PHYSICS LABORATORY
Johns Hopkins Road, Laurel, Maryland 20723-6099
Contract Number: N00024-97-C-8119; Task ACA

DISCLAIMER

This report was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor any agency thereof, nor any of their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof.

DISCLAIMER

**Portions of this document may be illegible
electronic image products. Images are
produced from the best available original
document.**

Applied Physics Laboratory
Laurel, Maryland 20723-6099

REENTRY RESPONSE
OF THE LIGHTWEIGHT RADIOISOTOPE HEATER UNIT
RESULTING FROM A CASSINI VENUS-VENUS-EARTH-JUPITER GRAVITY ASSIST
MANEUVER ACCIDENT

Sponsored by the United States Department of Energy
NE-50, 19901 Germantown Road
Germantown, MD 20874-1290

Approved by

Leah G. Everhart, Assistant Program Manager
Aerospace Nuclear Safety Program, JHU/APL

Eddie F. Lucero, Program Manager
Aerospace Nuclear Safety Program, JHU/APL

The Johns Hopkins University Applied Physics Laboratory
Johns Hopkins Road, Laurel, MD 20723-6099
Contract No. N00024-97-C-8119

Cassini/VVEJGA LWRHU Reentry Response Executive Summary

Reentry analyses consisting of ablation response, thermal response and thermal stress response have been conducted on the Lightweight Radioisotope Heater Unit (LWRHU) for Cassini/Venus-Earth-Jupiter-Gravity-Assist (VVEJGA) reentry conditions. Sequential ablation analyses of the LWRHU aeroshell, and the fuel pellet have been conducted in reentry regimes where the aeroshell has been deemed to fail. The failure criterion for ablation is generally assumed to be recession corresponding to 75% and 100% of the wall thickness. The 75% recession failure criteria allows for uncertainties that result mainly because of the high energies involved in the VVEJGA reentries compared to orbital decay reentries. Risk evaluations should consider the fact that for shallow flight paths the unit may disassemble at high-altitude as a result of ablation or may remain intact with a clad that had been molten.

Within the limitations of the methodologies and assumptions of the analyses, the results indicate that:

1. For a side-on stable LWRHU reentry, aeroshell ablation failures occur for all reentry angles. For the steep reentries, failure criteria are met shortly after the time of peak heating. For shallow reentry angles, failure occurs prior to the time of peak heating. In all cases, the fuel pellet containment would be released at altitudes greater than approximately 140,000 ft. For all cases, the released fuel pellet will melt, resulting in atmospheric source terms.

2. For a side-on spinning LWRHU reentry, aeroshell ablation failures are minimal. This orientation results in the least severe environment with only the capture angle, $\gamma = -5.2^\circ$, indicating aeroshell failure. Following aeroshell failure, the released fuel pellet melts. The reentries that indicate aeroshell survival through the hypersonic flight could show incremental ablation leading to failure during subsonic flight. Additionally, the $\gamma = -7^\circ$ reentry indicates the presence of melted clad and fuel within the aeroshell. Resolidification occurs following hypersonic flight; this reentry could result in a ground source term.

3. For the tumbling LWRHU reentry, the aeroshell survives for most angles. Only the shallow cases (at less than $\gamma = -15^\circ$), show ablation failure. For the tumbling cases, the ablation is most severe in the end cap region resulting in a breach in the threaded area. The fuel pellet released for the shallowest angles ($\gamma = -7^\circ$, and $\gamma = -5.2^\circ$) completely melt. Steeper angles ($\gamma = -10^\circ$ and greater) do not show melt. For the shallower angles, resolidification occurs following hypersonic flight.

4. For the thermostructural analyses, using both a 1% and 5% allowable strain, all reentry angles and orientations examined resulted in small localized failures, but aeroshell breach is not predicted for any case.

The analyses included in this report concentrate on VVEJGA reentry scenarios. Analyses reported previously have demonstrated that the LWRHU has adequate design margin to survive reentry from orbital decay scenarios and most injection scenarios at speeds up to escape speeds. The exception is a narrow range of flight path angles that produce multiple skip trajectories which may have excessive ablation.

TABLE OF CONTENTS

ABSTRACT	i
LIST OF TABLES	vi
LIST OF FIGURES.....	viii
ACRONYMS	xv
I. INTRODUCTION	1
II. MODULE DESCRIPTION	2
A. Geometry and Mass Properties.....	2
B. LWRHU Reentry Design Features.....	2
1. Component Design.....	2
2. System Design.....	3
III. REENTRY CONDITIONS	5
IV. GENERAL DESCRIPTION OF ANALYSES.....	6
V. AERODYNAMICS	7
VI. TRAJECTORY PARAMETERS.....	8
VII. THERMAL ANALYSES	9
A. General Discussion and Summary	9
B. Assumptions	9
1. Initial Reentry Conditions.....	9
2. Reentry Configuration.....	10
3. Reentry Orientation.....	10
4. Failure Criteria for Ablation and Thermal Response	10
• Ablation Failure Criterion.....	11
• Melt Failure Criterion	11
• Fuel Melt Disposition	12
5. LWRHU Sequential Breakup Scenario	12

C.	Thermal Models.....	13
1.	Reentry Thermal Analysis Program Limitations.....	13
2.	Thermal and Ablation Response Considerations	13
	• LWRHU Thermal Models.....	13
	• Interface Modeling	14
3.	Initial Value and Boundary Conditions	14
4.	Ablation Modeling	15
5.	Fuel Energy Source Term	18
D.	Material Properties.....	18
1.	Thermal Diffusion Properties	19
	• Fine Weave Pierced Fabric 3-D Carbon-Carbon	20
	• Thermal Conductivity	20
	• Thermal Capacitance	20
	• Pyrolytic Graphite.....	21
	• Thermal Conductivity	21
	• Thermal Capacitance.....	22
	• Platinum-30% Rhodium Alloy	23
	• Thermal Conductivity	23
	• Thermal Capacitance.....	23
	• Plutonium Dioxide.....	23
	• Thermal Conductivity	23
	• Thermal Capacitance.....	24
2.	Thermal Radiative Properties	24
	• Fine Weave Pierced Fabric 3-D Carbon-Carbon	25
	• Pyrolytic Graphite.....	25
	• 'C' Direction.....	25
	• 'A-B' Direction	26
	• Platinum-30% Rhodium	26
	• Plutonium Dioxide.....	26
3.	Phase Change Properties.....	26
	• Platinum-30% Rhodium	27
	• Carbon Eutectic Temperature	27
	• Latent Heat of Fusion.....	27
	• Plutonium Dioxide.....	28
	• Melt Temperature	28
	• Latent Heat of Fusion.....	28
E.	Aerothermodynamics	28
1.	General Methodology	29
2.	Reference Convective and Free Molecule Heating	30
3.	Reference (and Body Reference) Radiative Heating.....	30
4.	Body Reference Convective Heating.....	31

5.	Adjustments to Body Reference Heating Rates	32
•	Precursor Heating.....	32
•	Radiation Coupling	32
•	Catalytic Surface Effects.....	33
6.	Other Body Reference Variables	33
7.	Heating Factor Distributions.....	33
•	Side-on Stable Orientation.....	34
•	Cylindrical Surface.....	34
•	End Face	36
•	Side-on Spinning Orientation	36
•	Cylindrical Surface.....	36
•	End Face	37
•	Random Tumbling Orientation.....	37
•	Cylindrical Surface.....	38
•	End Face	38
8.	Corrections to Local Heating Rates.....	40
•	Low Density Effects	40
•	Surface Mass Transfer Effects, Convective Heating	40
•	Surface Mass Transfer Effects, Radiative Heating	40
9.	Fuel Pellet Aerothermodynamics	41
F.	Results of Analyses	42
1.	Side-on Stable Orientation.....	42
2.	Side-on Spinning Orientation	43
3.	Tumbling Approximations Orientation	44
•	Quasi-Tumbling LWRHU	44
•	Random Tumbling LWRHU	44
•	Tumbling Sphere.....	45
4.	Component Temperature and Aeroshell Recession	45
5.	Clad and Fuel State at Impact.....	45
6.	Sensitivity Analyses.....	46
G.	Bare Fuel Thermal Results	46
1.	Initial Conditions.....	47
2.	Trajectory Results and Discussion.....	48
3.	Side-on Stable LWRHU Release.....	49
4.	Side-on Spinning LWRHU Release	50
5.	Random Tumbling LWRHU Release.....	51
6.	Summary of Melt Fractions	51

VIII.	THERMOSTRUCTURAL ANALYSES.....	52
A.	General Description.....	52
B.	General Methodology.....	52
C.	Assumptions	53
D.	Thermostructural Models	53
1.	Thermoelastic Models.....	53
2.	Thermoplastic Models.....	54
E.	Mechanical Properties	57
F.	Results.....	58
1.	Side-on Stable	58
•	Side-on Stable Mechanical and Temperature Loads.....	58
•	Side-on Stable Runs.....	59
•	Side-on Stable Results	59
2.	Side-on Spinning.....	60
•	Side-on Spinning Mechanical and Temperature Loads	60
•	Side-on Spinning Runs	60
•	Side-on Spinning Results.....	61
3.	Random Tumbling	61
•	Random Tumbling Mechanical and Temperature Loads	61
•	Random Tumbling Runs.....	61
•	Random Tumbling Results	62
IX.	OTHER ENTRY CONDITIONS	63
•	Orbital decay, powered entry, etc.	63
X.	OTHER LAUNCH ACCIDENTS.....	64
XI.	REFERENCES	65

List of Tables

Table 1	General Description of the LWRHU Components
Table 2	Estimated Drag Coefficients for LWRHU Side-on Orientation
Table 3	Estimated Drag Coefficients for LWRHU Tumbling Orientation
Table 4	Estimated Drag Coefficients and Terminal Velocity for the LWRHU
Table 5	TDOF Trajectory Results
Table 6	LWRHU Thermal Response Modeling
Table 7	Initial Reentry Temperature Distribution for the LWRHU
Table 8	Cassini/VVEJGA Reentry Aerothermodynamic Engineering Methods for the LWRHU Configuration
Table 9	Side-on Stable LWRHU 3D Thermal Analyses Results
Table 10	Side-on Spinning LWRHU 3D Thermal Analyses Results
Table 11	Quasi-Tumbling LWRHU 3D Thermal Analyses Results
Table 12	Random Tumbling LWRHU 3D Thermal Analyses Results
Table 13	Tumbling Sphere LWRHU 3D Thermal Analyses Results
Table 14	Side-on Stable LWRHU Component Temperatures at 75% and 100% (burn-through) Failure
Table 15	Side-on Spinning LWRHU Component Temperatures at 75% and 100% (burn-through) Failure
Table 16	Quasi-Tumbling LWRHU Component Temperatures at 75% and 100% (burn-through) Failure
Table 17	Tumbling Sphere LWRHU Component Temperatures at 75% and 100% (burn-through) Failure
Table 18	Random Tumbling LWRHU Component Temperatures at 75% and 100% (burn-through) Failure

List of Tables (Continued)

Table 19	Side-on Spinning LWRHU 3D Clad and Fuel Temperature. Results for Cases not demonstrating 100% Ablation Failure.
Table 20	Quasi-Tumbling LWRHU 3D Clad and Fuel Temperature. Results for Cases not demonstrating 100% Ablation Failure.
Table 21	Tumbling Sphere LWRHU 3D Clad and Fuel Temperature. Results for Cases not demonstrating 100% Ablation Failure.
Table 22	Random Tumbling LWRHU 3D Clad and Fuel Temperature. Results for Cases not demonstrating 100% Ablation Failure.
Table 23	Aeroshell and End Cap Recession
Table 24	Initial Trajectory Conditions for Fuel Pellet Release
Table 25	Estimated Drag Coefficients and Bridging Parameters for Released Fuel Pellet
Table 26	Fuel Release Atmospheric Source Terms
Table 27	Side-on Stable LWRHU Thermostructural Analysis Results
Table 28	Side-on Spinning LWRHU Thermostructural Analysis Cases
Table 29	Side-on Spinning LWRHU Thermostructural Analysis Results
Table 30	Random Tumbling LWRHU Thermostructural Analysis Cases
Table 31	Random Tumbling LWRHU Thermostructural Analysis Results

List of Figures

Figure 1	Cross-Sectional View of LWRHU Assembly
Figure 2	LWRHU Aeroshell Body
Figure 3	LWRHU Clad Body
Figure 4	LWRHU Fuel Pellet
Figure 5	Variation of Initial Altitude Verses Flight Path Angle for Early Release of GPHS Module and LWRHU Entries; Cassini-VVEJGA Mission Profile
Figure 6	TDOF Results: LWRHU Side-on Representative VVEJGA Trajectory Profiles for Hypersonic Flight
Figure 7	TDOF Results: LWRHU Side-on Representative VVEJGA Reentry Altitude Histories
Figure 8	TDOF Results: LWRHU Tumbling Cylinder Representative VVEJGA Trajectory Profiles for Hypersonic Flight
Figure 9	TDOF Results: LWRHU Tumbling Cylinder Reentry Representative VVEJGA Altitude Histories
Figure 10	TDOF Results: LWRHU Tumbling Sphere Representative VVEJGA Trajectory Profiles for Hypersonic Flight
Figure 11	TDOF Results: LWRHU Tumbling Sphere Representative VVEJGA Altitude Histories
Figure 12	TDOF Results: LWRHU Side-on Stable and Spinning Representative Reentry Deceleration Histories
Figure 13	TDOF Results: LWRHU Tumbling Cylinder Reentry Representative Deceleration Histories
Figure 14	TDOF Results: LWRHU Tumbling Sphere Representative Reentry Deceleration Histories
Figure 15	TDOF Results: LWRHU Side-on Stable and Spinning Reference Convective Heating Histories
Figure 16	TDOF Results: LWRHU Tumbling Cylinder Reference Convective Heating Histories
Figure 17	TDOF Results: LWRHU Tumbling Sphere Reference Convective Heating Histories
Figure 18	TDOF Results: LWRHU Side-on Stable and Spinning Radiative Heating Histories

List of Figures (Continued)

- Figure 19 TDOF Results: LWRHU Tumbling Cylinder Radiative Heating Histories
- Figure 20 TDOF Results: LWRHU Tumbling Sphere Radiative Reference Heating Histories
- Figure 21 TDOF Results: LWRHU -90° Reentry Sample Steep Trajectory for Different Orientations
- Figure 22 TDOF Results: LWRHU -7° Reentry Sample Shallow Trajectory for Different Orientations
- Figure 23 TDOF Results: LWRHU Sample Reentry Deceleration Forces for Different Orientations
- Figure 24 TDOF Results: LWRHU -90° Reentry Sample Steep Heating Histories for Different Orientations
- Figure 25 TDOF Results: LWRHU -7° Reentry Sample Shallow Heating Histories for Different Orientations
- Figure 26 TDOF Results: LWRHU Side-on Total Pressure Behind Normal Shock
- Figure 27 TDOF Results: LWRHU Side-on Total Enthalpy Histories
- Figure 28 TDOF Results: LWRHU Tumbling Cylinder Total Pressure Behind Normal Shock
- Figure 29 TDOF Results: LWRHU Tumbling Cylinder Total Enthalpy Histories
- Figure 30 TDOF Results: LWRHU Tumbling Sphere Total Pressure Behind Normal Shock
- Figure 31 TDOF Results: LWRHU Tumbling Sphere Total Enthalpy Histories
- Figure 32 TDOF Results: LWRHU -90° Comparison of Total Enthalpy for Different Orientations
- Figure 33 TDOF Results: LWRHU -90° Comparison of Total Pressure for Different Orientations
- Figure 34 LWRHU Thermal Model: Quarter Section
- Figure 35 Fuel Pellet 2-D Side-on and 2-D Tumbling Thermal Models
- Figure 36 Thermal Conductivity Schedules for LWRHU Interface Gas Fills
- Figure 37 Surface Energy Balance - Reentry Thermal Analysis
- Figure 38 Surface Mass Balance - Reentry Thermal Analysis

List of Figures (Continued)

Figure 39	Thermochemical Ablation Regimes for Graphite
Figure 40	Thermal Conductivity Schedules for FWPF tm
Figure 41	Specific Heat Schedule for FWPF tm
Figure 42	Thermal Conductivity Properties for Pyrolytic Graphite
Figure 43	Specific Heat Schedule for Pyrolytic Graphite
Figure 44	Thermal Conductivity Schedules for Pt-30 Rh
Figure 45	Specific Heat Schedule for Pt-30 Rh
Figure 46	Thermal Conductivity Schedules for PuO ₂
Figure 47	Specific Heat Schedule for PuO ₂
Figure 48	Thermal Radiative Properties for LWRHU Constituent Materials
Figure 49	Aerothermodynamics Regimes for the Cassini / VVEJGA Reentries;
Side-on Stable LWRHU Configuration
Figure 50	Composite Plot Comparing Experimental Data with the Detra, Kemp,
and Riddell Correlation
Figure 51	Stagnation Velocity Gradient Correction on the Side-on LWRHU
Stagnation Convective Heating Rate (Without Geometry Scaling)
Figure 52	Hypersonic, Windward Circumferential Convective Heating Factor
Distributions
Figure 53	Hypersonic, Stagnation Line Convective Heating Factor Distributions
Figure 54	Hypersonic, Windward Circumferential Radiative Heating Factor
Distributions
Figure 55	Hypersonic, Stagnation line Radiative Heating Factor Distributions
Figure 56	Hypersonic, Circumferential Static Pressure Factor Distribution as a
Function of Axial Location; Side-On Orientation
Figure 57	Hypersonic, Angle of Attack Convective Heating Factor, Stagnation
Line of LWRHU's Cylindrical Surface; Tumbling Flight Orientation
Figure 58	Local Convective Heating Ratio on LWRHU's End Face, Zero Angle of
Attack; Random Tumbling Flight Orientation
Figure 59	Average Convective Heating Ratio to LWRHU's End Face as a Function
of Angle of Attack; Random Tumbling Flight Orientation

List of Figures (Continued)

- Figure 60 Comparison of Correlated and Experimental Static Pressure Distributions over LWRHU's End Face, Zero Angle of Attack; Random Tumbling Flight Orientation
- Figure 61 Blockage of Convective Heating Rate as a Function of the Mass Transfer Parameter
- Figure 62 Blockage of Stagnation Radiative Heating Rates Vs Injectant Mass Flux and Chemistry Constituency
- Figure 63 Continuum and Kinetic Flow Regimes with Threshold Values for Radiation Blockage
- Figure 64 RETAP Results: Comparison of Fuel Release Conditions with Sandia Melt Boundaries and FOILS EIS Studies
- Figure 65 RETAP Results: LWRHU -90° Side-on Stable VVEJGA Reentry
- Figure 66 RETAP Results: LWRHU -70° Side-on Stable VVEJGA Reentry
- Figure 67 RETAP Results: LWRHU -50° Side-on Stable VVEJGA Reentry
- Figure 68 RETAP Results: LWRHU -30° Side-on Stable VVEJGA Reentry
- Figure 69 RETAP Results: LWRHU -15° Side-on Stable VVEJGA Reentry
- Figure 70 RETAP Results: LWRHU -10° Side-on Stable VVEJGA Reentry
- Figure 71 RETAP Results: LWRHU -7° Side-on Stable VVEJGA Reentry
- Figure 72 RETAP Results: LWRHU -5.2° Side-on Stable VVEJGA Reentry
- Figure 73 RETAP Results: Side-on Stable LWRHU 3D -90° VVEJGA Reentry Ablation Failure Relative to Reference Heat Pulse
- Figure 74 RETAP Results: Side-on Stable LWRHU 3D -70° VVEJGA Reentry Ablation Failure Relative to Reference Heat Pulse
- Figure 75 RETAP Results: Side-on Stable LWRHU 3D -50° VVEJGA Reentry Ablation Failure Relative to Reference Heat Pulse
- Figure 76 RETAP Results: Side-on Stable LWRHU 3D -30° VVEJGA Reentry Ablation Failure Relative to Reference Heat Pulse
- Figure 77 RETAP Results: Side-on Stable LWRHU 3D -15° VVEJGA Reentry Ablation Failure Relative to Reference Heat Pulse
- Figure 78 RETAP Results: Side-on Stable LWRHU 3D -10° VVEJGA Reentry Ablation Failure Relative to Reference Heat Pulse

List of Figures (Continued)

- Figure 79 RETAP Results: Side-on Stable LWRHU 3D -7° VVEJGA Reentry Ablation Failure Relative to Reference Heat Pulse
- Figure 80 RETAP Results: Side-on Stable LWRHU 3D -5.2° VVEJGA Reentry Ablation Failure Relative to Reference Heat Pulse
- Figure 81 RETAP Results: Side-on Spinning LWRHU 3D-5.2° VVEJGA Reentry Recession Failure at Modeled Surface Nodes
- Figure 82 RETAP Results: Side-on Spinning LWRHU 3D -5.2° VVEJGA Reentry Ablation Failure Relative to Reference Heat Pulse
- Figure 83 RETAP Results: LWRHU -7° Side-on Spinning VVEJGA Reentry
- Figure 84 RETAP Results: Quasi-Tumbling Cylinder VVEJGA Reentry Recession Failure at Modeled Surface Nodes
- Figure 85 RETAP Results: Quasi-Tumbling VVEJGA Reentry Ablation Failure Relative to Reference Heat Pulse
- Figure 86 RETAP Results: Random Tumbling 3D LWRHU VVEJGA Reentry Recession Failure at Modeled Surface Nodes
- Figure 87 RETAP Results: Random Tumbling 3D LWRHU VVEJGA Reentry Ablation Failure Relative to Reference Heat Pulse
- Figure 88 RETAP Results: Tumbling Sphere VVEJGA Reentry Recession Failure at Modeled Surface Nodes
- Figure 89 RETAP Results: Tumbling Sphere VVEJGA Reentry Ablation Failure Relative to Reference Heat Pulse
- Figure 90 RETAP Results: Side-on Stable 3D LWRHU VVEJGA Recession Failure Comparison: JANNAF 89 and Lawrence Livermore Tables
- Figure 91 RETAP Results: Side-on Stable 3D LWRHU VVEJGA Comparison of Ablation Failure Relative to Reference Heat Pulse: JANNAF 89 and Lawrence Livermore Tables
- Figure 92 RETAP Results: Side-on Stable 3D LWRHU VVEJGA Failure Comparison: Gas-Radiation Cooling Effect
- Figure 93 Summary of Released Fuel Pellet Orientations Examined
- Figure 94 TDOF Fuel Pellet Results: Side-on Stable Velocity v. Altitude Profiles
- Figure 95 TDOF Fuel Pellet Results: Side-on Stable Altitude Histories
- Figure 96 TDOF Fuel Pellet Results: Reference Heating Rate Histories for Side-on Stable Breach Releasing Side-on Pellet

List of Figures (Continued)

- Figure 97 TDOF Fuel Pellet Results: Reference Heating Rate Histories for Side-on Stable Breach Releasing Tumbling Pellet
- Figure 98 TDOF Fuel Pellet Results: Reference Heating Rate History for Side-on Spinning Breach Releasing Side-on Pellet
- Figure 99 TDOF Fuel Pellet Results: Reference Heating Rate History for Side-on Spinning Breach Releasing Tumbling Pellet
- Figure 100 TDOF Fuel Pellet Results: Reference Heating Rate History for Tumbling Breach Releasing Side-on Pellet
- Figure 101 TDOF Fuel Pellet Results: Reference Heating Rate History for Tumbling Breach Releasing Tumbling Pellet
- Figure 102 RETAP Results: -5.2° Side-on Stable LWRHU (100% Ablated) Releasing Side-on Fuel Pellet; Thermal Response Through Centerline with Reference Convective Heating
- Figure 103 LWRHU Fuel Results: Comparison of -5.2° Stable LWRHU Releasing Stable Fuel Response at 1X and 3X Reference Convective Heating
- Figure 104 LWRHU Fuel Results: Comparison of -7° Stable LWRHU Releasing Stable Fuel Response at 1X and 3X Reference Convective Heating
- Figure 105 LWRHU Fuel Results: Comparison of -10° Stable LWRHU Releasing Stable Fuel Response at 1X and 3X Reference Convective Heating
- Figure 106 LWRHU Fuel Results: Comparison of -15° Stable LWRHU Releasing Stable Fuel Response at 1X and 3X Reference Convective Heating
- Figure 107 LWRHU Fuel Results: Comparison of -30° Stable LWRHU Releasing Stable Fuel Response at 1X and 3X Reference Convective Heating
- Figure 108 LWRHU Fuel Results: Comparison of -50° Stable LWRHU Releasing Stable Fuel Response at 1X and 3X Reference Convective Heating
- Figure 109 LWRHU Fuel Results: Comparison of -70° Stable LWRHU Releasing Stable Fuel Response at 1X and 3X Reference Convective Heating
- Figure 110 LWRHU Fuel Results: Comparison of -90° Stable LWRHU Releasing Stable Fuel Response at 1X and 3X Reference Convective Heating
- Figure 111 LWRHU Fuel Results: 75% Ablated Stable LWRHU Releasing Spinning Fuel Response at Reference Convective Heating
- Figure 112 LWRHU Fuel Results: 100% Ablated Stable LWRHU Releasing Spinning Fuel Response at Reference Convective Heating

List of Figures (Continued)

- Figure 113 LWRHU Fuel Results: 75% Ablated Stable LWRHU Releasing
Tumbling Fuel Response at Reference Convective Heating
- Figure 114 LWRHU Fuel Results: 100% Ablated Stable LWRHU Releasing
Tumbling Fuel Response at Reference Convective Heating
- Figure 115 LWRHU Fuel Results: 75% Ablated Spinning LWRHU Releasing Side-
on Stable Fuel, Response at Full Convective Heating
- Figure 116 LWRHU Fuel Results: 75% Ablated Tumbling LWRHU Releasing
Side-on Stable Fuel, Response at Full Convective Heating
- Figure 117 LWRHU Fuel Results: 75% Ablated Tumbling LWRHU Releasing
Spinning Fuel, Response at Full Convective Heating
- Figure 118 LWRHU Fuel Results: 75% Ablated Tumbling LWRHU Releasing
Tumbling Fuel, Response at Full Convective Heating
- Figure 119 Thermostructural Model for the LWRHU Aeroshell
- Figure 120 Temperature Loads on LWRHU Aeroshell Model
- Figure 121 Thermoplastic Stress-Strain Material Properties of FWPFtm
- Figure 122 Thermoelastic Stress-Strain Material Properties of FWPFtm
- Figure 123 Normal Strains of FWPF Unit Cell Model with Thermoelastic Material
Properties under Hydrostatic Compressive Loads
- Figure 124 LWRHU Aeroshell Free-Body Diagram
- Figure 125 LWRHU Side-on Stable, $\gamma = -90^\circ$, Strain Factors of Safety
- Figure 126 LWRHU Side-on Spinning, $\gamma = -90^\circ$, Strain Factors of Safety
- Figure 127 LWRHU Side-on Spinning, $\gamma = -50^\circ$, Strain Factors of Safety
- Figure 128 LWRHU Side-on Spinning, $\gamma = -7^\circ$, Strain Factors of Safety
- Figure 129 LWRHU Random Tumbling, $\gamma = -90^\circ$, Strain Factors of Safety
- Figure 130 LWRHU Random Tumbling, $\gamma = -50^\circ$, Strain Factors of Safety
- Figure 131 LWRHU Random Tumbling, $\gamma = -7^\circ$, Strain Factors of Safety

List of Acronyms

ABACUS	Not an Acronym
ACE	Aerotherm Chemical Equilibrium Code
ANSP	Aerospace Nuclear Safety Program
ANSPNL	ANSP Non-linear Code
CFD	Computational Fluid Dynamics
CMA	Charring Material Thermal Response
DEIS	Draft Environmental Impact Statement
DoE	U.S. Department of Energy
FEA	Finite Element Analysis
FEM	Finite Element Model
FEMAP	Finite Element Modeling and Post Processing
FS	Factor of Safety
FSAR	Final Safety Analysis Report
FWPF	Fine Weave Pierced Fabric
GPHS	General Purpose Heat Source
HNUS	Haliburton NUS
INT3-D	3-D Interpolation Code
JANNAF	Joint Army Navy NASA Air Force
JHU/APL	The Johns Hopkins University Applied Physics Laboratory
JPL	Jet Propulsion Laboratory
LANL	Los Alamos National Laboratory
LASL	Los Alamos Scientific Laboratory
LL	Lawrence Livermore
LMMS	Lockheed Martin Missiles and Space
LORAN-C	Langley Optimized Radiative Non-Equilibrium
LRAD-3	Louisiana State University Radiation Transport Model
LWRHU	Lightweight Radioisotope Heater Unit
MHW	Multihundred Watt
MSC	MacNeal-Schwendler Corporation
NASA	National Aeronautics and Space Administration
NASTRAN	NASA Structural Analysis
ORNL	Oak Ridge National Laboratory
PG	Pyrolytic Graphite
RACER	LMMS Flowfield Solver Code
RADICAL	Aerotherm's Radiation Transport Code
RAD/EQUIL	Aerotherm's Radiation/Equilibrium Transfer Code
RASLE	Radiation Shock Layer Equilibrium Code
RETAP	Reentry Thermal Analysis Program
RIFSP	NASA's Radiating, Inviscid Flow, Stagnation Point Code
SAR	Safety Analysis Report

List of Acronyms (Continued)

SoRI	Southern Research Institute
SRMU	Solid Rocket Motor Upgrade
TDOF	Three-Degree-of-Freedom Code
VEEGA	Venus-Earth-Earth Gravity Assist
VVEJGA	Venus-Venus-Earth-Jupiter-Gravity Assist
1-D	One-dimensional
2-D	Two-dimensional
3-D	Three-dimensional

I. INTRODUCTION

In the Aerospace Nuclear Safety Program (ANSP) effort associated with the Cassini Mission, The Johns Hopkins University Applied Physics Laboratory (JHU/APL) has been tasked by the U.S. Department of Energy (DoE) with the primary responsibility of assessing the survivability of the Lightweight Radioisotope Heater Unit (LWRHU) in an inadvertent entry into the Earth's atmosphere. This report constitutes the JHU/APL contribution to the Final Safety Analysis Report (FSAR) for the LWRHU. It includes methodology, assumptions, and results of thermal, ablation response, and thermostructural (thermal and mechanical stress) analyses.

The key personnel and their roles in this study are as follows: E. F. Lucero is the Program Manager for the JHU/APL Aerospace Nuclear Safety Program; L. G. Everhart is the Assistant Program Manager; P. T. Brenza: Solid Rocket Motor Upgrade (SRMU) Fire/LWRHU Thermal Response (under separate cover); L. G. Everhart: Thermal and Ablation Response Predictions; Thermal Analyses Code Development; D. W. Conn: Aerothermodynamic Methodology; LWRHU and Bare Fuel Thermal Models; Material Thermal Properties; Y. Chang: Thermoplastic Methodology; J. A. Ecker: Thermal Stress Analyses; E. F. Lucero and R. C. Sharbaugh: Aerodynamics and Motion Studies; and A. Combs: Program Secretary.

II. MODULE DESCRIPTION

A. Geometry and Mass Properties

The LWRHU is a thermal energy system operating from the radioactive decay of ^{238}Pu plutonium dioxide to deliver approximately one thermal watt of power and is employed aboard spacecraft to locally condition temperature sensitive structure and equipment over the spacecraft's mission lifetime. The LWRHU design shown in Figure 1 represents the Galileo configuration and remains unchanged for the Cassini mission. The LWRHU material constituency is defined in this figure and indicates a high temperature capability through extensive use of carbon materials. The geometric parameters and mass properties that are pertinent to the aerodynamic, thermal, and thermostructural analyses of the LWRHU and components, Figures 1-4, are described here for easy reference.

Figure 2 details the aeroshell geometry and shows the aerodynamic envelope of the primary reentry body (i.e., the full LWRHU assembly) to be a right cylinder with nominal dimensions of 25.95 mm in diameter and 31.95 mm in length. Figure 3 shows the clad and fuel assembly. The other reentry body of interest is the integral fuel pellet shown in Figure 4. For purposes of reentry analyses, this geometry was approximated as a right cylinder based on the pellet's total volume and maximum diameter of 6.00 mm. This approximation permitted double use of the aerothermodynamics defined for the analyses as discussed in Chapter VII.

Reference drawings providing detailed dimensional descriptions for all components are provided in Appendix B.1 of Reference 1. A detailed weight distribution (also taken from Reference 1) of the system's components is provided in Table 1. Total assembly weight is approximately 40.0 grams.

B. LWRHU Reentry Design Features

1. Component Design

At the component level, the primary reentry design elements for the LWRHU are the heat shield component (aeroshell); the thermal insulator components; and the fuel's structural containment (clad) component. The aeroshell is constructed from Fine Weave Pierced Fabric, FWPF[™] (TEXTRON Specialty Materials) three-dimensional (3-D) Cartesian weave carbon-carbon, which provides comparable energy accommodation and, depending on densification, comparable ablation performance to the predecessor graphites (e.g., POCO grades) used in earlier heat source designs. FWPF[™] was the material of choice for the aeroshell due to its superior fracture mechanics attributes. Its ability to arrest crack propagation (strain energy) will likely result in a potential thermostructural failure remaining a localized event as opposed to a catastrophic event as identified with bulk graphites.

Thermal insulation of the fuel containment assembly is provided by three pyrolytic graphite (PG) nested insulator sleeves and two PG insulator plugs. The direction perpendicular to the plane of deposition (the 'c' direction) is aligned in the radial direction for the cylindrical sleeves to provide low conductivity heat transmission for flight configurations represented by a side-on stable, side-on spinning or tumbling orientation. Similarly, the 'c' direction for the plugs is aligned in the axial direction to provide protection for end-on, end-over-end or tumbling flight orientations. Standoffs have been machined on the sleeves and the containment member to maintain open interface gaps to further increase thermal resistance to heat flow directed to the containment assembly. To prevent the formation of critical thermal paths to the containment component via the high thermal conductivity directions of the pyrolytic graphite insulators (i.e., parallel to the deposition plane or 'a-b' plane), the sleeves and plugs are mated in a stepped fashion. The stepped interface also prevents radiation transmission directly from the aeroshell's interior surface to the containment and provides a tortuous pathway for gas infiltration.

The LWRHU's remaining design element, the fuel's structural containment component, is fabricated from the noble alloy, Pt30Rh. This material meets all design requirements such as fuel compatibility, high melting point, high temperature strength and excellent oxidation resistance. Its key attribute, however, resides in its excellent ductility behavior in combination with a very low ductile to brittle transition temperature zone. These characteristics permit significant deformation of the containment shell in absorbing hard target impact energies and thereby reduces the likelihood of a breach upon reentry impact.

2. System Design:

Reentry design considerations at the systems level can generally be related to design strategies involving size, shape and weight. Taken collectively, they determine a reentry body's ballistic coefficient (β):

$$\beta = \frac{W}{C_D S_{ref}}$$

where

W = weight of the reentry body,

C_D = drag coefficient, and

S_{ref} = reference area for the drag coefficient.

A low β heat source design is desirable for several reasons including rapid deceleration with resulting lowered convective and radiative heating rates and reduced heat pulse flight periods; increased likelihood of sustained laminar flow; prolonged subsonic cooling; and, reduced impact velocities. Upon survival of the reentry heat pulse, the latter two considerations become important factors in determining fuel containment impact performance. The LWRHU's reduced weight and blunt geometry (i.e., high C_D) meets the design criteria for a low ballistic coefficient reentry body.

One of the system's design parameters, size, provides several positive reentry benefits. A small reentry body such as the LWRHU can inhibit boundary layer transition and the advent of turbulent heating; reduce radiative heating due to a thinner shock layer; and increase the likelihood for full scale ground testing to assist design validation. This last factor was instrumental in validating the LWRHU's end-on ablation design for the high probability orbital decay reentry environment via full scale arc-jet testing (Reference 2). Negative aspects of a small reentry body include increased convective stagnation and downstream heating and limited system thermal capacitance to accommodate the reentry heat load. This thermal capacitance limitation can be countered through judicious material selection, configuration and arrangement at the component level. This was illustrated earlier by the internal thermal design of the PG insulators.

III. REENTRY CONDITIONS

The mission profile for Cassini includes launch by the Titan IV/Centaur launch vehicle with injection into a VVEJGA trajectory. The VVEJGA trajectory involves one pass by the Earth with some small probability of accidental reentry. This mission profile results in a broad spectrum of possible reentry scenarios, ranging in severity from orbital decay to the very high speed VVEJGA reentries. Detailed analyses of typical reentry scenarios, other than VVEJGA, were provided in the Galileo FSAR for the LWRHU, Reference 1. The Cassini VVEJGA reentries are the primary subject of this report.

The Cassini/VVEJGA Earth reentry breakup analysis conducted by the Jet Propulsion Laboratory (JPL), References 3 and 4, provided the basis for the initial velocity and altitude conditions selected for the LWRHU analysis. A summary of these results is given in Reference 5. Note that JHU/APL chose to conduct the analyses for early release and upwind entry conditions, Figure 5. The initial velocity is 63,812 ft/s. The initial altitudes vary from 323 kft to 236 kft for -5.2° to -90° reentry angles, respectively.

Initial flight path angles (γ) of -90 , -70 , -50 , -30 , -15 , -10 , -7 , and the capture angle of -5.2 degrees were selected for analysis. The baseline 3-D model generated for the analysis is based on a side-on stable flight orientation. Four additional orientations are also used: side-on spinning, quasi-tumbling cylinder, tumbling sphere, and random tumbling cylinder, the last three being various approximations to a tumbling orientation for the LWRHU. The rationale and necessity for these selections are discussed in Section VII. The sequential analyses for the fuel pellet consider side-on stable, side-on spinning, and random tumbling orientations.

IV. GENERAL DESCRIPTION OF ANALYSES

The purpose of the LWRHU reentry analyses is to assess the survivability of the LWRHU under orbital, super-orbital, and VVEJGA reentry modes. Computer simulations are used to calculate trajectory parameters including radiative and convective heating rates. These parameters are used in further simulations to generate multi-dimensional ablation, thermal response, and thermal stress response of the LWRHU and sequential configurations, e.g., the fuel pellet.

The orbital and super-orbital (escape velocity conditions) reentry modes were addressed in the 1985 Galileo FSAR, Reference 6. For the present analyses, the VVEJGA entry modes are emphasized. A discussion of the other scenarios is given in Sections IX and X.

The reentry trajectory of the LWRHU was simulated at JHU/APL using a three-degree-of-freedom (TDOF) simulation. This TDOF program was used to generate, in addition to trajectory parameters, the heating rate, $\dot{q}$, stagnation pressure, P_t , and stagnation enthalpy, h_t , histories that are used as inputs to one-dimensional (1-D) and multi-dimensional thermal analysis programs. The 1-D Charring Material Thermal Response and Ablation (CMA) program generates preliminary thermal and ablation (recession) response information while the multi-dimensional Reentry Thermal Analysis Program (RETAP) generates detailed recession and temperature distributions. The distributions are used as inputs to programs that are used to evaluate the structural integrity of the module due to thermal and mechanical stresses - the McNeal Schwendler Corporation/National Aeronautics and Space Administration (NASA) Structural Analysis (MSC/NASTRAN) and Chang's Thermoplastic programs. These computer programs are more fully described in the pertinent sections on thermal and stress analyses, see Sections VII and VIII.

V. AERODYNAMICS

The LWRHU and LWRHU component aerodynamics used as inputs to the TDOF trajectory simulation consist of the drag coefficient,

$$C_D = \frac{\text{drag}(lbs)}{1/2 \rho V^2 S_{ref}}$$

where

ρ = density in slugs/ft³

V = velocity in ft/sec

S_{ref} = reference area for the drag coefficient

These are given as either a function of Mach number and altitude or as a function of Mach number in the continuum flow regime and a bridging function for interpolating between continuum and free molecule flow. A constant value of angle of attack is assumed. Side-on stable, side-on spinning, and tumbling orientations have been selected for LWRHU thermal ablation, and thermal stress analysis. The aerodynamic estimates used as inputs to the TDOF simulation, References 7 and 8, are given in Tables 2 and 3 for these orientations. Since aerodynamic data for cylinders of these low fineness ratios (≈ 1.2) are very sparse (especially in the free molecule regime), these aerodynamic estimates are based on a variety of data found on blunt bodies - disks, plates and some cylinders.

The drag coefficient at terminal velocity conditions of the LWRHU, and the terminal velocity were estimated, Reference 9, in support of impact tests performed by Los Alamos National Laboratory, Table 4. The cross-flow drag (and consequently terminal velocity) is highly dependent on the wall temperature. The transition from cold wall drag to hot wall drag is dependent on Reynolds' number and surface roughness. The expected ranges in these parameters for the LWRHU are such that either cold or hot values are possible, Table 4. The average is representative of a tumbling LWRHU.

For comparison, the drag coefficient for an ablated LWRHU approximating a spherical shape is given in Table 3. This value also applies to spherical fuel particles except that the reference area is the cross-sectional area of the sphere and the reference length is its diameter. The drag coefficient for the side-on and tumbling fuel pellets are also those of References 7 and 8 (Tables 2 and 3) but the reference area and length are those of the fuel pellet, i.e., for the side-on orientation $S_{ref} = D \times l = 0.000629 \text{ ft}^2$ and $D_{ref} = 0.0205 \text{ ft}$ and for the tumbling orientation $S_{ref} = \pi D^2/4 = 0.0354 \text{ ft}^2$.

VI. TRAJECTORY PARAMETERS

The output from the TDOF trajectory simulation is used as inputs to the thermal and thermostructural analysis codes. This output includes velocity, altitude and deceleration versus time as well as reference heating rates and other aerotherodynamic parameters.

The results of the TDOF simulations are presented in Table 5 and in Figures 6 through 25. The simulations are run through the hypersonic portion of flight for each angle. A Mach number of 5 is selected to indicate the end of hypersonic flight. Figures 6 and 7 show the representative trajectories developed for the side-on stable and side-on spinning orientations. Figure 6 is the velocity versus altitude profiles. Figure 7 is the time history of the altitudes. Similar diagrams are supplied in Figures 8 and 9, and 10 and 11 for the quasi and random tumbling cylinder, and the tumbling sphere orientations, respectively. The resulting deceleration profiles are shown in Figures 12 through 14. The extreme steep reentry angles result in g forces in excess of forty times those experienced by the extreme shallow reentry angles. The maximum peak deceleration, approximately 1050 gs, occurs for the -90° tumbling sphere reentry. The -5.2° side-on reentry will experience a peak deceleration of approximately 25 gs.

The heating rate histories are given in Figures 15 through 20. The reference convection and radiation portions are shown separately. Figure 15 is the convective heating for the side-on stable and spinning orientations. In this case the shallow reentry maximum heating rate is about four times less than that of the steep reentry. The conditions for reference convective heating are 1) a 1-ft radius sphere, 2) stagnation flow, 3) cold wall heating, 4) zero mass transfer, and 5) no radiation coupling. Similar results are shown for the tumbling cases in Figures 16 and 17. The reference radiative heating, Figures 18 through 20, shows a difference of about a factor of seven between the reentry extremes with the tumbling sphere experiencing the highest values. In each orientation, the maximum radiation heating dominates the heat pulse for steep flight path angles while peak convective heating dominates the shallow angles.

Figures 21 through 25 are provided to give a quick frame of reference for the trajectory difference induced by the LWRHU flight orientations. A sample steep (-90°) and shallow (-7°) reentry diagram is supplied for the altitude and velocity histories, deceleration profiles, and the convective and radiative heating histories. Figures 26 through 33 illustrate the stagnation pressure and total enthalpy histories.

VII. THERMAL ANALYSES

A. General Discussion/Summary

The ablation and thermal response analyses examine the reentry angles -5.2° (approximate capture angle), -7.0° , -10° , and -15° for the shallow cases and -30° , -50° , -70° , and -90° for steep cases. The following cases were investigated:

- Side-on Stable 3-D LWRHU.
- Side-on Spinning 3-D LWRHU.
- Tumbling Spherical 3-D LWRHU.
- Quasi-Tumbling Cylindrical 3-D LWRHU.
- Full Random Tumbling Cylindrical 3-D LWRHU.
- Effect of Carbon/Air Thermochemistry Table Selection examined at $\gamma = -15^\circ$, -30° , -50° , -70° , and -90° .
- Effects of gas dynamic/radiation coupling on convective heating examined for $\gamma = -90^\circ$.

The three tumbling orientations noted are various approximations to a LWRHU tumbling about its major axes.

B. Assumptions

1. Initial Reentry Conditions

The initial conditions for the generation of LWRHU thermal analysis is taken from the TDOF output listed in Table 5. The JPL early release zero wind conditions for the General Purpose Heat Source (GPHS) and LWRHU (References 3 and 4) were used as initial trajectory conditions. The JHU/APL selected entry, based on JPL communications, is for an upwind entry. These release conditions are illustrated in Figure 5. Note that although zero wind conditions from References 3 and 4 are used, the model simulations in TDOF involve upwind reentries into the Earth's atmosphere. JPL did not generate upwind release conditions but noted that the difference between upwind and zero wind were small. The upwind Earth reentry results in an increase in the initial velocity of approximately 3000 ft/s at the equator relative to a downwind entry. The increase in radiative and convective heating for this increased velocity profile causes possible failures to occur earlier than would occur for a downwind case; therefore, the upwind modeling provides the more conservative analysis approach.

The drag coefficient data used in developing appropriate reentry trajectories for the orientations examined are listed in Tables 2 and 3. The side-on stable and side-on spinning orientations utilize the same drag data, and the quasi-tumbling and random tumbling cylindrical orientations utilize the same drag data. Independent drag data are used of the tumbling sphere

orientation. Therefore, three different sets of trajectories are necessary to cover the selected model orientations.

2. Reentry Configurations

This study considered a simplified sequential breakup scenario consisting of (a) a full LWRHU assembly followed by (b) instantaneous release of the integral fuel pellet should failure events occur during the course of reentry. The fuel pellet is considered to be integral according to inputs from Dr. E. W. Johnson, Reference 10.

3. Reentry Orientation

The primary orientations assumed for the LWRHU assembly and subsequent breakup configurations was a sustained side-on stable attitude, a side-on spinning, and several approximations to a tumbling orientation. A side-on stable reentry orientation is a hotter condition than a dynamic, spinning or a tumbling mode and, of the three idealistic attitudes, previous studies indicate that a side-on stable orientation will more likely produce a clad melt event. Of all the in-flight failure modes, the clad melt event bears the greatest significance since it nearly always results in fuel release (if not during flight, then ultimately at impact).

It is judged that the tumbling orientation is the most likely of the three analyzed because of the low aspect ratio of the cylinder. The side-on stable is judged to be the least likely of the three (end-on which is probably even less likely was not considered for thermal analysis). The conditional probabilities suggested for these orientations are:

random tumbling: 0.6
side-on spinning: 0.3
side-on stable: 0.1

Two other flight orientations were examined that are termed 'quasi-tumbling cylinder' and 'tumbling sphere'. These orientations are fictitious artifices that were intended to provide qualitative indications of shape change effects on aeroshell ablation for a (random) tumbling LWRHU. The 'quasi-tumbling cylinder' represents the case where the side-on spinning aerothermodynamic factors (i.e., convective, radiative and free-molecule heating, pressure and recovery enthalpy) were applied to both the cylindrical surface and end face of the LWRHU thermal model and provides a lower bound estimate. As an upper bound, the 'tumbling sphere' case applied spinning sphere heating rates to both the cylindrical surface and end face. However, they represent extreme bounds on shape change effects since both orientations were examined over a reentry's entire heat pulse. It is expected that a LWRHU initially in a (random) tumbling orientation would likely degenerate into a shape and motion resembling a 'tumbling sphere' for shallow reentries possessing an extended heat pulse. Results reported for these two orientation cases should be viewed in a qualitative sense.

The fuel particle analyses conducted where failure is indicated for the LWRHU assembly assumes integral fuel pellets for all considered flight orientations: side-on stable, side-on spinning, and random tumbling. Conditional probabilities for fuel pellet orientations are not necessary since full fuel pellet melt is predicted for most cases.

4. Failure Criteria for Ablation and Thermal Response

The failure criteria for the ablation and melt failure modes were conservatively assigned in these studies in recognition of the uncertainties associated with the high energy Cassini/VVEJGA reentry thermal environments. It is noted that these uncertainty provisions are not the end result of sensitivity studies and accompanying statistical analyses but rather are subjectively selected on the basis of engineering judgment. In most cases, statistics are simply not available for the numerous environmental and response variables that determine these failure modes. Sensitivity analyses would have to be conducted to provide the effect of uncertainties on the LWRHU reentry response parameters and related failure conditions.

a. Ablation Failure Criterion

The ablation failure criterion for the prior Galileo/VEEGA reentry analyses was assigned at 50% recession of the wall thickness of the aeroshell member in its side-on stable flight orientation. This criterion was based, in part, on the use of a Joint Army, Navy, NASA, Air Force (JANNAF) $C_1 - C_7$ thermochemical equilibrium model and restricted to those immediate aeroshell regions overlaying the insulator sleeves and the fuel containment assembly. Further conservatism was imposed by assuming failure to occur when the stagnation array of aeroshell nodes met the 50% threshold. Therefore, aeroshell failure and release of the internals were considered to occur when the failure site was limited to a central angle, $\Delta\theta = \pm 15^\circ$ about the aeroshell's stagnation point.

The failure criteria assigned to the Cassini/VVEJGA analyses varied from the Galileo criteria in two regards. First, the recession threshold was increased to 75% of the wall thickness to account for a more severe thermochemical ablation model. The VVEJGA studies considered the Lawrence Livermore $C_1 - C_7$ equilibrium model which results in significantly greater total vapor pressures (and therefore recession rates) than the JANNAF model at equivalent surface pressures and 'elevated' temperatures. Second, since the VVEJGA studies were expanded to include a random tumbling flight orientation, the 75% criterion not only applied to the aeroshell wall overlaying the insulators and fuel containment but also to the wall thickness at the aeroshell/aeroshell end cap threaded interface.

For material ablation, the 75% wall thickness recession criterion discussed previously is deemed to denote a conservative point of probable aeroshell failure, but the 100% wall thickness recession is also of note. A 25% nonconservative approach illustrates a range

of uncertainty and could allow the aeroshell material to survive through the hypersonic flight region. The ablation failure results are only valid to the point of structural failure due to material loss or mechanical overloading.

b. Melt Failure Criterion

The melt failure criterion for the VVEJGA studies remains basically the same as assigned for the prior Galileo/Venus-Earth-Earth Gravity Assist (VEEGA) studies. The two components subject to melting are the fuel containment member (clad) and the fuel itself. The VVEJGA reentries result in localized pressures low enough to dismiss the possibility of a melt event for the carbon-carbon aeroshell and the PG insulators.

Two criteria are specified for the melt failure mode depending on the reentry configuration under consideration. For a full LWRHU reentry configuration, the sensitivity of a melt event to environmental uncertainties are somewhat damped by the presence of the PG insulators. For this situation, the failure threshold is assigned the true melt temperature minus the uncertainty allowance of 300°F. The clad's threshold value becomes 2790°F based on a carbon eutectic melt temperature of 3090°F (3550°R). This failure threshold is lower than the Galileo assignment (i.e., 2900°F) by conservatively choosing the lower bound of Pt30Rh's carbon eutectic range reported in the literature. The melt threshold for the fuel is 4812°R. For the current VVEJGA studies, the second criterion applies to the bare fuel pellet reentry configuration. The uncertainty allowance for this condition is assigned at 500°F since the sensitivity of unprotected fuel to environmental uncertainties will be greater than for the full LWRHU configuration. This assignment is obviously very subjective, being strongly dependent upon the time of release of the fuel within the reentry heat pulse. The bare fuel allowance results in a melt threshold of 4312°F.

Regarding the uncertainty band formed by the failure threshold (e.g., the 300 or 500°F temperature band on melt failure), the farther a response variable such as 'aeroshell recession' or 'clad temperature' is predicted to penetrate this uncertainty band, the greater the probability of occurrence for this failure event. Here probability is definable only in a qualitative sense (high, low, etc.)

c. Fuel Melt Disposition

A further conservatism contained in the VVEJGA analyses relates to the disposition of the fuel melt during reentry. The formation of a melt front on the reentering fuel pellet is assumed to be immediately stripped aerodynamically. The stripped molten material is assumed to further breakup in a cascading manner into a final aerosol state containing inhalable particulates. Therefore, the total mass fraction of the fuel pellet predicted to melt during reentry is equated to an atmospheric source term.

5. LWRHU Sequential Breakup Scenario

The sequential breakup scenario assumed for the side-on stable Galileo/VEEGA studies was basically the release of the fuel containment assembly (clad and fuel pellet) upon incipient failure of the aeroshell due to ablation. This was followed by complete release of the integral fuel pellet upon incipient failure of the containment due to melt. Incipient failure is defined as the initiation of a failure site at the immediate stagnation region of the respective aeroshell and containment thermal models. It was observed from the Galileo studies, however, that the containment shell melted almost immediately upon release from the aeroshell and provided very little time delay within the heat pulse for subsequent fuel release. Thus in the Cassini/VVEJGA studies complete release of the fuel pellet is assumed upon incipient failure of the aeroshell and/or the aeroshell end cap.

The 'full LWRHU assembly to fuel pellet reentry sequence' may be a highly conservative approach to the Cassini/VVEJGA reentry analyses. The qualification is that arc jet tests at convective heating rates 1/3 to 1/10 the predicted VVEJGA rates, and at much lower stagnation pressures, indicated catastrophic failure of the LWRHU in about twice the heat pulse interval. The sequence provides a bounding condition on early fuel release within the reentry heat pulse and subsequent generation of atmospheric source terms due to fuel melt. It recognizes no benefit from the internal insulators in delaying release of the fuel upon incipient failure of the aeroshell (re: Figure 1). Unfortunately, the dilemma in selecting a more realistic breakup scenario arises from the large uncertainties in defining local environments upon initial breach of the aeroshell. These uncertainties include augmentation of the convective heating at the local failure site, mechanical erosion effects at the failure site due to internal ram pressure and convective heating from the shock layer gases infiltrating throughout the assembly's open interfaces. The disposition of the PG insulators is another important factor in terms of either remaining integral to maintain thermal protection or fragmenting due to thermostructural loading. It should be clear that qualitatively, fuel release may be delayed beyond the release scenario selected for these studies but time of fuel release cannot be answered reliably in quantitative terms.

C. Thermal Models

1. Reentry Thermal Analysis Program Limitations

The principal demand in modeling the three-dimensional LWRHU assembly for this study was one in which generic classes of reentry flight motions could be adequately simulated by a single model. A side-on orientation was selected to represent the class of motions where the longitudinal axis (generatrix) is mostly perpendicular to the wind (including oscillatory motion) and a tumbling orientation was selected to portray the more dynamic class of motions. A 3-D model representing a quarter section of the LWRHU assembly was selected for these studies. Similarly, two separate two-dimensional fuel pellet thermal models are implemented.

The numerical solutions of the thermal diffusion equation were performed by the RETAP. This code has the capability to handle both nonlinear thermal properties and boundary conditions in multi-dimensional space; all the appropriate ablation models for a carbon-air system; multiple heat transfer modes for 'open' and 'shut' internal interfaces; and, aerothermodynamics at all velocity regimes either through a data input stream or by internal algorithms (e.g., low density and surface mass transfer corrections).

One principal shortcoming of RETAP is its inability to shrink a structure's thermal network in accordance with the code's surface ablation calculations. For the LWRHU simulations, a dimensionally stable network impacts the thermal and ablation response by increasing the aeroshell's thermal gradients (i.e., thermal stresses) while maintaining a large section modulus; increasing the aeroshell's computed ablation loss; decreasing peak clad temperatures; and, increasing clad impact temperatures. The effects influencing the thermostructural failure mode will be compensating while the effect on computed ablation loss introduces conservatism in assessing the ablation failure mode. The latter clad effects underestimate the evaluation of the clad melt and impact failure modes. The extent of these effects on clad failure assessments, while thought to be small, represents an uncertainty in the analyses that is countered by allowances in the failure criterion.

A second shortcoming involving the TDOF/RETAP code combination is the absence of ablation shape change feedback on flight dynamics and resulting aerothermodynamic input (via the TDOF code) on RETAP's computed response modes. Shape change is believed to have little effect for either the side-on stable or spinning flight orientations since increases in convective (or radiative) heating will be compensated by decreases in radiative (or convective) heating as well as a lower reentry ballistic coefficient due to changes in geometry (i.e., the LWRHU's effective leading radius), weight and aerodynamics. However, the absence of shape change effects for the random tumbling studies may lead to underestimated response predictions for shallow reentries (i.e., extended heat pulse periods) since the LWRHU would likely degenerate into a geometry resembling a sphere. This effect is an uncertainty in the analyses; the sensitivity to this shape has been investigated by using a spherical approximation.

The model development contained several simplifications for the common purpose of preserving RETAP's numerical stability at a reasonable computational time step. These simplifications included:

- a. The mass of the stand-offs machined on the insulator sleeves, clad, threaded end cap and the circumferential weld bead of the clad end cap were lumped into the proximate grid node of the stand-off's component. However, the gaps forced by these stand-offs were preserved in the model.

b. The threaded interface formed by the aeroshell and the end cap was assumed to be a homogeneous material rather than attempting to detail the thread form. This was accomplished by assuming the interface to be closed at a very high thermal contact conductance.

c. The spanner holes in the threaded end cap were omitted, resulting in a slight over specification of the end cap's mass (i.e., thermal capacitance) and omission of localized cavity heating effects. The effects of this omission on clad response was thought to be minor for the tumbling study and negligible for the side-on studies.

d. The fuel was modeled as an integral pellet rather than in some arbitrary orientation of fragments that might arise from the fuel's internal thermal stresses or from launch vibration environment(s).

e. The platinum-rhodium alloy shim was lumped into the near proximity fuel nodes rather than being modeled as a separate component. This resulted in a composite nodal structure in which the overall thermal capacitance was based on the participating materials thermal capacitance weighted by their volume fraction. The thermal conductivity and total hemispherical emittance properties of the composite assumed the fuel's schedule.

f. The modeling assumed the clad cap closures were identical rather than attempting to discriminate on the vented closure with attending frit.

2. Thermal and Ablation Response Considerations

There are two basic modeling requirements to be considered in addressing reentry environments. The first requirement is one of modeling the LWRHU's structural configuration in variables appropriate for solving the general thermal diffusion partial differential equation. This model is generally referred to as a thermal model or network since the thermal variables possess electrical analogies. The second modeling requirement is one of simulating the ablation processes operating at the LWRHU aeroshell's external surface. The ablation modeling is obviously coupled directly to the thermal environment as well as to the structural thermal network. These modeling requirements apply to the sequential breakup configurations as well.

a. LWRHU Thermal Models

Solutions to the thermal diffusion equation must be done numerically since, for reentry problems such as the VVEJGA scenarios, the equation itself is highly nonlinear and the required boundary conditions are nonlinear in both time and space. A numerical approach requires subdividing the various structural components into discrete elements or nodes with each of their center of mass being a spatial location for a calculated temperature history as the solution marches in time along the reentry trajectory. Each node is characterized by a thermal

capacitance and thermal conductance (connecting adjacent nodes) wherein the total composite is termed the thermal network. The 3-D thermal network for the LWRHU assembly considered in the side-on analyses is shown in Figure 34 and represents a cross-sectional view in cylindrical coordinates (R, θ) taken at the mid-plane of the assembly. The network is described by a $12R \times 7\theta$ notation for a total nodal count of 84. The second thermal model is shown in Figure 35. Figure 35.a shows the two-dimensional (2-D) side-on fuel pellet reentry configuration that would result from either an ablation or thermal stress failure of the LWRHU aeroshell. This model shows an enhanced spatial grid fineness for the pellet from that shown in Figure 34 to improve on the resolutions of melt mass fraction during reentry. The third model considered (Figure 35.b) was the 2-D tumbling fuel pellet configuration.

(1) Three-Dimensional LWRHU Assembly Model

The genesis for the quarter section 3-D LWRHU model was a model constructed during the development phases of the LWRHU to validate the assembly's reentry thermal design (circa: 1979/1980). A good portion of this model had to be reworked based on the Table 1 reference drawings, particularly regarding the insulator components. A typical longitudinal (i.e., radial, r - axial, z) cross-section of the LWRHU is shown in Table 6.a and provides regional representations of the thermal model simulation. The thermal model response regions are provided in Table 6.a and the thermal model interface regions in Table 6.b.

The resulting thermal model for the LWRHU assembly is shown in Figure 34. Figure 34.a presents the r - z cross-section for the stagnation segment (i.e., $\Delta\theta = 0^\circ$ to 15°) of the model and depicts the capacitance (lumped mass) and surface nodal locations and the corresponding nodal indices. It is noted that these are the nodes of interest for the side-on orientation studies. Figure 34.b presents the r - θ cross-section at the model's mid-span location ($z/L=0$). This cross-section closely parallels the 2-D thermal model considered in the Galileo studies except for a coarser nodal grid in the aeroshell and finer grids in the middle and outer sleeves. It is neither required nor practical to precisely model the LWRHU assembly in order to capture its thermal response behavior. Table 6.c outlines the simplifications considered in the construction of the model. The model is characterized by 331 capacitance nodes and approximately 475 surface nodes. The computational (stability) time step was typically in the range of 0.001 to 0.002 second which was more than adequate to capture the nonlinearities of the VVEJGA reentry problem. Material thermal properties used in computing nodal thermal capacitances and conductances are discussed in Section VII.D.

(2) Two-Dimensional Fuel Pellet Thermal Models

Following discussions with Dr. Ernest W. Johnson, EG&G/Mound, the release of fuel subsequent to incipient failure of the aeroshell was assumed to be in an integral pellet form rather than fragments. The fuel pellet shown in Figure 5 is essentially a right cylinder with chamfered ends. The pellet was modeled as a right cylinder based on its

maximum diameter and its total volume. This permitted use of the aerothermodynamics developed for the LWRHU assembly due to similarity in geometries. Upon release from the failed LWRHU, the pellet assumed the same basic flight orientations as considered for the LWRHU. The side-on stable and spinning studies adopted the Galileo's r - θ , mid-span model which is shown in Figure 35.a. For the random tumbling orientation, a simple r - z model was constructed which is shown in Figure 35.b. The basic objective for these models was to determine the mass fraction of the simulated pellet that melted during bare fuel reentry.

b. Interface Modeling

Table 6.a and Table 6.b indicate there are numerous interfaces in the interior of the LWRHU which will influence thermal energy transport to the critical clad components. The modes of heat transfer considered at an internal interface are dependent upon the local state of the interface. For 'open' interfaces (i.e., a gap between opposing components), the modes of heat transfer are typically (a) thermal radiation and (b) gaseous conduction if the intervening gap is gas filled. For 'shut' interfaces, solid conduction becomes the dominant heat transfer mode.

(1) Thermal Radiation Heat Transfer

In determining interface thermal radiation between opposing surface nodes, total hemispherical emittance data followed by total normal data were given top priority. These data are presented as a function of temperature in Section VII.D which discusses material properties. Based on these data, the radiation exchange factors for the various interfaces were determined on the basis of closely spaced parallel plates. This is a reasonable approximation for determining heat transfer for 'open' interfaces and provides a conservative estimate for 'shut' interfaces. Radiative heat transfer is assumed to occur only between the pair of opposing surface nodes at an interface. Heat transfer from a surface node to other nodes at the opposing surface of an interface is negligible due to the small gap sizes existing at the interfaces.

(2) Gaseous Conduction Heat Transfer

Open interface gaseous conduction is determined from the Fourier heat conduction law and therefore is sensitive to both the gas fill's thermal conductivity and the interface gap size. The remaining consideration for this heat transfer mode is the gap fill history during reentry.

Typically in past analyses, gaseous conduction was either neglected by assuming the open interfaces to be evacuated or determined on the basis of either a helium or air gas fill. This study developed interface thermal data for all three possibilities. The thermal conductivity schedules selected for the helium and air gas fills as a function of temperature are presented in Figure 36. These schedules were developed (from data from References 11

through 16) for a one atmosphere pressure rather than introducing bivariate dependency on both pressure and temperature. It is noted that over the anticipated temperature range of the LWRHU interfaces, pressure corrections on thermal conductivity are negligible (Reference 11). As a further justification, when interface temperatures are near maximum, radiation becomes the dominant heat transfer mode.

Determination of gap distributions for the interfaces represented an uncertainty in the analyses due to possible tolerance build-up permutations during assembly, internal component thermal expansion effects, etc. As a result, distributions were established for three hypothetical interface states: (a) 'perfect alignment', (b) 'translational displacement' and (c) 'thermal expansion'. These states and the gap specifications for the radial and axial interfaces in a side-on stable orientation are defined in Table 6.d. The assignment of interface states for each of the flight orientation cases is provided in Table 6.e.

Early LWRHU reentry design studies for parking orbit accident scenarios considered evacuated gaps during initial reentry that subsequently became filled with helium discharged from the plutonium dioxide fuel. Helium release was arbitrarily related to threshold temperature levels specified for the clad member (Reference 6). A more sophisticated helium release model as well as the modeling of air influx and efflux through the aeroshell's permeable wall resulted in a dilution of the helium effect over most of the heat pulse examined for a shallow reentry from parking orbit (i.e., a $\gamma_{\min}$ reentry). It was demonstrated that the thermal response of the clad using this sophisticated mixing (helium-air) model could be closely approximated by a one atmosphere air fill in the gaps from initial reentry to impact (Reference 6). For steeper reentries, the dilution of released helium becomes even greater due to greater mass flux of air through the permeable aeroshell at the higher windward pressure distributions. As the case for the Galileo studies, the simpler air fill model (from initial reentry) was chosen for all the VVEJGA flight orientation studies.

(3) Solid Conduction Heat Transfer

Solid conduction at 'shut' interfaces or localized segments such as the designed stand-offs is governed by the acting thermal contact conductance at the closure. Contact conductance is dependent upon numerous conditions including the material pair in contact, temperature, pressure, surface finish, gas fill, contact geometry, etc. Unfortunately, engineering data addressing these variables for the LWRHU material configuration are acutely absent. Table 6.e presents subjective interface thermal contact conductance schedules considered in prior LWRHU side-on stable analyses. For the VVEJGA study, a literature survey was conducted in an attempt to obtain data representative of the material pairs comprising the LWRHU's interfaces (References 17 to 23). This effort resulted in the schedules presented in Table 6.f for the indicated states for the side-on stable flight orientation. The contact conductances were valued according to qualitative compressive stress states (i.e., 'high' or 'low' contact pressures) with the high stress value being approximately three times the low stress value based on some limited FWPF carbon-

carbon conductance data (References 19 and 20). Due to lack of data, the contact conductances were held constant with temperature. Since interface closures involve engineering surfaces, contact will not be perfect but will be limited to surface asperities in direct contact. Consequently, there will be local voids at the interface that will also permit radiative and gaseous conduction transfer. Radiative transfer is computed according to Section VII.C.2.b.(1) and gaseous conduction is assumed to be a contributing component in the values presented in Table 6.f. The notes contained in Table 6.f indicate how these data were used for the side-on spinning and random tumbling flight orientations.

3. Initial Value and Boundary Conditions

The numerical solution of the thermal diffusion equation via the RETAP code requires an initial value of the LWRHU's temperature field and two boundary conditions for each spatial variable.

a. Initial Value

The initial temperature field for the LWRHU assembly remained the same as considered in the early LWRHU design studies and is presented in Table 7. This distribution represents the steady state operating temperature in a space environment. Use of this distribution implies the open interfaces within the assembly are in vacuum up to the time of release of the LWRHU from the parent spacecraft. The initial fuel temperature for bare fuel reentry scenarios equate to the pellet distributions at the time of incipient failure of the LWRHU's aeroshell.

b. Boundary Conditions

One of the required boundary conditions is met through specification of adiabatic surfaces during construction of a thermal model based on the structure's symmetry. The use of adiabatic surfaces are implied in the use of a quarter section thermal model for the LWRHU assembly shown in Figure 34. Similar use of adiabatic surfaces are contained in the 2-D models for the fuel pellet shown in Figure 35. The adiabatic surfaces contained in the r - θ fuel model do not reflect on the symmetry of the problem but were imposed to expedite the analyses through use of an existing Galileo model.

The second boundary condition is provided by the specification of energy balances specified at all internal surfaces of the LWRHU components and the aerodynamic (i.e., external) surface of the aeroshell. Whether the internal interfaces are represented by 'open' or 'shut' interfaces, the total thermal energy flux into a surface equals the total thermal energy flux away from the surface. The total energy flux is comprised of solid conduction, gaseous conduction and thermal radiation heat transfer modes in various combinations pending the particular configuration of the interface.

The energy balance at aerodynamic surfaces is arguably the prime relationship in the solution of a reentry problem in that it couples the thermal environment to the thermal and ablation response modes of the structure. The surface energy balance conducted at every surface node in the LWRHU or fuel pellet thermal models for the VVEJGA analyses is shown in Figure 37. The solution of the surface energy balance for the LWRHU's carbon-carbon aeroshell is simplified by the unity Lewis number analogy equating the local mass transfer coefficient to the local heat transfer coefficient. The assumption of a unity Lewis number for a carbon-air system represents a good approximation based on the multi-component reacting boundary layer solutions with ablation by Putz and Bartlett (Reference 24).

4. Ablation Modeling

a. Carbon-Carbon (Aeroshell, Aeroshell End Cap)

Figure 38 illustrates that the surface mass balance for an ablating carbon surface comprises a mass flux convected into a surface control volume in its solid phase equated to a mass flux convected (and diffused) out of the surface volume in its vapor phase (thermochemical ablation) as well as ejected in its solid phase (mechanical ablation). For the VVEJGA analyses, mechanical ablation was not explicitly considered but represents an uncertainty contained in the allowance specified by the ablation failure criterion (i.e., 75% aeroshell wall thickness). While an approximate mechanical ablation model has been developed at APL for bulk graphites (specifically, ATJ grade, Reference 25) based on the data of Lundell and Dickey (Reference 26), this model was not considered representative of 3-D carbon-carbon. The FWPF should have stronger resistance to mechanical effects due to the orthogonal weave construction, particularly for relatively low stagnation pressures characteristic of low ballistic coefficient reentry bodies such as the LWRHU.

Figure 39 illustrates the thermochemical ablation regimes for a carbon (or graphite)-air system and shows a sampling of the JANNAF '71 sublimation model and the diffusion-limited and moderate rate-limited oxidation models used in the Galileo/VEEGA analyses. Since the VVEJGA analyses were truncated to only the heat pulse flight period rather than full flight to impact, ablation considerations were limited to carbon's diffusion-limited oxidation and sublimation models. The diffusion-limited oxidation plateau in Figure 39 is based on a carbon monoxide reaction product and represents, in theory, the limiting solid carbon consumption rate for an oxidation process. The carbon monoxide based model was used in both the VEEGA and the VVEJGA analyses. As the name implies, this limit is reached when reaction rates become so rapid that the consumption rate of the reactant, oxygen, becomes limited to oxygen's ability to diffuse across the boundary layer to the reacting surface.

Two sublimation models were considered for these studies. The Lawrence Livermore (LL) carbon thermodynamics (characterized by vapor species C_1 through C_7 , References 27 and 28) and the 1986 JANNAF thermodynamics (C_1 through C_5 vapor species, Reference 29) were provided as input to the Aerotherm Chemical Equilibrium (ACE) code

(Reference 30) to develop equilibrium ablation models in the CMA code format (mass transfer parameter and wall gaseous enthalpy as a function of pressure and temperature, References 31 and 32). For a given set of carbon vapor thermodynamics, surface pressure, and surface temperature, the use of an equilibrium versus a nonequilibrium ablation model provides an upper bound on sublimation loss of carbon. It is noted that nonequilibrium ablation is a more realistic mode for the shallow low density reentry corridor but will progress, in the limit, toward equilibrium ablation rates at higher pressures associated with steeper reentries.

The LL model's total vapor pressure is significantly greater than the JANNAF model and was used to evaluate the LWRHU's aeroshell ablation failure mode. Use of the LL model was the basis for increasing the failure criterion to the 75% wall thickness value from the 50% value considered in the Galileo studies with the '71 JANNAF model. While an equilibrium model is more critical in evaluating the ablation failure mode, a nonequilibrium ablation model is more critical in evaluating the thermostructural failure mode due to higher surface temperatures and temperature gradients. The '86 JANNAF model was used as a substitute for a LL nonequilibrium model in the determination of aeroshell temperature distributions for thermostructural failure evaluation. The resulting '86 JANNAF model showed negligible differences in ablation parameters from the prior '71 JANNAF model used in the VEEGA analyses. Additional information on APL's sublimation and oxidation models can be found in References 25, 33 and 34.

The analyses did not consider melting as an ablation process due to the high pressures measured at carbon's triple point from early investigations (References 35 to 38) and more recently by Cezairliyan and Miller (Reference 39). These pressures range from 100 to 110 atmospheres which dwarfs the maximum stagnation pressures experienced across the VVEJGA reentry spectrum.

b. Plutonium Dioxide (Fuel Pellet)

Ablation modeling of the fuel pellet is much more complicated than the modeling of a carbon aeroshell due to the addition of a melting event. Fuel modeling is a moving boundary problem involving three layers consisting of a solid core topped by a melt layer topped by a vaporization/air mixture layer. Further modeling complications arise in describing the hydrodynamic behavior of the melt layer in reaction to aerodynamic loading (e.g. stripping due to shear loads, ballooning due to normal loads, etc).

The VVEJGA analyses circumvented these complications by taking a (presumably) conservative, simplistic approach to the fuel reentry problem. The same surface energy balance was used as indicated in Figure 37 but with substitution of plutonium dioxide thermochemistry to determine vaporization rates. However, at fuel melt temperatures, vapor pressure is still at low levels and does not represent a significant loss mechanism. The approach consisted of a thermal response analyses without inclusion of moving boundaries or shape change effects to determine the mass fraction of the pellet in the melt phase. This melt mass fraction was

equated as an atmospheric source term implying that the formation of a melt layer is immediately stripped from the pellet core into fine droplets with further breakup due to aerodynamic forces and heating into an inhalable mist. The fuel's heat of fusion effect was incorporated into the analyses through alteration of the material's thermal capacitance (i.e., density x specific heat product) schedule at the melt failure criterion's temperature (i.e., $T_{\text{fail}} = T_{\text{melt}} - 500^\circ\text{R}$).

Further perspectives on the fuel reentry problem are available in References 40 and 41.

5. Fuel Energy Source Term

The energy source term of the plutonium dioxide fuel was included in RETAP's thermal analyses despite its limited influence on clad thermal response during the VVEJGA heat pulse flight periods. Its principal influence resides in the evaluation of the LWRHU's impact failure mode by partially governing the clad's thermal response during subsonic flight to impact. The VVEJGA studies assumed the fuel's one thermal watt of energy was uniformly distributed over the entire pellet.

D. Material Properties

Determination of the thermal response of a reentry structure requires specification of the thermodynamic property (specific heat) and the transport property (thermal conductivity) for all materials involved in the design. The need to obtain numerical solutions to the heat diffusion equation is caused, in part, by the problem's nonlinearity resulting from the strong dependence on temperature of the above properties. In addition to these properties, the solution of the surface energy balance (Figure 37) requires information on the thermal radiation properties, absorptivity and emissivity, to determine absorbed shock layer radiation and surface re-radiation. Additionally, these properties are required to determine radiation transfer at the internal interfaces.

The constituent materials of the LWRHU are shown in Figure 1. Briefly, they are aeroshell body and aeroshell end cap: Fine Weave Pierced Fabric (FWPFtm) 3-D carbon-carbon; insulator bodies (sleeves) and insulator cap (end plug): pyrolytic graphite; clad body assembly (fuel containment) including end closures, shim and vent frit: platinum-30% rhodium alloy (Pt-30Rh); and, fuel pellet: plutonium dioxide (PuO_2).

The following schedules of thermal diffusion properties, thermal radiative properties and phase change properties defined herein for the LWRHU constituent materials were the product of a literature survey and evaluation in support of the Cassini/ VVEJGA reentry safety studies. In some instances, this resulted in a departure from the schedules considered for the prior LWRHU Galileo/VEEGA reentry studies (Reference 42).

Gaseous conduction at the interface gaps was based on the thermal conductivity of air (at 1 atmosphere) using the National Bureau of Standard's schedule for temperature at below 2500°R and the Yos model for temperatures greater than 2500°R (Reference 43).

High temperature problems such as reentry are not only difficult to address due to the involved physics but also due to the uncertainty of physical property data required for such evaluations. The thermophysical data used in the Cassini studies are not exceptional in that the high temperature entries are based on extrapolations, or engineering judgment, from a lower temperature data base and represent a major source of uncertainty in studies of this type. This is particularly true for the fuel reentry problem where the focus is on the behavior of a high temperature melt layer. Due to a void of data in the melt phase, all thermal properties at or beyond the melt temperature of Pt-30Rh and PuO_2 were maintained at constant values. It is also noted that data indicated in the form of symbols in the material property presented in the succeeding figures are not necessarily experimental values. They may represent selected points from curves that have been faired or fitted to data from theoretical or experimental investigations. The cited references should be explored if further clarification of such data is desired.

1. Thermal Diffusion Properties

Reentry thermal response calculations for the LWRHU require numerical solutions of the thermal diffusion equation and, thereby, definition of the density, specific heat and thermal conductivity properties of the constituent materials are required. Further, the thermal conductivity properties must be defined on a directional basis when necessary to account for material processing effects.

a. Fine Weave Pierced Fabric 3-D Carbon-Carbon

(1) Thermal Conductivity (directional property)

The directional thermal conductivity schedules for FWPF[™] carbon-carbon material are shown in Figures 40 (a), (b) and (c) for the X (=Y) axis, 45° off X-Y axes and Z axis respectively. Comparison of the Air Force (P⁴) and Department of Energy Southern Research Institute (SoRI) data References 44 through 46 are presented along with the variability band for the Air Force data. The X (and Y) axis thermal conductivity schedule for the Cassini studies (Figure 40) remains the same as defined for the Galileo studies and represents the mid-range of the variability band. Published Textron data (Reference 47) are consistent with the principal data sources.

The 45° off X-Y axes location should provide the maximum off axes effect in transforming directional Cartesian data to the LWRHU's cylindrical geometry. Figure 40 (b) shows that available 45° data (Reference 48) is very close to the recommended X-axis data. As a consequence, all baseline studies utilized the X-axis schedule to represent radial and

circumferential conductivities rather than introducing the complexity of transforming available conductivity data to a cylindrical coordinate system. The X-axis schedule was also used in this manner in the Galileo studies.

The recommended Z-axis conductivity schedule represents the mid-range of the principal data sources as well as values considered in early design studies of the LWRHU (Reference 49) and the GPHS (Reference 50). The recommended schedule falls on the upper bound of the Air Force data. The Galileo/VEEGA analyses did not consider Z-axis data since 2-D modeling of the LWRHU was restricted to the r - θ plane.

(2) Thermal Capacitance (density x specific heat)

The density considered in the Cassini studies is $124.1 \text{ lb}_m/\text{ft}^3$ and represents the average density of certification data for eight FWPF[™] billets used in the manufacture of GPHS flight quality modules for the Cassini mission (Reference 51). This value remains very close to the density of $124.24 \text{ lb}_m/\text{ft}^3$ considered for the Galileo studies.

The specific heat schedule is shown in Figure 41 and departs from the schedule considered for Galileo. The basis for the Cassini schedule is the JANNAF data for solid carbon (Reference 52). For comparable heating conditions, the aeroshell thermal response at elevated temperatures will be greater using the Cassini schedule and thereby represents a conservative change from the Galileo studies.

b. Pyrolytic Graphite

(1) Thermal Conductivity (directional property)

The directional thermal conductivity schedules for PG are shown in Figures 42 (a) and (b) for the direction perpendicular to the deposition plane (i.e., the 'c' axis direction) and the direction parallel to the deposition plane (i.e., the 'a-b' alias basal plane direction) respectively. This material is highly anisotropic due to its highly ordered crystallite orientation in the 'a-b' directions but with variation in the stacking (i.e., spacing and tilt angle) of the crystallite layers in the 'c' direction. The degree of anisotropy is very sensitive to the parameters of the carbon vapor deposition and annealing processes.

The 'c' direction thermal conductivity for PG is the critical thermal property in defining the insulation effectiveness of the LWRHU's thermal design. This direction is aligned with the radial direction of the insulator bodies (i.e., the nested insulator sleeves) and the axial direction of the insulator caps to arrest heat flow to the clad fuel assembly. Definition of the 'c' direction property is differentiated between the insulator sleeves (for a cylindrical geometry) and insulator caps (a plate geometry). Justification for this differentiation is based on conformance test data for these manufactured parts (References 53 and 54) as well as

similar behavior demonstrated for these geometries in an early Los Alamos Scientific Laboratory (LASL) investigation of PG thermal conductivity (Reference 55). The Morrison data were based on processing parameters similar to those specified for the manufacture of the Cassini insulators.

The solid curve in Figure 42 (a) is the recommended 'c' direction schedule for the insulator sleeves and is the product of a task force investigation during the early design phases of the GPHS (References 56 and 57). The variability of this schedule is $\pm 25\%$ as indicated by the cross-hatched area. The curve's low temperature peak has been validated by other experimental investigations (Reference 58). The recommended constant at the high temperature end (Reference 57) infers an absence of delaminations consistent with the requirements contained in the sleeve's acceptance specification (Reference 59). With delaminations, the conductivity schedule would demonstrate a nonlinear dependency on temperature (i.e., $\approx T^3$) due to radiative transmission. It was noted that the task force data (Reference 57) agreed well with other PG investigations having comparable carbon vapor deposition parameters (References 60 and 61). The recommended schedule, however, is lower than the aforementioned Morrison data at moderate temperature levels. It is noted that the conformance datum for the sleeve falls below the insulator acceptance range (a favorable condition). The recommended 'c' schedule was also used in the Galileo studies for the insulator sleeve components.

Figure 42 (a) also contains the Cassini 'c' schedule defined for the insulator caps. This schedule is guided by Morrison's plate data and follows the trend established by the insulator sleeve schedule by fairing into a plateau value at elevated temperatures. The conformance datum for the insulator caps is consistent with the recommended schedule and is located near the upper bound of the acceptance range. The Morrison data for both cylinder and plate geometries suggest the presence of delaminations in the test specimens as indicated by the rapid increase of conductivity as temperatures approach 4000 °R. These data were discounted in defining the 'c' schedule. Differentiation of the 'c' direction conductivity for the insulator caps was not an issue in the Galileo studies since thermal modeling was restricted to the LWRHU's midspan r- θ plane.

Availability of thermal conductivity data for PG in the 'a-b' directions was more restrictive than the 'c' direction data base. Figure 42 (b) indicates that the recommended schedule for the Cassini studies is based on the tabular schedule reported in Reference 49. This schedule conforms with the curve reported by Super-Temp Company (Reference 58) with both curves converging to a common plateau value at elevated temperatures. As in the 'c' direction data base, experimental data above 5000°F in the parallel direction are unavailable. The conformance data for both the insulator sleeves and caps are at or above the upper bound of the acceptance specification for the Cassini mission. No attempt was made to adjust the selected conductivity schedule to these higher data. In maintaining a lower estimate for the 'a-b' conductivity, the effect on clad assembly thermal response is conservative by reducing the amount of heat flow shunted away from the design's critical thermal paths in the 'c' direction. The recommended 'a-b' schedule was also used in the Galileo studies.

(2) Thermal Capacitance (density x specific heat)

The PG's density and specific heat values used in reducing the GPHS task force's thermal diffusion data to obtain 'c' direction thermal conductivity (Reference 57) was selected for the Cassini studies. The density was defined at $137.3 \text{ lb}_m/\text{ft}^3$ (2.2 g/cm^3) and conforms with the Cassini acceptance specification for the insulator parts. This value was also used in the Galileo studies.

The specific heat schedule is shown in Figure 43 by the solid line curve extending to approximately 4000°R . The schedule represents a polynomial fit of average specific heat data published at the Purdue Thermophysical Research Center (Reference 62). These data were also used in the Galileo studies. The figure also contains specific heat data published by Super-Temp (Reference 58) and by JANNAF (Reference 52) which show good agreement over this temperature range. The Cassini schedule departs from the Galileo schedule at 4000°R . This schedule is guided by Super-Temp and JANNAF (theoretical) data to a plateau value of $0.520 \text{ BTU}/(\text{lb}_m^\circ\text{R})$. The Galileo curve continues to increase at a constant slope. For comparable heat loads, the lower thermal capacitance defined for the Cassini study at elevated temperatures will result in a higher thermal response of the insulator parts and, therefore, greater heat flow to the clad assembly.

c. Platinum-30% Rhodium Alloy

(1) Thermal Conductivity

Figure 44 presents the Pt-30Rh thermal conductivity schedule for the Cassini studies. Oak Ridge National Laboratory (ORNL) recommended this schedule in support of early LWRHU design studies (Reference 63). Also contained in this figure are conductivity values for other platinum alloys including Pt 3008 (References 64 and 65), Pt-20Rh, the clad material used in the SNAP 19 heat source (Reference 66), and Pt-40Rh (Reference 67). The Cassini schedule remains the same as used in the Galileo studies up to a temperature of approximately 2500°R . At this temperature, the Cassini schedule's departure from Galileo is based on similar conductivity/temperature trends demonstrated by the sibling alloys, Pt-20Rh and Pt-40Rh. No attempt was made to integrate into the Cassini conductivity schedule the effects of self-annealing and resulting grain growth due to the clad's temperature response during reentry. The Cassini schedule is not increased beyond the carbon eutectic melting point of Pt-30Rh as indicated by the cross hatched region in this figure. For comparable heating conditions, the slight departure of the Cassini schedule to lower conductivity values at elevated temperatures will not significantly affect the thermal response (i.e., radial gradients) of the clad due to metals' intrinsically high conductivity properties. The end result on heat transmission to the fuel is minor.

(2) Thermal Capacitance (density x specific heat)

Quoted values for Pt-30Rh alloy's density range from 1093.8 (Reference 49) to 1100.7 lb_m/ft³ (Reference 68). The lower value was considered in both the Cassini and Galileo studies.

Figure 45 presents the specific heat schedule considered in both the Cassini and Galileo studies as recommended by ORNL (Reference 63). It is clear from this figure that the recommended schedule for Pt-30Rh is represented by the specific heat property for Pt 3008. This appears to be a reasonable substitute given the slightly higher values of this property for the sibling alloy, Pt-20Rh.

d. Plutonium Dioxide

(1) Thermal Conductivity

Figure 46 presents the thermal conductivity of PuO₂ considered for the Cassini and Galileo studies. The Cassini study uses the conductivity schedule proposed by Haliburton NUS Corporation (Reference 69) during the GPHS Draft Environmental Impact Statement (DEIS) effort. In the temperature region of interest, the principal difference between the two schedules is Cassini's increase in conductivity at elevated temperatures due to radiation transmission. This increase is consistent with the fuel pellet's porosity at approximately 87% theoretical density. Other fuel conductivity data (References 70 through 73) are included in this figure and generally indicate good agreement over the temperature range of 1000 to 3000°R.

The effect of the change in schedules for the reentry of a full LWRHU assembly is likely minor by slightly increasing the fuel's internal thermal response for comparable heat loads. The consequence, however, will be more visible for bare fuel reentry involving formation of a melt front. This front will now travel somewhat further into the interior of the fuel pellet (or fragment) and thereby increase estimated source terms.

(2) Thermal Capacitance (density x specific heat)

The thermal power of the Galileo LWRHU fuel pellets was 1.1 thermal watts corresponding to a nominal density of 87.4% theoretical (or 625.3 lb_m/ft³, Reference 74). The same fuel density was assumed for the Cassini study and has since been substantiated by reported values in the LWRHU FSAR (draft) for the Cassini mission (Reference 75).

The specific heat schedule for the Cassini studies is shown in Figure 47. It is slightly altered from the schedule considered for the Galileo effort. The principal difference occurs at low temperatures and is of little consequence in governing the thermal response

of fuel for reentry conditions. The change to the General Electric recommended schedule (Reference 70) for the Cassini studies was based solely on the fact it provided lower values of specific heat than for Galileo in the high temperature region of interest. The differences are small though ($\leq 5\%$), and should provide only a minor increase in fuel thermal response for comparable heat loads.

2. Thermal Radiative Properties

In defining thermal radiative properties for the LWRHU's constituent materials, all components were considered opaque including such non-metallic solids as the FWPFtm aeroshell parts and the PG insulator parts. The resulting restriction on radiation processes to solely a surface effect required that only emittance (ϵ) and absorptance (α) properties be defined for the LWRHU materials. Due to a lack of absorptance data, Kirchoff's law (Reference 76) was invoked (as an expedient) such that $\alpha = \epsilon$ for all materials. Whenever possible, emittance properties were defined as a function of temperature with priority given to data in the following descending categories: total hemispherical, total normal, low wavelength (λ) normal, or any λ normal. The latter categories imply gray body radiation.

a. Fine Weave Pierced Fabric 3-D Carbon-Carbon (directional property)

Total hemispherical emittance of outgassed FWPFtm carbon-carbon was measured at Purdue University with the resulting data fitted for the X(=Y) axis and for the 'average' of the data in the X and Z axes (Reference 77). The schedules presented in Figure 48 (a) are based on these FWPFtm curve fits with the off-axis schedule being equated to the 'average' data.

It is indicated from this figure that the expected maximum temperature region for the FWPFtm aeroshell during reentry exceeds the range of applicability for the FWPFtm curve fits. The Z-axis schedule (inferred from the available curve fits) is shown to exceed the limiting black body value in the neighborhood of 7000°R with the 'off-axis' schedule proceeding in that direction as well. As a result, the schedules for the Z and the 'off-axis' directions were revised to arbitrarily approach 0.95 at 8000°R as shown in this figure's caption.

The Galileo studies used the X-axis emittance schedule to determine radiative transmission in the radial direction. The recommended schedule was changed to the 'off-axis' emittance curve for the Cassini studies and will result in a slightly higher radial heat flux from the aeroshell to the outer insulator sleeve 'for comparable temperature conditions'.

b. Pyrolytic Graphite (directional property)(1) 'C' Direction

The recommended total hemispherical emittance schedules in the 'c' direction are shown in Figure 48 (b) to be differentiated on the basis of surface finish. The 'as-deposited' surface schedules labeled 'early GPHS design' dates back to earlier mission safety analyses (e.g., Pioneer SNAP-19, Reference 66). These normal emittance data were reported by Super-Temp (Reference 58) and are based on SORI spectral data (Reference 78) integrated over the wavelength range of 0.20 to 0.35 microns (μ). The GPHS task force took issue with this schedule and recommended a total hemispherical schedule based on the 'Kingery' slope as shown in this figure (References 49 and 56). This schedule was endorsed for the Galileo studies for all PG surfaces and selected for the Cassini studies for 'as-deposited' surfaces. A departure in the Cassini schedule occurs at 6000°R by continuing on to 0.95 at 8000°R rather than being arbitrarily truncated at 0.8 as indicated for the Galileo schedule. At these temperatures, this change will have a minor effect on radiative transmission between the outer insulator sleeve/aeroshell body and insulator cap/aeroshell end cap components.

The Cassini schedule for 'machined' PG surfaces is guided by the experimental total hemispherical data from a Russian investigation of surface conditions on emittance (Reference 79). This departure from the Galileo studies will noticeably increase radiative transmission involving machined PG components. The machining process acts to agitate crystallite orientations, resulting in a higher degree of emittance as indicated in this figure. The Cassini curve was extended out to the reference 0.95 value at 8000°R. It is noted that this investigation's 'as-deposited' data agree reasonably well with the Kingery curve.

(2) 'A-B' Direction

There are very little data available in the open literature for pyrolytic graphite's 'a-b' directional emittance. The curve shown in Figure 48 (c) is total normal data integrated from the spectral measurements of SORI and reported by Super-Temp (References 58 and 78). These data were used in the early LWRHU design studies (Reference 49) and selected for both the Cassini and Galileo studies.

c. Platinum-30%Rhodium

The literature survey did not reveal any emittance data for Pt-30Rh but did provide total hemispherical emittance data for a sibling alloy, Pt-13Rh (Reference 80), the platinum alloy, Pt3008 (Reference 49), and pure platinum (References 62, 79 and 81). This group of data is presented in Figure 48 (d) along with the arbitrary 'constant emittance' schedule of 0.2 used in the Galileo studies (References 49). The recommended Cassini schedule is shown to be a composite guided by the Pt3008 data at low to moderate temperatures, the Pt-13Rh data at the

higher temperatures and extended at constant slope to the carbon eutectic temperature. This change from the Galileo schedule will result in a minor increase in radiative transmission from the clad assembly to the fuel pellet during a full LWRHU assembly reentry.

d. Plutonium Dioxide

The total hemispherical emittance schedule presented in Figure 48(e) is based on the curve fit provided by LASL (Reference 71) and linearly extended beyond its applicable range to values nearing the black body limit at PuO_2 's melt temperature. The Cassini's schedule arbitrarily departs from the Galileo schedule to fair into the reference 0.95 value at the melting point to remain consistent with the emittance extrapolations considered for the FWPF and PG materials. This departure from the Galileo schedule will result in a minor reduction in radiation relief during bare fuel reentry and thereby sustain the melt front slightly longer for critical reentries.

3. Phase Change Properties

The remaining thermophysical properties requiring definition for the LWRHU reentry studies are associated with phase changes for the Pt-30Rh and PuO_2 materials and include solid/liquid latent heats and associated melting temperatures. In the case of Pt-30Rh, the melt condition is defined as the carbon eutectic temperature resulting from contact of the clad body and clad caps with their PG neighbors. Additionally, the latent heat of vaporization for PuO_2 for the liquid/vapor phase change becomes a requirement if a 'stable' melt layer is formed on a reentering fuel pellet or fragment.

Solid/vapor phase change considerations for the FWPF[™] and PG materials are provided by the carbon-air thermochemistry models discussed in Section VII C. Liquefaction of these materials is not considered in these studies since LWRHU reentry surface pressures will be considerably lower than carbon's (graphite's) equilibrium triple point values (i.e., approximately 100 atmospheres).

a. Platinum-30%Rhodium

(1) Carbon Eutectic Temperature

Figures 44 and 45 show a carbon eutectic temperature band (the cross-hatched region) that ranges from 3550 to 3660°R. The upper bound of this eutectic range is the temperature typically quoted for this alloy (Reference 49) and considered in the Galileo studies. The lower bound temperature is an estimated value of Pt-30Rh in contact with a POCO grade of graphite (Reference 65). Since the alloy's carbon eutectic temperature is sensitive to the particular type of graphite, and since the graphite partner associated with the upper bound value could not be identified, the lower temperature was considered for the Cassini studies. This

represents a conservative change from the Galileo framework by slightly lowering the clad melt failure criterion and thereby resulting in a slightly earlier failure occurrence in a critical reentry heat pulse.

(2) Latent Heat of Fusion (ΔH_f)

The literature search did not reveal direct values for $\Delta H_{f,Pt-30Rh}$. Alternatively, a composite value was determined as the product of the weight fractions of the participating elements and their respective ΔH_f values. The latent heats of fusion for platinum and rhodium (Reference 81) are given as:

$$\begin{aligned}\Delta H_{f,Pt} &= 43.2 \text{ BTU/lb}_m \text{ and} \\ \Delta H_{f,Rh} &= 99.5 \text{ BTU/lb}_m\end{aligned}$$

with the resulting value for Pt-30Rh determined as:

$$\Delta H_{f,Pt-30Rh} = 60.1 \text{ BTU/lb}_m.$$

This value is slightly higher than the value considered for the Galileo studies at 57.5 BTU/lb_m and will slightly inhibit the progression of a melt front for bare fuel reentries.

b. Plutonium Dioxide

(1) Melt Temperature

The melt temperature of PuO₂ for use in the GPHS Cassini/VVEJGA studies was recommended by Martin Marietta AstroSpace (Reference 51) at:

$$T_{\text{melt,PuO}_2} = 4812 \text{ }^\circ\text{R}.$$

The recommendation is based on cited temperatures in several references (References 83 through 85). This value was also used in the LWRHU Galileo and Cassini studies. Eutectic formation of PuO₂ with Pt-30Rh alloy was not considered in either study.

(2) Latent Heat of Fusion (ΔH_f)

There are several values quoted for the heat of fusion for PuO₂ including:

$$\begin{aligned}\Delta H_{f,PuO_2} &= 112.0 \text{ BTU/lb}_m \text{ (General Electric, Reference 85),} \\ \Delta H_{f,PuO_2} &= 117.0 \text{ BTU/lb}_m \text{ (LASL, Reference 70) and} \\ \Delta H_{f,PuO_2} &= 101.0 \text{ BTU/lb}_m \text{ (Aerotherm Corporation, Reference 88).}\end{aligned}$$

The Cassini study considered an average of the above values:

$$\Delta H_{f, \text{PuO}_2} (\text{ave}) = 110.0 \text{ BTU/lb}_m$$

which is slightly lower than the above General Electric value used in the Galileo studies.

E. Aerothermodynamics

Due to the high energies of the VVEJGA reentries, the aerothermodynamics for the LWRHU are complicated by the addition of shock layer radiation as a mode of heat transfer. Furthermore, both the radiative and convective modes are influenced by chemistry effects that further complicate the reentry environments. This is illustrated in Figure 49 which shows thresholds for both the dissociation and ionization processes as well as the kinetic threshold as overlays on the trajectory tracks for the various reentry angles of the Cassini-VVEJGA reentry map. These thresholds are very approximate but serve to illustrate the various aerothermodynamic regimes encountered by a LWRHU reentry. Also, it is noted that the kinetic threshold shown here is for a one-foot radius-sphere; however, for the smaller LWRHU leading edge, this threshold will be translated to lower altitudes since, for this geometry, the forward (stagnation) shock layer thickness is considerably smaller relative to required kinetic relaxation distances. This figure indicates that the high energy VVEJGA reentries result in a highly ionized (and therefore radiating) shock layer in the stagnation region. It also indicates that nonequilibrium chemistry is probably a consideration in the maximum heating region for most of the reentry zones. This has implications regarding both the radiative and convective heat transfer modes as will be discussed later.

LWRHU aerothermodynamics occurring during the hypersonic heat pulse for the Cassini/VVEJGA class of reentries can be characterized by a multicomponent, reactive flow field with strong gas dynamic/radiation and ablation coupling. Additionally, for certain regions in the VVEJGA reentry corridor, the LWRHU will experience chemical and thermodynamic nonequilibrium flow fields. The high energy states and complexity of the VVEJGA reentry flow fields require numerical solutions for surface aerothermodynamics using advanced computational fluid dynamics (CFD) techniques such as the Lockheed Martin Missiles and Space (LMMS) flow field solver (RACER) and the Langley Optimized Radiative Non-Equilibrium (LORAN-C) codes employed in the GPHS/VVEJGA analyses (Reference 89). The LWRHU/VVEJGA reentry analyses were not supported by such CFD facilities. The available means for this study were engineering methods used in prior reentry safety studies, model/method syntheses from available experimental and numerical data and engineering judgment. Recognizing the broad range of uncertainties associated with this approach, the VVEJGA reentry analyses were steered in a conservative direction through (a) specification of failure mode criteria, (b) imposed structural breakup sequence of the LWRHU, (c) selection of thermophysical data and (d) selection of environment/response models.

The following discussion along with Table 8 provides a brief commentary on the considerable LWRHU aerothermodynamics defined for the (a) side-on stable, (b) side-on spinning and (c) random tumbling flight orientations. Table 8 contains quick look summaries of the computational methods. Also included in this section is an extensive list of references providing further background material. For the VVEJGA studies, aerothermodynamics were defined only for the hypersonic flow regime ($M_\infty \geq 5.0$) encompassing the reentry heat pulse period.

1. General Methodology, Full LWRHU Assembly

The development of VVEJGA aerothermodynamics for the LWRHU reentry simulations follows the same general computational flow as employed in the Galileo/VEEGA studies. This flow is described by four sequential steps:

- a. The initial step requires determination of reference convective and radiative heating rates as a function of reentry flight time using JHU/APL's TDOF trajectory code (Reference 90).
- b. The reference convective and radiative heating rate histories from the TDOF results are transformed to corresponding body reference heating rates on the LWRHU.
- c. Local heating rate distributions are determined from heating factor (i.e., local to body reference heating rate ratio) distributions times the body reference heating rate determined in (ii).
- d. Local heating rate distributions are corrected for low density and surface mass transfer effects due to thermochemical ablation.

The TDOF reference heating rates provide the required trajectory time dependency while the heating rate distributions are typically held constant with time in the hypersonic regime and provide spatial dependency.

2. Reference Convective and Free Molecule Heating, Full LWRHU Assembly

Convective heating is considered in the generic sense to represent surface energy transport due to both 'particle' conduction and mass diffusion for a multicomponent flow field in the continuum flow regime and transitional heating (including the above processes) in the kinetic (low density) flow regime. For continuum flow, reference convective heating represents a laminar, stagnation heating rate to a 1-foot radius, smooth, cold wall sphere in absence of surface mass transfer or radiation coupling effects. Predictions are based on the Detra, Kemp and Riddell correlation (Reference 91) which was developed from numerical and experimental data largely representative of a dissociated shock layer (References 92, 93). As indicated from Figure 50, the

correlation performs well against high energy shock tube data that extend well into the ionization regime. It has been demonstrated that this correlation matches the data aggregate's least squares fit and is superior to a number of the early ionization stagnation theories (Reference 94).

The reference heating rate in the free molecule flow regime is represented by the total available flow energy, $(\rho_\infty V_\infty)^3/2$, to a surface perpendicular to the particle stream with a thermal accommodation coefficient of unity (Reference 95). This reference value also equates to the body reference condition represented by the LWRHU's mid-span stagnation condition in a side-on stable orientation.

3. Reference (and Body Reference) Radiative Heating, Full LWRHU Assembly

The TDOF reference and body reference radiative heating rates are equivalent in the VVEJGA study and represent the same stagnation conditions discussed above for the free molecule heating condition. The mid-span location was selected to isolate the heating rates from flow expansion effects occurring at the cylindrical end stations (end effects). The radiative heating rate tables developed by Sutton and Hartung (Reference 96) represent numerical solutions from NASA's Radiating, Inviscid Flow, Stagnation Point (RIFSP) code (Reference 97) for a broad matrix of velocity and altitude conditions over a spherical nose radii range from 0.05 to 10.0 meters. The code utilizes the radiation equilibrium transport model (RAD/EQUIL) (References 98 and 99) which provides for both atomic and continuum radiation transfer mechanisms in air and has demonstrated reasonable performance against numerous ground-based and flight experimental test data (Reference 100). This matrix of data has been incorporated into the TDOF code and is accessed by a user supplied effective spherical radius for the reference LWRHU geometry. The equivalent spherical radius for the side-on LWRHU configuration was based on equating the LWRHU's stagnation shock layer thickness (i.e., shock standoff for adiabatic flow) with the stagnation shock standoff for a spherical geometry with nose radius R (Reference 101). Downstream heating distributions were determined from a radiating flow field code for transverse cylinders which uses an approximate radiation transport model. This code, obtained from the NASA-Langley Research Center (Olstad, Reference 102) is felt to provide a good engineering approximation for downstream heating histories in the form of the ratio: $\dot{q}(local) / \dot{q}(stag)$. These ratios are subsequently reduced using the stagnation values obtained from Aerotherm's Radiation/Equilibrium Transfer Code (RAD/EQUIL).

The neglect of the shock layer's radiation cooling for VVEJGA's high energy flight conditions leads to an overestimation of the effective spherical radius and thereby a conservative estimate of radiative heating at the body reference location. For added conservatism, it is noted that the data are products of inviscid flow field solutions and are not adjusted in the VVEJGA studies for the shock layer's cooler viscous sublayer (presumably a self-absorption effect). It has been argued that this effect can noticeably reduce surface radiation (Reference 103).

based on comparisons of the Sutton-Hartung data with solutions obtained with the Radiation Shock Layer Equilibrium (RASLE) code (Reference 104). It is further argued that an equilibrium radiation transport model (i.e., the RAD/EQUIL code) likely overestimates radiative heating for the VVEJGA 'shallow' reentries where nonequilibrium flow phenomena are present.

4. Body Reference Convective Heating, Full LWRHU Assembly

As previously indicated for the radiative heating mode, the body reference condition was the mid-span location of the LWRHU in a side-on stable orientation. Here again, the mid-span convective heating rates are assumed unaffected by end effects. Transformation of the TDOF reference heating rates to the body reference location accounts for flow dimensionality (axisymmetric vs two-dimensional flows), stagnation velocity gradients (sphere vs transverse cylinder) and scaling effects (body radii, reference sphere to LWRHU leading edge). The stagnation velocity gradient ratio of a transverse cylinder to a sphere of equal radii is very close to unity in the hypersonic regime as indicated in Figure 51 (Reference 105). The full conversion factor for velocity gradient and scaling effects are described by

$$\frac{q_{GEO,c}}{q_{ref,c}} = MF * \left(\frac{\beta_{GEO}}{\beta_s}\right)^{0.5} * \left(\frac{1}{\sqrt{2}}\right)^{\delta} * \left(\frac{R_s}{b/2.0}\right)^{0.5} * \left[\sqrt{1 + \left(\frac{b}{1}\right)^{0.5}}\right]^{\delta'}$$

where $\frac{q_{GEO,c}}{q_{ref,c}}$ = geometry specific stagnation convective heat flux ratio

b, l = width, length of reentry body

R_s = reference sphere radius (=12")

$q_{ref,c}$ = reference sphere stagnation heating rate

β_s = stagnation velocity gradient parameter for sphere

β_{GEO} = stagnation velocity gradient parameter for specific geometry

δ = geometric constant

0 for axisymmetric flow,

1 for 2-D planar flow (cylinder) or 3-D flat plate

δ' = geometric constant

0 for planar flow (transverse flow), or axisymmetric

1 for 3-D flat plate normal flow.

MF = weighting factor for supersonic or subsonic heating, usually at unity

5. Adjustments to Body Reference Heating Rates

a. Precursor Heating

The body reference radiative heating rates were adjusted for precursor effects. This effect essentially represents a feedback of energy into the shock layer and an incremental increase in surface radiation due to absorption of radiation emitted from the hot shock layer by the cool ambient air upstream of the leading shock wave. The compression of this higher

enthalpy ambient stream leads to higher shock layer enthalpies and a fractional recovery of the shock layer energy lost by radiation cooling. Data on this effect are scattered and highly dependent upon flight velocities. Based on some early investigations (References 106 to 110), an approximate model was formulated in which stagnation radiative heating rates were increased by 15% for velocities at or greater than 65K fps and linearly decreased from this value at 65K to 0% at 40K fps. This effect is second order compared to the uncertainties associated with radiative heating at VVEJGA level energies but has been included in the simulations to acknowledge its presence during VVEJGA reentries.

b. Radiation Coupling

Another effect attributed to high intensity shock layer radiation is its coupling effect on convective heating. The coupling effect identifies the changes in the enthalpy and concentration surface gradients defining convective heating due to radiation cooling of the shock layer and self-absorption in the viscous sublayer. The data from the GPHS/VVEJGA studies did not provide insight on this interaction due to the overlying presence of reactive and radiating ablation products. Literature (References 110 to 113) revealed conflicting data on this effect for non-ablating surfaces but, in general, suggested that coupling increased convective heating to large radii bodies and decreased heating to small radii bodies such as the LWRHU. Based on this observation, the VVEJGA studies neglected any coupling adjustments to body reference convective heating rates which suggests further conservatism in the analyses. This effect becomes muted for massive blowing of ablating surfaces that blocks surface convective heating to diminished levels (i.e., at or near zero surface gradients in the ablation layer).

c. Catalytic Surface Effects

Catalytic recombination effects on body reference convective heating was not considered in these studies due to the absence of recombination coefficient data for carbon-carbons in the open literature. The use of the Detra, Kemp and Riddell equation to predict reference heating rates infers thermochemical equilibrium surface conditions via its excellent correlation of numerical equilibria stagnation data (Reference 92). The assumption of a thermochemical equilibrium surface boundary condition provides a close approximation to a fully catalytic surface (Reference 114) and hence, maximum convective heating rates relative to catalytic surface reactions.

6. Other Body Reference Variables:

Two other aerothermodynamic body reference variables required in the studies are the total enthalpy (based on the stream's total kinetic energy) and stagnation pressure (aft of the leading shock wave). Neither of these body reference variables are considered to be influenced by end effects and both equate to the reference histories provided by the TDOD code. Similar to the body reference heating rate data, these body reference variables are reduced by

recovery enthalpy and static pressure factors (again, local to reference ratios) specific to the LWRHU's local values as a function of time. Local recovery enthalpy allows adjustments to convective heating for 'hot wall' effects and to reduce convective heating to a Stanton Number in evaluating the numerical solution's surface energy boundary condition. Local static pressure assists in evaluating local thermochemical ablation mass fluxes due to the ablation model's bivariate dependency on surface temperature and pressure.

7. Heating Factor Distributions

Heating factor distributions were developed for three general flight orientations:

- side-on stable,
- side-on spinning and
- random tumbling.

From a heating viewpoint, the side-on stable orientation was an expedient model to represent the class of motions where the longitudinal axis (generatrix) is mostly perpendicular to the wind, 90° angle of attack, α . The expediency relates to the ability to estimate aerothermodynamics for the side-on orientation with available computational means while generally providing a conservative estimate of the response parameters for the VVEJGA environment. The possible exception is a psuedo-steady angle of attack orientation; however, the means to estimate shock layer radiation at angle of attack were not available for these studies. Furthermore, ablation shape change effects on flight trajectory, flight motion and aerothermodynamics for such an orientation are first order and cannot be estimated with JHU/APL's current arsenal of codes. Also, the end-on stable case was not examined specifically since it proved to be less critical than the side-on stable orientation in the Galileo/VEEGA studies (Reference 115) and is not a likely flight orientation due to the LWRHU's small fineness ratio.

Again, from a heating viewpoint, the LWRHU random tumbling orientation represents flight motions which possess angular rotation about the longitudinal axis. Given the small fineness ratio of the LWRHU and chaotic release conditions from the Cassini spacecraft, this is a highly likely flight orientation. It inherently contains greater uncertainty in estimating heating factor distributions. The side-on spinning orientation has full rotation about the LWRHU's longitudinal axis.

a. Side-On Stable Orientation, Full LWRHU Assembly

Since the LWRHU's ablation failure criterion is declared as an incipient breach of the aeroshell in the stagnation region, construction of heating factor distributions for this orientation are essentially focused on the windward flow field region of the LWRHU. The

VVEJGA baseline studies considered only the Option 1 heating factor distributions presented in the following figures.

(1) Cylindrical Surface

Figure 52 compares theoretical (References 116 to 118) versus experimental (References 118 to 120) circumferential convective (continuum) heating rates for a transverse cylinder over a central angle (θ) range of 90° . The VVEJGA studies use factor distribution based on the Kemp/Rose/Detra theory instead of the Galileo/VEEGA distribution (i.e., Lees $M_\infty = 3.0$ distribution) since it bounded most of the downstream experimental data. Figure 52 indicates the VVEJGA model is slightly conservative relative to the VEEGA model at the downstream locations. The free molecule heating factor distribution ($\cos(\theta)$ function) remained the same as considered in the Galileo/VEEGA studies.

Figure 53 compares an early LWRHU design curve for axial heating distributions along the stagnation line (Reference 121) versus experimental data measured for the MultiHundred Watt (MHW) heat source, a right cylinder configuration (Reference 119). The experimental data were chosen as the better axial stagnation heating distribution model for the VVEJGA studies since the LWRHU design distribution was largely based on conservative engineering judgment. The local circumferential factor distribution as a function of axial distance from the mid-span location becomes the product of Figures 52 and 53 Option 1 distributions. Figure 53 also indicates the free molecule axial heating factor distribution along the stagnation line is absent of end effects.

Circumferential radiative heating factor distributions were estimated from a radiating inviscid flow field code using an approximate (step) radiation transport model (References 102 and 122). Three trajectories, representative of the shallow, moderate and steep class of VVEJGA reentries were examined. To account for uncertainty in the radiation transport step model, the distribution selected for the VVEJGA studies was a trigonometric function ($\cos^{3/2}(\theta) + B\sin^2(\theta)$) that bounded the numerical data. This model not only introduced conservatism in the forward windward region of the LWRHU but also eliminated the time dependency of the numerical data. The VVEJGA distribution model and associated numerical data for a flight path angle of -90° is presented in Figure 54.

The only data source providing a suggestion of axial radiative heating distributions was the end face radial heating distributions generated by LMMS for the right cylinder simulation of a broadface stable GPHS module. The end effects (i.e., flow expansion) for the right cylinder's axisymmetric flow will be more exaggerated than the three-dimensional flow for the side-on LWRHU in reducing radiative heating rates. Figure 55 presents distributions determined by LMMS for the GPHS simulation with and without ablation (Reference 123). Using the guidance provided by LMMS on zero ablation distribution, the LWRHU's VVEJGA model was defined to provide a reduced influence from end effects. Here

again, the circumferential radiative heating factor distributions as a function of axial location were assumed to be the product of the VVEJGA distributions recommended in Figures 54 and 55.

Several sources of static pressure factor distributions for transverse cylinders (References 124 to 126) were examined during this study with all demonstrating the expected Newtonian behavior in the near stagnation region. The curve fit distributions of Miller (Reference 124) were selected for the VVEJGA model since they provided both circumferential and axial variations and correspondingly lower pressures at the mid-span location ($z/L = 0$) than the Galileo/VEEGA model (Gregorek and Korkan, Reference 125). For a fixed surface temperature, a lower static (surface) pressure will translate to a higher aeroshell ablation mass flux for the VVEJGA studies. The VVEJGA, VEEGA and the modified Newtonian pressure distributions are compared in Figure 56. To expedite data input, the windward recovery enthalpy factor distribution remained the same as the Galileo/VEEGA model. This distribution was based on an isentropic, perfect gas (calorically and thermally perfect) expansion using the Gregorek and Korkan static pressure distribution.

Leeward side aerothermodynamic distributions ($90^\circ \leq \theta \leq 180^\circ$) were approximated by setting the free molecule and radiation distribution factors to zero, the convective heating factor at 6% to 8% and the static pressure at about 2% to 4%. The recovery enthalpy factor was arbitrarily set at unity which acts to underestimate ablation losses; however, the wake region is well beyond the 'region of influence' for aeroshell ablation failures for this orientation.

(2) End Face

Similar to the leeward side of the cylindrical surface, aerothermodynamic parameters for the end face were approximated since this face is not influential in the side-on stable orientation. The radiative and free molecule factor distributions were set to zero and the convective heating distribution at a constant value of 10% to provide a conservative value to reduce end losses. The recovery enthalpy and static pressures were set to the leeward values which will affect prediction accuracy of ablation losses but in a non-critical ablation region.

b. Side-On Spinning Orientation, Full LWRHU Assembly

(1) Cylindrical Surface

For this flight orientation, the spin rates were assumed high enough to permit smearing (i.e., integration over a θ range of 0° to 180°) of the distributions determined for the side-on stable case. Consequently, for any given axial location, all aerothermodynamic 'spin' factors were considered circumferentially uniform on the cylindrical surface. No adjustments were made to the side-on stable free molecule factor distributions in obtaining the free molecule spin factor. Similarly, no adjustments were made to the convective

heating factor distributions developed as a function of axial location; however, the radiative heating factor distributions were adjusted on the leeward side from the prior zero heating specification to a range varying from 10% at $\theta = 120^\circ$ to 5% at 180° . This introduces a slight conservatism in the radiative spin factor and is based on the rationale that a low velocity wake structure may raise base temperatures to sufficient levels to emit accountable levels of radiation.

The leeward factor distributions for recovery enthalpy and pressure become significantly more influential for the spinning case since they now contribute directly to the uniform spinning factors used to determine thermochemical ablation. A study was conducted that examined hypersonic wake flow field literature to establish more realistic recovery enthalpy distribution in the wake region. Upon determining that the LWRHU's near wake flow field structure was laminar (References 127, 128), the spherical, low density temperature data of Dogra, et al. (Reference 129) were selected for the VVEJGA shallow reentry class (i.e., for $\gamma \leq 15^\circ$). For the moderate to steep reentry classes ($\gamma \geq 15^\circ$), the only high density data that appeared useful were the blunt cone data of Bulmer (Reference 130). For low velocity, recirculation flow in the wake, the ratio of local recovery to stagnation temperature data (as determined from Bulmer's local static to stagnation temperature ratios) were equated to the local recovery enthalpy ratio. The windward distribution remained the same as indicated for the side-on stable case.

A second study was conducted to more accurately describe static pressures in the leeward flow field. Literature revealed that the leeward separation point for supersonic, two-dimensional (2-D) flow for transverse cylinders was approximately 120° (References 131 to 133) followed by a constant static pressure field in the wake. In determining the pressure spin factors, the pressure distributions for the side-on stable case were adjusted in the wake region using Gregorek and Korkan's static pressure factor (i.e., 2%).

(2) End Face

All the aerothermodynamic factors remained the same as assigned for the side-on stable case.

c. Random Tumbling Orientation, Full LWRHU Assembly

The random tumbling flight orientation represents a likely class of motion for the LWRHU. For purposes of analyses, this motion was depicted as a spinning right cylinder that was also rotating over a total angle of attack sweep of 90° . As an expedient for conducting the study, it was assumed that rotational rates were sufficiently large to permit smearing of the heating factor distributions as a function of θ and α . Clearly, to define aerothermodynamics for this motion, free molecule, convective and radiative heating factor distributions would need to be determined as a function of angular displacement for the LWRHU's body axis system. Program constraints did not permit development of this bank of data via CFD technology. Alternatively, the approximate methodology of Klett (Reference 134) was followed closely to define the free

molecule and convective heating random tumbling factors. Klett's study developed methods for determining drag coefficients and convective heating to a right cylinder for both the free molecule and laminar continuum flow regimes at orientations of end-on, side-on, end-over-end and random tumbling. The random tumbling factor for radiative heating essentially came down to use of engineering judgment in determining angle of attack dependency.

For all aerothermodynamic parameters, the random tumbling factor was assumed to be the product of the local spin factor times the stagnation line angle of attack factor. As with the other flight orientation cases, the random tumbling factors were ratios in which the denominator represented the parameter's body reference value. All spin factors were based on the results of the prior side-on spinning study.

(1) Cylindrical Surface

A study was conducted that examined stagnation line convective heating theory and experimental data for yawed (or swept), circular cylinders (References 118, 120, 135 to 140) to obtain an engineering relationship for α dependency. Defining $\alpha = 0^\circ$ as the LWRHU's end-on orientation along the wind velocity vector, and yaw (λ) = 0° as flow perpendicular to a transverse cylinder, then α becomes the complement of λ (i.e., $\alpha = 90^\circ - \lambda$). The engineering relationship of Sayano and Greenwald (Reference 139) was chosen due to its simplistic form and its good agreement with the experimental data of Bergquaum (Reference 140). Bergquaum measured convective heating as a function of yaw angle at various axial stations along a 1.25-inch diameter right circular cylinder. End effects could only be qualitatively assessed. The data indicate that end effects on convective heating rates to the cylindrical surface occur more noticeably at low angles of attack and therefore do not greatly affect the integrated average. Sayano and Greenwald's convective heating factor distribution is shown in Figure 57 with the data at 0° representing Klett's flat plate data at the LWRHU's thermal model nodal stations. The random tumbling free molecule heating factor was taken directly from Klett.

Applicable data or theories for stagnation line shock layer radiation on cylindrical surfaces at angle of attack were not available for this study. Consequently, shock layer radiation dependency on angle of attack was assumed to take a similar functional form as demonstrated for θ (i.e., the side-on stable distribution). The function used a $\cos(\alpha)$ dependency rather than $\cos(\alpha)^{3/2}$ to allow for uncertainties in developing the random tumbling factor.

The product of the spin factor times the stagnation line angle of attack factor was also considered for the static pressure factor and is believed to result in conservatively low pressure values (relative to thermochemical ablation). Carroll's curve fit of mid-span experimental data for cylinders (Reference 118) was used to express stagnation line pressure as a function of α . The recovery enthalpy factor utilized Feller's expression for stagnation line recovery temperature (Reference 135) as a function of sweep angle and, once again, implies perfect gas flow theory.

(2) End Face

The convective and radiative heating factor distributions were integrated over an α sweep of 180° and normalized to the stagnation heating value at $\alpha = 0^\circ$ (the end-on orientation). The normalization parameter was subsequently transformed to the body reference heating rates. For convective heating, this transformation involved considerations of changes in flow dimensionality (i.e., axisymmetric vs 2-D flow) and stagnation velocity gradient (flat face cylinder vs. transverse cylinder, References 105, 141). For radiative heating, the transformation assumed a ratio of the effective spherical radii (disc to transverse cylinder) raised to a power n . The effective spherical radii were based on relationships for adiabatic shock layers (References 101, 142) and the power n was determined from the tabular data of Sutton and Hartung (Reference 78).

Klett has curve fitted the convective heating distribution on the end face at $\alpha = 0^\circ$ based on available flat face cylinder experimental data (References 117, 143 and 144). This heating factor distribution is shown in Figure 58. Klett has reported the average heating to a disc at angle of attack relative to the average heating at the $\alpha = 0^\circ$ position based on a composite of experimental data (References 144, 145), laminar flat plate theory at $\alpha = 90^\circ$ and representative values of base heating at $\alpha = 180^\circ$ (References 146, 147). This average heating distribution is shown in Figure 59. Rather than applying uniform heating over the end face based on the integrated average heating over the 180° α sweep, this study redistributed the heating over radial lengths of the LWRHU thermal model's end face nodes, $(\Delta r/R)_{i=1,2,\text{etc}}$ in proportion to the local integrated heating over the $(\Delta r/R)_{i=1,2,\text{etc}}$ to the integrated average over the entire face using the $\alpha = 0^\circ$ heating factor distribution of Figure 58. Use of the data in Figures 58 and 59 provided the angle of attack average per end face node in the proper form prior to transformation to the body reference condition. The angle of attack factor for free molecule heating was taken directly from Klett which was based on a reduced form of Oppenheim's theory for flat plates at α for windward, uniform heating (Reference 148) and zero leeward side heating ($90^\circ \leq \alpha \leq 180^\circ$).

Literature did not provide guidance on shock layer radiative heating distributions for discs at angle of attack; however, the flow field of a disc at angle of attack is three-dimensional which will act to reduce radiative heating levels due to flow expansion effects. This 3-D effect was assumed to be related to the disc's local sweep angle. Due to lack of data, this study was simplified by assuming uniform heating at the stagnation value over the disc at $\alpha = 0^\circ$ whereas the average windward heating ($0^\circ \leq \alpha \leq 90^\circ$) was the integrated product of the heating variation with angle of attack and disc leading edge sweep angle. Both of the variations assumed the general trigonometric functional form as discussed for the angle of attack and spin angle for the cylindrical section. On the leeward side, the average heating factor (relative to the $\alpha = 0^\circ$ stagnation value) was conservatively assumed to be 10%.

Similar to the radiative heating dilemma, static pressure and recovery enthalpy data for a disc at angle of attack were also unavailable for this study. Time constraints did not permit investigation of flat plate literature. Consequently, engineering judgement was implemented commencing with the requirement that the disc be treated as a constant (average) pressure surface. The average static pressure factor at $\alpha = 0^\circ$ was based on the integration of Love's correlation for a flat face cylinder (Reference 149). This distribution along with experimental data for this configuration (References 141, 150), is shown in Figure 60. The average disc pressure at angle of attack (relative to the average at $\alpha = 0^\circ$) was assumed to have the same functional form as considered for the cylindrical surface. The resulting integrated average was further reduced by an arbitrary factor of 0.75 to account for 3-D flow effects. Recovery enthalpies at windward angles of attack were determined from isentropic flow theory based on the average static pressure ratio as a function of α . For the leeward α range, recovery enthalpies were guided by recovery temperature data in cylindrical wakes as a function of yaw angle (Reference 136). This resulted in assuming a constant recovery enthalpy factor of 0.8.

8. Corrections to Local Heating Rates

a. Low Density Effects

The local convective heating rates are corrected for low density effects identified with the kinetic flow regimes (Reference 151) using the bridging relationship of Matting (Reference 152). This bridging relationship is a simple exponential function based on the current, local ratio of the limiting free molecule to thin shear layer (high density) convective heating rates with the convective heating rate corrected for vorticity effects. This density correction is applied to the heating rates associated with the spinning and random tumbling orientations, and to the windward regions for stable orientation. Once the heating ratio exceeds a value of ten, the bridging value has essentially merged to the high density continuum value and this correction is zero.

b. Surface Mass Transfer Effects, Convective Heating

The blowing (or blockage) effect on convective heating due to thermochemical ablation is based on the correlation of Putz and Bartlett (Reference 153). The correlation is based on a matrix of multicomponent, reacting boundary layer solutions for a carbon/air system in thermochemical equilibria. This correlation represents both similar and non-similar (i.e., downstream) solutions and accounts for boundary layer mass addition and homogeneous reactions on local surface enthalpy gradients. Unfortunately, the Putz and Bartlett correlations did not permit stable solutions for the high energy VVEJGA reentries in regions producing high ablation rates. This instability was also experienced in the Galileo studies and the corrective action (Reference 154) involving the substitution of the generic Mickley-Spalding blowing correlation (Reference 155) was also adopted for the VVEJGA studies. As indicated in

Figure 61, the Mickley-Spalding correlation provides an upper bound on convective heating blockage relative to the preferred Putz and Bartlett expression.

c. Surface Mass Transfer Effects, Radiative Heating

The general effect of carbon thermochemical ablation on shock layer radiation is to reduce surface radiation by self-absorption in a carbon vapor laden viscous sublayer. This form of blockage was modeled for the VVEJGA studies from the early investigations of Moss and others (References 97, 156, and 157) and the more recent studies by Gupta, et al. (Reference 111). Regarding the investigations of Moss and Gupta, radiation/ablation coupled solutions were performed using a viscous shock layer technique for multicomponent, reacting gas mixtures in thermochemical equilibria with radiation transport models, the Louisiana State University Radiation Transport model (LRAD-3) (Moss) and Aerotherm's Radiation Transport code (RADICAL) (Gupta, et al.), and injectants of air and carbon phenolic. The high carbon yield of carbon phenolic ablation species was assumed representative of the FWPFtm carbon-carbon ablation products. Figure 62 presents the numerical data and the VVEJGA model for continuum, stagnation flow and indicates that carbon vapor blockage can account for approximately 40% of incident radiation at high ablation rates. The VVEJGA model was assumed to be valid at downstream locations and to linearly decrease from the continuum value at a rarefaction threshold (Cheng's parameter, Figure 63) to zero at the free molecule threshold (Reference 158, 159). The rarefaction threshold is representative of a fully merged shock layer, and the molecular threshold is to account for low density effects in the kinetic flow regimes. Cheng's rare faction parameter, K_r , is defined as $K_r^2 = 0.6/(K_n M_\infty^{0.5})$ where K_n is Knudsen's number.

Radiative and ablative coupled flow solutions in the kinetic regimes are neither available nor well understood at this time. However, a rational conjecture is that increased rarefaction of the shock layer (and more specifically, the ablation sublayer) should reduce the effectiveness of the sublayer blockage due to the reduced number densities and absorption cross sections of the injectant species.

9. Fuel Pellet Aerothermodynamics

By modeling the fuel pellet as a right cylinder, the aerothermodynamics of the full LWRHU assembly could be directly employed to define the aerothermodynamics of the pellet. The general methodology and the determination of body reference heating rates remained the same except for geometry scaling effects (i.e., change in the cylindrical radius). Furthermore, the heating factor distributions developed for the LWRHU were assumed valid for the pellet by adjusting the LWRHU data for the various flight orientations according to the pellet thermal model's r/R (local nodal to end face radii) location of radial surface nodes and, likewise, the z/L (local nodal to mid-span axial length) location of the axial nodes. No adjustments were made to the circumferential distributions used to define the side-on stable and spinning orientations.

F. Result of Analyses

The RETAP simulations are used to generate the thermal and ablation response of the LWRHU model exposed to the previously discussed trajectory environments. The overall material ablation failure results are illustrated in Figure 64. This diagram shows the altitude and velocity at which each reentry analysis resulted in a 75% wall thickness recession. As indicated, all reentry angles for the side-on stable orientation will result in failure. This represents the most extreme reentry orientation. Also shown in Figure 64 is a representation of the fuel (PuO_2) melt boundary developed at Sandia National Laboratory for a 250- μm sphere in a stable orientation, Reference 161. The altitude and velocity of expected fuel release conditions for the Cassini mission LWRHU are well in excess of the melt/no melt boundary shown in the diagram.

1. Side-on Stable Orientation, LWRHU

The most severe recession case examined for the side-on stable orientation is the -90° reentry flight path. As indicated in Figure 65-A, The surface temperature nears 8000 °R in approximately 2 seconds. The heat pulse is of such short duration, though, that the internal components, specifically the clad and fuel, do not show significant thermal response. Figure 65-B shows the mass transfer parameter from the Lawrence Livermore thermochemistry tables for the surface response. The diagram shows that the surface material is well into the sublimation region within 0.25 seconds and rapidly drops back down into the diffusion limited regime once the heat pulse is removed. The wall recession (see Figure 65-C) associated with the mass transfer parameter demonstrates failure in less than 2 seconds and complete burn through within 2.27 seconds. For the surface nodes that indicated ablation failure, Figure 65-D contains information when each of the failures occurred. As indicated, all of the surface nodes within the modeled stagnation line exhibit wall thickness failure at about the same time. The combination of nodes 85 and 64 failing meet the fuel release criteria, and this is the point where aeroshell failure is assumed.

Figures 66 through 72 contain similar information for the remaining side-on stable reentry angles. Only slight differences from the -90° case are seen for the -70° reentry. For the shallower angles, as the trajectory flight time is increased, a decrease in mass transfer parameter and an increased amount of surface recession (due to lower pressures and longer exposure) is seen. Also, as the flight time lengthens the internal components show significant thermal response. Failure, however, occurs before the internal components encroach on their melt temperatures.

The location within the trajectory at the point of aeroshell breach is of significant importance for determining the end state disposition of fuel released into the atmosphere. Figures 73 through 80 show the point of ablation failure relative to the reentry heat pulse for each reentry angle. For the steep reentries, the 75% failure criteria are met shortly after the time of peak heating. For decreasing reentry angles, the relative location of ablation failure to the heat pulse is shifted towards the ascent side of the heat pulse. For the shallow reentry angles, full wall burn-through occurs by the time peak heating is reached. Since it is assumed that the clad

and fuel assemblies will be released when the aeroshell is breached, with immediate removal of the clad material, sufficient amount of the heat pulse remains to cause vaporization of the fuel prior to ground impact.

The side-on stable reentry results are summarized in Table 9. Peak heating data and both 75% and 100% recession data are shown for each angle. As shown in this table, aeroshell burn through will occur well within the hypersonic portion of flight. As a matter of reference, several pertinent response temperatures at time of failure are noted in Table 9. These data further indicate that although the internal components show greater response for shallow angles, no melting occurs at the time of clad release.

2. Side-on Spinning Orientation, LWRHU

The side-on spinning orientation results in the least severe environment for the LWRHU model. As summarized in Table 10, only one case, the -5.2° reentry, indicates aeroshell failure. While this case meets the necessary conservative failure criteria, it does not indicate 100% burn through and it could survive the hypersonic flight and be intact at the time it impacts the ground. Figure 81 shows the recession failure time of the modeled surface nodes for the -5.2° reentry. Figure 82 shows the point of ablation failure relative to the reentry heat pulse. As indicated in both of these diagrams, the aeroshell does not fail due to ablation until about 112 seconds into the trajectory.

Although the remaining V- γ selections survive the hypersonic flight, the long trajectory allows significant thermal response of the internal components, especially for the shallow reentry angles. The component thermal response for the -7° reentry case is shown in Figure 83. It represents the intensity of the internal heating for an LWRHU that survives the Cassini VVEJGA reentry. Melting of the clad will occur for reentry by the end of hypersonic flight. Also, the fuel rapidly approaches the point of melting.

Therefore, under certain flight conditions, clad and fuel melt within an unbreached aeroshell are distinct possibilities. The effects of melted clad and fuel material on the internal heating and aeroshell surface response have not been addressed in this analysis. Reference 162 indicates that fuel capsule temperatures can be significantly higher in flight than in a test environment. This effect is due to inertial loading which induces greater thermal contact conductance at the interface standoffs.

The current analyses are conducted with air filled gaps. References 163 and 164 discuss the possibilities of various gases or a vacuum occupying the gap spaces prior to material melt. These references demonstrate how contact resistance can be altered by various flight conditions. It is unknown what effect melted material could have on the gap conductance; therefore, molten materials from the clad and fuel could force the thermal conductance to be significantly different than the current results indicate. Due to inertial effects, the conductance in

the stagnation region would increase. The appropriate material properties and variations in contact resistance during melting are not sufficiently understood to allow consideration at this time. The occurrence of clad melt is therefore registered as a melt failure and registered as a source term.

3. Tumbling Approximations, LWRHU

a. Quasi-Tumbling Cylindrical LWRHU Orientation

The quasi-tumbling cylindrical orientation of the LWRHU is only slightly more severe than the side-on spinning orientation. Table 11 summarizes the responses for the quasi-tumbling orientation. Only the extreme shallow angles, -5.2° and -7° reentries, show aeroshell failure. The -5.2° reentry shows 100% aeroshell burn through just prior to the end of the hypersonic flight. The -7° reentry indicates that 75% wall recession will occur at about half way through the hypersonic flight. Figure 84 shows the times of recession failure of the modeled surface nodes and Figure 85 shows the point of ablation failures relative to the reentry heat pulses. Again, the aeroshell breach releases molten material, and an aeroshell impacting at ground level could release material registered as a ground source term.

b. Random Tumbling Cylindrical LWRHU Orientation

Much like the quasi-tumbling cylindrical orientation of the LWRHU, the random tumbling orientation shows aeroshell survival for most orientation reentries. Only the shallow cases, less than -15° reentries, show a 75% aeroshell wall thickness failure. All reentries indicate that 100% aeroshell burn through will not occur (see Table 12). Figures 86 and 87 show the times of recession failure of the modeled surface nodes, and the point of ablation failures relative to the reentry heat pulses, respectively. Again, the aeroshell breach releases molten material.

While the other orientations indicate that the aeroshell provides the critical path for ablation failure, this orientation shows that the ablation is most severe in the end cap region. Failure would occur by breaking out the end cap to release the internal components. This orientation was expected to represent the lower boundary of material ablation for all of the non-stable cases. Indeed, the aeroshell tends to survive, but it also represents the most severe conditions for end cap ablation. The lower boundary is somewhere between the quasi and random tumbling orientations.

c. Tumbling Sphere Orientation, LWRHU

The most severe approximation to the tumbling orientation examined is that of the tumbling sphere. This orientation was expected to represent the upper boundary of material ablation for all of the non-stable orientations. Burn-through failure of 100% occurs for the convectively dominated shallow reentry heat pulses. Only the steepest, radiatively

dominated heat pulses do not show 100% failure. All cases, though, show at least 75% wall recession. Figure 88 shows the times of recession failure of the modeled surface nodes. The timing of the failures, relative to the heat pulse, oppose the trend established by the side-on stable case. Shallow angles show failure significantly after the peak heating while the steeper cases fail close to the time of peak heating. This is illustrated in Figure 89 and summarized in Table 13.

4. Component Temperature and Aeroshell Recession

Since the condition of the LWRHU components at the point of ablation failure or impact are important in determining the fuel source terms, additional temperature and recession data are supplied in table format. Tables 14 through 18 contain the average, maximum and minimum component temperatures for each orientation and flight path that exhibit ablation failure. Separate tables are supplied for the 75% and the 100% failure criteria; for example, Tables 14-A and 14-B contain the 75% and 100% failure data, respectively, for the side-on stable orientation. Listed at the bottom of these tables are the melt temperatures for the clad and fuel materials.

For the conditions that do not indicate 100% burn-through failure, the clad and fuel temperature histories over the heat pulse are important. (Note that the end of the trajectory is Mach 5.0 and not impact.) Maximum temperature data are supplied in Tables 19-A through 22-B, with the A providing clad data and B providing fuel data. For the conditions that indicate melting of the pertinent material, the trajectory flight period during the melt phase is supplied. Sometimes the material will resolidify prior to the end of the trajectory. For the cases that do not demonstrate resolidification, the end of the hypersonic flight time is used as the end of the melt temperatures.

Also, for the conditions that do not indicate 100% burn-through failure, the amount of recession to which the aeroshell and the end cap are subjected is listed in Tables 23-A through 23-D. These recession data are supplied as a percentage of the original modeled wall thickness at the modeled points. Table 23-D is the recession percentage for the random tumbling cylinder orientation. One data point within that table (for -5.2° reentry) indicates that 100% recession occurred, but this reentry angle is listed as not showing a condition of 100% burn through. In this case, only one of the aeroshell's extreme edge surface nodes (node 85, refer to Figure 26 for node positions) shows full ablation which is deemed insufficient to allow break out of the end cap, and therefore no burn-through failure.

5. Clad and Fuel State at Impact

Additional analyses were performed for representative cases that indicated clad/fuel melt during hypersonic flight to determine the thermal condition of the clad and fuel at impact. For the spinning cases, RETAP runs conducted at $\gamma = -7^\circ$ and -15° well into subsonic flight show that both clad and fuel cool down to approximately 1100°R. Similar results were obtained for

the tumbling cases at $\gamma = -7^\circ$ and -10° . Therefore, any clad and fuel contained within the aeroshell sufficiently resolidifies prior to ground impact. There was insufficient ablation during the supersonic and subsonic flight to induce further aeroshell failure.

6. Sensitivity Analyses

A brief examination of the sensitivity to the thermochemistry data used (JANNAF or Lawrence Livermore) is conducted using representative side-on stable LWRHU trajectories (-15° , -30° , and -90°). Figure 90 shows the time of 75% and 100% surface recession results for both thermochemistry tables. As expected, the JANNAF thermochemistry data obtains later failure (with higher temperatures) than the Lawrence Livermore data, but only by a maximum of approximately 0.2 seconds for each case. Figure 91 shows the time of failure relative to the heat pulse. Only the -90° , 100% ablation failure delays burn through until near the end of the heat pulse. The -30° reentry shows burn through near the peak of the radiative heat pulse, and the -15° reentry shows failure at the peak of the convective heat pulse.

The effect of the gas dynamic-radiation coupling is examined, also. This effect is examined for the -90° side-on stable LWRHU only. Additionally, the JANNAF data are used in this analysis. Figure 92 shows the time at 75% and 100% surface recession and the time of failure relative to the heat pulse for the condition of full blockage and no blockage (a factor of 1.3, and 1.0, respectively, on the convective heat pulse). As indicated, the gas dynamic-radiation coupling factor has a more significant effect on the failure time than the different thermochemistry data discussed previously. The 75% ablation failure is shifted to about 1.8 s from 2.1 s when this effect is included in the analyses. Without coupling, the 100% ablation failure occurs near the end of the heat pulse; with coupling, the 100% ablation failure occurs near the peak of the heat pulse. While the differences in burn-through times are only between 0.3 s to 0.4 s in the trajectory, it is a very critical time in the trajectory because the heat load remaining impacts the fuel state.

G. Bare Fuel, Thermal and Ablation Results

The fuel pellet, as illustrated in Figure 4, is a cylinder of dimensions 8.06 mm by 6.25 mm capped with small 50° conical frustums 0.643 mm long with a maximum diameter of 6.0 mm. The resultant fuel volume is 275.271 mm^3 . The plutonium oxide density and weight are 10.017 g/cm^3 and 2.664 g, respectively.

The fuel pellet thermal analysis requires appropriate surface thermochemistry data for the PuO_2 . Temperature dependent enthalpy data, in the form of input data, from the Aerotherm Chemical Equilibrium (ACE) code were obtained from Mr. B. Laub, of Aerotherm (Reference 165). These data were used to run ACE for the desired pressure and mass transfer parameter values. The resulting thermochemistry tables were converted to the form required for use in RETAP. The maximum mass transfer parameter data generated by ACE was 3.5.

1. Initial Conditions

A thermal analysis is performed on an intact fuel pellet for every condition of accidental LWRHU reentry that indicates ablation failure. The initial conditions for generating reentry trajectories for these released fuel pellets are listed in Table 24. The time of modeled wall section failure does not necessarily indicate the time at which the fuel pellet would break free from the remaining aeroshell. For purposes of trajectory generation, the release time is determined by averaging the time of failure for vital sections of the aeroshell. The release times are determined based on the occurrence of one of two assumed conditions that would allow release of an intact fuel containment assembly. The conditions are the failure of the aeroshell region overlaying the insulator sleeves for a central angle of $\pm 15^\circ$, and the failure of the aeroshell and end cap region that would degrade the integrity of the end cap threads for a central angle of 30° thereby allowing disengagement of the end cap. For example, referring to Figure 34, the average time of ablation failure for nodes 1, 22, and 43 signifies time of pellet release. Alternatively, the average time of ablation in the end cap region leading to failure at nodes 64 and 85 signifies pellet release.

The motion behavior of a released pellet is not known apriori. When a LWRHU breach occurs, the pellet could slip out and orient side-on into the flow stream in a stable manner or in a spinning manner. More likely, it would be flipped out and either tumble or trim to a preferred oscillation about an edge. Without full six degree of freedom modeling and full understanding of the initial forces on a pellet breaking free of an aeroshell, it cannot be determined what is the expected orientation of a released fuel pellet. For this reason, limiting cases are examined: full random tumbling condition (representative of most severe oscillation motions); side-on stable or spinning (representative of least severe oscillation motions). Figure 93 is a flow diagram that illustrates all conditions of release and orientation for the current TDOF trajectory generations. A total of forty trajectories are generated to cover all expected conditions for a fuel pellet released from a LWRHU exhibiting ablation failure. The analyses encompass the following cases.

- a. Side-on stable 2-D fuel pellet released from a breached side-on stable LWRHU at $\gamma = -5.2^\circ, -7.0^\circ, -10^\circ, -15^\circ, -30^\circ, -50^\circ, -70^\circ$, and -90° for upwind entries. Released conditions generated for both 75% and 100% wall recession leading to LWRHU breach.
- b. Side-on spinning 2-D fuel pellet released from a breached side-on stable LWRHU at $\gamma = -5.2^\circ, -7.0^\circ, -10^\circ, -15^\circ, -30^\circ, -50^\circ, -70^\circ$, and -90° for upwind entries. Released conditions generated for both 75% and 100% wall recession leading to LWRHU breach.
- c. Full random tumbling cylindrical (R-Z model) 2-D fuel pellet released from a breached side-on stable LWRHU at $\gamma = -5.2^\circ, -7.0^\circ, -10^\circ, -15^\circ, -30^\circ, -50^\circ, -70^\circ$, and -90° for upwind entries. Released conditions generated for both 75% and 100% wall recession leading to LWRHU breach.

- d. Side-on stable 2-D fuel pellet released from a breached side-on spinning LWRHU at $\gamma = -5.2^\circ$ for upwind entries. Released conditions generated for 75% wall recession leading to LWRHU breach.
- e. Side-on spinning 2-D fuel pellet released from a breached side-on spinning LWRHU at $\gamma = -5.2^\circ$ for upwind entries. Released conditions generated for 75% wall recession leading to LWRHU breach.
- f. Full random tumbling cylindrical (R-Z model) 2-D fuel pellet released from a breached side-on spinning LWRHU at $\gamma = -5.2^\circ$ for upwind entries. Released conditions generated for 75% wall recession leading to LWRHU breach.
- g. Side-on stable 2-D fuel pellet released from a breached full random tumbling LWRHU at $\gamma = -5.2^\circ, -7.0^\circ$, and -10° for upwind entries. Released conditions generated for 75% wall recession leading to LWRHU breach.
- h. Side-on spinning 2-D fuel pellet released from a breached full random tumbling LWRHU at $\gamma = -5.2^\circ, -7.0^\circ$, and -10° for upwind entries. Released conditions generated for 75% wall recession leading to LWRHU breach.
- i. Full random tumbling cylindrical (R-Z model) 2-D fuel pellet released from a breached full random tumbling LWRHU at $\gamma = -5.2^\circ, -7.0^\circ$, and -10° for upwind entries. Released conditions generated for 75% wall recession leading to LWRHU breach.

The drag coefficient data for side-on and tumbling pellets are listed in Table 25. The side-on stable and side-on spinning orientations utilize the same drag data. The initial velocity of the fuel pellets at the time of release varies between 59.5 kft/s and 20.9 kft/s with the lowest velocity at release noted for the -5.2° reentry of a spinning LWRHU. The initial altitudes vary from 245 kft and 126 kft.

2. Trajectory Results and Discussion

The results of the TDOF simulations are presented in Figures 94 through 101. Figure 94 contains the velocity verses altitude profiles for each LWRHU orientation releasing a side-on fuel pellet. Figure 95 gives the altitude histories. For alternate fuel orientations at release, only minor deviations in the trajectory data were noted. The reference heating rate histories are contained in Figures 96 through 101. Figure 96 illustrates (a) the convective and (b) the radiative heating rates for the side-on stable and spinning fuel orientations after release from breached side-on stable LWRHUs. Figure 97 illustrates the same information for a tumbling fuel pellet. Similar data for fuel pellets released from breached side-on spinning LWRHUs (Figures 98 and 99), and from breached tumbling LWRHUs (Figures 100 and 101) are shown. Of particular note is the very

low heating levels demonstrated for the pellet released from the spinning LWRHU. This is due to breach occurring very late in the LWRHU trajectory, well past the heat pulse.

3. Side-on Stable LWRHU Release of Fuel Pellet

For all fuel pellets released from a side-on stable LWRHU, the heating rates were too severe to allow proper software convergence when the full geometry conversion effect on convective heating is incorporated. The full correct geometry influence is a factor of about 7.25. The severe heat pulses introduce rapidly changing conditions and lead to solution oscillations beginning sometime after the material temperatures reach approximately 6500°R - 7000°R . The model generally shows convergence using the reference stagnation heating for a 1-ft sphere, and for a geometry influence on the convective heating of around 3. An exception typically occurs for the surface stagnation point which usually exceeds 7000°R under reference heating conditions for a side-on stable pellet, because oscillations occur for any node that exceeds 6500 - 7000°R . This occurs in part due to tabulated thermochemistry data ending in this temperature region, and in part due to numerical limitations within the software.

The code response is to force divergent oscillations about the true value until the heat load begins to decrease. The average values between consecutive computational time steps show a smooth rise in thermal response with respect to the rising heat input. On the cooling portion, the solution shows a convergent oscillation until the thermal response is within tabulated values. The repercussion is that the hot surface (i.e. stagnation point) behaves alternately as a large heat source and heat sink. It is expected that the net result allows a reasonable approximation to appropriate internal conduction, but not exact solutions. Since the melt temperature of the PuO_2 material is well below the oscillation range, it is not reasonable to expect accurate solutions over 7000°R due to uncertainties in material properties above melting point.

The problem is in determining when sufficient heat is conducted to the pellet center to induce full pellet melting. As illustrated in Figure 102, the leeward surface of the side-on stable fuel pellet (node 7) shows the lowest thermal response to the environment. Melting in this leeward region, therefore, will be used to indicate full pellet melt. Although the uncertainty band on the melting of PuO_2 has been noted to be 300°F - 500°F , 4812°R is marked on each thermal response diagram. Also of note in Figure 102 is the thermal dwell illustrated by several nodes at approximately 4200°R . This anomaly is due to the heat of fusion consideration and a limiting condition within the enthalpy data. The dwell shows up for every node that heats up or cools (relatively) slowly through the 4000 - 4400°R region.

a. Side-on Stable Fuel Pellet

The thermal responses of node 7 for a side-on stable pellet released from a side-on stable LWRHU are shown in Figures 103 through 110. Each Figure contains the response diagrams for release from both a 75% and 100% ablation failed LWRHU. In all cases, the

pellet does not show full melting when subjected to reference convective heating, indicated as 1X. Full melting does occur in all cases, though, when the pellet is subjected to three times (3X) the referenced heating. Furthermore, the melt temperature is exceeded almost immediately upon release from the LWRHU. All fuel pellets, then, become radiological source terms a very brief time after release from the LWRHU. Results indicating full pellet melt (4812°R) with 1X or 3X reference heating imply that it is logical to assume full pellet melt with a heating factor of 7.25.

b. Side-on Spinning Fuel Pellet

Figures 111 and 112 show the thermal responses of a side-on spinning pellet released from a side-on stable LWRHU under representative reentry angles (-7°, -15°, -90°). Since all surface locations are subjected to identical heat loads, these figures illustrate the temperatures from the surface to the center of the fuel pellet (noted as nodes 1, 8, 9, 10 for surface to center). Figure 111 contains the response diagrams for release from 75% ablation failed LWRHU, and Figure 112 shows the same for 100% ablation release. In most instances, only the reference convective heating environment was required to induce full pellet melting. The steep reentry cases show an exception. At release from a 75% ablated LWRHU, the center portion did not melt, but when subjected to 3X the convective heating environment, it showed complete melt. Only for the later release (100% ablation of the LWRHU) did the pellet show partial survival. Furthermore, only a small difference in center node response was indicated between the 1X and 3X environments. It is possible, then, that only the outer part of the late released, steep reentry pellet would vaporize.

The surface nodes in Figures 111 and 112 for the steeper angles illustrated oscillatory behavior discussed previously. For -15° in Figure 111, the oscillation was not severe, and it is shown by the data in the graph. For -90°, however, the oscillation was severe, and was removed, as indicated by the plotted response beginning later than the other nodes. For all remaining diagrams, if the node response plot starts at a later release time, it is due to removal of oscillating data that first converged in excess of 7000°R. For cases where the node first converged at lower temperatures, then heated to greater than 6500-7000°R, the oscillating data was removed but a line connecting the beginning and ending of oscillation will be shown, as in the -15° case in Figure 112.

c. Tumbling Fuel Pellet

The release of a tumbling pellet results in much the same behavior as that noted for the spinning pellet. Figures 113 and 114 for a pellet released under the same representative reentry angles. For the tumbling pellet, a different model (refer to Figure 36) was used, and the representative nodes are tracked in the diagrams: two surface symmetry nodes (1, and 15), and the center node (4). Again, under 1X reference convective heating environments, the shallow angles show full pellet melt, and only surface melting is shown for the steeper angles. 3X

heating was not sufficient to raise the center thermal response to a melting level. It is possible that only the outer part of the steep reentry pellet would vaporize.

4. Side-on Spinning LWRHU Release of Fuel Pellet

The side-on spinning LWRHU demonstrated only one condition of failure: 75% ablation at -5.2° reentry. The stable, spinning, and tumbling pellet results are shown in Figure 115. Prior to failure, the internal fuel pellet reached approximately 4800°R before cooling down to about 4300°R at the time of release. It is unlikely that the integrity of the pellet structure would be intact at the time of release. Assuming the pellet to be undamaged, though, the analyses indicate that only release of a side-on stable pellet would result in remelting (see Figure 115). The test cases run for a pellet release from a spinning LWRHU are conducted with full geometry conversion effect on the convective heating input; approximately 7.25X.

5. Random Tumbling LWRHU Release of Fuel Pellet

The random tumbling LWRHU fuel pellet release cases are conducted with a full geometry conversion effect also. The stable, spinning, and tumbling pellet results are shown in Figures 116, 117, and 118, respectively. Under these three conditions, only the shallowest angles (-5.2° and -7°) indicate full pellet melt. The -10° reentry conditions show that no melting would occur. For any pellet released from a tumbling LWRHU (the most probable orientation), any reentry angle of 10° or greater will result in no high altitude vaporization based on current available response data.

6. Summary of Melt Fractions

A survey of the temperature states of the nodes modeled in the thermal analysis of the fuel pellet was made to obtain an indication of the melt volume (mass). The results are tabulated in Table 26. Table 26 illustrates the volume percentage of the fuel pellet that will melt and be counted as atmospheric source terms. Two melt temperatures are listed: 4812°R and 4312°R to illustrate the uncertainty. In general for the side-on stable LWRHU where release due to ablation was obtained at all entry angles, 100% fuel melt was obtained. For a spinning LWRHU at $\gamma = -5.2^\circ$, and for cases of a tumbling LWRHU orientation at $\gamma = -5.2^\circ$ and -7° , the melt fraction was also 100%. These releases occur at altitudes greater than about 125,000 feet. For a random tumbling LWRHU reentering at $\gamma \geq 10^\circ$, no atmospheric source terms occur. Instead, these are considered ground source terms.

VIII. THERMOSTRUCTURAL ANALYSIS

A. General Description

The thermostructural response of the LWRHU for inadvertent reentry is analyzed with two primary analysis tools: MSC/NASTRAN, and a thermoplastic (temperature-dependent plastic) analysis program called ANSP Non-linear (ANSPNL). A third program Finite Element Modeling and Post Processing (FEMAP) is used for graphical pre- and post-processing. MSC/NASTRAN is a commercial general-purpose finite element analysis (FEA) program that performs structural and thermal analyses, and is used for thermoelastic (temperature-dependent elastic) analysis here. The thermoplastic analysis program ANSPNL is a custom code written by Mr. Y. Chang of JHU/APL specifically for this problem [References 166-171]. It performs additional analyses on stresses calculated by MSC/NASTRAN, and accounts for the different nonlinear material behaviors of the FWPF at different elevated temperatures and loadings.

Thermostructural analyses were conducted for those LWRHU orientations where ablation failure was not indicated by the thermal analysis, as discussed in Section VII. The exception is the side-on stable orientation where ablation failure was indicated at all reentry angles. For this orientation, thermostructural analyses were conducted to check out the procedures. The general methodology, assumptions, thermostructural models, mechanical properties, loadings, and results of thermostructural analysis of the LWRHU are described in more detail in following sections.

B. General Methodology

Assuming LWRHU release, three reentry orientations are considered: side-on stable, side-on spinning, and random tumbling. For each reentry orientation, significant trajectory points are chosen for analysis. These are generally points of highest mechanical loadings, heat fluxes, temperatures, gradients, material burn-through, or combinations of these. Thermal loads are obtained for these points, and the temperatures from the thermal analysis are mapped onto a finite element model (FEM) of the LWRHU with a 3-D Interpolation program (INT3D), written by Mr. J. Ecker of JHU/APL. The deceleration loads are obtained from the TDOF analysis, and the pressure loads are obtained from the thermal analyses using RETAP. These loads are translated into the FEM. The thermoelastic material properties of the FWPF are used in the finite element analysis, and elemental thermoelastic stresses are generated. These are then input directly into the thermoplastic analysis program ANSPNL, where the temperature-dependent plastic material properties of the FWPF are considered. The thermoplastic strains are obtained iteratively. The final converged strains are compared to strain allowables at temperature for each strain component, and the thermostructural integrity of the LWRHU is assessed. More detailed descriptions of these steps are provided in following sections.

C. Assumptions

There are various assumptions used in the thermostructural analysis of the LWRHU. Material properties used are the best available, and some material properties are extrapolated at higher temperatures where test data are not available. The analysis occurs at points in the trajectories where maximum mechanical and thermal loadings occur, and assumes a linear, not a timestepping analysis. That is, each loaded state is assumed to be path-independent. There are assumptions inherent to the thermoplastic analysis method itself. The thermoplastic analysis method assumes that a finite element is equivalent to a unit cell; this assumption becomes more reasonable as the stress gradients within a finite element approach zero. Also, strain continuity between elements is not assured, as the thermoplastic analysis method decouples each element from its neighbors in performing the iterations. Certain material behaviors are not modeled, such as: strain rate effects, creep, dynamic effects, stress relaxation, and ablation. Future analyses will consider the reduction in wall thickness caused by ablation.

Only compression material properties are used for compression and tension behavior, for both thermoelastic and thermoplastic analyses. For thermoelastic material behavior, test data show that compression and tension material properties are similar. For thermoplastic material behavior, test data show that the compression stress-strain behavior is more nonlinear (i.e., more strain deformation) than for tension. Since the analysis uses factors of safety (FS), where $FS = \text{material allowable strain or strength} \div \text{calculated strain or stress}$, and $FS < 1.0$ indicates failure, use of the thermoplastic compression material properties for both compression and tension behavior is conservative.

It is assumed that in order for a breach of the LWRHU aeroshell to occur, failure must be extensive. This is because the material can still carry load when the strain allowable is exceeded, as described in Section VIII E, Mechanical Properties. Since there is no well-defined measure of the extent of failure over the surface of the aeroshell, perhaps a better measure would be failure through the thickness of the aeroshell. Also, overall failure of a composite generally requires interaction of all components of the composite material. Thus this criterion for breach will be used: breach is indicated when a factor of safety less than 1.0 is seen through the entire thickness of the aeroshell for all three normal directions x, y, and z at any point on the aeroshell.

D. Thermostructural Models

1. Thermoelastic Models

The thermostructural models are the MSC/NASTRAN finite element models for thermoelastic analysis and the thermoplastic analysis models. The thermoelastic finite element models are described first. A full LWRHU is shown in Figure 1, and the portion that is modeled is shown in Figure 119. Only the outer aeroshell, which is fabricated of a three-dimensional weave carbon-carbon composite, FWPF, is modeled. The FEM covers 180° and half

the length of the LWRHU. This quarter-model considers the relationship between the LWRHU geometry and the FWPF material, and the symmetries of the loadings. The geometry of the model is described in cylindrical coordinates, while the Cartesian weave FWPF material is described in Cartesian coordinates. This material orientation causes the material properties to vary sinusoidally over the circumference of the LWRHU. A full cycle of material property variation occurs over a 90° segment of the structure, so that modeling a 180° segment allows for two full cycles of material property variation to be covered, while also allowing for consideration of the windward and leeward sides of the aerodynamic loads, the temperature loads, and the deceleration loads. Axisymmetric boundary conditions are applied at the $\theta = 0^\circ$ and the 180° interfaces of the model, and symmetric boundary conditions are applied at the $z = L / 2$ interface. The MSC/NASTRAN model of the LWRHU was used for all three configurations, each with its own loadset. The mechanical loads on the model are the internal and external pressures on the aeroshell, the decelerations on the aeroshell, and the forces of the internal components on the aeroshell caused by deceleration. The temperature loads on the model for all three configurations are shown in Figure 120.

There are some modeling techniques which have to be observed for thermostructural analysis of the LWRHU with MSC/NASTRAN, Version 68, in order to obtain correct results. These techniques and the errors which they avoid are detailed in Reference 166.

2. Thermoplastic Models

The material behavior of FWPF is nonlinear, and this nonlinear behavior becomes more pronounced with elevated temperatures (Figure 121), hence the term "thermoplastic." Note that the thermoelastic material properties (Figure 122) are the initial tangent moduli of the thermoplastic material properties of Figure 121. Since the LWRHU is expected to encounter temperatures well above 5000°F during an inadvertent reentry, it is paramount that this nonlinear behavior be modeled. But this modeling is complex. FWPF has six strain components (3 normal and 3 shear), and each of these six strain components exhibits its own unique thermoplastic behavior. Also, the six strain components are coupled, not independent.

A number of strategies to model the thermoplastic behavior of FWPF were investigated. MSC/NASTRAN can perform thermoelastic analysis of orthotropic composite materials, but not thermoplastic analysis. MSC/NASTRAN has a capability called initial anisotropy, wherein the material initially deforms according to the anisotropic constitutive equation, but subsequent nonlinear deformation is calculated assuming that the material is isotropic. This clearly is insufficient for accurate representation of heat sources fabricated of FWPF. The finite element program ABAQUS was explored, but it would require user-written modifications to incorporate the thermoplastic material properties. It was ultimately decided to write a post-processor program to MSC/NASTRAN thermoelastic analysis.

The development of the thermoplastic analysis program ANSPNL is documented in References 166 through 171. The thermoplastic analysis method has as its basic goal an extension of the finite element codes' capability for thermoelastic analysis into the thermoplastic region. The method for thermoplastic analysis of carbon-carbon composites consists of three basic parts, which are described next.

First, the nonlinear stress-strain data of each strain component at each temperature are used to develop material property vs. strain energy density equations of the form

$$MP = A \left[1 - B \left(\frac{U}{U_o} \right)^C \right] \quad (1)$$

where

MP = material property E or G, psi

A = initial value of material property, psi

B = initial curvature

C = rate of change of curvature

U_o = unit strain energy density, 1 psi

U = strain energy density, psi

according to the strategy of Jones [Reference 172]. The stress, strain, and strain energy density are highly interdependent. Curve-fit coefficients are set up for each nonlinear strain component at each temperature. These coefficients are interpolated for temperatures intermediate to those at which the data are defined. The moduli are assumed to become negligible above 8000° F, and the coefficients are extrapolated with that constraint, for temperatures above those for which test data exist.

The second part begins with the elemental stresses in the material coordinate system from a thermoelastic finite element analysis using MSC/NASTRAN, described earlier in Section VIII. D1. These stresses are applied to the stress-strain constitutive Equation (2),

$$\begin{Bmatrix} \epsilon_x \\ \epsilon_y \\ \epsilon_z \\ \gamma_{xy} \\ \gamma_{yz} \\ \gamma_{zx} \end{Bmatrix} = \begin{bmatrix} \frac{1}{E_x} & \frac{-\nu_{xy}}{E_x} & \frac{-\nu_{zx}}{E_z} & 0 & 0 & 0 \\ & \frac{1}{E_x} & \frac{-\nu_{zx}}{E_z} & 0 & 0 & 0 \\ & & \frac{1}{E_z} & 0 & 0 & 0 \\ & & & \frac{1}{G_{xy}} & 0 & 0 \\ & & & & \frac{1}{G_{yz}} & 0 \\ & & & & & \frac{1}{G_{zx}} \end{bmatrix} \begin{Bmatrix} \sigma_x \\ \sigma_y \\ \sigma_z \\ \tau_{xy} \\ \tau_{yz} \\ \tau_{zx} \end{Bmatrix} + \Delta T \begin{Bmatrix} \alpha_x \\ \alpha_y \\ \alpha_z \\ 0 \\ 0 \\ 0 \end{Bmatrix} \quad (2)$$

sym

where

σ = normal stress, psi

ϵ = normal strain, in/in

τ = shear stress, psi

γ = shear strain, in/in

E = modulus, psi

$E_x = E_y \neq E_z$

G = shear modulus, psi

ν = Poisson's ratio

ΔT = change in temperature, °F

α = coefficient of thermal expansion, in/in/°F

Equation (2) is modified to allow iteration on strains based on the dependence of the thermoplastic material properties on strain energy density and temperature developed in the first part above:

$$(MP_x)_i = f[(U_x)_i] = f\left(\frac{\sigma_x \cdot (\epsilon_x)_i}{2}\right) \text{ or } f\left(\frac{\tau_x \cdot (\gamma_x)_i}{2}\right) \quad (3)$$

where

$MP = E$ or G

x = direction: x , y , z , xy , yz , or zx

i = index on iteration

The material properties in Equation (2) are replaced by terms of the form of Equation (3) to allow for iteration. The iteration is done on an element-by-element basis. Since the thermoelastic moduli are the initial tangent moduli of the thermoplastic stress-strain curves, the thermoelastic stresses can be used as initial values in the thermoplastic analysis. The finite element mesh must be fine enough

so that each finite element represents a unit cell. A unit cell is traditionally defined as the smallest portion of a composite weave which still retains all the essential characteristics of the composite. In finite element analysis, the largest elements (i.e., coarsest mesh size) which can accurately represent the strain distribution in the structure are desirable to minimize model size and cost. Consequently, the definition of a unit cell is modified here to be the largest volume represented by a finite element where the stress gradients are small. The stress-strain constitutive equation can then be applied to the stresses of each finite element individually. Iteration on the stress-strain constitutive equation continues until convergence (successive values of strain energy density within 0.5% (0.005) for each strain component).

The third part is a variation on the second. The majority of the elements converge readily, but for those elements which do not, and which oscillate about an apparent value, Gauss-Seidel iteration with successive under-relaxation is used to accelerate convergence. This simple strategy anticipates that the next iteration will overshoot the desired value, so a multiplier less than 1 is imposed on the increment. In equation form,

$$u_{i,j}^{k+1'} = u_{i,j}^{k'} + \omega \cdot (u_{i,j}^{k+1} - u_{i,j}^{k'}) \quad (4)$$

where

- u = value of the iterant
- k = iteration level
- ω = relaxation parameter
- i,j = indices on iterant variants
- ' = replaced value

Here, the iterants are the strain vectors described by Equation (2) as modified by Equation (3). The three parts of the thermoplastic analysis method have been coded into computer programs: ANSPNL3, ANSPNL4, and ANSPNL5, respectively. Different loadings of the same structure, and different structures of the same material, require the execution of just the last two parts.

The thermoplastic analysis program ANSPNL can be used for axisymmetric structures with material whose principal axes are aligned with the Cartesian coordinate system, such as the LWRHU or the GIS. This was verified in Reference 170. The finite element formulation of an axisymmetric structure maintains the proper boundary conditions and strain conditions so that the postprocessing thermoplastic analysis program ANSPNL does not have to make modifications to consider these aspects.

E. Mechanical Properties

Test data for mechanical properties of FWPF over the temperatures and loadings of interest for reentry analysis are limited. Two sources of data are the Southern Research Institute

(SoRI) and the Los Alamos National Laboratory (LANL) [References 173, 174]. (The references contain technical data whose export is restricted by the Arms Export Control Act, and therefore the data are not included in this report.) The formats of the data from the two sources differ. The LANL data essentially reports ultimate strength only. The SoRI data come in the form of stress-strain plots. These are much more useful in terms of supplying nonlinear data for nonlinear analysis, or in this case, for thermoplastic analysis. SoRI also supplied ultimate strength data. It should be noted that the LANL ultimate strength data were approximately 20% higher than the SoRI data. These differences may be attributable to different test methods or to natural variation of test samples. We shall focus here on the SoRI data.

Fine Weave Pierced Fabric consists of xy weave fabric pierced in the z-direction by pultruded rods, forming an orthogonal weave composite, which is then infiltrated and impregnated with organic precursor, pyrolyzed under pressure, and graphitized. The material properties in the x and y directions are identical, while the material properties in the z direction are different. In addition, the tension properties in any direction are different from the compression properties in that same direction. Compression and shear data of FWPF at various elevated temperatures up to 5500° F from SoRI are used in the analysis here (Figure 121).

A strain allowable of 1% (0.01 in/in) is used in the thermostructural analysis to assess factors of safety (FS), where $FS = \text{material allowable strain or strength} \div \text{calculated strain or stress}$. A factor of safety = 1.0 indicates that calculated strain is equal to the allowable strain. Stress at 1% strain is arbitrarily chosen by SoRI in reporting the ultimate compressive strength, but SoRI reported that FWPF will continue to support load beyond the 1% value, probably beyond 5% strain [Reference 175]. Note that the 1% strain should be considered a lower bound compressive strength, indicating not catastrophic failure, but a point of increased plastic deformation. Thus the factors of safety on strains reported here based on 1% strain allowables should be viewed as very conservative. Since the thermostructural analysis here considers plastic deformation, a 5% strain allowable could probably be used. For reference, the factors of safety are also calculated using a 5% strain allowable for each of the three reentry orientations.

Composite materials can have properties and behaviors which are different from those of isotropic materials. Two classic examples are: the Poisson's ratio ν for a composite can be greater than 0.5, and a composite can have a negative coefficient of thermal expansion α . For the FWPF composite material under the mechanical and thermal loadings of interest here, compressive (i.e., negative) stresses can result in tensile (i.e., positive) strains. Thus a body such as the LWRHU aeroshell fabricated of FWPF under the pressure and acceleration forces and the temperature loads of reentry, can result in compressive stresses at a point on the body for some or all material directions, but concurrently result in tensile strains for some or all material directions at the same point on the body. This phenomenon can be explained by examining the stress-strain constitutive equation for FWPF, Equation (2), where each strain term is coupled with all stress terms and with the ΔT term.

To demonstrate, a study was conducted on a unit cell model using thermoelastic material properties for FWPF, arbitrary compressive stresses of $\sigma_x = \sigma_y = \sigma_z = -10,000$ psi, and temperatures ranging from 70 to 7000° F. The resulting strains are plotted vs. temperature in Figure 123. In the plots of Figure 123, note that some strains are tensile (positive) at certain temperatures, and around 5000° F, all the strains are tensile, even though the stresses are all compressive (negative). Other combinations of compressive stresses also show some or all tensile strains. The study is documented in Reference 176. This material behavior was also observed for the thermoplastic analysis of the LWRHU, reported in following sections.

F. Results of Analysis

1. Side-on Stable

(a) Side-on Stable Mechanical and Temperature Loads

The pressures, decelerations, and temperatures for various reentry angles and times were obtained from the RETAP code. These had to be translated to MSC/NASTRAN format and to the LWRHU finite element model. The temperatures were mapped from the thermal model (Figure 119) to the finer mesh of the finite element model (Figure 34) with the INT3D code. The derivation of the mechanical loads for the FEM of the LWRHU side-on stable configuration follows. A free-body diagram of the aeroshell is shown in Figure 124. The mechanical loads on the aeroshell in the x-direction are given by

$$P_x = p_x + a_x + c_x \quad (5)$$

where P = integrated pressure force, external

p = integrated pressure force, internal

a = acceleration force on aeroshell

c = contact force of internal components on aeroshell

The RETAP code does not necessarily balance the integrated pressure force with the force caused by the deceleration, so the decelerations were calculated separately for input to the FEM. First, the external pressures only from RETAP were applied on the model. Then the pressures were integrated over the areas upon which they act to get a net force in the x-direction. Then the deceleration force was set equal to this force from the pressures, and a deceleration was calculated from $F = ma$, where m = mass of the LWRHU aeroshell and its internal components, and a = acceleration or deceleration. Then in the model, acceleration was applied on the aeroshell alone. The contact forces of the internal components on the aeroshell were obtained by multiplying the mass of the internal components by the acceleration, then distributing these forces as pressures over the contact area as a cosine distribution. Finally the internal and external pressures were applied to the model.

(b) Side-on Stable Runs

The reentry angle and times for which thermostructural analyses were performed are $\gamma = -90^\circ$ at 0.10, 0.40, 0.60, 0.80, 1.00, 1.20, 1.40, 1.60, 1.80, 2.00, 2.15, 2.35, 2.50, and 2.75 seconds. For the side-on stable orientation, only the reentry angle of $\gamma = -90^\circ$ was analyzed for thermostructural effects, since the thermal analysis showed ablation failure at all reentry angles (see Table 9), and further thermostructural analysis was not deemed necessary. The results of thermostructural analyses are discussed in Section VIII. F.1.c.

The mechanical and temperature loads described in Section VIII. F.1.a were applied to the LWRHU finite element model with thermoelastic material properties. The elemental stresses in the material coordinate system were then read into the thermoplastic analysis program ANSPNL4. Those elements which did not converge readily were run through the iteration program ANSPNL5 with the same algorithm, but with a successive under relaxation iteration scheme. The thermoplastic strains were iterated until convergence ($dU < 0.005$). Most elements converged within 0.5%, but some converged to higher values of 1%. For those in the latter situation, the factors of safety on strain were high, so no further effort was expended to get finer convergence.

(c) Side-on Stable Results

Table 27 shows the time of initial indicated failure using a strain allowable of 0.01 in/in, and the time with the lowest factor of safety during each trajectory. Also shown for reference is the time of initial indicated failure using a strain allowable of 0.05 in/in, if failure is predicted. For each of these times, the element number, the factor of safety, and the material direction are provided. Figure 125 shows the contour plots for factors of safety on strains, where a strain allowable of 0.01 in/in is used, for the timestep at which the lowest factor of safety is indicated for the steep reentry angle. The location of the element with the lowest factor of safety is shown in Figure 125. Almost all of the normal strains are tensile. From the criterion for breach described in Section VIII. C (Assumptions), breach is not indicated from a thermostructural standpoint. Note that the contour plots of factors of safety with a strain allowable of 0.05 in/in can be obtained by multiplying the FS levels by 5.

The significance of considering thermoplastic material behavior is demonstrated by comparison to thermoelastic analysis results for the $\gamma = -90^\circ$ side-on stable configuration. Thermoelastic analysis results are based on comparisons of predicted stresses to stress allowables. Thermoelastic analysis predicts failure starting at 0.40 sec, whereas thermoplastic analysis predicts failure starting at 1.00 sec.

2. Side-on Spinning

(a) Side-on Spinning Mechanical and Temperature Loads

The pressures, decelerations, and temperatures for various reentry angles and times were obtained from the Reentry Thermal Analysis Program (RETAP) code. The methodology for converting temperatures from RETAP to the LWRHU FEM for the side-on spinning configurations is similar to that for the side-on stable configuration, but the methodology for obtaining decelerations is different. For side-on spinning, the thermal analysis model spreads the pressure loads over the circumference of the LWRHU model to simulate spinning. Following the same strategy as for the pressures loads, the derivation of the decelerations also assumes an equal distribution over the circumference. To determine the decelerations for the 180° NASTRAN model, the RETAP pressures were integrated in the direction normal to the symmetry plane to obtain forces, and decelerations were calculated from the forces. Since the decelerations were assumed equal in all radial directions, these decelerations on the aeroshell were then radially distributed evenly over 180°, as were the contact forces calculated from decelerations of the internal components. Finally the internal and external pressures were applied to the model.

(b) Side-on Spinning Runs

A listing of the reentry angles and times for which thermostructural analyses for side-on spinning were performed is shown in Table 28. For the side-on spinning orientation, reentry angles of $\gamma = -7^\circ, -10^\circ, -15^\circ, -30^\circ, -50^\circ, -70^\circ$, and -90° were analyzed for thermostructural effects, since the thermal analysis did not show ablation failure at these reentry angles (see Table 10). The results of thermostructural analyses are discussed in Section VIII. F.2.c.

The mechanical and temperature loads described in Section VIII. F.2.a were applied to the LWRHU finite element model with thermoelastic material properties. The elemental stresses in the material coordinate system were then read into the thermoplastic analysis program ANSPNL4. Those elements which did not converge readily were run through the iteration program ANSPNL5 with the same algorithm, but with a successive under relaxation iteration scheme. The thermoplastic strains were iterated until convergence ($dU < 0.005$). Most elements converged within 0.5%, but some converged to higher values of 7%. For those in the latter situation, the factors of safety on strain were high, so no further effort was expended to get finer convergence.

(c) Side-on Spinning Results

Table 29 shows the time of initial indicated failure using a strain allowable of 0.01 in/in, and the time with the lowest factor of safety during each trajectory. Also shown for reference is the time of initial indicated failure using a strain allowable of 0.05 in/in, if failure is predicted. For each of these times, the element number, the factor of safety, and the material direction are provided. Figures 126 through 128 show the contour plots for factors of safety on strains, where a strain allowable of 0.01 in/in is used, for the timestep at which the lowest factor of safety is indicated for the shallow, intermediate, and steep reentry angles, respectively.

The locations of the elements with the lowest factors of safety are shown in Figures 126 through 128. Almost all of the normal strains are tensile. From the criterion for breach described in Section VIII. C, breach is not indicated from a thermostructural standpoint. Note that the contour plots of factors of safety with a strain allowable of 0.05 in/in can be obtained by multiplying the FS levels by 5.

3. Random Tumbling

(a) Random Tumbling Mechanical and Temperature Loads

The random tumbling configuration is similar to the side-on spinning, but adds an additional pressure load in the longitudinal direction. Determination of the decelerations in the longitudinal direction is straightforward, similar to the methodology described in Section VIII. F.1.a.

(b) Random Tumbling Runs

A listing of the reentry angles and times for which thermostructural analyses for random tumbling were performed is shown in Table 30. For the random tumbling orientation, reentry angles of $\gamma = -15^\circ, -30^\circ, -50^\circ, -70^\circ$, and -90° were analyzed for thermostructural effects, since the thermal analysis did not show ablation failure at these reentry angles (see Table 12). The results of thermostructural analyses are discussed in Section VIII. F.3.c.

The mechanical and temperature loads described in Section F.3.a were applied to the LWRHU finite element model with thermoelastic material properties. The elemental stresses in the material coordinate system were then read into the thermoplastic analysis program ANSPNL4. Those elements which did not converge readily were run through the iteration program ANSPNL5 with the same algorithm, but with a successive under relaxation iteration scheme. The thermoplastic strains were iterated until convergence ($dU < 0.005$). Most elements converged within 0.5%, but some converged to higher values of 6%. For those in the latter situation, the factors of safety on strain were high, so no further effort was expended to get finer convergence.

(c) Random Tumbling Results

Table 31 shows the time of initial indicated failure using a strain allowable of 0.01 in/in, and the time with the lowest factor of safety during each trajectory. Also shown for reference is the time of initial indicated failure using a strain allowable of 0.05 in/in, if failure is predicted. For each of these times, the element number, the factor of safety, and the material direction are provided. Figures 129 through 131 show the contour plots for factors of safety on strains, where a strain allowable of 0.01 in/in is used, for the timestep at which the lowest factor of safety is indicated for the shallow, intermediate, and steep reentry angles, respectively.

The locations of the elements with the lowest factors of safety are shown in Figures 129 through 131. Almost all of the normal strains are tensile. From the criterion for breach described in Section VIII. C, breach is not indicated from a thermostructural standpoint. Note that the contour plots of factors of safety with a strain allowable of 0.05 in/in can be obtained by multiplying the FS levels by 5.

IX. OTHER REENTRY CONDITIONS

Reentry analysis for other reentry scenarios including parking orbits, minimum gamma entries, and explosions were addressed in Appendix G of Reference 1. Except for the explosion scenario, the analyses conducted for this Safety Analysis Report (SAR) include those conditions both in scope and in modelling the problem. The results, documented in Reference 1 showed that no ablation failure of the LWRHU nor fuel melt is expected of the orbital decay or minimum gamma entries based on the assumptions used therein (multiple skips are not included). The previous SAR (Reference 1) examined an orbital and ascent explosion. This previous study showed that for an assumed bare clad entry, clad melt, but not fuel melt, would occur.

X. OTHER LAUNCH ACCIDENTS

Another Cassini accident scenario analyzed by JHU/APL is a ground launch accident in which a LWRHU module lays on Titan SRMU burning propellant. The predicted thermal response of the LWRHU to this accident is documented by P. T. Brenza in References 177 and 178. Because it is not a reentry accident scenario it is not included in this report but is mentioned here for completeness.

XI. REFERENCES

SECTION II

1. Johnson, E. W., Light Weight Radioisotope Heater Unit Safety Analysis Report (LWRHU-FSAR), Vol. I, Reference Design Document, Monsanto Research Corporation Report MLM-3293, Miamisburg, OH, October 1985.
2. Lutz, S. A., "Lightweight Radioisotope Heater Unit Module Ablation Response Testing at the NASA Ames 20 MW Aerodynamic Heating Facility: Final Test Report," BFD-2-90-011, The Johns Hopkins University Applied Physics Laboratory, 15 May 1990.

SECTION III

3. McDonald, A., "RTG Module Release Conditions for Inadvertent Earth Reentry of the Cassini Spacecraft During the VVEJGA Earth Flyby on 8-17-99, Revisited," JPL Interoffice Memorandum 312/94.6-759, 27 May 1994.
4. FAX from Angus McDonald, JPL, to Eddie Lucero, JHU/APL, dated 30 November 1994, Re: LWRHU Release Conditions.
5. Brenza, P. T., "Release Conditions for GPHS and LWRHU Reentry Thermal Analysis for the Cassini-VVEJGA FSAR," JHU/APL AM-94-D0035, BFD-2-94-027, October 11, 1994.

SECTION IV

6. Johnson, E. W., Light Weight Radioisotope Heater Unit Safety Analysis Report (LWRHU-SAR), Vol. II, Accident Model Document, Appendix G., Monsanto Research Corporation Report MLM-3293, Miamisburg, OH, October 1995.
7. Lucero, E. F., "Estimated Continuum and Free Molecular Aerodynamics and Bridging Parameters for the LWRHU," JHU/APL BFD-2-88-004, 2 March 1988.
8. Lucero, E. F., "Estimated Drag for GPHS at Angles of Attack, γ_R , of 30° and 90°, for GIS at $\gamma_R=27^\circ$ and for a Tumbling LWRHU Module for Mach Numbers Subsonic to Hypersonic," JHU/APL AM-91-D0005 (BFD-2-91-004), 28 January 1991.
9. Lucero, E. F., "Estimated Subsonic Aerodynamics and Terminal Velocity for the RTG, GPHS Module, GIS, Fuel Clad, and LWRHU," BFD-2-87-023, 10 December 1987.

SECTION VII. B. 2.

10. Communications of 24 June 1996, 10 July 1996, and 12 July 1996 from Dr. E. W. Johnson, Lamb Assoc., on Using Fuel Integral Fuel Pellet for Reentry Response Analysis.

SECTION VII. C.

11. Vargaftik, N. B., "Heat Conductivity of Gases and Liquids," FTD-MT-24-135-71, Foreign Technology Division, Wright-Patterson Air Force Base, Ohio, November 1971.
12. Collins, D. I. and Grief, R., International Journal of Heat and Mass Transfer, Volume 1, page 56, 1966.
13. Thermodynamics and Transport Properties of Gases, National Bureau of Standards Circular 564, 1955.
14. Yos, J. M., "Transport Properties of Nitrogen, Hydrogen, Oxygen and Air to 33000 °K," RAD-TM-63-7, Avco Corporation, Wilmington, MA, March 1963.
15. Gardiner, G. K., "A Critical Survey of Six Thermodynamic and Transport Properties of Air," NWC TP 4997, Naval Weapons Center, February 1971.
16. Bade, W. L., et al., American Rocket Society Journal, Volume 31, page 1151, 1961.
17. Eck, M. B., "Final Report on Earth Swingby Reentry," FOILS ENGINEERING, under NASA-JPL contract 959658, 22 November 1993.
18. "Final Report for the General Purpose Heat Source - Radioisotope Thermoelectric Generator Program," GESP-7209, General Electric Company - Astro Space Division, 1 February 1991.
19. Williams, R. K., "Review and Interpretation of Contact Conductance Measurements on FWPF Interfaces," Intra-Laboratory Correspondence, Oak Ridge National Laboratory, 5 May 1980.
20. Letter to R. Hartman, General Electric - Astro Space Division from R. L. Heestrand, Oak Ridge National Laboratory, Subject: "Contact Conductance Data," 4 February 1980.
21. Cross, R. W. and Fletcher, L. S., "Thermal Contact Conductance of Uranium Dioxide - Zircalloy Interfaces," AIAA Paper 78-85, AIAA 16th Aerospace Sciences Meeting, January 1978.

22. Minges, M. L., "Thermal Contact Resistance - Volume 1: A Review of the Literature," AFML-TR-65-375, Air Force Systems Command, Wright-Patterson Air Force Base, Ohio, April 1966.
23. Letter to R. Hartman, General Electric - Astro Space Division, from C. Alexander, Battelle Columbus Laboratories, discusses the contact conductance measured at the chamfered FWPFtm / pyrolytic graphite interface of the General Purpose Heat Source aeroshell, 31 March 1981.
24. Putz, R. E. and Bartlett, E. P., "Heat Transfer and Ablation Rate Correlations for Reentry Heat Shield and Nosetip Applications," AIAA Paper No. 72-91, AIAA 10th Aerospace Sciences Meeting, San Diego, CA, January 1972.
25. Perini, L. L., "Review of Graphite Ablation Theory and Experimental Data," ANSP-M-1, JHU/APL, Laurel, MD, December 1976.
26. Lundell, J. H. and Dickey, R. R., "Graphite Ablation at High Temperatures," AIAA Paper No. 71-418, AIAA 6th Thermophysics Conference, Tullahoma, TN, April 1971.
27. Leider, H. R., et. al., "Thermodynamic Properties of Carbon Up to the Critical Point," Carbon, Vol. 11, pp 555-563, 1973.
28. Lee, E. L. and Sanborn, R. H., "Extended and Improved Thermal Functions for the Gaseous Carbon Species C₁ - C₇ from 298 to 10000 °K," High Temperature, Sciences, Vol. 5, pp 438 - 453, 1973.
29. JANNAF Thermochemical Tables, 3rd Edition, National Bureau of Standards, 1986.
30. "User's Manual - Aerotherm Chemical Equilibrium (ACE) Surface Thermochemistry Program, Version 2," Aerotherm Corporation, June 1966.
31. "User's Manual - Aerotherm Charring Material Thermal Response and Ablation Program, Version 3, Volume 1: Program Description and Sample Problems," AFRPL-TR-70-92, Air Force Rocket Propulsion Laboratory, April 1970.
32. "An Analysis of the Coupled Chemical Reacting Boundary Layer and Charring Ablator - Parts I through VI," Reports NASA CR-1060 to NASA CR-1065, Aerotherm Corporation, June 1968.
33. Chan, C. C., "Upgrade of Graphite Surface Thermochemistry Tables," AM-93-E018, JHU/APL, Laurel, MD, 5 February 1993.

34. Hunter, L. W., "The Ablation Rate of Burning Carbon and In-Depth Heat Flux," ANSP-260 (also BBP-84-153), JHU/APL, Laurel, MD, 27 July 27 1984.
35. Jones, M. T., "The Phase Diagram of Carbon," National Carbon Research Laboratories, Report No. PRC-3, January 1958.
36. Palmer, H. B. and Shelef, M., Chemistry and Physics of Carbon, Volume 1, Marcel-Dekker, New York, 1965.
37. Bundy, F. P., "Melting of Graphite at Very High Pressure," Journal of Chemical Physics, Vol. 36, No.2, p 618, February 1963.
38. Schoessow, G. J., "Graphite Triple Point and Solidus-Liquidus Interface Experimentally Determined Up to 1000 Atmospheres," Physics Review Letter, Vol. 21, p.738, 1968.
39. Cezairliyan, A. and Miller, A. P., "Measurement of the Radiance Temperature (at 655 nm) of Melting Graphite Near Its Triple Point by a Pulse-Heating Technique," International Journal of Thermophysics, Vol. 11, No. 4, p. 643, 1990.
40. Conn, D. W., "Perspectives of the Fuel Reentry Problems - ANSP Planning," ANSP-282, JHU/APL, Laurel, MD, 14 March 1986.
41. March, E. B., "Thermal and Ablation Response of Small Spherical Particles for Reentry - Summary Report," SC-RR-68-547, Sandia Laboratories, Albuquerque, New Mexico, October 1968.

SECTION VII. D

42. Aerospace Nuclear Safety Program, "Reentry Response of the Light Weight Radioisotope Heater Unit Resulting From a Venus-Earth-Earth Gravity Assist Maneuver Accident," JHU/APL-M-19, Johns Hopkins University/Applied Physics Laboratory, October 1988.
43. Gardiner, G., A Critical Survey of Six Thermodynamic and Transport Properties of Air, NWC TP 4997, Naval Weapons Center, China Lake, CA, February 1971.
44. Waeber, K. R., "Comparison of DoE Sponsored FWPF[™] Data with that from the Air Force P⁴ Program," ANSP-167, Johns Hopkins University/Applied Physics Laboratory, 18 September 1979.
45. Waeber, K. R., "Summary of Mechanical and Thermal Property Information for AVCO's Fineweave Pierced Fabric," ANSP-187, Johns Hopkins University/Applied Physics Laboratory, 16 July 1980.

Applied Physics Laboratory
Laurel, Maryland 20723-6099

46. Letter to F. Schumann (Teledyne Isotopes) from G. F. Fornaro (Southern Research Institute), Subject: "Thermal Expansion Test Data on GE 3DCC and FWPF[™]," 14 June 1979.
47. O'Connor, T. and Mazzola, J. H., Textron Specialty Materials Data Sheet, "Representative Properties, 3-D Fineweave Pierced Fabric[™] Block".
48. Letter, "Preliminary Data Package for P⁴ FWPF Material Properties" with Enclosure: "PAN Carbon-Carbon Fine Weave Pierced Fabric Preliminary Data Package," Southern Research Institute, 24 August 1978.
49. J. C. Uzzell, "Handbook of Thermal Properties for Nuclear Power System Reentry Analysis," ANSP-169, The Johns Hopkins University Applied Physics Laboratory, October 1979.
50. Technical Information Exchange Meeting between Applied Physics Laboratory and General Electric Company, Purpose: "Comparison of the GPHS Thermal Properties" with principals P. T. Brenza (APL) and J. Loffreda (GE Astro-Space).
51. Letter to W.D. Owings (U.S. Department of Energy) from R.J. Hemler (Martin Marietta Astro Space), Subject: "Material Properties for the GPHS," 22 July 1994.
52. D. R. Stull and H. Prophet (Project Directors), JANAF Thermochemical Tables (Second Edition), National Bureau of Standards, June 1971.
53. Y. Shah (Manager, Quality Assurance), "Certificate of Conformance" (for Insulator Caps), Certificate Number 94202, BF Goodrich, Aerospace Super-Temp, 25 November 1994.
54. Fax to T. C. Craft (EG&G Mound Applied Technologies) from Y. Shah, (BF Goodrich, Aerospace Carbon Products), containing: "Certificate of Test" (for Insulator Tubes), 26 January 1995.
55. B. H. Morrison, et al., "Thermal Diffusivity of Pyrolytic Graphite From 23 to 1900°C," LA-DC-8307, Los Alamos Scientific Laboratory, 1966.
56. Memo to 'GPHS Task Force' from R. N. R. Mulford (Los Alamos Scientific Laboratory), Subject: "Pyrolytic Graphite Thermal Conductivity and Emittance," 27 July 1979.
57. Memo to 'GPHS Task Force' from R. N. R. Mulford (Los Alamos Scientific Laboratory), Subject: "Thermal Conductivity of Pyrolytic Graphite," 24 September 1979.

58. W. H. Smith and D. H. Leeds, "Pyrolytic Graphite," Modern Materials, Volume 7, Academic Press, Inc., New York and London, 1970.
59. E. Howell, "Acceptance Specification, Pyrolytic Graphite, Plate and Cylinder," SPA790171-Issue D (U), EG&G Mound Applied Technologies, 17 March 1994.
60. Y. S. Touloukian and D. P. DeWitt (Ed), Curve 30/Table 7 in Thermophysical Properties of Matter, Volume 8 - Thermal Radiative Properties, Nonmetallic Solids, Thermophysical Properties Research Center, Plenum Press, New York, 1972.
61. J. Roque', High Temperature - High Pressure, Volume 9, pp.207-210, 1977.
62. Y. S. Touloukian (Editor), Thermophysical Properties of High Temperature Solid Materials, Volume I: Elements, pages 782, 783, Thermophysical Properties Research Center, Purdue University, The MacMillan Company, New York, 1967.
63. Letter to J. C. Hagan (JHU/APL) from A. C. Schaffhauser, (Oak Ridge National Laboratory), Subject: "Transmittal of Pt-30% Rh Thermal Data," February 1979.
64. Letter to J. C. Hagan (JHU/APL) from J. R. Keiser (Oak Ridge National Laboratory), Subject: "Transmittal of Properties of Pt-3008," ORNL Letter No. 0815-26-78, 15 August 1978.
65. "SNAP 19/Pioneer F Safety Analysis Report; Volume II: Accident Model Document," INSD-2873-42-2, Teledyne Isotopes, December 1970.
66. Y. S. Touloukian and D. P. DeWitt (Ed), Thermophysical Properties of Matter, Volume 2, Part I: Nonferrous Binary Alloys, pages 403, 404, Thermophysical Properties Research Center, Plenum Press, New York, 1972.
67. Letter to S. E. Bronisz (Los Alamos Scientific Laboratory) from A. C. Schaffhauser (Oak Ridge National Laboratory), Subject: "Data on Pt-3008 for RHU Application," 4 December 1978.
68. ASM Handbook, Volume 2: Properties and Selection: Nonferrous Alloys and Special-Purpose Materials, Formerly 10th Edition, Metals Handbook.
69. Firstenberg, H., "Proposed High Temperature Thermal Conductivity of PuO₂ (DRAFT)," Halliburton NUS Corporation, October 1993.

70. Letter to Messrs. S. E. Bronisz (LASL), M. T. Goldstone (SR) and E. W. Johnson MRC) from R. Hartman (General Electric), Enclosure: "Fuel Thermal Properties Used in Analysis," 29 January 1980.
71. T. K. Keenan, et al., "Data Sheets for PPO Radioisotope Fuel," LA-5160-MS, Revision 1, Los Alamos Scientific Laboratory, December 1975.
72. Conn, D. W., "PuO₂ Microsphere Reentry Studies: Thermal Properties," ANSP-275, The Johns Hopkins University Applied Physics Laboratory, 16 August 1985.
73. "Final Safety Analysis Report for the Ulysses Mission - Volume 1: Reference Design Document," UL-FSAR-002, General Electric Astro-Space, March 1990.
74. Johnson, E. W., "Light-Weight Radioisotope Heater Unit Safety Analysis Report (LWRHU-SAR), Volume 1: A. Introduction and Executive Summary, B. Reference Design Document (RDD)," Mound Report MCM-3293, October 1985.
75. Johnson, E. W., "Light-Weight Radioisotope Heater Unit (LWRHU) Draft of Final Safety Analysis Report (FSAR) for the Cassini Mission," Lamb Associates, Inc., 30 June 1996.
76. Touloukian, Y. S. and Ho, C. H., Thermophysical Properties of Selected Aerospace Materials, Part I: Thermal Radiation Properties, Thermophysical and Electronic Properties Information Center, University of Purdue, 1976.
77. Letter to A. Schock (Fairchild Industries) from G. Wei (Oak Ridge National Laboratory), Subject: "Total Hemispherical Emittance of FWPF[™] C-C," 8 January 1980.
78. Plunkett, J. D., et al., "The Spectral and Integrated Emissivity of Carbon and Graphite" In Proceedings of the Fourth Conference on Carbon, pp 457-481, Pergamon, Oxford, 1960.
79. Dmitriev, A. A. and Lutkov, A. I., "Integral Hemispherical Degree of Blackness of Graphite," High Temperature, (volume unknown, refer to D. Conn, APL).
80. Glawe, G. E. and Shepard, C. E., "Some Effects of Exposure to Exhaust-Gas Streams on Emittance and Thermoelectric Power of Bare-Wire Platinum Rhodium-Platinum Thermocouples," NACA TN 3253, August 1954.
81. Davisson, C. and Weeks, J. R. Jr., "The Relation Between the Total Thermal Emissive Power of a Metal and its Electrical Resistivity," Journal Optical Society America and Review of Scientific Instruments, Volume 8, Number 5, May 1924.

82. Hampel, C. A. (Ed.), Rare Metals Handbook, 2nd Edition, Robert Krieger Publishing Company, Inc., Huntington, N.Y., 1971.
83. Aitken, E. A. and Evans, S. K., "Liquid/Solid Transformations in the U-Pu-O System," General Electric Company Vallecitos Nuclear Center, Pleasanton, California, January 1968.
84. Grave, G. R., et al., "Plutonium-238 Isotopic Power Sources: A summary Report," MLM-1270 AEC R&D Report, Mound Laboratory, Miamisburg, Ohio, 19 August 1965.
85. Laube, M., Plutonium, Pergamon Press, Oxford, England, (The MacMillan Company, New York, N.Y.), 1964 (pp 8-29, 47-62 and 174-187).
86. Loffreda, J., "Plutonium Dioxide Particle Re-Entry," Program Information Request/Release No. 6624, 13 January 1986.
87. Lundberg, R. E., et al., "A Study of the Behavior of Small Spheres During Reentry," Sandia Report SC-CR-67-635, Aerotherm Corporation, June 1967.
88. 'Pears, C. D., "Some Problems in Emittance Measurements at the Higher Temperatures and Surface Characterization", Southern Research Institute,' received from A. Schaffhauser, Oak Ridge National Laboratory, circa 1978.

SECTION VII E

89. Bhutta, B. A., et al., "New Technique for the Computation of Severe Reentry Environments," AIAA Paper 96-1861, 31st AIAA Thermophysics Conference, June 1996.
90. Perini, L. L., "User's Manual for the 3DOF Trajectory Computer Program," ANSP-M-6, The Johns Hopkins University Applied Physics Laboratory (JHU/APL), Laurel, MD, September 1973.
91. Detra, R. W., et al., "Addendum to 'Heat Transfer to Satellite Vehicles Re-entering the Atmosphere,'" Jet Propulsion, Vol. 27, No. 12, December 1957.
92. Fay, J. A. and Riddell, F. R., "Stagnation Point Heat Transfer in Dissociated Air," Journal of the Aeronautical Sciences, Vol. 25, No. 2, February 1958.
93. Rose, R. H. and Starks, W. L., "Stagnation Point Heat Transfer Measurements in Dissociated Air," Journal of the Aeronautical Sciences, Vol. 25, No. 2, February 1958.
94. Perini, L. L., "Compilation and Correlation of Experimental, Hypersonic, Stagnation Point Convective Heating Rates," ANSP-M-4, JHU/APL, Laurel, MD, July 1972.

95. Probstein, R. F., "Heat Transfer in Rarefied Gas Flow," in Theory and Fundamental Research in Heat Transfer, Proceedings of ASME Annual Meeting, November 1960, Pergamon Press, New York City, NY, 1963.
96. Sutton, K. and Hartung, L. C., "Equilibrium Radiative Heating Tables for Earth Entry," NASA Technical Memorandum 102652, Langley Research Center, May 1990.
97. Sutton, K., "Characteristics of Coupled Nongray Radiating Gas Flows with Ablation Products Effects About Blunt Bodies During Planetary Entries," PhD Thesis, North Carolina State University, Raleigh, North Carolina, 1973.
98. Nicolet, W. E., "Advanced Methods for Calculating Radiation Transport in Ablation-Product Contaminated Boundary Layers," NASA CR-1656, Aerotherm Corporation, September 1970.
99. Nicolet, W. E., "User's Manual for the Generalized Radiation Transfer Code (RAD/EQUIL)," Report to UM-69-9, Aerotherm Corporation, Mountain View, CA, October 1969.
100. Sutton, K., "Air Radiation Revisited," AIAA Paper 84-1733, AIAA 19th Thermophysics Conference, Snowmass, CO, June 1984; also in Progress in Astronautics and Aeronautics: Thermal Design of Aeroassisted Orbital Transfer Vehicles, ed. H. F. Nelson, Vol. 96, AIAA, New York, 1985.
101. Ambrosio, A. and Wortman, A., "Stagnation Point Shock Detachment Distance for Flow Around Spheres and Cylinders," Journal of the Aeronautical Sciences, Vol. 29, No. 2, February 1962.
102. Olstad, W., "Program to Compute the Inviscid Radiating Flow About a Circular Cylinder," Informal transmittal from W. Olstad, NASA-Langley Research Center, Hampton, VA, 13 December 1973.
103. Eck, M. B., 'References 9 and 10' contained in the report "Final Report on Earth Swingby Reentry," FOILS Engineering, prepared under NASA-JPL Contract 959658, November 1993.
104. Nicolet, W. E. and Balakrishnan, A., "Radiating Shock Layer Environment (RASLE) User's Manual," Aerotherm Report UM-79-10/AS, Acurex Corporation/Aerotherm Aerospace Systems Division, Mountain View, CA, July 1979.

105. Perini, L. L., "Compilation of Experimental Stagnation Point Velocity Gradients and Heat Transfer Data in Subsonic and Supersonic Flow," ANSP-068, The Johns Hopkins University Applied Physics Laboratory, Laurel, MD, August 1975.
106. Lasher, L. E. and Wilson, K. H., "Effect of Shock Precursor Heating on Radiative Flux to Blunt Bodies", NASA CR-1265, Lockheed Missile and Space Company, Palo Alto, CA, February 1969.
107. Anderson, J. D., "An Engineering Survey of Radiating Shock Layers", AIAA Journal, Vol. 7, No.9, September 1969.
108. Liu, J. T. C., "Influence of Upstream Absorption on the Stagnation Region Shock Layer Radiation," AIAA Journal, Vol. 8, No. 10, October 1970.
109. Coleman, W. D., et. al., "Effects of Environmental and Ablator Performance Uncertainties on Heat Shielding Requirements for Hyperbolic Entry Vehicles," Journal of Spacecraft and Rockets, Vol. 5, No. 11, November 1968.
110. Rigdon, W. S., et. al., "Stagnation Point Heat Transfer During Hypervelocity Atmospheric Entry," NASA CR-1462, McDonnell Douglas Corporation, February 1970.
111. Gupta, R., et. al., "Viscous-Shock-Layer Solutions with Coupled Radiation and Ablation Injection for Earth Entry," AIAA Paper 90-1697, AIAA/ASME 5th Joint Thermophysics and Heat Transfer Conference, June 1990.
112. Howe, J. and Viegas, J., "Solutions of the Ionized Radiating Shock Layer Including Reabsorption and Foreign Species Effects and Stagnation Region Heat Transfer," NASA TR R-159, NASA Ames Research Center, 1963.
113. Hoshizaki, H. and Wilson, K., "Convective and Radiative Heat Transfer During Superorbital Entry," NASA CR-584, Lockheed Missile and Space Company, Palo Alto, CA, September 1966.
114. Scott, C. D., "Wall Catalytic Recombination and Boundary Conditions In Nonequilibrium Hypersonic Flows - With Applications," in Advances in Hypersonics, Volume II: Modeling Hypersonic Flows, (eds) J. Bertin, J. Periaux, J. Ballman, Birkhauser Boston Press, Cambridge, MA, 1992.
115. JHU/APL ANSP-M-19, "Reentry Response of the Light Weight Radioisotope Heater Unit Resulting From a Venus-Earth-Earth Gravity Assist Maneuver Accident," Laurel, MD, October 1988.

116. Lees, L., "Laminar Heat Transfer Over Blunt-Nosed Bodies at Hypersonic Flight Speeds," Jet Propulsion, Vol. 26, No. 4, April 1956.
117. Kemp, N. H., et. al., "Laminar Heat Transfer Around Blunt Bodies in Dissociated Air," Journal of the Aeronautical Sciences, Vol. 26, No. 7, July 1959.
118. Carroll, H. R., "General Heating Distributions on the Tumbling Infinite Cylinder," AIAA Paper 78-42, AIAA 16th Aerospace Sciences Meeting, Huntsville, Alabama, January 1978.
119. Knight, D., "MHW Aerodynamic Heating Test Final Report," PIR 4665, General Electric Missile and Space Division, Valley Forge, PA, 5 October 1973.
120. Bertin, J. J., et al., "Flow Field Measurements for Space-Shuttle-Related Cylindrical Configuration in Hypersonic Streams," AIAA Paper 72-294, AIAA 7th Thermophysics Conference, San Antonio, TX, April 1972.
121. Schock, A., "Light-Weight Radioisotope Heater Unit," Report FSEC-ESD-217-81/181, Fairchild Space and Electronics Company, Germantown, MD 20767, 3 April 1981.
122. Olstad, W., "Nongray Radiating Flow about Smooth Symmetrical Bodies," AIAA Journal, Vol. 9, No. 1, January 1971.
123. "Monthly Technical Report for the Period 27 June through 31 July 1994," Martin Marietta Astro Space, King of Prussia, PA, Figure 3-4, Document No. RR16, Cassini RTG Program, 24 February 1995.
124. Miller, W. H., "Pressure Distributions on Single and Tandem Cylinders Mounted on Flat Plate for Mach Number 5.0 Flow," Defense Research Laboratory, DRL-538, 1 June 1966.
125. Gregorek, G. M. and Korkan, K. D., "An Experimental Observation of the Mach and Reynolds Number Independence of Cylinders in Hypersonic Flow," AIAA Journal, Vol. 1, No. 1, January 1963.
126. Bertram, M. H. and Everhart, P. E., Figure 6 in "An Experimental Study of the Pressure and Heat-Transfer Distribution on a 70 Degree Sweep Slab Delta Wing in Hypersonic Flow," NASA TR R-153, December 1963.
127. Webb, W. L., et al., "Hypersonic Wake Transition," AIAA Journal, Vol. 1, No. 3, March 1963.

128. Slattery, R. and Clary, W., "Experimental Measurement of Turbulent Transition, Motion, Statistics and Gross Radial Growth Behind Hypervelocity Objects," Physics of Fluids, Vol. 5, pp. 849-855.
129. Dogra, V. K., et. al., "Hypersonic Rarefied Flow Past Spheres Including Wake Structure," Journal of Spacecraft and Rockets, Vol. 31, No. 5, September-October .1994.
130. Bulmer, B. M., "Heat-Transfer Measurements in a Separated Laminar Base Flow," Journal of Spacecraft and Rockets, Vol. 14, No. 11, November 1977.
131. Sykes, D. M., "The Supersonic and Low Speed Flows Past Circular Cylinders of Finite Length Supported at One End," Journal of Fluid Mechanics, Vol. 12, Part 3.
132. Gowen, F. E. and Perkins, E. W., "Drag of Circular Cylinders for Wide Range of Reynolds Number and Mach Number," NACA TN 2960, June 1953.
133. Token and Oguro, "Experimental Investigation of Hypersonic Flow Around 2-D Circular Cylinders," ARL 65-212, Aeronautical Research Laboratories, October 1965.
134. Klett, R. D., "Drag Coefficients and Heating Ratios for Right Circular Cylinders in Free-Molecular and Continuum Flow From Mach 10 to 30," SC-RR-64-2141, Sandia Laboratory, Albuquerque, NM, December 1964.
135. Feller, W. V., "Investigation of Equilibrium Temperatures and Average Laminar Heat-Transfer Coefficients for the Front Half of Swept Circular Cylinders at a Mach Number of 6.9," NACA RM L55F08C, Langley Aeronautical Laboratory, August 1955.
136. Beckwith, I. E. and Gallagher, J. J., "Local Heat Transfer and Recovery Temperatures on Yawed Cylinders at Mach Number of 4.15 and High Reynolds Numbers," NASA TR R-104, Langley Research Center, 1961.
137. Beckwith, I. E., "Similar Solutions for the Compressible Boundary Layer on a Yawed Cylinder with Transpiration Cooling," NASA TR R-42, 1959.
138. Amirkabirian, I. and Bertin, J. J., "Aerothermodynamic Environment About a Highly Swept Wing Leading Edge," Journal of Spacecraft and Rockets, Vol. 24, No. 3, May-June 1967.
139. Sayano, S. and Greenwald, G. F., "Approximate Method for Calculating Heat Transfer to Yawed Cylinders in Laminar Flow," Journal of Spacecraft and Rockets, Vol. 10, No. 2, February 1973.

140. Bergquaum, J. E., "Aerodynamic Heating Investigation on Cylindrical Configuration in AEDC Tunnel (R-128)," Lockheed Rpt LMSC805538, Lockheed Missile and Space Company, Sunnyvale, CA, November 1965.
141. Trimmer, L. L. and Clark, E. L., "Stagnation-Point Velocity Gradients for Spherical Segments in Hypersonic Flow," AIAA Journal, Vol. 7, No.10, October 1969.
142. Serbin, H., "Supersonic Flow Around Blunt Bodies," Journal of the Aeronautical Sciences, Vol. 25, No. 1, January 1958.
143. Stoney, W. E., Jr. and Swanson, A. G., "Heat Transfer Measured on a Flat-Face Cylinder in Free Flight at Mach Numbers up to 13.9," NACA RM-L-57E13, 17 June 1957.
144. Klett, R. D. (9312) to Clark, A. J., Jr., (9312), Internal Memo "RFD-2 Aeroheating Hot Shot Test Conducted at Rhodes and Bloxson, October 8-12, 1963," Unclassified, Sandia Laboratories, 21 November 1963.
145. "Investigation of Re-entry Destruction of Nuclear Auxiliary Powerplants," Report AVCO-RAD-TR-61-28, Unclassified, October 1961.
146. Larson, H. K., "Heat Transfer in Separated Flows," Journal of the Aerospace Sciences, Vol. 26, No. 11, November 1959.
147. Powers, E. W., et al., "A Shock Tube Investigation of Heat Transfer in the Wake of a Hemisphere-Cylinder, with Application to Hypersonic Flight," Journal of the Aerospace Sciences, Vol. 26, No. 1, January 1959.
148. Oppenheim, A. K., "Generalized Theory of Convective Heat Transfer in a Free-Molecular Flow," Journal of the Aeronautical Sciences, Vol. 23, No. 1, January 1953.
149. Love, E. S., et al., "Some Topics in Hypersonic Body Shaping," AIAA Paper No. 69-181, AIAA 7th Aerospace Sciences Meeting, New York City, NY, January 1969.
150. Matthews, R. K. and Eaves Jr., R. H., "Comparison of Theoretical and Experimental Pressure and Heat Transfer Distributions on Three Blunt Nosed Cylinders In Hypersonic Flow," AEDC-TR-67-148, Arnold Engineering Development Center, Tullahoma, TN, September 1967.
151. Probstein, R. F., "Shock Wave and Flow Field Development in Hypersonic Re-Entry," ARS Journal, February 1961.

152. Matting, F. W., "Approximate Bridging Relations in the Transitional Regime Between Continuum and Free-Molecule Flows," Journal of Spacecraft and Rockets, Vol. 8, No. 1, January 1971.
153. Putz, K. E. and Bartlett, E. P., "Heat-Transfer and Ablation-Rate Correlations for Reentry Heatshield and Nosetip Applications," AIAA Paper 72-91, AIAA 10th Aerospace Sciences Meeting, San Diego, CA, January 1972.
154. Chan, C. C., "Oscillation and Non-convergence of CMA Results During High Velocity Galileo-VEEGA Reentries," Internal Memo BFD-2-90-025, JHU/APL, 28 September 1990.
155. Spalding, D. B., "A Standard Formulation of the Steady Convective Mass-Transfer Problem," International Journal of Heat and Mass Transfer, Vol.1, 1960.
156. Moss, J. N., "Radiative Viscous-Shock-Layer Solutions with Coupled Ablation Injection," AIAA Journal, Vol. 14, No. 9, September 1976.
157. Garrett, L. B., et al., "An Implicit Finite-Difference Solution to the Viscous Shock Layer Including the Effects of Radiation and Strong Blowing," NASA TR R-388, NASA Langley Research Center, November 1972.
158. Conn, D. W., "Heat Source Ablation Blockage of Shock Layer Radiation," Internal Memo BFD-2-92-016, JHU/APL, 31 August 1992.
159. Everhart, L. G., "TDOF and RETAP Code Modifications to Include Mass Flux Blockage and Cheng's Rarefaction Parameter Calculations," Internal Memo BFD-2-92-020, JHU/APL, 14 December 1992.
160. Perini, L. L., "Heat and Mass Transfer Correlation Equations for Subliming Graphite in High Speed Flow," ANSP-M-11, JHU/APL, August 1974.

SECTION VII. F.

161. Minges, M. L., "Thermal Contact Resistance - Volume 1: A Review of the Literature," AFML-TR-65-375, Air Force Systems Command, Wright-Patterson Air Force Base, Ohio, April 1966.
162. Conn, D. W., Reentry Safety Evaluation of Radioisotope Heater Unit (RHU)-Voyager Mission, Vol. I: Steep Angle Superorbital Reentry Thermal Response and Shallow Angle Reentry Ablation Response, JHU/APL, April 1978, Unpublished.

- 163. Perini, L. L., "Impact Temperature of the Light Weight Radioisotope Heater Unit (LWRHU)," JHU/APL, ANSP-225, BFD-4-82-016, 3 November 1982.
- 164. Perini, L. L., "Air Infiltration into the General Purpose Heat Source (GPHS) During Reentry," JHU/APL, ANSP-238, BFD-4-83-025, 3 August 1983.
- 165. Facsimile communication from Dr. B. Laub, Aerotherm Corporation to L. G. Everhart, on Thermochemical Data for PuO_2 , 25 July 1996.

SECTION VIII

- 166. Chang, Y., "Errors in MSC/NASTRAN for Thermostructural Analysis," JHU/APL Memorandum AM-96-E087, 28 August 1996.
- 167. Chang, Y., "Extensions to the Approximate Thermoplastic Analysis Method Using Fine Weave Pierced Fabric Material Properties," JHU/APL Memorandum AM-95-E150/BFD-2-95-014, 5 July 1995.
- 168. Chang, Y., "Updated Material Properties Data for Fine Weave Pierced Fabric in the Thermoplastic Analysis Program," JHU/APL Memorandum AM-96-E026, 15 March 1996.
- 169. Chang, Y., "A Limitation of the SAAS III Finite Element Analysis Program, and a Proposed Solution for Cassini Thermostructural Analysis," JHU/APL Memorandum AM-96-E045, 15 April 1996.
- 170. Chang, Y., "Thermoplastic Analysis of Axisymmetric Structures Fabricated of Cartesian Weave Fine Weave Pierced Fabric," JHU/APL Memorandum AM-96-E053, 23 May 1996.
- 171. Chang, Y., "A Thermoplastic Analysis Method for Three-Dimensional Weave Carbon-carbon Composites," Proceedings of the Space Technology Applications International Forum (STAIF-97), Albuquerque, NM, 26-30 January 1997.
- 172. Jones, R. M., "Modeling Nonlinear Deformations of Carbon-Carbon Composite Materials," AIAA Journal, Vol. 18, No. 8, August 1980.
- 173. "Evaluation of Carbon-Carbon Composites for The Pan Pilot Production Program (P⁴)," Southern Research Institute, AFML-TR-78-2, Volume II, May 1979.
- 174. Cull, T. A., "Status Report: FWPF Graphite Mechanical Properties Tests," Los Alamos National Laboratory NMT-9:ADM90-C026, 2 May 1990.

175. Waeber, K. R., "Fine Weave Pierced Fabric Compressive Failure Response: Consultation with Southern Research Institute," JHU/APL Memorandum ANSP-272, BFD-4-85-006, 7 May 1985.
176. Chang, Y., "Checkout of MSC/NASTRAN for Thermoelastic Analysis of Carbon-Carbon Composite Materials," JHU/APL Memorandum AM-94-E239/BFD-2-94-035, 12 December 1994.

SECTION X

177. Brenza, P. T., "Thermal Response of a LWRHU to Titan SRMU Fuel Fragment Fires for the Cassini Mission," JHU/APL AM-96-D015, 13 August 1996.
178. Facsimile to Dr. E. W. Johnson, from P. T. Brenza, "One Dimensional Predictions of LWRHU Thermal Response to Titan SRMU Propellant Fires," 27 November 1996.

Additional References for Table 8

- 8.1 NASA Ames Research Staff, "Equations, Tables and Charts for Compressible Flow," NASA Report 1135, 1953.
- 8.2 Wittliff, C. E. and Curtis, J. T., "Normal Shock Wave Parameters in Equilibrium Air," Report CAL-111, Cornell Aeronautical Laboratory, August 1962.
- 8.3 Marrone, P. V., "Normal Shock Waves in Air: Equilibrium Composition and Flow Parameters for Velocities from 26,000 to 50,000 Ft/Sec," Report AG-1729-A-2, Cornell Aeronautical Laboratories, August 1962.
- 8.4 "SNAP-27 Safety Report, Volume II: Accident Model Document, Supplement No. 1, Appendix P - Reentry Evaluation of GLFC and LM," DIN: 6300-300PRI, Isotope Power Systems Operation/Missile and Space Division," General Electric Co., September 1968.

Table 1
General Description of the LWRHU Components

<u>Component</u>	<u>Material</u>	<u>Material Specification</u>	<u>Drawing Number</u>	<u>Typical Weight, g</u>
Fuel Pellet	PuO ₂	--	AYC-790106	2.664
Frit Vent	Pt	SPA-790605	AYC-790098	5.702
Clad Cap, Vent End	Pt-30Rh	SPA-790139	AYC-790099	
Clad Cap, Closure End	Pt-30Rh	SPA-790139	AYC-790105	
Clad Body	Pt-30Rh	SPA-790139	AYC-790100	
Shim	Pt-30Rh	SPA-790139	AYC-790101	
Insulator Cap*	PG	SPA-790171	AYC-790381	2.532
Outer Insulator Body	PG	SPA-790171	AYC-790382	3.166
Middle Insulator Body	PG	SPA-790171	AYC-790383	1.486
Inner Insulator Body	PG	SPA-790171	AYC-790384	0.624
Aeroshell End Cap	FWPF	SPA-790053	AYC-790385	2.543
Aeroshell Body	FWPF	SPA-790053	AYC-790380	<u>21.070</u>
TOTAL WEIGHT				= 39.787

*Two Required

Applied Physics Laboratory
Laurel, Maryland 20723-6099

TABLE 2. Estimated Drag Coefficients and Bridging Parameters Used in Side-on Trajectories.*

Bridging Variable	Side-on Stable or Spinning LWRHU			
R_N	0.147 ft			
E_D	0.00			
S_{REF}	0.008924 ft ²			
D_{REF}	0.08513 ft			
SWMCH **	3.0			
Tabulated C_D	M	C_D	Alt	C_D
	0.0	0.554	0.0	1.20
	0.5	0.554	100000.	1.20
	0.6	1.26	200000.	1.24
	0.9	2.00	230000.	1.32
	1.0	2.10	235000.	1.33
	1.1	2.00	250000.	1.37
	1.3	1.70	300000.	1.62
	1.5	1.37	350000.	2.05
	1.8	1.26	400000.	2.10
	2.0	1.24		
	2.3	1.21		
	2.5	1.20		
	40.0	1.20		
	100.0	1.20		
<p>* Modified from AM-91-D0005, "Estimated Drag for GPHS at Angles of Attack, α_R, of 30° and 90°, for GIS at $\alpha_R = 27^\circ$ and for a Tumbling LWRHU Module for Mach Numbers Subsonic to Hypersonic," by E. F. Lucero, dated 28 January 1991.</p> <p>** Mach Number at which calculations switch from bridging drag coefficients to tabulated drag coefficients.</p>				

c:\tdof\dragco2.tab (wp5.2)

Applied Physics Laboratory
Laurel, Maryland 20723-6099

TABLE 3. Estimated Drag Coefficients and Bridging Parameters Used in Tumbling Trajectories.*

Bridging Variable	Random Tumbling Cylinder	Tumbling Sphere	Quasi-Tumbling Cylinder			
C _{DC}	0.00	1.02	1.90			
C _{DFH}	0.00	2.04	2.95			
R _N	0.147 ft	0.0477 ft	0.147 ft			
E _D	0.00	0.0	2.20			
S _{REF}	0.008924 ft ²	0.00714 ft ²	0.00569 ft ²			
D _{REF}	0.08514 ft	0.0954 ft	0.08513 ft			
SWMCH **	0.9	3.0	3.0			
Tabulated C _D	M	C _D	M	C _D	M	C _D
	0.0	0.554	0.0	0.55	0.0	0.94
	0.5	.554	0.2	0.57	0.2	0.94
	0.6	1.26	0.4	0.58	0.5	0.96
	0.9	2.00	0.6	0.62	0.6	1.53
	1.0	2.10	0.8	0.69	0.8	2.04
	1.1	2.0	0.9	0.91	1.0	2.35
	1.3	1.60	1.0	1.04	1.2	2.28
	1.5	1.37	1.2	1.11	1.4	2.02
	1.8	1.26	1.4	1.13	1.6	1.95
	2.0	1.24	1.6	1.12	1.8	1.92
	2.3	1.21	2.0	1.11	2.0	1.90
	2.5	1.20	3.0	1.06	3.0	1.90
	40.0	1.20	4.0	1.02	10.0	1.90
			50.0	1.02	100.0	1.90
			100.0	1.02		

* Modified from AM-91-D0005, "Estimated Drag for GPHS at Angles of Attack, α_R, of 30° and 90°, for GIS at α_R = 27° and for a Tumbling LWRHU Module for Mach Numbers Subsonic to Hypersonic," by E. F. Lucero, dated 28 January 1991.

** Mach Number at which calculations switch from bridging drag coefficients to tabulated drag coefficients.

c:\tdof\dragco.tab (wp51)

Estimated Drag Coefficients and Terminal Velocity for the LWRHU.

Axial		Crossflow		Average		
Sea Level	10K ft	Sea Level	10K ft	Sea Level	10K ft	
115 (35)	134 (41)	129 (39)	151 (46)	122 (37)	142 (43)	Cold
		108 (33)	126 (38)	112 (34)	130 (40)	Hot

Applied Physics Laboratory

Laurel, Maryland 20723-6099

TABLE 5. TDOF Trajectory Results.

Reentry Angle (°)	5.2°	7.0°	10.0°	15°	30°	50°	70°	90°
SIDE-ON								
Max Q_{rad} (Btu/ft ² s)	147.91	559.44	1300.822	2709.51	7022.15	11061.55	13139.76	13649
Max Q_{conv} (Btu/ft ² s)	1527.66	2133.25	2714.57	3408.54	4752.14	5843.53	6379.77	6463.98
Max M_{∞}	73.66	73.74	73.86	73.88	73.71	73.32	72.105	71.172
Max P_{12} (atm)	0.2653	0.5396	0.9643	1.5882	3.4019	5.4631	6.8072	7.2403
Max Decel (Gs)	38.34	74.55	132.48	217.09	461.8	738.83	919.12	977.09
Time of Max Q_{rad} (sec)	28.77	18.78	12.03	7.47	3.75	2.38	2.03	1.92
Time of Max Q_{conv} (sec)	23.45	15.61	10.00	6.30	3.20	2.18	1.88	1.77
Time of Max M_{∞} (sec)	7.00	4.00	1.00	0.00	0.00	0.00	0.00	0.00
Time of Max P_{12} (sec)	30.50	22.60	14.23	9.02	4.65	3.08	2.53	2.37
Time of Max Decel (sec)	29.67	22.40	14.13	9.02	4.65	3.08	2.53	2.37
Time at End of Heat Pulse (sec)	69.20	38.20	23.23	14.59	7.40	4.93	4.04	3.79
Time at $M_{\infty} = 5$ (sec)	218.40	59.00	33.10	19.80	9.70	6.20	5.10	4.70
Reentry Angle (°)	5.2°	7.0°	10.0°	15°	30°	50°	70°	90°
TUMBLING CYLINDER								
Max Q_{rad} (Btu/ft ² s)	162.42	613.13	1398.42	2858.31	7266.43	11279.45	13351.78	13861.8
Max Q_{conv} (Btu/ft ² s)	1589.89	2220.79	2807.32	349.43	4832.44	5919.34	6452.9	6535.79
Max M_{∞}	73.63	73.78	73.86	73.88	73.71	73.32	72.105	71.172
Max P_{12} (atm)	0.2134	0.5645	0.9974	1.631	3.4596	5.5254	6.8695	7.2969
Max Decel (Gs)	28.86	76.34	134.89	220.57	467.86	747.23	929	986.81
Time of Max Q_{rad} (sec)	29.61	19.15	12.19	7.51	3.75	2.38	2.03	1.92
Time of Max Q_{conv} (sec)	24.08	15.70	10.02	6.37	3.20	2.18	1.88	1.72
Time of Max M_{∞} (sec)	8.00	3.50	1.00	0.00	0.00	0.00	0.00	0.00
Time of Max P_{12} (sec)	32.01	22.31	14.13	8.99	4.65	3.03	2.53	2.37
Time of Max Dec (sec)	32.01	22.31	14.14	8.99	4.65	3.03	2.53	2.37
Time at End of Heat Pulse (sec)	96.90	38.21	23.24	14.54	7.40	4.88	4.28	4.07
Time at $M_{\infty} = 5$ (sec)	280.20	59.15	33.10	19.60	9.65	6.80	5.51	5.27

Applied Physics Laboratory
Laurel, Maryland 20723-6099

TABLE 5. TDOF Trajectory Results. (cont.)								
Reentry Angle (°)	5.2°	7.0°	10.0°	15°	30°	50°	70°	90°
TUMBLING SPHERE								
Max Q_{rad} (Btu/ft ² s)	226.72	966.49	2398.57	4777.05	11237.55	16943.79	20902.36	21963.9
Max Q_{conv} (Btu/ft ² s)	1656.94	2411.81	3194.79	4080.49	5797.59	7222.54	7941.81	8048.32
Max M_{∞}	73.61	73.79	73.86	73.88	73.71	73.32	72.105	71.172
Max $P_{t,2}$ (atm)	0.2541	0.7447	1.4054	2.4073	5.2545	8.4305	10.4947	11.1568
Max Decel (Gs)	25.39	67.84	128.04	219.29	478.69	768.03	956.08	1016.4
Time of Max Q_{rad} (sec)	30.51	21.19	13.12	8.11	3.90	2.80	2.27	2.16
Time of Max Q_{conv} (sec)	24.58	17.33	11.35	6.99	3.61	2.45	2.02	12.91
Time of Max M_{∞} (sec)	8.00	3.50	1.00	0.00	0.00	0.00	0.00	0.00
Time of Max $P_{t,2}$ (sec)	33.83	24.83	15.76	10.00	4.95	3.25	2.67	2.51
Time of Max Decel (sec)	31.86	24.83	15.76	9.94	4.95	3.25	2.67	2.51
Time at End of Heat Pulse (sec)	104.03	42.73	25.00	15.50	7.80	5.02	4.12	3.83
Time at $M_{\infty} = 5$ (sec)	324.51	63.80	34.51	20.55	9.65	6.14	4.99	4.67
$P_{t,2}$ - Total pressure behind a normal shock wave								
M_{∞} - Free stream Mach number								
Q_{rad} - Reference radiative heat flux; RAD/EQUIL, inviscid stagnation streamline flow field, effective spherical radius								
Q_{conv} - Reference convective heat flux; 1 ft radius sphere, stagnation flow, cold wall, zero mass transfer								
End of Heat Pulse - $Q_{rad} \rightarrow 0$ and $Q_{conv} \rightarrow 100$ (Btu/ft ² s)								
c:\tdof\intab.xls								

Table 6

LWRHU Thermal Response Modeling

a.) LWRHU Thermal Model Response Regions

Region Number	Component	Material
1	aeroshell body	FWPF carbon-carbon
2	aeroshell end cap	FWPF carbon-carbon
3	outer insulator body	pyrolytic graphite
4	middle insulator body	pyrolytic graphite
5	inner insulator body	pyrolytic graphite
6	clad body	Pt-30Rh alloy
7	clad end cap	Pt-30Rh alloy
8	fuel pellet (with shim)	$^{238}\text{PuO}_2$
9	insulator cap-layer 1	pyrolytic graphite
10	insulator cap-layer 2	pyrolytic graphite
11	insulator cap-layer 3	pyrolytic graphite
12	insulator cap-layer 4	pyrolytic graphite
13	insulator cap-layer 5	pyrolytic graphite

REGIONAL REPRESENTATIONS OF THE LWRHU THERMAL MODEL

Table 6 (Continued)

LWRHU Thermal Response Modeling

b.) LWRHU Interface Regions, Side-On Orientation

A. Radial

Region	Interface Components
1	aeroshell body/outer insulator body
2	outer insulator body/middle insulator body
3	middle insulator body/inner insulator body
4	inner insulator body/clad body
5	clad body/fuel pellet
6	aeroshell body/insulator cap-layer 5
7	outer insulator body/insulator cap-layer 4
8	outer insulator body/insulator cap-layer 3
9	middle insulator body/insulator cap-layer 2
10	inner insulator body/insulator cap-layer 1
11	aeroshell body/aeroshell end cap

B. Axial

12	insulator cap-layer 5/aeroshell end cap
13	outer insulator body/insulator cap-layer 5
14	outer insulator body/insulator cap-layer 4
15	middle insulator body/insulator cap-layer 3
16	inner insulator body/insulator cap-layer 2
17	clad body/insulator cap-layer 1
18	clad end cap/insulator cap-layer 1
19	fuel pellet (with shim)/clad end cap

C. Circumferential

None

Table 6 (Continued)
LWRHU Thermal Response Modeling

c.) Representative Interface States for the Side-on Stable LWRHU Assembly

I. Radial Interfaces

Interface Regions	Interface States					
	A. Perfect alignment ⁽ⁱ⁾		B. Translational displacement ⁽ⁱⁱ⁾		C. Thermal expansion ⁽ⁱⁱⁱ⁾	
	state	gap (mils)	state ($\theta=45^\circ$)	gap (mils)	state	gap (mils)
1. Aeroshell body outer insulator body (#1) • local stand-off ^(iv) • main ^(iv)	open open	3.0 6.1	open open	1.0 4.0	shut open	0.0 3.1
2. Outer insulator body middle insulator body (#2) • local stand-off • main	open open	2.7 5.8	open open	1.3 4.4	shut open	0.0 3.1
3. Middle insulator body inner insulator body (#3) • local stand-off • main	open open	2.9 5.8	open open	1.1 6.3	shut open	0.0 2.9
4. Inner insulator body clad body (#4) • local stand-off • main	open open	5.1 10.1	open open	1.6 6.6	shut open	0.0 5.0
5. Clad body fuel pellet • main ^(v) (#5)	open	6.9	open	2.4	shut	0.0
6. Aeroshell body insulator cap (#6) • main	open	2.5	open	1.0	shut	0.0
7. Outer insulator body insulator cap (#7) • main	open	2.0	open	2.3	shut	0.0
8. Outer insulator body insulator cap (#8) • main	open	2.4	open	2.7	shut	0.0
9. Middle insulator body insulator cap (#9) • main	open	2.5	open	4.2	shut	0.0
10. Inner insulator body insulator cap (#10) • main	open	1.8	open	3.0	shut	0.0
11. Aeroshell body aeroshell end cap (#11) • main	shut	0.0	shut	0.0	shut	0.0

Table 6 (Continued)
LWRHU Thermal Response Modeling
c.) Representative Interface States for the Side-on Stable LWRHU Assembly

II. Axial Interfaces

Interface Regions	Interface States			
	A. Perfect alignment ⁽ⁱ⁾		B. Thermal expansion ⁽ⁱⁱ⁾	
	state	gap (mils)	state ($\theta=45^\circ$)	gap (mils)
12. Aeroshell end cap insulator cap (#12) • local stand-off • main	shut open	0.0 4.9	shut open	0.0 4.9
13. Outer insulator body insulator cap (#13) • main	open	3.0	shut	0.0
14. Outer insulator body insulator cap (#14) • main	open	3.0	shut	0.0
15. Middle insulator body insulator cap (#15) • main	shut	0.0	shut	0.0
16. Inner insulator body insulator cap (#16) • main	open	3.0	shut	0.0
17. Clad body insulator cap (#17) • local stand-off • main	open open	5.0 8.0	shut open	0.0 3.0
18. Clad end cap insulated cap (#18) • local stand-off • main	open open	5.0 8.0	shut open	0.0 3.0
19. Fuel-shim clad end cap • main (#19)	open	5.0	open	5.0

Table 6 (Continued)
LWRHU Thermal Response Modeling

Notes:

- (i) Perfect alignment state
 - radial: all internal components co-aligned along the aeroshell's longitudinal axis.
 - axial: all internal component's play uniformly distributed fore and aft; assembly pre-loaded to remove minimum play (i.e., middle insulator body/insulator cap).
 - gap size: room temperature, nominal dimensions.
- (ii) Translational displacement state
 - radial: forward (i.e., windward displacement of all internal components along the forward stagnation line ($\theta=0^\circ$) due to flight deceleration.
 - gap size: room temperature, nominal dimensions; represented by gap at an aeroshell body central angle, $\theta=45^\circ$; modeled by law of cosines.
- (iii) Thermal expansion state
 - gap size: hypothetical representation in which heated state of the components results in closure of all radial and axis interfaces except where constrained by stand-offs.
- (iv) Translational displacement state:
 - For the initial segment of an interface ($0^\circ \leq \theta \leq 15^\circ$ Figure 34), the contact area of the segment is assumed to be over an area of $0^\circ \leq \theta \leq 5^\circ$ to distinguish between an engineering surface and an ideally smooth surface (point contact).
- (v) Exception to rate (iv):
 - The initial segment of the clad body/fuel pellet interface is assumed to be fully in contact.

Table 6 (Continued)
LWRHU Thermal Response Modeling
d.) Assignment of Interface States

Flight Orientation	Shallow Reentries ($\gamma \leq 15^\circ$)	Steep Reentries ($\gamma > 15^\circ$)
1. Side-on stable ^(a)		
• radial interfaces	te	td
• axial interfaces	te	pa
2. Side-on spinning ^(b)		
• radial interfaces	te	te
• axial interfaces	te	pa
3. Random tumbling ^(c)		
• radial interfaces	te	te
• axial interfaces	te	te

legend:

te: 'thermal expansion' interface state
 td: 'translational displacement' interface state
 pa: 'perfect alignment' interface state

notes:

- (a) for shallow reentries, both radial and axial interfaces are assumed to thermally expand to closure (except where constrained by stand-offs) due to durated heat pulse; for steep reentries, high inertia loading will shift interior components forward with radial interfaces closing in the stagnation region but axial interfaces affected neither by thermal expansion or inertia effects.
- (b) same assignments as side-on stable except now radial interfaces for all reentries are closed (except where constrained by stand-offs) to further simulate simultaneous closure at all circumferential locations due to high spin rates.
- (c) same assignments as side-on spinning except now all radial and axial interfaces for all reentries are closed (except where constrained by stand-offs) to further simulate simultaneous closure at all locations due to high rotational rates about all three axes.

Table 6 (Continued)

LWRHU Thermal Response Modeling

**e.) Thermal Contact Conductances
Prior Side-on Stable LWRHU Analyses**

Interface Region		Contact Conductance, $\text{BTU hr}^{-1} \text{ft}^{-2} \text{R}^{-1}$	
		3-D Design ^(a) side-on stable	2-D Galileo/VEEGA ^(b) side-on stable
Radial:	1	1000	10^5 (perfect)
	2	500	10^5 (perfect)
	3	500	10^5 (perfect)
	4	500	10^5 (perfect)
	5	2000	10^5 (perfect)
	6	1000	
	7	0 (open)	
	8	0 (open)	
	9	0 (open)	
	10	0 (open)	
	11	10^7 (perfect)	
Axial:	12	0 (open)	
	13	0 (open)	
	14	0 (open)	
	15	0 (open)	
	16	0 (open)	
	17	0 (open)	
	18	0 (open)	
	19	0 (open)	

Notes:

- (a) All axial interface regions were arbitrarily kept 'open' in this study to channel heat flow into the claded fuel assembly.
- (b) This study modeled the mid-span section of the LWRHU; for conservatism, assumed perfect thermal contact at all interfaces.

Table 6 (Continued)
LWRHU Thermal Response Modeling

f.) Thermal Contact Conductances
Based on Interface States and Compressive Stress States,
Side-on Stable Flight Orientation

Stress State	Interface States			
	Thermal Expansion high	low	Translational Displacement high	low
Contact Conductances (BTU hr ⁻¹ ft ⁻² R ⁻¹)				
I. Radial Interfaces				
region materials				
#1 FWPF/PG	3500		3500	
#2 PG/PG	1500		1500	
#3 PG/PG	1500		1500	
#4 PG/Pt30Rh	2250		2250	
#5 Pt30Rh/PuO ₂	150		150	
#6 PWPF/PG	3500			1000
#7 PG/PG		500	not applicable	
#8 PG/PG		500	not applicable	
#9 PG/PG		500	not applicable	
#10 PG/PG		500	not applicable	
#11 FWPF/FWPF		10 ⁷		10 ⁷
II. Axial Interfaces region material	Thermal Expansion		Perfect Alignment	
#12 ^(a) FWPF/PG	3500		3500	
#13 PG/PG	1500		not applicable	
#14 PG/PG	1500		not applicable	
#15 PG/PG	1500		1500	
#16 PG/PG		500	not applicable	
#17 Pt30Rh/PG		750	not applicable	
#18 Pt30Rh/PG		750	not applicable	
#19 Pt30Rh/Pt30Rh	not applicable		not applicable	

Notes: (a) The aeroshell end cap insulator cap interface (#12) and the insulator cap/middle insulator body (#15) were assumed in a high compression state due to pre-loading during assembly.

(b) For the side-on spinning flight orientation, all radial interfaces for the 'thermal expansion' and the "translational displacement" interface states were assumed to be in a high compression state due to high rotational rates about the longitudinal axis.

(c) For the random tumbling flight orientation all radial and axial interfaces were assumed to be in a high compression state for the 'thermal expansion' interface state due to high rotational rates about all three axes.

Table 7
Initial Reentry Temperature Distribution
LWRHU Assembly

Component	Initial Node	Final Node	Temperature, °R
Aeroshell Body	1	126	560.0
Aeroshell End Cap	127	210	560.0
Outer Insulator Sleeve (upper layer)	211	231	780.0
Outer Insulator Sleeve (lower layer)	435	462	780.0
Middle Insulator Sleeve (upper layer)	232	252	875.0
Middle Insulator Sleeve (lower layer)	463	483	875.0
Inner Insulator Sleeve	253	266	1105.0
Clad	267	280	1405.0
Fuel Pellet	281	308	1410.0
Clad End Cap	309	322	1405.0
End Insulator-Region 13	323	350	870.0
End Insulator-Region 12	351	378	880.0
End Insulator-Region 11	379	399	890.0
End Insulator-Region 10	400	420	900.0
End Insulator-Region 9	421	434	910.0

TABLE 8
Summary of LWRHU Assembly Engineering Models
Cassini/VEEJGA Aerothermodynamics^(a)

Aerothermodynamics	Engineering Models ^(b)	Features/Discussion
I. Reference Parameters^(c)		
1. Convective heat flux		1. 'particle' conduction and mass diffusion heat flux, BTU ft ⁻² sec ⁻¹
• reference conditions		• 1 ft sphere; continuum, laminar stagnation heating; cold wall; zero mass transfer and radiation coupling.
• model... $q_{c,ref}$	• $[17,600/(R)^{0.5}] (\rho_{\infty}/\rho_{sl})^{0.5} (V_{\infty}/V_c)^{3.15}$, Btu/ft ² sec ⁻¹ ; Figure 50	• good agreement in dissociation/ionization regimes; based on Fay & Riddell theory and shock tube heat transfer data.
• documentation ^(d)		• (i) correlation and experimental data.
(i) Detra, Kemp and Riddell, ref. 91		(ii) background and underlying theory.
(ii) Fay and Riddell, ref. 92		
2. Shock layer radiative heat flux		2. Btu ft ⁻² sec ⁻¹
• reference conditions		• stagnation streamline heat flux based on inviscid, equilibrium flow; effective spherical radius for side-on LWRHU at mid-span.
• models... $q_{r,ref}$	•	•
(i) radiation transport	(i) RAD/EQUIL code	(i) detailed spectral absorption coef; continuum and atomic line transport, thermodynamic equilibria; self-absorption.
(ii) flow field	(ii) Radiating Inviscid Flow Stagnation Point (RIFSP) code.	(ii) radiation coupled, inviscid, stagnation streamline flow field.
(iii) effective spherical radius ^(e) , side-on LWRHU	(iii) $R_{eff\ sph} = 2.70 R_{LWRHU}$	(iii) conservative estimate of effective radius based on adiabatic shock standoff correlations.
• documentation		•
(i) Nicolet, ref. 99		(i) user's manual, RAD/EQUIL code
(ii) Sutton & Hartung, ref. 96		(ii) radiation tables based on RAD/EQUIL - RIFSP solutions.
(iii) Ambrosio & Wortman, ref. 101		(iii) adiabatic stagnation shock stand-off correlations

Aerothermodynamics	Engineering Models ^(b)	Features/Discussion
I. (continued)		
3. Free molecule heat flux <ul style="list-style-type: none"> • reference condition • model...$q_{fm, ref}$ • documentation (i) Probst, ref. 95 	<ul style="list-style-type: none"> • $(\rho_{\infty} V_{\infty})^3 / 2 J$ 	3. Btu ft ⁻² sec ⁻¹ <ul style="list-style-type: none"> • unit thermal accommodation coefficient. (i) background and theory.
4. Pressure <ul style="list-style-type: none"> • reference conditions • model...$p_{2, ref}$ • documentation (i) Wittliff & Curtis, ref. 8.2 (ii) Marrone, ref. 8.3 	<ul style="list-style-type: none"> • $\approx \gamma p_{\infty} (M_{\infty})^2$ 	4. stagnation pressure aft of normal shock, atmospheres. <ul style="list-style-type: none"> • normal shock jump conditions; thermodynamic equilibrium air. • $\gamma \approx 1.35$ to correlate 'real gas' normal shock data. • (i) normal shock tables; thermodynamic equilibrium air. (ii) same as (i).
5. Enthalpy <ul style="list-style-type: none"> • reference conditions • model...$H_{t, ref}$ • documentation (i) NASA 1135, ref. 8.1 	<ul style="list-style-type: none"> • $h_{\infty} + (V_{\infty})^2 / 2gJ$ 	5. stagnation enthalpy, Btu lbm ⁻¹ <ul style="list-style-type: none"> • 1-D inviscid, adiabatic flow. • (i) compressible flow and shock wave tables, perfect air.
II. Body Reference Parameters^(f)		
1. Convective heat flux <ul style="list-style-type: none"> • reference conditions • model...$q_{c, b, ref} / q_{c, ref}$ • documentation (i) Perini, ref. 105 	<ul style="list-style-type: none"> • $1/(2)^{0.5} (\beta_{so, LWRHU} / \beta_{ref})^{0.5} (R_{ref} / R_{LWRHU})^{0.5}$ Figure 51 	1. Btu ft ⁻² sec ⁻¹ <ul style="list-style-type: none"> • see I.1 discussion; mid-span of side-on LWRHU. • transformation from ref sphere to side-on LWRHU at mid-span. • (i) stagnation velocity gradient (β) theory and exp data for various geometries.

Aerothermodynamics

Engineering Models^(b)

Features/Discussion

II. (continued)

2. Shock layer radiative heat flux

2. see I.2 discussion

3. Free molecule heat flux

3. see I.3 discussion

4. Pressure

4. see I.4 discussion

5. Enthalpy

5. see I.5 discussion

III. Adjustments, Body Reference Parameters

1. Precursor heating factor

- model... $F_{r,pc}$
- documentation
 - (i) Lasher & Wilson, ref. 106

$$\bullet \approx 1.0 + 6.0E-6 (65000-40000)$$

1. multiplier on body reference radiative heat flux; pre-shock heating effect

- 15% increase at 65,000 fps; engineering judgement based on limited numerical precursor data.
- (i) background theory; numerical data.

2. Radiation coupling factor

- model... $F_{c,rc}$
- documentation
 - (i) Howe & Viegas, ref. 112
 - (ii) Hoshizaki & Wilson, ref. 113

$$\approx 1.0 - 8.57E-6 (65000-30000)$$

2. multiplier on body reference convective heat flux; modification of $q_{c,bref}$ surface gradients due to shock layer radiation effects.

- 30% decrease at 65,000 fps; engineering judgement based on limited small radius body coupling data; analyses considered no adjustment due to uncertainty in data; conservative.
- (i) numerical data.
- (ii) numerical data.

Aerothermodynamics

Engineering Models^(b)

Features/Discussion

IV. Local Parameter Factors^(a), Side-On Stable (SOS) Orientation,A. Cylindrical Surface SOS Factors, $F(\theta, \alpha, z/L)_{X_{SOS}, CS}$ 1. General Method, $F(\theta, \alpha=90, z/L)_{X_{SOS}, CS}$ 1. $[F(\theta, 90, 0) F(0, 90, z/L)]_{X_{SOS}, CS}$ 2.a Convective factor, θ -direction

• model

(i) $F(\theta, 90, 0)_{C_{SOS}, CS}, \theta \leq 90^\circ$ (ii) $F(\theta, 90, 0)_{C_{SOS}, CS}, \theta \geq 90^\circ$

(i) Figure 52 (Kemp, Rose and Detra)

(ii) 6 to 8%

• documentation

(i) Kemp, Rose and Detra, ref. 117

(ii) Lees, ref. 116

(iii) SNAP-27, ref. 8.4

2.b Convective factor, z/L -direction• model... $F(0, 90, z/L)_{C_{SOS}, CS}$

• Figure 53, (Multi-Hundred Watt Heat Source experimental data).

• documentation

(i) Knight, ref. 119

A. angle of attack, $\alpha=^\circ$ for a side-on orientation.1. Local parameter (x) factor is the product of the local θ value at mid-span times the local axial value along the stagnation line.

- (i) thermodynamic equilibrium theory; slightly more conservative than the Galileo/VEEGA model (Lees).
- (ii) engineering judgement based on SNAP-27 base heating survey; values not influential on aeroshell stagnation response.

- (i) VEEGA theoretical model; experimental data.
- (ii) VEEGA theoretical model.
- (iii) theoretical and experimental base heating schedules.

• stagnation line heating distributions for right cylinder geometry.

- (i) Multi-Hundred Watt experimental heating distributions.

Aerothermodynamics	Engineering Models ^(b)	Features/Discussion
IV. (continued)		
3.a Shock layer radiative factor, θ -direction		
• model		
(i) $F(\theta, 90, 0)_{r, \text{sol}, \text{cs}}, \theta \leq 90^\circ$	(i) $\approx \cos^{3/2} \theta + B \sin^2 \theta$, B fitted graphically, Figure 54	(i) function bounds NASA-LRC (Olstad) inviscid, radiating flow field numerical data; 6 step model for absorption coefficient; continuum and atomic line transport; thermodynamic equilibria; self-absorption; radiation cooling.
(ii) $F(\theta, 90, 0)_{r, \text{sol}, \text{cs}}, \theta \geq 90^\circ$	(ii) zero base heating	(ii) engineering judgement based on Olstad code's data; values not influential on aeroshell stagnation response.
• documentation		
(i) Olstad, ref. 102		(i) user's guide for the Olstad code.
(ii) Olstad, ref. 112		(ii) background theory; uv spectra contribution to absorption coefficient updated in the code.
3.b Shock layer radiative factor, z/L -direction		
• model... $F(0, 90, z/L)_{r, \text{sol}, \text{cs}}$	• Figure 55	• engineering judgement based on CFD radial distributions for a flat faced cylinder (GPHS-Lockheed Martin) with and without ablation.
• documentation		
(i) Cassini RTG Program MTPR, ref. 123		(i) CFD heating distributions for the broadface stable GPHS module.
4.a Free molecule heating factor, θ -direction		
• model		
(i) $F(\theta, 90, 0)_{\text{fm}, \text{sol}, \text{cs}}, \theta \leq 90^\circ$	(i) Figure 52, $\cos(\theta)$	
(ii) $F(\theta, 90, 0)_{\text{fm}, \text{sol}, \text{cs}}, \theta \geq 90^\circ$	(ii) zero base heating	(ii) values not influential on aeroshell stagnation response.
• documentation		
(i) Probstein, ref. 95		(i) background and theory.

Aerothermodynamics

Engineering Models^(b)

Features/Discussion

IV. (continued)

4.b Free molecule heating factor, z/L -direction

- $F(0,90,z/L)_{fm,so,cs}$

- uniform at 1.00, (bref value)

- no variation along stagnation line due to end effects.

5. Static pressure factor, θ & z/L directions

- model

- (i) $F(\theta,90,z/L)_{p,so,cs}$, $\theta \leq 90^\circ$

- Figure 56

- (i)

- (i) circumferential pressure factors as a function of axial distance.

- $C_p(\theta)/C_{p,bref} = 0.261 + 0.441\cos\theta + 0.217\cos2\theta + 0.064\cos3\theta + 0.016\cos4\theta + 0.005\cos5\theta - 0.001\cos6\theta$, $z/L = 0.0$.

- $C_p(\theta)/C_{p,bref} = 0.250 + 0.431\cos\theta + 0.230\cos2\theta + 0.079\cos3\theta + 0.018\cos4\theta + 0.005\cos5\theta - 0.001\cos6\theta$, $z/L = 0.5$.

- $C_p(\theta)/C_{p,bref} = 0.219 + 0.401\cos\theta + 0.242\cos2\theta + 0.106\cos3\theta + 0.035\cos4\theta + 0.014\cos5\theta - 0.003\cos6\theta$, $z/L = 1.0$.

- (ii) 2 to 4%

- (ii) based on experimental data base.

- documentation

- (i) Miller, ref. 124

- (ii) Gregorek and Korkan, ref. 125

- (i) correlations and experimental data.

- (ii) correlation and experimental data; Galileo/VEEGA.

6. Recovery enthalpy factor, θ & z/L directions

- model

- (i) $F(\theta,90,z/L)_{Hr,so,cs}$, $\theta \leq 90^\circ$

- (ii) $F(\theta,90,z/L)_{Hr,so,cs}$, $\theta \geq 90^\circ$

- documentation

- (i) NASA Report 1135, ref. 8.1

- (ii) Gregorek and Korkan, ref. 125

- Galileo/VEEGA model for windward and leeward factors.

- (i) isentropic expansion to Gregorek's pressure distribution; uniform axial distribution; thermodynamic equilibrium air; recovery enthalpy ratio equated to recovery temperature ratio (infers perfect gas).

- (ii) Galileo/VEEGA model; arbitrarily set to 100% which underestimates leeward ablation; not influential on aeroshell stagnation response.

- (i) compressible gas dynamics tables.

- (ii) static pressure distribution driving isentropic expansion.

Aerothermodynamics

Engineering Models^(b)

Features/Discussion

IV. (continued)

B. End Face SOS Factors, $F(\delta, \alpha, r/R)_{X_{sos,ef}}$

1. Convective heating factor

- model... $F(\delta, 90, r/R)_{c,sos,ef}$ • 10%, uniform distribution over face.

2. Radiative & free molecule heating factors

- models... $F(\delta, 90, r/R)_{r,sos,ef}$ • 0%
- ... $F(\delta, 90, r/R)_{fm,sos,ef}$

3. Static pressure & recovery enthalpy factors

- models... $F(\delta, 90, r/R)_{p,sos,ef}$ • same as IV.A.5,6
- ... $F(\delta, 90, r/R)_{Hr,sos,ef}$

B. Factors approximated since this surface not influential on aeroshell stagnation response for this flight orientation.

- conservative estimate in strong expansion flow region; act to reduce energy losses from end face.

- same models as leeward factors for cylindrical surface.

V. Parameter Factors, Side-On Spinning (SOSP) Orientation

A. Cylindrical Surface SOSP Factors, $F(\theta, 90, z/L)_{X_{sosp,cs}}$

A. assumes high spin rates to permit smearing via integration of local parameter factors established for the side-on stable orientation. Local leeward factors are now influential on aeroshell response and have been adjusted as noted.

1. General Method

$$1. F(\theta, 90, z/L)_{X_{sosp,cs}} = \int F(\theta, 90, z/L)_{X_{sosp,cs}} d\theta, 0^\circ \leq \theta \leq 180^\circ$$

2. Convective, free molecule heating spin factors

3. Shock layer radiative heating local factor

- model... $F(\theta, 90, z/L)_{r,sosp,cs}, \theta \geq 90^\circ$ • 10% at $\theta=120^\circ$ to 5% at $\theta=180^\circ$.

2. no leeward adjustments on local factor models presented and discussed in IV.A.2,4.

3. adjusted leeward local radiation factors.

- engineering judgement; conservative estimate.

Aerothermodynamics	Engineering Models ^(b)	Features/Discussion
V.A. (continued)		
4. Static pressure spin factor		4. adjusted leeward local static pressure factors.
• model... $F(\theta, 90, z/L)_{p, sosp, cs}$	• 2% at $\theta \geq 120^\circ$	• adjusted base separated flow according to experimental data of Gregorek and Korkan.
• documentation		•
(i) Gregorek and Korkan, ref. 125		(i) experimental data and correlation.
5. Recovery enthalpy spin factor		5. adjusted leeward local recovery enthalpy factors.
• model... $F(\theta, 90, z/L)_{Hr, sosp, cs}$	• $H_r(\theta)/H_r(0) \approx T_r(\theta)/T_r(0)$	• identity based on adiabatic, perfect air; assumes base Mach # ≈ 0.5 ; recovery factor, $r = 0.85$.
(i) shallow reentries, $\gamma \leq 15^\circ$		(i) numerical temperature data of Dogra, et. al. for laminar base flow.
(ii) steep reentries, $\gamma \geq 15^\circ$		(ii) experimental temperature data of Bulmer for laminar base flow.
• documentation		
(i) Dogra, ref. 129		
(ii) Bulmer, ref. 130		
B. End Face SOSP Factors, $F(\delta, \alpha, r/R)_{X, sosp, ef}$		B. same models as IV.B; not influential on aeroshell stagnation response.
VI. Parameter Factors, Random Tumbling (RT) Orientation		
		VI. random tumbling involves 3-axis rotation wherein both surfaces are influential on aeroshell response; assumes high rotational rates about axes to permit smearing via integration on θ and α .

Aerothermodynamics

Engineering Models^(b)

Features/Discussion

VI. A. (continued)

A. Cylindrical Surface RT Factors

1. General Method

- model... $F(\theta, \alpha, z/L)_{X, rt, cs} = [F(\theta, 90, z/L)_{X, sopp, cs} F(0, \alpha, 0)_{X, rt, cs}]$
 $F(0, \alpha, 0)_{X, rt, cs} = (1/\int 2\pi \sin \alpha d\alpha) \int F(0, \alpha, 0)_{X, rt, cs} 2\pi \sin \alpha d\alpha, 0^\circ \leq \theta \leq 90^\circ$
- documentation
 (i) Klett, ref. 134

2. Convective heating local α factor

- model... $F(0, \alpha, 0)_{c, rt, cs} = \cos^{1.1} \alpha + 0.05 \sin^2 \alpha$, Figure 57
- documentation
 (i) Sayano & Greenwald, ref. 139
 (ii) Berquaum, ref. 140

3. Shock layer radiative heating local α factor

- model... $F(0, \alpha, 0)_{r, rt, cs} = \cos \alpha + 0.10 \sin^2 \alpha$

4. Free molecule heating random

- tumbling factor... $F(\theta, \alpha, z/L)_{fm, rt, cs} \quad 4. \approx 0.26$

1. random tumbling factor X is the product of the of the spin factor for parameter X (from Section V.A.) times the angle of attack factor of parameter X's stagnation value at midspan.

- modification of Klett's method for random tumbling right cylinder.
- (i) drag coefficient and convective heating; right cylinder geometry; variety of flight attitudes.

2. convective heating at stagnation line's midspan location as a function of α .

- conservative estimate; bounds experimental data in low α range.
- (i) background and correlation.
 (ii) experimental stagnation data at α .

3. no available numerical or experimental data for cylinders at α ; model based on engineering judgement.

- guided by side-on stable convective and radiative heating local factor distributions (refer to IV.A.2a,3a).

4. taken directly from Klett.

Aerothermodynamics

Engineering Models^(b)

Features/Discussion

VI. A. (continued)

5. Static pressure local α factor

- model... $F(0, \alpha, 0)_{p,rt,\alpha}$

$$\bullet = 0.015 \cos^2 \alpha + \sin^2 \alpha,$$

- correlation based on shuttle's external tank experimental test data at α .

- documentation

(i) Carroll, ref. 118

(i) correlation, experimental data (external tank).

6. Recovery enthalpy local α factor

- model... $F(0, \alpha, 0)_{hr,rt,\alpha}$

$$\bullet \approx r_n \cos^2(90-\alpha) + r_t \sin^2(90-\alpha)$$

$r_n = 1.0$, stagnation recovery factor

$r_t = 0.85$, laminar (flat plate) recovery factor

- assumes recovery temperature ratio equates to recovery enthalpy ratio; implies perfect air gas dynamics; no end effects.

- documentation

(i) Feller, ref. 135

(ii) Beckwith & Gallagher, ref. 136

(i) background, correlation, experimental data.

(ii) experimental data.

B. End Face RT Factors

1. Convective heating local α factor

- model

(i) $F(-, \alpha, r/R)_{c,rt,ef}$, $\alpha \leq 90^\circ$

(i)

$[q_c(r/R)/q_c(0)]_{\alpha=0} \approx 1.0 + 0.6 (r/R)^{3.3}$, Figure 58...
Figure 59 schedule...

$$1/(2)^{0.5} (\beta_{ef,LWRHU} / \beta_{so,LWRHU})^{0.5} \dots$$

- (i) sweep angle effects not considered; factor comprised of end face heating distribution at $\alpha=0^\circ$, average end face heating as $f(\alpha/\alpha=0^\circ)$ and transformation of normalization variable back to body reference value.

end face heating distribution at $\alpha=0^\circ$,
average heating to end face at $\alpha/\alpha=0^\circ$.
normalization to body reference condition.

Aerothermodynamics

Engineering Models^(b)

Features/Discussion

VI. B. (continued)

1. (continued)

• model

(ii) $F(-, \alpha, r/R)_{r,ef}, \alpha \geq 90^\circ$

(ii) $[q_c(\alpha)/q_c(0)]_{\alpha=0} \approx 0.20 @ \alpha=90^\circ$ to
0.05 @ $\alpha=180^\circ$

• documentation

(i) Klett, ref. 134

(ii) Stoney, ref. 143

(iii) Kemp, et. al., ref. 117

(iv) Trimmer, ref. 141

2. Shock layer radiative heating local factor

• model

(i) $F(\delta, \alpha, r/R)_{r,ef}, \alpha \leq 90^\circ$

(i) $R_{eff\ sph,ef} = 1.545(K-1)^{0.5} R_{LWRHU} \dots$

$R_{eff\ sph,bref} = 2.70 R_{LWRHU} \dots$

$F(0,0,r/R)_{r,ef} = (R_{eff\ sph,ef} / R_{eff\ sph,bref})^n, n=0.40 \text{ steep } \dots$
 $n=0.65 \text{ shallow } \dots$

$q(\delta,0,r/R)_{r,ef} / q(0,0,r/R)_{r,ef} = \cos^{1.1} \delta, 0 \leq \delta \leq 90^\circ \dots$

$q(0,\alpha,r/R)_{r,ef} / q(0,0,r/R)_{r,ef} = \cos^{1.5} \alpha + 0.10 \sin^2 \alpha, \dots$

(ii) $F(\delta, \alpha, r/R)_{r,ef}, \alpha \geq 90^\circ$

(ii) 10%, $90^\circ \leq \alpha \leq 180^\circ$

(ii) engineering judgement; conservative, uniform heating on leeward end face as a $f(\alpha)$.(i) background, theory, heating at $\alpha=0^\circ$, Fig.D. 10.(ii) experimental data at $\alpha=0^\circ$.

(iii) same as (ii).

(iv) stagnation velocity gradients, experimental data, correlation.

2. uniform windward heating at $\alpha=0^\circ$; average heating is integrated product of sweep (δ) and angle of attack (α) dependency.

•

(i) effective spherical radius by equating stagnation shock stand-offs for sphere and disc; adiabatic shock layer.

effective spherical radius, body reference condition. transformation of $\alpha=0^\circ$ end face heating to body reference condition as a normalization factor.engineering judgement; dependency on end face local sweep angle based on cylindrical surface α behavior.engineering judgement; dependency on end face α based on cylindrical surface θ behavior.

(ii) engineering judgement; uniform heating.

Aerothermodynamics

Engineering Models^(b)

Features/Discussion

VI.B. (continued)

2. (continued)

• documentation

(i) Serbin, ref. 142

(ii) Sutton & Hartung, ref. 96

(i) stagnation shock stand-off correlations, sphere and disc.

(ii) radiation tables; used to determine exponent 'n' in IV.B.2(i).

3. Free molecule heating local α factor

• model

(i) $F(--, \alpha, r/R)_{fm, rt, ef}, 0^\circ \leq \alpha \leq 90^\circ$ (i) 0.255(ii) $F(--, \alpha, r/R)_{fm, rt, ef}, 90^\circ \leq \alpha \leq 180^\circ$ (ii) 0.00

• documentation

(i) Klett, ref. 134

(i) directly from Klett.

(i) background and theory.

4. Static pressure local α factor

• model

(i) $F(--, \alpha, r/R)_{p, rt, ef}, 0^\circ \leq \alpha \leq 90^\circ$ (i)
Figure 60 schedule ...
 $F_{3-D} (\sin^2 \alpha + 0.015 \cos^2 \alpha) \dots$

$$F_{3-D} \approx 0.75 \dots$$

(ii) $F(--, \alpha, r/R)_{p, rt, ef}, 90^\circ \leq \alpha \leq 180^\circ$ (ii) ≈ 0.015 4. assumed end face to be a constant (average) pressure surface but attenuated by a 3-D flow factor (F_{3-D}) to account for flow expansion effects.(i)
static pressure distribution at $\alpha=0^\circ$.
engineering judgement; static pressure dependency on α based on stagnation line α dependency for cylindrical surface.engineering judgement; attempt to account for flow expansion effects due to disc edge effects.
(ii) engineering judgement; constant (average) value.

Aerothermodynamics	Engineering Models ^(b)	Features/Discussion
VI.B. (continued)		
4. (continued)		
• documentation		•
(i) Love, et. al., ref. 149		(i) end face pressure distribution at $\alpha=0^\circ$.
(ii) Carroll, ref. 118		(ii) stagnation line pressure distribution at α .
5. Recovery enthalpy		5. constant (average) recovery enthalpy at α based on isentropic expansion to static pressure ratio determined in 4. as $f(\alpha)$.
• model		•
(i) $F(--, \alpha, r/R)_{Hr, rt, ef}, 0^\circ \leq \alpha \leq 90^\circ$	(i) $Hr(\alpha)/Hr(0) \approx Tr(\alpha)/Tr(0)$	(i) engineering judgement; isentropic expansion to end face's static pressure as $f(\alpha)$; used $\gamma \approx 1.2$ to represent real gas expansion.
(ii) $F(--, \alpha, r/R)_{Hr, rt, ef}, 90^\circ \leq \alpha \leq 180^\circ$	(ii) ≈ 0.80	(ii) engineering judgement; conservative estimate based on leeward recovery temperature experimental data.
• documentation		•
(i) Beckwith & Gallagher, ref. 136		(i) experimental recovery temperature data in the wake of yawed cylinders.
VII. Corrections to Local Heating Rates		
1. Low density correction, convective heating		1. correcting convective heating based on continuum (i.e., high density) theory or data for rarefied flow effects during early reentry.
• model... $F_{c, low p}$	• $q_{c, local} \{1 - \exp[-(q_{fm, local}/q_{c, local})]\}$, $q_{c, local}$ corrected for vorticity	• semi-empirical engineering bridging relationship based on kinetic theory; assumed to be valid at all locations for sos,rt orientations and windward locations for so.

Aerothermodynamics	Engineering Models ^(b)	Features/Discussion
VII. (continued)		
1. (continued)		
• documentation		•
(i) Matting, ref. 152		(i) theory and experimental data.
2. Surface mass transfer (ablation), convective heating		
• model	•	•
(i) primary	(i) Putz-Bartlett correlation,	(i) Putz and Bartlett provides blowing effects including localized combustion, injectant chemistry on surface gradients; produced unstable solutions.
(ii) secondary	(ii) Mickley-Spalding correlation, (refer to Figure 61 schedules)	(ii) classical blowing relationship; implemented in analyses to provide stable solutions; smaller reduction in convective heating than Putz and Bartlett; assumed valid at all locations.
• documentation		•
(i) Putz and Bartlett, ref. 153		(i) theory, experimental data and correlations.
(ii) Spalding, ref. 155		(ii) foundation for Mickley-Spalding correlation.
3. Surface mass transfer (ablation), radiative heating		
• model	• synthesized from data of Gupta, Moss, etc; refer to Figure 62 schedule	• assumed valid at all locations and to linearly decrease from continuum value at merged shock layer threshold to zero at the free molecule threshold.
• documentation		
(i) Gupta, et.al., ref. 111		(i) numerical data.
(ii) Moss, ref. 156		(ii) numerical data.

115

- Convention:**

$F(.,.)$...the local parameter factor as a function of flight or geometry variables.

subscript c...LWRHU surface cs cylindrical surface
 ef end face

-- ...indicates variable is not in use in determining the factor.

Nomenclature:

bref	body reference condition.
BTU	British thermal unit.
C_p	pressure coefficient, (local pressure - free stream pressure)/ dynamic pressure.
$C_{p,bref}$	pressure coefficient at the body reference condition for the parameter, pressure.
F	multiplication factor on an aerothermodynamic parameter.
$F_{c,rc}$	multiplication factor on convective heating due to radiation coupling effects.
$F_{c,low\ \rho}$	multiplication factor on convective heating due to low density effects.
$F_{r,pc}$	multiplication factor on radiative heating due to precursor effects.
ft	length in feet.
g	gravitational acceleration constant, ft sec^{-2} .
h_∞	freestream static enthalpy, BTU lbm^{-1} .
H_r	recovery enthalpy, BTU lbm^{-1} .
$H_{t,ref}$	reference enthalpy (i.e., total freestream enthalpy), BTU lbm^{-1} .
J	Joule's constant, ft-lb/BTU .
lbm	mass in pounds.
M_∞	freestream Mach Number.
MTPR	monthly technical progress report.
p_∞	freestream static pressure, atmosphere.
$P_{t2,ref}$	reference pressure (i.e., total pressure aft of normal shock wave), atmosphere.
$q_{c,bref}$	convective heating at body reference condition, $\text{BTU ft}^{-2} \text{sec}^{-1}$.
$q_{c,local}$	convective heating at local nodal stations of thermal model, $\text{BTU ft}^{-2} \text{sec}^{-1}$.
$q_{c,ref}$	reference convective heating (i.e., laminar stagnation heating, 1 ft sphere), $\text{BTU ft}^{-2} \text{sec}^{-1}$.
$q_{fm,local}$	free molecule heating at local nodal stations of thermal model, $\text{BTU ft}^{-2} \text{sec}^{-1}$.
$q_{m,ref}$	reference free molecule heating (i.e., normal incidence to surface), $\text{BTU ft}^{-2} \text{sec}^{-1}$.
$q_{r,ref}$	reference radiative heating (i.e., stagnation heating at mid-span of side-on LWRHU), $\text{BTU ft}^{-2} \text{sec}^{-1}$.
r/R	radial distance on end face from longitudinal axis normalized by the LWRHU radius.
rt (also RT)	abbreviation for 'random tumbling' flight orientation.
R	body radius, ft.
RTG	radioisotope thermoelectric generator.
$R_{eff\ sph}$	effective spherical radius, ft.
R_{LWRHU}	LWRHU aeroshell outer radius, ft.
R_{ref}	reference body radius, ft.
sec	time in seconds.

Table 8, Page 17

Nomenclature (continued):

sos (also SOS)	abbreviation for side-on stable flight orientation.
sosp	side-on spinning flight orientation.
Tr	recovery temperature, °R.
V_c	satellite circular velocity (26,000), ft/sec.
V_∞	freestream velocity, ft/sec.
X	generic symbol for an aerothermodynamic parameter.
z/L	axial distance on cylindrical surface from LWRHU mid-span normalized by mid-span distance.
α	angle of attack, degrees.
β	stagnation velocity gradient.
$\beta_{\text{ref, LWRHU}}$	LWRHU end face stagnation velocity gradient at $\alpha=0^\circ$, i.e., for a flat face cylinder end-on.
β_{ref}	reference stagnation velocity gradient, i.e., for a unit sphere.
$\beta_{\text{so, LWRHU}}$	side-on LWRHU stagnation velocity gradient, i.e., for a transverse cylinder.
δ	angle of sweep when LWRHU end face is at an angle of attack, degrees.
γ	flight path angle; also, specific heat ratio.
θ	central (or circumferential) angle, degrees.
ρ_{sl}	sea level density, lbm ft ⁻³ .
ρ_∞	freestream density, lbm ft ⁻³ .

Applied Physics Laboratory

Laurel, Maryland 20723-6099

TABLE 9. Side-On Stable LWRHU 3D Thermal Analyses Results

Reentry Angle	-5.2°	-7.0°	-10°	-15°	-30°	-50°	-70°	-90°
Time of M=5	218.4	59.0	33.1	19.8	9.7	6.2	5.1	4.7
Time of Peak Qconv	23.45	15.61	10.00	6.30	3.20	2.18	1.88	1.77
Peak Ref Qconv	1527.66	2133.25	2714.57	3408.54	4752.14	5843.53	6379.77	6463.98
Time of Peak Qrad	28.77	18.78	12.03	7.47	3.75	2.38	2.03	1.92
Peak Ref Qrad	147.91	559.44	1300.82	2709.51	7022.15	11061.55	13139.76	13649.0
Time at 75% Ablation	22.61 Node 1	14.41 Node 1	9.39 Node 1	6.10 Node 1	3.36 Node 64	2.40 Node 64	2.06 Node 64	1.97 Node 64
Altitude at 75% Ablation	242813.0 Node 1	226161.7 Node 1	211150.0 Node 1	195188.7 Node 1	169057.5 Node 64	151804.9 Node 64	143076.2 Node 64	139728.6 Node 64
Velocity at 75% Ablation	59462.9 Node 1	58959.2 Node 1	58145.9 Node 1	56990.2 Node 1	54339.6 Node 64	51865.0 Node 64	50022.1 Node 64	48846.3 Node 64
Surface Temp at Failure	6033.6 Node 1	6206.4 Node 1	6347.5 Node 1	6504.0 Node 1	6752.0 Node 64	6926.4 Node 64	7012.8 Node 64	7041.4 Node 64
Clad Temp at Failure	1635.9 Node 267	1213.8 Node 267	959.0 Node 267	804.2 Node 267	753.5 Node 267	761.4 Node 267	770.5 Node 267	773.6 Node 267
Fuel Temp at Failure	1223.8 Node 281	921.9 Node 281	821.2 Node 281	816.9 Node 281	858.9 Node 281	891.0 Node 281	903.0 Node 281	906.2 Node 281
Time at 100% Ablation	25.05 Node 1	15.94 Node 1	10.49 Node 1	6.89 Node 1	3.81 Node 64	2.73 Node 64	2.35 Node 64	2.27 Node 64
Altitude 100% Ablation	238193.6 Node 1	218778.7 Node 1	202042.7 Node 1	184649.3 Node 1	157780.0 Node 64	139596.5 Node 64	130280.9 Node 64	126327.4 Node 64
Velocity 100% Ablation	57483.3 Node 1	56495.5 Node 1	55144.7 Node 1	53193.4 Node 1	49367.3 Node 64	45299.1 Node 64	42253.7 Node 64	40259.1 Node 64
Surface Temp at Failure	6060.9 Node 1	6255.6 Node 1	6408.0 Node 1	6567.2 Node 1	6814.5 Node 64	6981.4 Node 64	7053.3 Node 64	7063.9 Node 64
Clad Temp at Failure	1849.9 Node 267	1352.8 Node 267	1064.7 Node 267	868.1 Node 267	761.0 Node 267	757.4 Node 267	763.2 Node 267	765.1 Node 267
Fuel Temp at Failure	1394.1 Node 281	1004.6 Node 281	857.4 Node 281	821.1 Node 281	846.9 Node 281	879.7 Node 281	892.6 Node 281	895.6 Node 281

For Model Node Locations, refer to Figure 34.

75% Ablation implies 0.133 inches

100% Ablation implies 0.177 inches

Reference Q_{rad} is for RAD/EQUIL, inviscid stagnation streamline flow field, effective spherical radius, mid-span LWRHUReference Q_{conv} is for 1 ft radius sphere, stagnation flow, cold wall, zero mass transfer

All Reentry Angles utilize Lawrence Livermore Thermochemistry Tables,

All Times are given in seconds

All Temperature are given in °F

All Altitudes are given in feet

All Velocities are given in ft/s

All heating rate data are given in Btu/ft²s

c:\wp51\leahmem\rhufail2.tab

TABLE 10. Side-On Spinning LWRHU 3D Thermal Analyses Results

Reentry Angle	-5.2°	-7.0°	-10°	-15°	-30°	-50°	-70°	-90°
Time of M=5	218.4	59.0	33.1	19.8	9.7	6.2	5.1	4.7
Time of Peak Qconv	23.45	15.61	10.00	6.30	3.20	2.18	1.88	1.77
Peak Ref Qconv	1527.66	2133.25	2714.57	3408.54	4752.14	5843.53	6379.77	6463.98
Time of Peak Qrad	28.77	18.78	12.03	7.47	3.75	2.38	2.03	1.92
Peak Ref Qrad	147.91	559.44	1300.82	2709.51	7022.15	11061.55	13139.76	13649.0
Time at 75% Ablation	112.80 Node 34	NF	NF	NF	NF	NF	NF	NF
Altitude at 75% Ablation	237633.0 Node 34	NF	NF	NF	NF	NF	NF	NF
Velocity at 75% Ablation	20851.0 Node 34	NF	NF	NF	NF	NF	NF	NF
Surface Temp at Failure	3291.4 Node 34	NF	NF	NF	NF	NF	NF	NF
Clad Temp at Failure	3756.5 Node 278	NF	NF	NF	NF	NF	NF	NF
Fuel Temp at Failure	3824.23 Node 304	NF	NF	NF	NF	NF	NF	NF
Time at 100% Ablation	NF	NF	NF	NF	NF	NF	NF	NF
Altitude 100% Ablation	NF	NF	NF	NF	NF	NF	NF	NF
Velocity 100% Ablation	NF	NF	NF	NF	NF	NF	NF	NF
Surface Temp at Failure	NF	NF	NF	NF	NF	NF	NF	NF
Clad Temp at Failure	NF	NF	NF	NF	NF	NF	NF	NF
Fuel Temp at Failure	NF	NF	NF	NF	NF	NF	NF	NF

For Model Node Locations, refer to Figure 34.

75% Ablation implies 0.133 inches

100% Ablation implies 0.177 inches

Reference Q_{rad} is for RAD/EQUIL, inviscid stagnation streamline flow field, effective spherical radius, mid-span LWRHU

Reference Q_{conv} is for 1 ft radius sphere, stagnation flow, cold wall, zero mass transfer

All Reentry Angles utilize Lawrence Livermore Thermochemistry Tables,

All Times are given in seconds

All Temperature are given in °F

All Altitudes are given in feet

All Velocities are given in ft/s

All heating rate data are given in Btu/ft²s

c:\wp51\leahmem\rhufail2.tab

TABLE 11. Quasi-Tumbling Cylinder LWRHU 3D Thermal Analyses Results

Reentry Angle	-5.2°	-7.0°	-10°	-15°	-30°	-50°	-70°	-90°
Time of M=5	280.2	59.15	33.1	19.6	9.65	6.8	5.51	5.27
Time of Peak Qconv	24.08	15.70	10.02	6.37	3.20	2.18	1.88	1.72
Peak Ref Qconv	1589.89	2220.79	2807.32	3497.43	4832.44	5919.34	6452.90	6535.79
Time of Peak Qrad	29.61	19.15	12.19	7.51	3.75	2.38	2.03	1.92
Peak Ref Qrad	162.42	613.13	1398.42	2858.31	7266.43	11279.45	13351.78	13861.8
Time at 75% Ablation	48.56 Node 67	29.02 Node 67	NF	NF	NF	NF	NF	NF
Altitude at 75% Ablation	225402.7	177508.3	NF	NF	NF	NF	NF	NF
Velocity at 75% Ablation	38198.7	28129.3	NF	NF	NF	NF	NF	NF
Surface Temp at Failure	5126.13 Node 67	5504.38 Node 67	NF	NF	NF	NF	NF	NF
Clad Temp at Failure	3853.22 Node 274	2946.87 Node 274	NF	NF	NF	NF	NF	NF
Fuel Temp at Failure	3610.73 Node 295	2348.73 Node 295	NF	NF	NF	NF	NF	NF
Time at 100% Ablation	247.19 Node 67	NF	NF	NF	NF	NF	NF	NF
Altitude 100% Ablation	192133.5	NF	NF	NF	NF	NF	NF	NF
Velocity 100% Ablation	12413.9	NF	NF	NF	NF	NF	NF	NF
Surface Temp at Failure	2858.17 Node 67	NF	NF	NF	NF	NF	NF	NF
Clad Temp at Failure	2921.54 Node 267	NF	NF	NF	NF	NF	NF	NF
Fuel Temp at Failure	2938.00 Node 281	NF	NF	NF	NF	NF	NF	NF

For Model Node Locations, refer to Figure 34.

75% Ablation implies 0.133 inches

100% Ablation implies 0.177 inches

Reference Q_{rad} is for RAD/EQUIL, inviscid stagnation streamline flow field, effective spherical radius, mid-span LWRHU

Reference Q_{conv} is for 1 ft radius sphere, stagnation flow, cold wall, zero mass transfer

All Reentry Angles utilize Lawrence Livermore Thermochemistry Tables,

All Times are given in seconds

All Temperature are given in °F

All Altitudes are given in feet

All Velocities are given in ft/s

All heating rate data are given in Btu/ft²s

c:\wp51\leahmem\rhufail2.tab

Applied Physics Laboratory
Laurel, Maryland 20723-6099

TABLE 12. Full Random Tumbling LWRHU 3D Thermal Analyses Results

Reentry Angle	-5.2°	-7.0°	-10°	-15°	-30°	-50°	-70°	-90°
Time of M=5	280.2	59.15	33.1	19.6	9.65	6.8	5.51	5.27
Time of Peak Qconv	24.08	15.70	10.02	6.37	3.20	2.18	1.88	1.72
Peak Ref Qconv	1589.89	2220.79	2807.32	3497.43	4832.44	5919.34	6452.90	6535.79
Time of Peak Qrad	29.61	19.15	12.19	7.51	3.75	2.38	2.03	1.92
Peak Ref Qrad	162.42	613.13	1398.42	2858.31	7266.43	11279.45	13351.78	13861.8
Time at 75% Ablation	65.185 Node 108	27.78 Node 108	24.98 Node 108	NF	NF	NF	NF	NF
Altitude at 75% Ablation	231373.1	179975.0	141132.5	NF	NF	NF	NF	NF
Velocity at 75% Ablation	31548.1	30586.7	11100.3	NF	NF	NF	NF	NF
Surface Temp at Failure	4801.03 Node 107	5615.30 Node 107	4067.90 Node 108	NF	NF	NF	NF	NF
Clad Temp at Failure	4318.99 Node 267	2660.20 Node 309	2647.14 Node 309	NF	NF	NF	NF	NF
Fuel Temp at Failure	4237.36 Node 295	2160.24 Node 295	2158.06 Node 295	NF	NF	NF	NF	NF
Time at 100% Ablation	NF	NF	NF	NF	NF	NF	NF	NF
Altitude 100% Ablation	NF	NF	NF	NF	NF	NF	NF	NF
Velocity 100% Ablation	NF	NF	NF	NF	NF	NF	NF	NF
Surface Temp at Failure	NF	NF	NF	NF	NF	NF	NF	NF
Clad Temp at Failure	NF	NF	NF	NF	NF	NF	NF	NF
Fuel Temp at Failure	NF	NF	NF	NF	NF	NF	NF	NF

For Model Node Locations, refer to Figure 34.

75% Ablation implies 0.133 inches

100% Ablation implies 0.177 inches

Reference Q_{rad} is for RAD/EQUIL, inviscid stagnation streamline flow field, effective spherical radius, mid-span LWRHU

Reference Q_{conv} is for 1 ft radius sphere, stagnation flow, cold wall, zero mass transfer

All Reentry Angles utilize Lawrence Livermore Thermochemistry Tables,

All Times are given in seconds

All Temperature are given in °F

All Altitudes are given in feet

All Velocities are given in ft/s

All heating rate data are given in Btu/ft²s

c:\wp51\leahmem\rhufail2.tab

Applied Physics Laboratory

Laurel, Maryland 20723-6099

TABLE 13. Tumbling Sphere LWRHU 3D Thermal Analyses Results

Reentry Angle	-5.3°	-7.0°	-10°	-15°	-30°	-50°	-70°	-90°
Time of M=5	324.51	63.80	34.51	20.55	9.65	6.14	4.99	4.67
Time of Peak Qconv	24.58	17.33	11.35	6.99	3.61	2.45	2.02	1.91
Peak Ref Qconv	1656.94	2411.81	3194.79	4080.49	5797.59	7222.54	7941.81	8048.32
Time of Peak Qrad	30.51	21.19	13.12	8.11	3.90	2.80	2.27	2.16
Peak Ref Qrad	226.72	966.49	2398.57	4777.05	11237.55	16943.79	20902.36	21963.9
Time at 75% Ablation	32.71 Node 64	19.88 Node 64	12.75 Node 64	8.29 Node 64	4.49 Node 64	3.30 Node 64	3.12 Node 64	3.86 Node 64
Altitude at 75% Ablation	224672.3	201387.7	183640.0	166047.1	139616.7	118440.5	101941.1	86350.0
Velocity at 75% Ablation	51752.8	52203.4	51312.9	49312.2	44813.5	36493.7	24633.2	8921.24
Surface Temp at Failure	5802.16 Node 64	6029.35 Node 64	6192.28 Node 64	6343.48 Node 64	6560.7 Node 64	6640.4 Node 64	6343.5 Node 64	6108.86 Node 64
Clad Temp at Failure	2844.79 Node 274	1949.39 Node 274	1439.41 Node 274	1104.50 Node 274	795.61 Node 274	720.3 Node 267	715.1 Node 267	694.6 Node 309
Fuel Temp at Failure	2370.99 Node 295	1460.01 Node 295	1062.69 Node 295	890.32 Node 295	846.9 Node 281	866.77 Node 281	871.8 Node 281	865.5 Node 295
Time at 100% Ablation	38.49 Node 67	22.59 Node 64	14.60 Node 64	9.74 Node 64	6.08 Node 64	NF	NF	NF
Altitude 100% Ablation	221040.9	191710.8	171186.9	150845.1	114332.0	NF	NF	NF
Velocity 100% Ablation	47163.7	46846.6	44377.5	39709.9	22984.2	NF	NF	NF
Surface Temp at Failure	5765.95 Node 67	6044.65 Node 64	6205.18 Node 64	6324.84 Node 64	6061.5 Node 64	NF	NF	NF
Clad Temp at Failure	3296.18 Node 274	2238.94 Node 274	1648.47 Node 274	1271.68 Node 274	960.9 Node 274	NF	NF	NF
Fuel Temp at Failure	2903.49 Node 295	1719.18 Node 295	1208.29 Node 295	967.30 Node 295	856.1 Node 295	NF	NF	NF

For Model Node Locations, refer to Figure 34.

75% Ablation implies 0.133 inches

100% Ablation implies 0.177 inches

Reference Q_{rad} is for RAD/EQUIL, inviscid stagnation streamline flow field, effective spherical radius, mid-span LWRHUReference Q_{conv} is for 1 ft radius sphere, stagnation flow, cold wall, zero mass transfer

All Reentry Angles utilize Lawrence Livermore Thermochemistry Tables,

All Times are given in seconds

All Temperature are given in °F

All Altitudes are given in feet

All Velocities are given in ft/s

All heating rate data are given in Btu/ft²s

c:\wp51\leahmem\rhufail2.tab

Table 14A. Side-on Stable LWRHU 3D Component Temperatures at Failure (75% Ablated)								
Reentry	-90° (2)	-70° (2)	-50° (2)	-30° (2)	-15° (1)	-10° (1)	-7° (1)	-5.2° (1)
75 % Fail Time	1.96616	2.05516	2.39577	3.36169	6.09997	9.39213	14.41483	22.61389
Avg AeroShell	5452.0193	5478.2588	5530.6356	5595.1521	5597.7893	5541.1770	5448.8789	5285.1187
Max Aeroshell	7045.9102	7017.3086	6930.8984	6755.9102	6503.9766	6351.5742	6206.3867	6033.5703
Min Aeroshell	3328.4753	3409.6121	3629.8784	4061.1343	4614.1328	4819.3594	4889.8984	4812.6641
Avg End Cap	4434.3628	4500.1078	4656.7568	4915.8691	5127.4048	5153.1960	5110.9134	4983.2692
Max End Cap	5666.1563	5678.6797	5657.8945	5584.6406	5475.7734	5492.0352	5459.0586	5364.1289
Min End Cap	3112.5569	3200.1338	3466.8687	4005.3608	4631.2344	4840.3125	4908.9727	4835.3242
Avg Out Sleeve	2518.0308	2575.2455	2758.1268	3106.6879	3582.3098	3810.3045	4015.9680	4216.8582
Max Out Sleeve	5258.7813	5331.3242	5553.8828	5852.5703	5991.8359	5950.7813	5881.3320	5775.1719
Min Out Sleeve	747.8887	767.6475	839.6711	1027.9900	1460.9282	1831.6091	2279.3157	2848.6450
Avg Mid Sleeve	662.8381	677.6812	733.8875	886.2973	1246.4917	1560.8896	1953.7409	2501.0115
Max Mid Sleeve	760.0847	781.2122	859.7593	1065.6262	1548.5032	1933.3140	2392.3347	2972.2124
Min Mid Sleeve	590.1060	599.4023	636.2686	743.0627	994.5774	1238.5000	1560.4260	2066.0557
Avg In Sleeve	593.9981	599.2815	621.9705	698.4615	901.3259	1115.1557	1406.1136	1869.5860
Max In Sleeve	596.1294	601.3823	623.9844	700.7617	904.8298	1118.3967	1410.0156	1876.2700
Min In Sleeve	591.9036	597.2200	620.0042	696.3699	898.0251	1111.9028	1401.7407	1862.3264
Avg Clad	774.9070	771.7232	762.1307	753.1737	806.7236	971.7393	1222.3169	1643.8018
Max Clad	781.4653	778.2971	768.6082	758.4150	810.6221	978.0496	1229.9531	1651.8779
Min Clad	766.0762	763.0959	754.3909	748.4192	802.6941	963.8508	1212.3428	1634.2603
Avg Fuel	896.8124	893.4793	880.9162	848.9968	814.5463	824.2805	927.8196	1235.3806
Max Fuel	929.1697	926.8726	917.3643	886.9546	830.8838	830.2512	947.0793	1271.0479
Min Fuel	886.8303	883.1592	869.5510	836.7656	808.6201	808.2751	876.0017	1139.7498
Avg End Plug	1423.6846	1464.8266	1607.6382	1934.8764	2394.5532	2745.2142	3083.3926	3449.5940
Max End Plug	3815.5601	3898.6655	4164.3359	4627.3477	4950.4258	5105.5781	5177.0313	5175.7422
Min End Plug	587.6721	597.3330	623.6125	696.6714	872.9519	1090.1831	1391.2522	1861.0664
All reentry angles utilize Lawrence Livermore Thermochemistry tables to obtain conservative ablation response.								
All Time values are given in seconds.								
All Temperature values are given in °F.								
Clad (Pt30Rh) melt temperature (eutectic - 300°): 2790 °F								
Fuel (238PuO2) melt temperature: 4350 °F (uncertainty allowance 500°: 3850°F)								
(1): Failure criteria met at stagnation point node 1.								
(2): Failure criteria met by burn through of outer aeroshell edge.								
(3): Failure criteria met by burn through at end cap and outer aeroshell edge.								

Applied Physics Laboratory

Laurel, Maryland 20723-6099

Table 14B. Side-on Stable LWRHU 3D Component Temperatures at Failure (100% Ablated)								
Reentry	-90° (2)	-70° (2)	-50° (2)	-30° (2)	-15° (2)	-10° (1)	-7° (1)	-5.2° (1)
100% Fail Time	2.26608	2.35209	2.72673	3.81389	6.88542	10.49374	15.94396	25.05252
Avg AeroShell	5645.1701	5675.8478	5726.2553	5768.3047	5729.8446	5642.6265	5526.3868	5332.3356
Max Aeroshell	7067.5469	7057.6719	6986.5977	6819.5898	6566.8906	6408.0117	6255.6016	6060.8711
Min Aeroshell	3846.2397	3917.3452	4136.7344	4564.2617	5011.2305	5098.0117	5062.8672	4901.5977
Avg End Cap	4717.4773	4785.8364	4943.5153	5169.0756	5307.6519	5282.3071	5203.6030	5038.6837
Max End Cap	5646.1602	5680.7461	5698.7188	5633.8984	5629.5117	5610.4063	5544.0625	5415.2617
Min End Cap	3616.3796	3690.7866	3954.6187	4470.8906	4967.4023	5072.6836	5059.6367	4915.6602
Avg Out Sleeve	2841.5191	2884.3386	3054.0471	3387.6679	3825.4651	4028.3029	4208.1074	4381.1605
Max Out Sleeve	5648.2344	5688.3438	5850.7500	6058.1719	6115.4766	6048.3516	5958.9375	5825.3047
Min Out Sleeve	833.5437	852.3655	934.0063	1159.7693	1665.1018	2081.5347	2553.7759	3130.1987
Avg Mid Sleeve	725.2012	739.6831	803.8648	984.3104	1401.0395	1756.3983	2183.9109	2771.6827
Max Mid Sleeve	848.2161	868.1045	955.7598	1193.8801	1742.4358	2172.0249	2658.4292	3249.5276
Min Mid Sleeve	628.9209	638.6311	682.6064	809.8623	1103.7566	1381.7319	1745.8582	2323.9822
Avg In Sleeve	616.8625	623.0451	652.7706	749.1513	991.3385	1238.4430	1566.8575	2107.7504
Max In Sleeve	618.8604	625.0195	654.8555	751.5581	994.5378	1241.3882	1571.5039	2115.7825
Min In Sleeve	614.9077	621.1152	650.9695	746.6609	988.3494	1235.0955	1561.7732	2099.1526
Avg Clad	766.0747	763.9742	757.7363	760.1752	871.7457	1072.4301	1361.9030	1857.1454
Max Clad	772.5950	770.4529	763.8765	764.3833	876.7693	1079.4592	1369.9109	1865.3643
Min Clad	758.0686	756.2078	751.1118	757.1748	865.9873	1063.3364	1351.5046	1848.2397
Avg Fuel	885.7640	882.6328	869.4892	837.8826	819.8391	860.3701	1012.5109	1408.4650
Max Fuel	921.1360	918.6763	907.3936	873.0430	824.9812	871.4241	1037.6699	1452.3860
Min Fuel	874.7686	871.4060	857.5427	826.3350	817.8196	830.4724	944.5747	1290.2034
Avg End Plug	1628.5545	1664.6448	1815.0839	2166.5808	2645.4067	2989.4652	3310.1810	3660.4258
Max End Plug	4238.9844	4297.1094	4527.9180	4932.7578	5185.2969	5285.3242	5308.8711	5261.0547
Min End Plug	618.6765	624.5613	652.8394	745.7434	962.9636	1218.0955	1558.1333	2095.8318
All reentry angles utilize Lawrence Livermore Thermochemistry tables to obtain conservative ablation response.								
All Time values are given in seconds.								
All Temperature values are given in °F.								
Clad (Pt30Rh) melt temperature (eutectic - 300°): 2790 °F								
Fuel (238PuO2) melt temperature: 4350 °F (uncertainty allowance 500°: 3850°F)								
(1): Failure criteria met at stagnation point node 1.								
(2): Failure criteria met by burn through of outer aeroshell edge.								
(3): Failure criteria met by burn through at end cap and outer aeroshell edge.								

The Johns Hopkins University
Applied Physics Laboratory
Laurel, Maryland 20723-6099

Table 15A. Side-on Spinning LWRHU 3D Component Temperatures at Failure (75% Ablated)								
Reentry	-90°	-70°	-50°	-30°	-15°	-10°	-7°	-5.2° (1)
75% Fail Time	NF	NF	NF	NF	NF	NF	NF	112.7978
Avg AeroShell								3223.5455
Max Aeroshell								3307.5691
Min Aeroshell								3082.2903
Avg End Cap								3097.1628
Max End Cap								3155.1782
Min End Cap								3040.8677
Avg Out Sleeve								3423.9866
Max Out Sleeve								3603.8457
Min Out Sleeve								3278.7793
Avg Mid Sleeve								3660.6702
Max Mid Sleeve								3724.4663
Min Mid Sleeve								3597.6311
Avg In Sleeve								3750.7172
Max In Sleeve								3752.7515
Min In Sleeve								3748.6382
Avg Clad								3757.1633
Max Clad								3767.7593
Min Clad								3746.8960
Avg Fuel								3838.0920
Max Fuel								3872.6499
Min Fuel								3824.1499
Avg End Plug								3470.9350
Max End Plug								3735.4741
Min End Plug								3215.8882
All reentry angles utilize Lawrence Livermore Thermochemistry tables to obtain conservative ablation response.								
All Time values are given in seconds.								
All Temperature values are given in °F.								
Clad (Pt30Rh) melt temperature (eutectic - 300°): 2790 °F								
Fuel (238PuO2) melt temperature: 4350 °F (uncertainty allowance 500°: 3850°F)								
(1): Failure criteria met at stagnation point node 1.								
(2): Failure criteria met by burn through of outer aeroshell edge.								
(3): Failure criteria met by burn through at end cap and outer aeroshell edge.								

Applied Physics Laboratory
Laurel, Maryland 20723-6099

Table 15B. Side-on Spinning LWRHU 3D Component Temperatures at Failure (100% Ablated)								
Reentry	-90°	-70°	-50°	-30°	-15°	-10°	-7°	-5.2°
100% Fail Time	NF	NF	NF	NF	NF	NF	NF	NF
Avg AeroShell								
Max AeroShell								
Min AeroShell								
Avg End Cap								
Max End Cap								
Min End Cap								
Avg Out Sleeve								
Max Out Sleeve								
Min Out Sleeve								
Avg Mid Sleeve								
Max Mid Sleeve								
Min Mid Sleeve								
Avg In Sleeve								
Max In Sleeve								
Min In Sleeve								
Avg Clad								
Max Clad								
Min Clad								
Avg Fuel								
Max Fuel								
Min Fuel								
Avg End Plug								
Max End Plug								
Min End Plug								
All reentry angles utilize Lawrence Livermore Thermochemistry tables to obtain conservative ablation response.								
All Time values are given in seconds.								
All Temperature values are given in °F.								
Clad (Pt30Rh) melt temperature (eutectic - 300°): 2790 °F								
Fuel (238PuO2) melt temperature: 4350 °F (uncertainty allowance 500°: 3850°F)								
(1): Failure criteria met at stagnation point node 1.								
(2): Failure criteria met by burn through of outer aeroshell edge.								
(3): Failure criteria met by burn through at end cap and outer aeroshell edge.								

The Johns Hopkins University
Applied Physics Laboratory
Laurel, Maryland 20723-6099

Table 16A. Quasi-Tumbling Cylinder LWRHU 3D Component Temperatures at Failure (75% Ablated)								
Reentry	-90°	-70°	-50°	-30°	-15°	-10°	-7° (3)	-5.2° (3)
75% Fail Time	NF	NF	NF	NF	NF	NF	29.0223	48.5642
Avg AeroShell							5520.5252	5429.7624
Max AeroShell							5551.5703	5439.7813
Min AeroShell							5469.9883	5409.7578
Avg End Cap							5529.9528	5425.4840
Max End Cap							5559.5391	5436.8047
Min End Cap							5489.1094	5411.5977
Avg Out Sleeve							4981.5689	5138.2996
Max Out Sleeve							5532.5078	5427.7500
Min Out Sleeve							4237.6133	4750.2461
Avg Mid Sleeve							3828.9300	4497.1700
Max Mid Sleeve							4246.8984	4753.0313
Min Mid Sleeve							3391.5583	4226.4297
Avg In Sleeve							3138.1312	4058.8790
Max In Sleeve							3147.8472	4065.7358
Min In Sleeve							3128.4832	4052.0601
Avg Clad							2838.3250	3847.0204
Max Clad							2846.8945	3853.2163
Min Clad							2830.2170	3840.8765
Avg Fuel							2269.1820	3565.1768
Max Fuel							2348.7317	3610.7334
Min Fuel							2046.2280	3423.6755
Avg End Plug							4523.5690	4863.9375
Max End Plug							5493.7461	5400.3477
Min End Plug							3055.5117	3977.8960
All reentry angles utilize Lawrence Livermore Thermochemistry tables to obtain conservative ablation response.								
All Time values are given in seconds.								
All Temperature values are given in °F.								
Clad (Pt30Rh) melt temperature (eutectic - 300°): 2790 °F								
Fuel (238PuO2) melt temperature: 4350 °F (uncertainty allowance 500°: 3850°F)								
(1): Failure criteria met at stagnation point node 1.								
(2): Failure criteria met by burn through of outer aeroshell edge.								
(3): Failure criteria met by burn through at end cap and outer aeroshell edge.								

Applied Physics Laboratory
Laurel, Maryland 20723-6099

Table 16B. Quasi-Tumbling Cylinder LWRHU 3D Component Temperatures at Failure (100% Ablated)								
Reentry	-90°	-70°	-50°	-30°	-15°	-10°	-7°	-5.2° (3)
100% Fail Time	NF	NF	NF	NF	NF	NF	NF	247.18666
Avg AeroShell								2864.4654
Max AeroShell								2877.0173
Min AeroShell								2848.4414
Avg End Cap								2867.84804
Max End Cap								2878.5427
Min End Cap								2858.3259
Avg Out Sleeve								2910.80594
Max Out Sleeve								2950.604
Min Out Sleeve								2880.3157
Avg Mid Sleeve								2948.08125
Max Mid Sleeve								2951.1235
Min Mid Sleeve								2945.4312
Avg In Sleeve								2937.98219
Max In Sleeve								2938.2349
Min In Sleeve								2937.731
Avg Clad								2915.96777
Max Clad								2921.542
Min Clad								2909.8687
Avg Fuel								2935.42832
Max Fuel								2943.5115
Min Fuel								2931.2773
Avg End Plug								2922.00642
Max End Plug								2947.4216
Min End Plug								2884.907
All reentry angles utilize Lawrence Livermore Thermochemistry tables to obtain conservative ablation response.								
All Time values are given in seconds.								
All Temperature values are given in °F.								
Clad (Pt30Rh) melt temperature (eutectic - 300°): 2790 °F								
Fuel (238PuO2) melt temperature: 4350 °F (uncertainty allowance 500°: 3850°F)								
(1): Failure criteria met at stagnation point node 1.								
(2): Failure criteria met by burn through of outer aeroshell edge.								
(3): Failure criteria met by burn through at end cap and outer aeroshell edge.								

Applied Physics Laboratory

Laurel, Maryland 20723-6099

Table 17A. Tumbling Sphere 3D Component Temperatures at Failure (75% Ablated)								
Reentry	-90° (3)	-70° (3)	-50° (3)	-30° (3)	-15° (3)	-10° (3)	-7° (3)	-5.3° (3)
75 % Fail Time	3.86365	3.11726	3.29719	4.48906	8.28594	12.74505	19.88202	32.70866
Avg AeroShell	5558.7222	6341.0996	6504.5803	6449.9597	6287.9409	6153.8247	6004.8872	5790.9483
Max Aeroshell	5890.1289	6458.4805	6644.1328	6563.2891	6345.1289	6193.2422	6030.0859	5802.8945
Min Aeroshell	5136.3906	6215.3086	6216.3164	6237.4258	6177.5508	6075.1289	5952.3125	5765.0820
Avg End Cap	5624.6251	6189.9015	6309.4880	6317.2033	6227.2821	6115.6509	5982.1629	5779.2953
Max End Cap	5865.7852	6365.0391	6638.3867	6560.5898	6343.1992	6191.6875	6028.4570	5799.6641
Min End Cap	5303.8789	5759.9648	5758.5664	5945.3828	6054.0859	5998.9961	5906.4688	5742.2227
Avg Out Sleeve	3983.2040	3947.3818	3945.1258	4131.6771	4466.0288	4667.3001	4871.2021	5078.5189
Max Out Sleeve	5873.4336	6060.9688	6033.4297	6105.8438	6088.5703	6002.5313	5897.1445	5731.2852
Min Out Sleeve	1539.6396	1286.9590	1317.3655	1611.7285	2345.9707	2904.8994	3508.0454	4208.7500
Avg Mid Sleeve	1217.8190	1021.0766	1046.0740	1278.2316	1891.9074	2402.1556	3015.7131	3802.9595
Max Mid Sleeve	1488.2434	1224.5898	1255.9844	1561.5559	2332.8423	2909.2185	3519.6824	4216.7070
Min Mid Sleeve	947.6833	816.8040	834.9231	995.2656	1453.9788	1892.3882	2501.3877	3371.1113
Avg In Sleeve	844.6361	744.0649	758.0465	885.0367	1281.4778	1668.1779	2233.0526	3125.0709
Max In Sleeve	845.0247	744.3894	758.3599	885.4604	1283.2642	1672.2324	2240.0754	3134.4211
Min In Sleeve	844.2444	743.7385	757.7310	884.6091	1279.6831	1664.1938	2226.1050	3115.7803
Avg Clad	766.9660	713.7166	719.5846	792.6063	1097.3669	1431.0064	1940.8461	2836.5791
Max Clad	769.1343	715.1174	720.3379	795.6130	1104.5242	1439.3525	1949.4131	2844.8101
Min Clad	764.6570	712.6626	718.7402	788.9343	1086.7610	1418.4167	1929.1174	2829.0022
Avg Fuel	854.9799	867.6332	863.1073	844.0947	880.4851	1034.8048	1408.8282	2294.9405
Max Fuel	885.9080	904.4661	899.5007	870.0623	890.3223	1062.6917	1460.0942	2370.9878
Min Fuel	844.4392	854.8735	850.5464	835.2742	853.7139	959.4138	1271.6101	2081.1045
Avg End Plug	2780.8820	2483.9395	2509.4254	2844.2383	3439.9568	3782.9444	4135.6807	4553.7282
Max End Plug	5463.3828	5347.4063	5337.5781	5585.8555	5799.7148	5801.5977	5760.0781	5652.4258
Min End Plug	821.8838	730.6895	743.0676	860.4067	1251.4243	1636.2646	2178.7661	3045.2324
All reentry angles utilize Lawrence Livermore Thermochemistry tables to obtain conservative ablation response.								
All Time values are given in seconds.								
All Temperature values are given in °F.								
Clad (Pt30Rh) melt temperature (eutectic - 300°): 2790 °F								
Fuel (238PuO2) melt temperature: 4350 °F (uncertainty allowance 500°: 3850°F)								
(1): Failure criteria met at stagnation point node 1.								
(2): Failure criteria met by burn through of outer aeroshell edge.								
(3): Failure criteria met by burn through at end cap and outer aeroshell edge.								

The Johns Hopkins University
Applied Physics Laboratory
Laurel, Maryland 20723-6099

Table 17B. Tumbling Sphere 3D Component Temperatures at Failure (100% Ablated)								
Reentry	-90°	-70°	-50°	-30° (3)	-15° (3)	-10° (3)	-7° (3)	-5.3° (3)
100% Fail Time	NF	NF	NF	6.07463	9.73822	14.59903	22.58565	38.49133
Avg AeroShell				6141.9284	6300.8413	6180.2205	6027.2332	5759.2880
Max Aeroshell				6241.4297	6327.3594	6206.1680	6045.5660	5766.3090
Min Aeroshell				6038.1602	6237.6641	6124.7340	5988.1600	5742.4300
Avg End Cap				6150.7568	6264.3327	6151.3916	6008.1988	5751.5641
Max End Cap				6231.2500	6323.7852	6204.0700	6043.0700	5763.5590
Min End Cap				6046.9414	6153.2539	6067.7700	5951.4060	5727.4690
Avg Out Sleeve				4404.1469	4660.9623	4839.2450	5025.5135	5201.1135
Max Out Sleeve				6180.5859	6165.3555	6062.8240	5941.1090	5716.8050
Min Out Sleeve				2083.2874	2680.3191	3216.5600	3806.7550	4513.3710
Avg Mid Sleeve				1657.9400	2179.4726	2698.9852	3324.4078	4157.9092
Max Mid Sleeve				2058.2021	2679.3176	3227.6440	3818.8060	4519.5390
Min Mid Sleeve				1261.7856	1680.2869	2164.8440	2815.8560	3778.1540
Avg In Sleeve				1109.4705	1478.6187	1907.6970	2539.4981	3555.3559
Max In Sleeve				1110.5583	1481.5764	1913.2360	2547.8830	3564.4970
Min In Sleeve				1108.3728	1475.6997	1902.2440	2531.1810	3546.2680
Avg Clad				955.0087	1263.7271	1639.8526	2230.1924	3288.4045
Max Clad				960.9380	1271.7185	1648.5050	2238.9680	3296.1810
Min Clad				946.5957	1251.6584	1627.0730	2219.2580	3283.3530
Avg Fuel				855.6467	948.7069	1170.6903	1656.1866	2829.8105
Max Fuel				856.1072	967.2979	1208.2650	1719.1870	2903.4930
Min Fuel				851.7817	898.1194	1069.9370	1487.1370	2613.6730
Avg End Plug				3307.0530	3695.7643	4004.7377	4344.3812	4764.7490
Max End Plug				5875.6406	5932.4453	5894.2270	5824.7540	5657.8200
Min End Plug				1079.3208	1449.1777	1868.5750	2471.4690	3470.8680
All reentry angles utilize Lawrence Livermore Thermochemistry tables to obtain conservative ablation response.								
All Time values are given in seconds.								
All Temperature values are given in °F.								
Clad (Pt30Rh) melt temperature (eutectic - 300°): 2790 °F								
Fuel (238PuO2) melt temperature: 4350 °F (uncertainty allowance 500°: 3850°F)								
(1): Failure criteria met at stagnation point node 1.								
(2): Failure criteria met by burn through of outer aeroshell edge.								
(3): Failure criteria met by burn through at end cap and outer aeroshell edge.								

Applied Physics Laboratory
Laurel, Maryland 20723-6099

Table 18A. Random Tumbling LWRHU 3D Component Temperatures at Failure (75% Ablated)								
Reentry	-90°	-70°	-50°	-30°	-15°	-10° (3)	-7° (3)	-5.2° (3)
75% Fail Time	NF	NF	NF	NF	NF	24.98222	27.77724	65.18513
Avg AeroShell						4149.179643	5528.193583	4738.573538
Max AeroShell						4269.4453	5615.3945	4801.0273
Min AeroShell						4005.6265	5476.3789	4687.2305
Avg End Cap						4240.040132	5590.939221	4787.903471
Max End Cap						4383.6992	5605.582	4811.7891
Min End Cap						4112.1563	5562.457	4764.4023
Avg Out Sleeve						4113.14468	4903.120667	4731.093196
Max Out Sleeve						4320.3633	5506.043	4763.6289
Min Out Sleeve						3847.6538	4086.0796	4705.3281
Avg Mid Sleeve						3514.133507	3666.280469	4608.013581
Max Mid Sleeve						3854.8335	4097.0234	4705.6328
Min Mid Sleeve						3154.3435	3217.6753	4503.2422
Avg In Sleeve						2928.995543	2961.107357	4426.678286
Max In Sleeve						2937.0413	2970.394	4429.3555
Min In Sleeve						2921.0503	2951.8906	4424.0234
Avg Clad						2647.042205	2659.809124	4312.439548
Max Clad						2655.1936	2668.3528	4318.9883
Min Clad						2638.9338	2651.0188	4302.6797
Avg Fuel						2082.162363	2084.312725	4225.287119
Max Fuel						2158.054	2160.2412	4237.3594
Min Fuel						1873.4236	1875.6672	4182.4766
Avg End Plug						3911.470053	4431.661936	4687.942015
Max End Plug						4425.3398	5501.4375	4817.3164
Min End Plug						2851.8689	2882.3777	4363.7656
All reentry angles utilize Lawrence Livermore Thermochemistry tables to obtain conservative ablation response.								
All Time values are given in seconds.								
All Temperature values are given in °F.								
Clad (Pt30Rh) melt temperature (eutectic - 300°): 2790 °F								
Fuel (238PuO2) melt temperature: 4350 °F (uncertainty allowance 500°: 3850°F)								
(1): Failure criteria met at stagnation point node 1.								
(2): Failure criteria met by burn through of outer aeroshell edge.								
(3): Failure criteria met by burn through at end cap and outer aeroshell edge.								

Applied Physics Laboratory

Laurel, Maryland 20723-6099

Table 18B. Random Tumbling LWRHU 3D Component Temperatures at Failure (100% Ablated)								
Reentry	-90°	-70°	-50°	-30°	-15°	-10°	-7°	-5.2°
100% Fail Time	NF	NF	NF	NF	NF	NF	NF	NF
Avg AeroShell								
Max Aeroshell								
Min Aeroshell								
Avg End Cap								
Max End Cap								
Min End Cap								
Avg Out Sleeve								
Max Out Sleeve								
Min Out Sleeve								
Avg Mid Sleeve								
Max Mid Sleeve								
Min Mid Sleeve								
Avg In Sleeve								
Max In Sleeve								
Min In Sleeve								
Avg Clad								
Max Clad								
Min Clad								
Avg Fuel								
Max Fuel								
Min Fuel								
Avg End Plug								
Max End Plug								
Min End Plug								
All reentry angles utilize Lawrence Livermore Thermochemistry tables to obtain conservative ablation response.								
All Time values are given in seconds.								
All Temperature values are given in °F.								
Clad (Pt30Rh) melt temperature (eutectic - 300°): 2790 °F								
Fuel (238PuO2) melt temperature: 4350 °F (uncertainty allowance 500°: 3850°F)								
(1): Failure criteria met at stagnation point node 1.								
(2): Failure criteria met by burn through of outer aeroshell edge.								
(3): Failure criteria met by burn through at end cap and outer aeroshell edge.								
c:\retap\burn\b90.xls								

Applied Physics Laboratory
Laurel, Maryland 20723-6099

TABLE 19.A Side-On Spinning LWRHU 3D CLAD Temperature Results for Cases not Demonstrating 100% Ablation Failure.

Reentry Angle	-5.2°	-7.0°	-10°	-15°	-30°	-50°	-70°	-90°
Time of M=5	218.4	59.0	33.1	19.8	9.7	6.2	5.1	4.7
Initial Temperature	945.3	945.3	945.3	945.3	945.3	945.3	945.3	945.3
Maximum Temperature	4269.7	3608.7	3010.3	1242.6	1339.1	978.4	945.3	945.3
Time at maximum Temperature	74.50	50.50	32.70	11.09	10.05	9.50	0.0	0.0
Time at Melt ¹ Temperature	36.01 - 176.50	31.75 - 59.0	30.21 - 33.1	No Melt	No Melt	No Melt	No Melt	No Melt
Time at Melt ² Temperature	41.51 - 149.51	36.25 - 59.0	No Melt	No Melt	No Melt	No Melt	No Melt	No Melt
Time at Melt ³ Temperature	46.01 - 130.01	42.25 - 59.0	No Melt	No Melt	No Melt	No Melt	No Melt	No Melt

All Reentry Angles utilize Lawrence Livermore Tables.

All Times are given in seconds

All Temperature are given in °F

¹ Conservative Clad Melt Temperature (Upper Eutectic - 500) = 2900 °F

² Clad Eutectic Temperature (lower bound) = 3090 °F

³ Clad Melt Temperature (upper bound) = 3470 °F

c:\wp51\leahmem\rhumelt.tab

TABLE 19.B. Side-On Spinning LWRHU 3D Fuel Temperature Results for Cases not Demonstrating 100% Ablation Failure.

Reentry Angle	-5.2°	-7.0°	-10°	-15°	-30°	-50°	-70°	-90°
Time of M=5	218.4	59.0	33.1	19.8	9.7	6.2	5.1	4.7
Initial Temperature	950.3	950.3	950.3	950.3	950.3	950.3	950.3	950.3
Maximum Temperature	4260.4	3573.7	2711.5	1338.5	989.8	950.3	950.3	950.3
Time at maximum Temperature	79.01	56.50	32.70	11.09	9.50	0.0	0.0	0.0
Time at Melt ¹ Temperature	No Melt	No Melt	No Melt	No Melt	No Melt	No Melt	No Melt	No Melt

All Reentry Angles utilize Lawrence Livermore Tables.

All Times are given in seconds

All Temperature are given in °F

¹ Fuel Melt Temperature = 3850 - 4350 °F

c:\wp51\leahmem\rhumelt.tab

TABLE 20.A Quasi-Tumbling Cylinder LWRHU 3D CLAD Temperature Results for Cases not Demonstrating 100% Ablation Failure.

Reentry Angle	-5.2°	-7.0°	-10°	-15°	-30°	-50°	-70°	-90°
Time of M=5	280.2	59.15	33.1	19.6	9.65	6.8	5.51	5.27
Initial Temperature	945.3	945.3	945.3	945.3	945.3	945.3	945.3	945.3
Maximum Temperature	Failed 100%	3779.0	3140.1	2322.0	1349.8	1064.9	945.3	945.3
Time at maximum Temperature		51.01	32.70	19.63	9.50	6.80	0.0	0.0
Time at Melt ¹ Temperature		30.00 - 59.15	27.71 - 33.1	No Melt	No Melt	No Melt	No Melt	No Melt
Time at Melt ² Temperature		34.50 - 59.15	No Melt	No Melt	No Melt	No Melt	No Melt	No Melt
Time at Melt ³ Temperature		39.00 - 59.15	No Melt	No Melt	No Melt	No Melt	No Melt	No Melt

All Reentry Angles utilize Lawrence Livermore Tables.

All Times are given in seconds

All Temperature are given in °F

¹ Conservative Clad Melt Temperature (Upper Eutectic - 500) = 2900 °F² Clad Eutectic Temperature (lower bound) = 3090 °F³ Clad Melt Temperature (upper bound) = 3470 °F

c:\wp51\leahmem\rhumelt.tab

Applied Physics Laboratory
Laurel, Maryland 20723-6099

TABLE 20.B. Quasi-Tumbling Cylinder LWRHU 3D Fuel Temperature Results for Cases not Demonstrating 100% Ablation Failure.

Reentry Angle	-5.2°	-7.0°	-10°	-15°	-30°	-50°	-70°	-90°
Time of M=5	280.2	59.15	33.1	19.6	9.65	6.8	5.51	5.27
Initial Temperature	950.3	950.3	950.3	950.3	950.3	950.3	950.3	950.3
Maximum Temperature	Failed 100%	3742.6	2841.1	1819.0	1015.7	950.3	950.3	950.3
Time at maximum Temperature		57.00	32.70	19.63	9.50	0.0	0.0	0.0
Time at Melt ¹ Temperature		No Melt	No Melt	No Melt	No Melt	No Melt	No Melt	No Melt

All Reentry Angles utilize Lawrence Livermore Tables.

All Times are given in seconds

All Temperature are given in °F

¹ Fuel Melt Temperature = 3850 - 4350 °F

c:\wp51\leahmem\rhumelt.tab

TABLE 21.A Tumbling Sphere LWRHU 3D CLAD Temperature Results for Cases not Demonstrating 100% Ablation Failure.

Reentry Angle	-5.2°	-7.0°	-10°	-15°	-30°	-50°	-70°	-90°
Time of M=5	280.2	59.15	33.1	19.6	9.65	6.8	5.51	5.27
Initial Temperature	945.3	945.3	945.3	945.3	945.3	945.3	945.3	945.3
Maximum Temperature	Failed 100%	Failed 100%	Failed 100%	Failed 100%	Failed 100%	971.0	945.3	945.3
Time at maximum Temperature						5.90	0.0	0.0
Time at Melt ¹ Temperature						No Melt	No Melt	No Melt
Time at Melt ² Temperature						No Melt	No Melt	No Melt
Time at Melt ³ Temperature						No Melt	No Melt	No Melt

All Reentry Angles utilize Lawrence Livermore Tables.

All Times are given in seconds

All Temperature are given in °F

¹ Conservative Clad Melt Temperature (Upper Eutectic - 500) = 2900 °F

² Clad Eutectic Temperature (lower bound) = 3090 °F

³ Clad Melt Temperature (upper bound) = 3470 °F

c:\wp51\leahmem\rhumelt.tab

Applied Physics Laboratory
Laurel, Maryland 20723-6099

TABLE 21.B. Tumbling Sphere LWRHU 3D Fuel Temperature Results for Cases not Demonstrating 100% Ablation Failure.

Reentry Angle	-5.2°	-7.0°	-10°	-15°	-30°	-50°	-70°	-90°
Time of M=5	280.2	59.15	33.1	19.6	9.65	6.8	5.51	5.27
Initial Temperature	950.3	950.3	950.3	950.3	950.3	950.3	950.3	950.3
Maximum Temperature	Failed 100%	Failed 100%	Failed 100%	Failed 100%	Failed 100%	950.3	950.3	950.3
Time at maximum Temperature						0.0	0.0	0.0
Time at Melt ¹ Temperature						No Melt	No Melt	No Melt

All Reentry Angles utilize Lawrence Livermore Tables.

All Times are given in seconds

All Temperature are given in °F

¹ Fuel Melt Temperature = 3850 - 4350 °F

c:\wp51\leahmem\rhumelt.tab

TABLE 22.A. Full Random Tumbling LWRHU 3D CLAD Temperature Results for Cases not Demonstrating 100% Ablation Failure.								
Reentry Angle	-5.2°	-7.0°	-10°	-15°	-30°	-50°	-70°	-90°
Time of M=5	280.2	59.15	33.1	19.6	9.65	6.8	5.51	5.27
Initial Temperature	945.3	945.3	945.3	945.3	945.3	945.3	945.3	945.3
Maximum Temperature	4383.8	3704.4	3081.9	2280.6	1332.9	945.3	945.3	945.3
Time at maximum Temperature	72.50	51.01	32.70	19.63	9.51	0.0	0.0	0.0
Time at Melt ¹ Temperature	35.51 - 195.00	30.51 - 59.15	28.71 - 33.1	No Melt	No Melt	No Melt	No Melt	No Melt
Time at Melt ² Temperature	39.50 - 160.01	34.50 - 59.15	No Melt	No Melt	No Melt	No Melt	No Melt	No Melt
Time at Melt ³ Temperature	45.00 - 140.00	40.50 - 59.15	No Melt	No Melt	No Melt	No Melt	No Melt	No Melt
<p style="text-align: center;">All Reentry Angles utilize Lawrence Livermore Tables. All Times are given in seconds All Temperature are given in °F ¹ Conservative Clad Melt Temperature (Upper Eutectic - 500) = 2900 °F ² Clad Eutectic Temperature (lower bound) = 3090 °F ³ Clad Melt Temperature (upper bound) = 3470 °F</p>								

c:\wp51\leahmem\vrhumelt.tab

TABLE 22.B. Full Random Tumbling LWRHU 3D Fuel Temperature Results for Cases not Demonstrating 100% Ablation Failure.

Reentry Angle	-5.2°	-7.0°	-10°	-15°	-30°	-50°	-70°	-90°
Time of M=5	280.2	59.15	33.1	19.6	9.65	6.8	5.51	5.27
Initial Temperature	950.3	950.3	950.3	950.3	950.3	950.3	950.3	950.3
Maximum Temperature	4343.3	3668.9	2781.5	1785.5	1006.3	950.3	950.3	950.3
Time at maximum Temperature	80.01	55.51	32.70	19.62	9.51	0.0	0.0	0.0
Time at Melt ¹ Temperature	No Melt	No Melt	No Melt	No Melt	No Melt	No Melt	No Melt	No Melt

All Reentry Angles utilize Lawrence Livermore Tables.

All Times are given in seconds

All Temperature are given in °F

¹ Fuel Melt Temperature = 3850 - 4350 °F

c:\wp51\leahmem\rhumelt.tab

Applied Physics Laboratory
Laurel, Maryland 20723-6099

Table 23A. Aeroshell and End Cap Recession of Non-Ablation Failed Cases.				
Side-on Spinning	Reentry Angle	Maximum %	Minimum %	Average %
Aeroshell	-90°	39.3212	36.1086	36.9151
	-70°	41.4119	38.1555	38.9817
	-50°	44.8683	41.8642	42.6548
	-30°	51.3610	49.0145	49.7113
	-15°	53.7185	52.1494	52.8271
**	-10°	65.4644	62.2808	63.8321
**	-07°	73.6362	66.4695	70.7165
* , **	-5.2°	86.5695	72.7542	81.3264
End Cap	-90°	0.3797	0.3520	0.3680
	-70°	0.4019	0.3721	0.3889
	-50°	0.4585	0.4189	0.4391
	-30°	0.6785	0.5471	0.6050
	-15°	0.8836	0.5782	0.7342
	-10°	1.6580	1.2107	1.4294
	-07°	2.1585	1.6212	1.8826
	-5.2°	3.4250	2.8872	3.1550
* - Although exceeds 75% wall ablation, did not meet breach criterion.				
** - Conditions exceeding approximately 65% wall recession could lead to breach if diffusion limited and kinetic oxidation included after M<5.				
c:\retap\bum\recess2.xls				

Applied Physics Laboratory

Laurel, Maryland 20723-6099

Table 23B. Aeroshell and End Cap Recession of Non-Ablation Failed Cases.				
Tumbling Cylinder	Reentry Angle	Maximum %	Minimum %	Average %
Aeroshell	-90°	44.2546	38.4875	40.0692
	-70°	46.8338	41.0682	42.6526
	-50°	50.9908	45.3311	46.8896
	-30°	58.7006	53.4140	54.8615
	-15°	66.9486	62.9141	64.0310
	-10°	75.1192	71.8435	72.7656
	-07°	84.8627	82.1746	82.9516
	-5.2°	Failed	Failed	Failed
	-90°	37.3928	26.9778	31.2330
	-70°	39.8526	29.1575	33.5018
End Cap	-50°	43.8920	33.0136	37.4002
	-30°	51.4959	41.2624	45.3937
	-15°	60.2735	52.3963	55.5612
	-10°	68.5384	62.4324	64.9009
	-07°	77.9941	73.4654	75.2951
	-5.2°	Failed	Failed	Failed
	-90°	37.3928	26.9778	31.2330
	-70°	39.8526	29.1575	33.5018
	-50°	43.8920	33.0136	37.4002
	-30°	51.4959	41.2624	45.3937
* - Although exceeds 75% wall ablation, did not meet breach criterion.				
** - Conditions exceeding approximately 65% wall recession could lead to breach if diffusion limited and kinetic oxidation included after M<5.				

Applied Physics Laboratory

Laurel, Maryland 20723-6099

Table 23C. Aeroshell and End Cap Recession of Non-Ablation Failed Cases.				
Tumbling Sphere	Reentry Angle	Maximum %	Minimum %	Average %
Aeroshell *, **	-90°	80.3627	73.9492	75.6894
*, **	-70°	84.1096	77.7198	79.4555
*, **	-50°	92.4288	86.2203	87.9098
	-30°	Failed	Failed	Failed
	-15°	Failed	Failed	Failed
	-10°	Failed	Failed	Failed
	-07°	Failed	Failed	Failed
	-5.2°	Failed	Failed	Failed
End Cap**	-90°	71.3551	54.5022	61.3128
**	-70°	74.9535	57.6741	64.6482
*, **	-50°	83.0465	65.3200	72.4182
	-30°	Failed	Failed	Failed
	-15°	Failed	Failed	Failed
	-10°	Failed	Failed	Failed
	-07°	Failed	Failed	Failed
	-5.2°	Failed	Failed	Failed
* - Although exceeds 75% wall ablation, did not meet breach criterion.				
** - Conditions exceeding approximately 65% wall recession could lead to breach if diffusion limited and kinetic oxidation included after M<5.				

Applied Physics Laboratory

Laurel, Maryland 20723-6099

Table 23D. Aeroshell and End Cap Recession of Non-Ablation Failed Cases.				
Random Tumbling	Reentry Angle	Maximum %	Minimum %	Average %
Aeroshell	-90°	40.2604	28.2748	31.8398
	-70°	42.6972	30.3193	34.0118
	-50°	46.7188	33.5451	37.4934
	-30°	54.2207	39.6279	44.0622
**	-15°	63.3520	46.7553	51.9490
**	-10°	71.8153	53.1420	59.1168
* **	-07°	81.6661	59.9972	67.1470
* **	-5.2°	100.0000	74.6819	83.3361
End Cap	-90°	35.2299	23.2524	28.1505
	-70°	37.5456	25.0813	30.1857
	-50°	41.4284	28.3601	33.6990
	-30°	48.9075	35.3114	40.8161
**	-15°	63.4946	48.4557	54.5151
**	-10°	70.6059	56.9141	62.5115
* **	-07°	78.2335	65.6654	70.8553
* **	-5.2°	89.8476	79.5930	83.8660
* - Although exceeds 75% wall ablation, did not meet breach criterion.				
** - Conditions exceeding approximately 65% wall recession could lead to breach if diffusion limited and kinetic oxidation included after M<5.				

Table 24
Initial Trajectory Conditions for Fuel Pellet Release from Side-On Stable Reentry.

TDOF RUN 75% FAILURE RELEASE STABLE/SPINNING AND TUMBLING:

GAMMA	-5.2°	-7°	-10°	-15°	-30°	-50°	-70°	-90°
Time (sec)	22.71	14.46	9.42	6.03	3.40	2.42	2.08	1.93
Altitude (ft)	242612	225948	210991	196168	167990	150716	141748	141359
Velocity (ft/s)	59388	58897	58099	57281	53938	51380	49356	49666

TDOF RUN 100% FAILURE RELEASE STABLE/SPINNING AND TUMBLING:

GAMMA	-5.2°	-7°	-10°	-15°	-30°	-50°	-70°	-90°
Time (sec)	25.16	15.99	10.52	6.80	3.88	2.78	2.41	2.22
Altitude (ft)	238007	218569	201817	185982	156208	137837	127925	128318
Velocity (ft/s)	57388	56414	55060	53742	48538	44136	40462	41754

Applied Physics Laboratory

Laurel, Maryland 20723-6099

TABLE 25. Estimated Drag Coefficients and Bridging Parameters for Released Pellet *

Bridging Variable	Side-on Stable or Spinning Fuel				Tumbling Fuel Cylinder	
R_N					0.0354 ft	
S_{REF}	0.000629 ft ²				0.00033 ft ²	
D_{REF}	0.0205 ft				0.02051 ft	
SWMCH **	3.0				3.0	
Tabulated C_D	M	C_D	Alt	C_D	M	C_D
	0.0	0.554	0.0	1.20	0.0	0.94
	0.5	0.554	100000.	1.20	0.2	0.94
	0.6	1.26	200000.	1.24	0.5	0.96
	0.9	2.00	230000.	1.32	0.6	1.53
	1.0	2.10	235000.	1.33	0.8	2.04
	1.1	2.00	250000.	1.37	1.0	2.35
	1.3	1.70	300000.	1.62	1.2	2.28
	1.5	1.37	350000.	2.05	1.4	2.02
	1.8	1.26	400000.	2.10	1.6	1.95
	2.0	1.24			1.8	1.92
	2.3	1.21			2.0	1.90
	2.5	1.20			3.0	1.90
	40.0	1.20			10.0	1.90
	100.0	1.20			100.0	1.90
** Mach Number at which calculations switch from bridging drag coefficients to tabulated drag coefficients.						

c:\tdof\dragco3.tab (wp51)

Applied Physics Laboratory

Laurel, Maryland 20723-6099

Table 26. Fuel Release Atmospheric Source Terms.

Reentry Angle (γ°)	Orientation (see key at end of Table)	Nodes $\geq 4812^\circ\text{R}$	Nodes $\geq 4312^\circ\text{R}$	Volume $\geq 4812^\circ\text{R}$	Volume $\geq 4312^\circ\text{R}$
5.2	1: 75%ablated	all	all	100%	100%
7.0	1: 75%ablated	all	all	100%	100%
10.0	1: 75%ablated	all	all	100%	100%
15.0	1: 75%ablated	all	all	100%	100%
30.0	1: 75%ablated	all	all	100%	100%
50.0	1: 75%ablated	all except 20,23,24,26,27	all	69%*	100%
70.0	1: 75%ablated	all except 20-28	all except 24,26,27	58%*	87%*
90.0	1: 75%ablated	all except 20-28	all except 24,26,27	58%*	87%*
5.2	1:100%ablated	all	all	100%	100%
7.0	1:100%ablated	all	all	100%	100%
10.0	1:100%ablated	all	all	100%	100%
15.0	1:100%ablated	all	all	100%	100%
30.0	1:100%ablated	all except 21,23,24,26,27	all	72%*	100%
50.0	1:100%ablated	1-17	1-17	51%*	51%*
70.0	1:100%ablated	1-9, 11,14	1-9, 11,12,14,17	26%*	41%*
90.0	1:100%ablated	1-9, 11,14	1-9, 11,12,14,17	26%*	41%*
5.2	2: 75%ablated	all	all	100%	100%
7.0	2: 75%ablated	all	all	100%	100%
10.0	2: 75%ablated	all	all	100%	100%
15.0	2: 75%ablated	all	all	100%	100%
30.0	2: 75%ablated	all	all	100%	100%
50.0	2: 75%ablated	all	all	100%	100%
70.0	2: 75%ablated	all	all	100%	100%
90.0	2: 75%ablated	all	all	100%	100%

Applied Physics Laboratory
Laurel, Maryland 20723-6099

Table 26. Fuel Release Atmospheric Source Terms.					
Reentry Angle (γ°)	Orientation (see key at end of Table)	Nodes $\geq 4812^\circ\text{R}$	Nodes $\geq 4312^\circ\text{R}$	Volume $\geq 4812^\circ\text{R}$	Volume $\geq 4312^\circ\text{R}$
5.2	2:100%ablated	all	all	100%	100%
7.0	2:100%ablated	all	all	100%	100%
10.0	2:100%ablated	all	all	100%	100%
15.0	2:100%ablated	all	all	100%	100%
30.0	2:100%ablated	all	all	100%	100%
50.0	2:100%ablated	1-8, 11,14,17,2 0,23,26	1-9, 11,12,14,1 5,17,18,20 ,21,23,24, 26,27	56%*	89%*
70.0	2:100%ablated	1-8, 11,14,17,2 0,23,26	1-8, 11,14,17,2 0,23,26	56%*	56%*
90.0	2:100%ablated	1-8, 11,14,17,2 0,23,26	1-8, 11,14,17,2 0,23,26	56%*	56%*
7.0	3: 75%ablated	all	all	100%	100%
15.0	3: 75%ablated	all	all	100%	100%
90.0	3: 75%ablated	all	all	100%	100%
7.0	3:100%ablated	all	all	100%	100%
15.0	3:100%ablated	all	all	100%	100%
90.0	3:100%ablated	1,2,5,6, 9,10,11, 13,14,15	1,2,5,6, 9,10,11, 12,13,14,1 5	66%*	70%*
5.2	4: 75%ablated	only surface nodes	all	~2%**	100%
5.2	5: 75%ablated	none	all	~0%**	100%
5.2	6: 75%ablated	none	all	~0%**	100%
5.2	7: 75% ablated	all	all	100%	100%
7.0	7: 75% ablated	all except 5,6,7,20,2 1,23,24,26 ,27	all	63%	100%
10.0	7: 75% ablated	none	none	~0%	~0%
5.2	8: 75% ablated	all	all	100%	100%

Applied Physics Laboratory
Laurel, Maryland 20723-6099

Table 26. Fuel Release Atmospheric Source Terms.

Reentry Angle (γ°)	Orientation (see key at end of Table)	Nodes $\geq$ 4812°R	Nodes $\geq$ 4312°R	Volume $\geq$ 4812°R	Volume $\geq$ 4312°R
7.0	8: 75% ablated	all	all	100%	100%
10.0	8: 75% ablated	none	none	~0%	~0%
5.2	9: 75% ablated	all	all	100%	100%
7.0	9: 75% ablated	all	all	100%	100%
10.0	9: 75% ablated	none	none	~0%	~0%
<p>* Expected to show 100% melt: analysis conducted at less than $\frac{1}{2}$ expected convective heating rate (velocity gradient scaling factor of 3 vice ~7.25).</p> <p>** Although released pellet temperature does not reach melt, full fuel melt was obtained prior to release; potential resolidification prior to release, but release temperature exceeded 4312°R. These conditions should be considered as full {100%} atmospheric source terms.</p> <p style="text-align: right;">c:\wp51\leahmem\fuelmelt.tab</p>					

Orientation Key:

- 1 Side-on Stable LWRHU releasing Side-on Stable Fuel Pellet
- 2 Side-on Stable LWRHU releasing Side-on Spinning Fuel Pellet
- 3 Side-on Stable LWRHU releasing Random Tumbling Fuel Pellet
- 4 Side-on Spinning LWRHU releasing Side-on Stable Fuel Pellet
- 5 Side-on Spinning LWRHU releasing Side-on Spinning Fuel Pellet
- 6 Side-on Spinning LWRHU releasing Random Tumbling Fuel Pellet
- 7 Random Tumbling LWRHU releasing Side-on Stable Fuel Pellet
- 8 Random Tumbling LWRHU releasing Side-on Spinning Fuel Pellet
- 9 Random Tumbling LWRHU releasing Random Tumbling Fuel Pellet

Applied Physics Laboratory
 Laurel, Maryland 20723-6099

Table 27 - Side-On Stable LWRHU Thermostructural Analysis Results (NF = No Failure)

Reentry Angle γ	-90°
Time of Initial Failure (.01 strain allowable)	1.00 sec
Element No.	3949
Factor of Safety-Direction	.82-z
Time of Lowest FS (.01 strain allowable)	2.35 sec
Element No.	3895
Factor of Safety-Direction	.61-z
Time of Initial Failure (.05 strain allowable)	NF
Element No.	
Factor of Safety-Direction	

Table 28 - Side-on Spinning LWRHU Thermostructural Analysis Cases

Reentry Angle γ	Times (sec.)
-7°	3.00, 9.00, 13.00, 16.00, 19.00, 20.00, 21.00, 22.00
-10°	12.41, 14.00
-15°	7.90, 9.02
-30°	4.20, 4.60
-50°	0.60, 1.40, 2.70, 2.90, 3.10, 4.05
-70°	2.25, 2.50
-90°	0.40, 0.60, 0.80, 1.00, 1.40, 1.80, 2.15, 2.35

Applied Physics Laboratory
Laurel, Maryland 20723-6099

Table 29 - Side-On Spinning LWRHU Thermostructural Analysis Results (NF = No Failure)

Reentry Angle γ	-7°	-10°	-15°	-30°	-50°	-70°	-90°
Time of Initial Failure (.01 strain allowable)	13.00	12.41	7.90	4.20	1.40	2.25	1.40
Element No.	1865	1865	10	10	1865	1865	1865
Factor of Safety-Direction	.97-z	.88-z	.84-z	.79-z	.86-z	.78-z	.92-z
Time of Lowest FS (.01 strain allowable)	20.00	12.41	7.90	4.20	2.90	2.50	2.35
Element No.	1865	1865	10	10	10	1865	1865
Factor of Safety-Direction	.93-z	.88-z	.84-z	.79-z	.77-z	.77-z	.77-z
Time of Initial Failure (.05 strain allowable)	NF	NF	NF	NF	NF	NF	NF
Element No.							
Factor of Safety-Direction							

Table 30 - Random Tumbling LWRHU Thermostructural Analysis Cases

Reentry Angle γ	Times (sec.)
-15°	2.00, 4.00, 6.00, 7.90, 8.50, 9.00, 9.50
-30°	4.10, 4.60
-50°	0.40, 1.00, 1.80, 2.80, 3.00, 3.10, 3.50
-70°	2.25, 2.50
-90°	0.40, 0.80, 1.80, 2.15, 2.35, 2.60

Applied Physics Laboratory
Laurel, Maryland 20723-6099

Table 31 - Random Tumbling LWRHU Thermostructural Analysis Results (NF = No Failure)

Reentry Angle γ	-15°	-30°	-50°	-70°	-90°
Time of Initial Failure (.01 strain allowable)	4.00	4.10	1.00	2.25	.80
Element No.	3610	3960	2934	3948	3103
Factor of Safety-Direction	1.00-z	.80-z	.98-z	.76-z	.86-z
Time of Lowest FS (.01 strain allowable)	7.90	4.10	2.80	2.25	2.15
Element No.	3966	3960	3954	3948	3948
Factor of Safety-Direction	.86-z	.80-z	.77-z	.76-z	.75-z
Time of Initial Failure (.05 strain allowable)	NF	NF	NF	NF	NF
Element No.					
Factor of Safety-Direction

Figure 1 - Cross-sectional view of LWRHU assembly (from Ref. 1)

Matl-FWPF 30 graphite

Dimensions in mm: W = 39.787 g (TYP) for LWRHU assembly

Figure 2- LWRHU aeroshell body (from Ref. 1)

Dimensions in mm: W = 8.366 g (TYP) for CLAD/FUEL assembly

Figure 3- LWRHU clad body (from Ref. 1)

Dimensions in mm: W = 2.664 g (TYP)

Figure 4 - LWRHU fuel pellet (from Ref. 1)

Fig. 5 Variation of initial altitude versus flight path angle for early release conditions of GPHS module and LWRHU reentries; Cassini-VVEJGA mission profile (from Refs. 3 and 4)

Figure 6. Cassini Mission TDOF Results
LWRHU Side-on Stable and Side-on Spinning
Representative VVEJGA Trajectory Profiles for Hypersonic Flight

Figure 7. Cassini Mission TDOF Results
LWRHU Side-on Stable and Side-on Spinning
Representative VVEJGA Reentry Altitude History

Figure 8 Cassini Mission TDOF Results
LWRHU Tumbling Cylinder Reentry
Representative VVEJGA Trajectories for Hypersonic Flight

Reentry angles shown in descending order left to right: -90°, -70°, -50°, -30°, -15°, -10°, -7°, -5.2°
 TDOF Run through M = 5

Figure 9. Cassini Mission TDOF Results
LWRHU Tumbling Cylinder Reentry
Representative VVEJGA Altitude History

Reentry angles shown in descending order left to right: -90°, -70°, -50°, -30°, -15°, -10°, -7°, -5.2°
 TDOF Run through M = 5

c:\tdof\ttdofoc16.xls

**Figure 10. Cassini Mission TDOF Results
 LWRHU Tumbling Sphere
 Representative VVEJGA Trajectories for Hypersonic Flight**

**Figure 11. Cassini Mission TDOF Results
 LWRHU Tumbling Sphere
 Representative VVEJGA Altitude History**

Figure 12. Cassini Mission TDOF Results
 LWRHU Side-on Stable and Spinning
 Representative Reentry Deceleration Histories

Figure 13. Cassini Mission TDOF Results
LWRHU Tumbling Cylinder Reentry
Representative Reentry Deceleration Histories

c:\tdoftaallf8.xls

Figure 14. Cassini Mission TDOF Results
 LWRHU Tumbling Sphere
 Representative Reentry Deceleration Histories

Reentry angles shown in descending order left to right: -90° , -70° , -50° , -30° , -15° , -10° , -7° , -5.2° inset
 TDOF run through M = 5

c:\relap\cassini\lball18.xls

**Figure 15. Cassini Mission TDOF Results
 LWRHU Side-on Stable and Spinning
 Steep Reentry Reference Convective Heating Histories**

TDOF Run through M=5
 Reentry angles shown in descending order left to right: $-90^\circ, -70^\circ, -50^\circ, -30^\circ$

Shallow Reentry Reference Convective Heating Histories

Reentry angles shown in descending order left to right: $-15^\circ, 10^\circ, -7^\circ, -5.2^\circ$
 TDOF Run through M=5

c:\tdof\tdofoc16.xls

Q_{conv} : 1 ft R sphere, stagnation flow, cold wall, zero mass transfer

Figure 16. Cassini Mission TDOF Results
LWRHU Tumbling Cylinder
Steep Reentry Reference Convective Heating Histories

Reentry angles shown in descending order left to right: $-90^\circ, -70^\circ, -50^\circ, -30^\circ$

Shallow Reentry Reference Convective Heating Histories

Reentry angles shown in descending order left to right: $-15^\circ, 10^\circ, -7^\circ, -5.2^\circ$
 Qconv: 1 ft R sphere, stagnation flow, cold wall, zero mass transfer

c:\tdof\taallf7.xls

**Figure 17. Cassini Mission TDOF Results
 LWRHU Tumbling Sphere
 Steep Reentry Reference Convective Heating Histories**

TDOF Run through M=5
 Reentry angles shown in descending order left to right: $-90^\circ, -70^\circ, -50^\circ, -30^\circ$

Shallow Reentry Reference Convective Heating Histories

TDOF Run through M=5
 Reentry angles shown in descending order left to right: $-15^\circ, 10^\circ, -7^\circ, -5.2^\circ$
 Q_{conv} : 1 ft R sphere, stagnation flow, cold wall, zero mass transfer

c:\tdof\ballf7.xls

Figure 18. Cassini Mission TDOF Results
LWRHU Side-on Stable and Spinning
Steep Reentry Reference Radiative Heating Histories

TDOF Run through M=5

Reentry angles shown in descending order left to right: $-90^\circ, -70^\circ, -50^\circ, -30^\circ$

Shallow Reentry Reference Radiative Heating Histories

TDOF Run through M=5

Reentry angles shown in descending order left to right: $-15^\circ, -10^\circ, -7^\circ, -5.2^\circ$

Qrad: RAD/EQUIL, inviscid stagnation streamline flow, black body, effective spherical radius

c:\tdof\tdofoc16.xls

Figure 19. Cassini Mission TDOF Results
LWRHU Tumbling Cylinder
Steep Reentry Reference Radiative Heating Histories

TDOF Run through M=5

Reentry angles shown in descending order left to right: $-90^\circ, -70^\circ, -50^\circ, -30^\circ$

Shallow Reentry Reference Radiative Heating Histories

TDOF Run through M=5

Reentry angles shown in descending order left to right: $-15^\circ, -10^\circ, -7^\circ, -5.2^\circ$

Qrad: RAD/EQUIL, inviscid stagnation streamline flow, black body, effective spherical radius

Figure 20. Cassini Mission TDOF Results
LWRHU Tumbling Sphere
Steep Reentry Reference Radiative Heating Histories

Reentry angles shown in descending order left to right: $-90^\circ, -70^\circ, -50^\circ, -30^\circ$

Shallow Reentry Reference Radiative Heating Histories

c:\tdof\tballf7.xls

Reentry angles shown in descending order left to right: $-15^\circ, -10^\circ, -7^\circ, -5.2^\circ$
 Qrad: RAD/EQUIL, inviscid stagnation streamline flow, black body, effective spherical radius

**FIGURE 21. Cassini Mission TDOF Results
LWRHU -90° VVEJGA Reentry
Sample Steep Trajectory for Different Orientations**

TDOF Results Through Mach = 5

c:\tdof\tumble.xls

**Figure 22. Cassini Mission TDOF
LWRHU -07° Reentry
Sample Shallow Altitude History for Different Orientations**

TDOF Results Through Mach = 5

Sample Shallow Velocity History for Different Orientations

TDOF Results Through Mach = 5

c:\tdof\tumble.xls

Figure 23. Cassini Mission TDOF Results LWRHU
Sample Shallow Reentry Deceleration Forces for Different
Orientations

Sample Steep Reentry Deceleration Forces for Different
Orientations

**FIGURE 24. Cassini Mission TDOF Results
LWRHU -90° Reentry
Sample Steep Radiative Heating History for Different Orientations**

Sample Steep Convective Heating History

c:\tdof\tumble.xls

Figure 25. Cassini Mission TDOF Results
LWRHU -7° Reentry
Sample Shallow Radiative Heating History for Different Orientations

TDOF Results Through Mach = 5

TDOF Results Through Mach = 5

c:\tdof\tumble.xls

**Figure 26. Cassini Mission TDOF Results
LWRHU Side-on
Shallow Reentry Total Pressure Behind Normal Shock**

Steep Reentry Total Pressure Behind Normal Shock

**Figure 27. Cassini Mission TDOF Results
LWRHU Side-on
Shallow Reentry Total Enthalpy**

Steep Reentry Total Enthalpy

Figure 28. Cassini Mission TDOF Results
LWRHU Tumbling Cylinder
Steep Reentry Total Pressure Behind Normal Shock

TDOF Run through M=5

Reentry angles shown in descending order left to right: $-90^\circ, -70^\circ, -50^\circ, -30^\circ$

Shallow Reentry Total Pressure Behind Normal Shock

TDOF Run through M=5

c:\tdof\taallf7.xls

Reentry angles shown in descending order left to right: $-15^\circ, 10^\circ, -7^\circ, -5.2^\circ$

**Figure 29. Cassini Mission TDOF Results
LWRHU Tumbling Cylinder
Steep Reentry Total Enthalpy**

Reentry angles shown in descending order left to right: -90° , -70° , -50° , -30°

Shallow Reentry Total Enthalpy

c:\tdof\taallf7.xls

**Figure 30. Cassini Mission TDOF Results
LWRHU Tumbling Sphere
Steep Reentry Total Pressure Behind Normal Shock**

Shallow Reentry Total Pressure Behind Normal Shock

Figure 31. Cassini Mission TDOF Results
LWRHU Tumbling Sphere
Steep Reentry Total Enthalpy

Shallow Reentry Total Enthalpy

Figure 32. Cassini Mission TDOF Results
-90° Reentry LWRHU
Comparison of Total Enthalpy for Different Orientations

Figure 33. Cassini Mission TDOF Results
-90° Reentry LWRHU
Comparison of Total Pressure for Different Orientations

R-Z Cross-section of stagnation sector ($\theta = 0^\circ - 15^\circ$) LWRHU assembly

Component; wall thickness or radius
material; outer radius

• Capacitance (mass) nodes
⊙ Surface (zero mass) nodes

Note: All internal surfaces assigned surface nodes; omitted for clarity purposes.

Figure 34. LWRHU thermal model, quarter section

Figure 35. (a) R-θ thermal model, side-on flight orientation (adapted from Galileo/VEEGA)
(b) Fuel pellet R-Z thermal model, random tumbling flight orientation.

Figure 36. Thermal conductivity schedules for LWRHU interface gas fills.

Boundary condition: $\sum_i \dot{q}_i = 0$ where

- $\dot{q}_{conv}$ = Boundary layer convective transfer comprised of gaseous conduction transfer $(-k_{tg} \partial T / \partial r)_{g, r=w}$ and diffusion transfer $\rho \sum_i D_{ij} H_i (\partial k_i / \partial r)_{r=w}$
 - $\dot{q}_{rad, in}$ = Shock layer radiative transfer
 - $\dot{q}_{rad, out}$ = Surface emissive transfer, $\sigma \epsilon_h T_w^4$
 - $\dot{q}_{cond}$ = Solid conduction (Fourier) transfer, $-k_{ts} (\partial T / \partial r)_{s, r=w}$
 - $\dot{q}_{mass, in}$ = Mass flux transfer-solid phase, $\dot{m} H_{ws}$
 - $\dot{q}_{mass, out}$ = Mass flux transfer-gaseous phase, $\dot{m} H_{wg}$
- } Energy transfer due to thermochemical ablation

Figure 37 - Surface Energy Balance - Reentry Thermal Analysis

Boundary condition: $\sum_i \dot{m}_i = 0$

- $\dot{m}_s$ ~ Mass flux due to ablation, solid phase
- $\dot{m}_t/c_g$ ~ Mass flux due to thermochemical ablation, gaseous phase
- $\dot{m}_m$ ~ Mass flux due to mechanical ablation, solid phase

Figure 38. Surface Mass Balance - Reentry Thermal Analysis

Figure 39- Thermochemical Ablation Regimes for Graphite

Figure 40 Thermal conductivity schedules for Fine Weave Pierced Fabric[™] (FWPF[™]) carbon-carbon composite; FWPF[™]: product of AVCO Systems Division.

96-6374

Figure 41 Specific heat schedules for Fine Weave Pierced Fabrictm (FWPFtm) carbon-carbon composite; FWPFtm: product of AVCO Systems Division.

96-6374

(a) Thermal conductivity schedules; perpendicular to deposition plane.

(b) Thermal conductivity schedules; parallel to deposition plane.

Figure 42 Thermal conductivity properties for pyrolytic graphite.

96-6374

Figure 43 Specific heat schedules for pyrolytic graphite.

96-6374

Figure 44 Thermal conductivity schedules for Pt-30 Rh.

Figure 45 Specific heat schedules for Pt-30 Rh.

96-6374

Figure 46 Thermal conductivity schedules for PuO_2 . Figure 47 Specific heat schedules for PuO_2 .

96-6374

(a) Directional emittance, FWPFtm carbon-carbon

(b) Perpendicular to deposition plane, pyrolytic graphite

(c) Parallel to deposition plane, pyrolytic graphite

Figure 48 Thermal radiative properties for LWRHU's constituent materials.

96-6374

(d) Platinum and platinum alloys

(e) Plutonium dioxide

Figure 48 (continued) Thermal radiative properties for LWRHU's constituent materials.

96-6374

Figure 49. Cassini Mission
 Aerothermodynamic Regimes for the Cassini / VVEJGA Reentries
 Tumbling LWRHU Configuration

c:\tdof\taai18.xls

Figure 50 Composite Plot Comparing Experimental Data
 With the Detra, Kemp, and Riddell Correlation 94

Figure 51 Stagnation Velocity Gradient Correction on the Side-on LWRHU Stagnation Convective Heating Rate (Without Geometry Scaling)

Figure 52 Hypersonic, windward circumferential convective heating factor distributions; cold-wall, non-ablating LWRHU; side-on stable flight orientation.

96-6374

Figure 53 Hypersonic stagnation line convective heating factor distributions; cold wall, non-ablating LWRHU; side-on stable flight orientation.

96-6374

Figure 54 Hypersonic, windward circumferential radiative heating factor distributions; black body, non-ablating LWRHU; side-on stable flight orientation.

96-6374

Figure 55 Hypersonic, stagnation line radiative heating factor distributions; LWRHU side-on stable flight orientation.

96-6374

Figure 56 Hypersonic circumferential static pressure factor distribution as a function of axial location; LWRHU side-on flight orientation.

96-6374

Figure 57 Hypersonic, angle of attack convective heating factor, stagnation line of LWRHU's cylindrical surface; random tumbling flight orientation.

Figure 58 Local convective heating ratio on LWRHU's end face; zero angle of attack; random tumbling flight orientation. (Curve from Figure 10, Klett, ref. 134).

96-6374

Figure 59 Average convective heating ratio to LWRHU's end face as a function of angle of attack; random tumbling flight orientation (curve from figure 11, Klett, ref. 134).

96-6374

Figure 60 Comparison of correlated and experimental static pressure distributions over the LWRHU's end face; zero angle of attack; random tumbling flight orientation.

96-6374

Figure 61 Blockage of convective heating rate as a function of the mass transfer parameter, β' , continuum flow regimes (reproduced from ref. 160).

96-6374

Figure 62 Blockage of stagnation radiative heating rates versus injectant mass flux and chemical constituency; continuum flow regimes.

96-6374

Figure 63 Continuum and Kinetic Flow Regimes with Threshold Values for Radiation Blockage

**Figure 64. Cassini Mission RETAP Results
Comparison of Fuel Release Conditions with
Sandia Melt Boundaries and FOILS EIS Studies**

c:\retap\fuelcom.xls

Figure 65. Cassini Mission RETAP Results
LWRHU -90° Side-on Stable VVEJGA Reentry

A. Component Thermal Response

Analysis utilizes Lawrence Livermore Thermochemistry Data

C. Surface Node Recession Response

c:\retap\cassini\l90srt1.xls

B. Surface Node Mass Transfer Parameter Response

D. Recession Failure For Modeled Surface Nodes

re: Fig.34 for node location

**Figure 66. Cassini Mission RETAP Results
LWRHU 3D -70° Side-on Stable VVEJGA Reentry**

A. Component Thermal Response

Analysis utilizes Lawrence Livermore Thermochemistry Tables

B. Surface Node Mass Transfer Parameter Response

D. Recession Failure for Modeled Surface Nodes

re: Fig. 34 for node locations

C. Surface Node Recession

c:\retap\cassini\la70srt1.xls

Figure 67. Cassini Mission RETAP Results
LWRHU 3D -50° Side-on Stable VVEJGA Reentry

Figure 68. Cassini Mission RETAP Results
LWRHU 3D -30° Side-on Stable VVEJGA Reentry

Figure 69. Cassini Mission RETAP Results
LWRHU 3D -15° Side-on Stable VVEJGA Reentry

A. Component Thermal Response

B. Surface Node Mass Transfer Parameter Response

C. Surface Node Recession

D. Recession Failure for Modeled Surface Nodes

Figure 70. Cassini Mission RETAP Results
LWRHU 3D -10° Side-on Stable VVEJGA Reentry

Figure 71. Cassini Mission RETAP Results
LWRHU 3D -7° Side-on Stable VVEJGA Reentry

c:\retap\cassini\ao7spec1.xls

Figure 72. Cassini Mission RETAP Results
LWRHU 3D -5.2° Side-on Stable VVEJGA Reentry

A. Component Thermal Response

B. Surface Node Mass Transfer Response

C. Surface Node Recession

D. Recession Failure at Modeled Surface Nodes

c:\retap\cassini\c05shf1.xls

re: Fig. 34 for node locations

Figure 73. Cassini Mission RETAP Results
 Side-on Stable LWRHU 3D -90° VVEJGA Reentry
 Ablation Failure Relative to Heat Pulse

**Figure 74. Cassini Mission RETAP Results
 Side-on Stable LWRHU 3D -70° VVEJGA Reentry
 Ablation Failure Relative to Heat Pulse**

c:\tdof\tdof16ap.xls

Qrad: RAD/EQUIL inviscid stagnation streamline flow, black body, effective spherical radius

Qconv: 1ft R sphere, stagnation flow, cold wall, zero mass transfer

Figure 75. Cassini Mission RETAP Results
Side-on Stable LWRHU 3D -50° VVEJGA Reentry
Ablation Failure Relative to Heat Pulse

Figure 76. Cassini Mission RETAP Results
Side-on Stable LWRHU 3D -30° VVEJGA Reentry
Ablation Failure Relative to Heat Pulse

Qrad: RAD/EQUIL, inviscid stagnation streamline flow, black body, effective spherical radius

Qconv: 1ft R sphere, stagnation flow, cold wall, zero mass transfer

**Figure 77. Cassini Mission RETAP Results
 Side-on Stable LWRHU 3D -15° VVEJGA Reentry
 Ablation Failure Relative to Heat Pulse**

c:\tdof\tdof16ap.xls

Qrad: RAD/EQUIL, inviscid stagnation streamline flow, black body, effective spherical radius

Qconv: 1ft R sphere, stagnation flow, cold wall, zero mass transfer

**Figure 78. Cassini Mission RETAP Results
Side-on Stable LWRHU 3D -10° VVEJGA Reentry
Ablation Failure Relative to Heat Pulse**

c:\tdof\tdof16ap.xls

Grad: RAD/EQUIL, inviscid stagnation streamline flow, black body, effective spherical radius

Qconv: 1ft R sphere, stagnation flow, cold wall, zero mass transfer

**Figure 79. Cassini Mission RETAP Results
Side-on Stable LWRHU 3D -7° VVEJGA Reentry
Ablation Failure Relative to Heat Pulse**

Figure 80. Cassini Mission RETAP Results
Side-on Stable LWRHU 3D -5.2° VVEJGA Reentry
Ablation Failure Relative to Heat Pulse

Qrad: RAD/EQUIL, inviscid stagnation streamline flow, black body, effective spherical radius

Qconv: 1ft R sphere, stagnation flow, cold wall, zero mass transfer

Figure 81. Cassini Mission RETAP Results
Side-on Spinning LWRHU 3D -05.2° VVEJGA Reentry
Recession Failure at Modeled Surface Nodes

c:\retap\cassini\sp05bmt.xls

re: Fig. 34 for node locations

Figure 82. Cassini Mission
 Side-on Spinning LWRHU 3D -5.2° VVEJGA Reentry
 Ablation Failure Relative to Heat Pulse

Qrad: RAD/ESQUL inviscid stagnation streamline flow, black body, effective spherical radius
 Qconv: 1/4 R sphere, stagnation flow, cold wall, zero mass transfer

Figure 83. Cassini Mission RETAP Results
LWRHU 3D -07° Side-on Spinning VVEJGA Reentry
Component Thermal Response

c:\retap\cassini\spnsp107.xls

**Figure 84. Cassini Mission RETAP Results
Recession Failure at Modeled Surface Nodes**

**Figure 85. Cassini Mission RETAP Results
 Ablation Failure Heat Pulse Relative to Heat Pulse**

Quasi-Tumbling Cylinder -07°

Quasi-Tumbling Cylinder -05.2° Reentry

c:\dofita05f7.xls

Qrad: RAD/EQUIL, inviscid stagnation streamline flow, black body, effective spherical radius Qconv: 1 ft R sphere, stagnation flow, cold wall, zero mass transfer

Figure 86. Cassini Mission RETAP Results
Random Tumbling 3D LWRHU VVEJGA Reentry
Recession Failure at Modeled Surface Nodes
-5.2° Reentry

c:\retap\cassini\mdm5bm.xls

re: Fig 34 for node locations

**Figure 87. Cassini Mission RETAP Results LWRHU 3D
 Ablation Failure Relative to Heat Pulse
 -05.2° Random Tumbling Reentry**

-07° Random Tumbling Reentry

-10° Random Tumbling Reentry

c:\tdof\1a10f5710.xls

Qrad: RAD/EQUIL, inviscid stagnation streamline flow, black body, effective spherical radius Qconv: 1ft R sphere, stagnation flow, cold wall, zero mass transfer

**Figure 88. Cassini Mission RETAP Results
 Tumbling Sphere VVEJGA Reentry
 Recession Failure at Modeled Surface Nodes
 -90° Reentry**

-70° Reentry

-50° Reentry

**Figure 88. (Continued) Cassini Mission RETAP Results
Tumbling Sphere VVEJGA Reentry
Recession Failure at Modeled Surface Nodes
-30° Reentry**

-15° Reentry

-10° Reentry

**Figure 88.(Continued) Cassini Mission RETAP Results
 Tumbling Sphere VVEJGA Reentry**

-5.2° Reentry

re: Fig 34 for node locations

Figure 89. Cassini Mission RETAP Results
Ablation Failure Relative to Heat Pulse
-90° Tumbling Sphere Reentry

-70° Tumbling Sphere Reentry

-50° Tumbling Sphere Reentry

-30° Tumbling Sphere Reentry

c:\tdof\tbf7all.xls

Qrad: RAD/EQUIL, inviscid stagnation streamline flow, black body, effective spherical radius
Qconv: 1 ft R sphere, stagnation flow, cold wall, zero mass transfer

**Figure 89.(Continued) Cassini Mission RETAP Results
 Ablation Failure Relative to Heat Pulse**

Figure 90 Cassini Mission RETAP Results
Recession Failure Comparison: JANNAF 89 and Lawrence Livermore
Side-on Stable 3D LWRHU -90° VVEJGA Reentry

Side-on Stable 3D LWRHU -30° VVEJGA Reentry

Side-on Stable 3D LWRHU -15° VVEJGA Reentry

Figure 91 Cassini Mission RETAP Results Side-on Stable LWRHU
 Comparison of Ablation Failure Relative to Heat Pulse

Figure 92 Cassini Mission RETAP Results
Side-on Stable 3D LWRHU 3D -90° Reentry
Recession Failure Comparison: Gas-Radiation Cooling Affect

Ablation Failure Relative to Heat Pulse

INITIAL CONDITIONS FOR TDOF RUNS

Angles ->	-5.2°	...	For Gammas -5.2 to -90°				Only for -5.2°	Only for -5.2, -7, -10°		
			75%	100%				-5.2°	-7°	-10°
				-90°	-5.2°	-90°				
Time(s)	22.7		1.93		25.16	2.22	112.8	65.18	27.78	24.98
Vel-Rel	59388		49666		57388	41753	20850	31548	30587	11094
Alt (ft)	242612		141359		238007	128318	237633	231373	179975	141124

Figure 93
Summary of Released Fuel Pellet
Orientations Examined

Applied Physics Laboratory
Laurel, Maryland 20723-6099

Figure 94 CASSINI MISSION, LWRHU FUEL TDOF RESULTS
SIDE ON STABLE LWRHU 75% AEROSHELL BURNTHROUGH
RELEASING FUEL PELLET SIDE-ON STABLE OR SPINNING

Figure 95 CASSINI MISSION, LWRHU FUEL TDOF RESULTS
SIDE ON STABLE LWRHU 75% AEROSHELL BURNTHROUGH
RELEASING FUEL PELLET SIDE-ON STABLE OR SPINNING

Figure 96A. Cassini Mission TDOF Fuel Results
**Reference Convective Heating Rate History for Side-on Stable 75%
Breach Releasing Side-on Fuel Pellet**

Figure 96B. Cassini Mission TDOF Fuel Results
Radiative Heating Rate History for Side-on Stable 75% Breach
Releasing Side-on Fuel

**Figure 96C. Cassini Mission TDOF Fuel Results
Reference Convective Heating Rate History for Side-on
Stable 100% Breach Releasing Side-on Fuel Pellet**

Figure 96D. Cassini Mission TDOF Fuel Results
Reference Radiative Heating Rate History for Side-on Stable
100% Breach Releasing Side-on Fuel Pellet

Figure 97. Cassini Mission TDOF Fuel Results
Heating Rate History for Side-on Stable 75% Breach Releasing
Tumbling Pellet

Heating Rate History for Side-on Stable 100% Breach Releasing
Tumbling Pellet

c:\tdof\fuel\sosf0700.xls

Figure 98. Cassini Mission TDOF Fuel Results
Reference Heating Rate History for Side-on Spinning 75% Breach
Releasing Side-on Fuel Pellet

Figure 99. Cassini Mission TDOF Fuel Results
Reference Heating Rate History for Side-on Spinning 75% Breach
Releasing Tumbling Fuel Pellet

Figure 100. Cassini Mission TDOF Fuel Results
Heating Rate History for Tumbling 75% Breach Releasing Side-on Pellet

Figure 101. Cassini Mission TDOF Fuel Results
Heating Rate History for Tumbling 75% Breach Releasing Tumbling Fuel

Figure 102. Cassini Mission -5.2° Side-on Stable LWRHU 100% Ablated Releasing Side-on Stable Fuel Pellet
Thermal Response Through Centerline Reference Convective Heating

Figure 103. Cassini Mission LWRHU Fuel Results
Comparison of -5.2° Stable LWRHU Releasing Stable Fuel
Response at 1X and 3X Reference Convective Heating
75% Ablated

100% Ablated

Figure 104. Cassini Mission LWRHU Fuel Results
Comparison of -7.0° Stable LWRHU Releasing Stable Fuel
Response at 1X and 3X Reference Convective Heating
75% Ablated

100% Ablated

**Figure 105. Cassini Mission LWRHU Fuel Results
Comparison of -10° Stable LWRHU Releasing Stable Fuel
Response at 1X and 3X Reference Convective Heating
75% Ablated**

100% Ablated

Figure 106. Cassini Mission LWRHU Fuel Results
Comparison of -15° Stable LWRHU Releasing Stable Fuel
Response at 1X and 3X Reference Convective Heating
75% Ablated

100% Ablated

Figure 107. Cassini Mission LWRHU Fuel Results
Comparison of -30° Stable LWRHU Releasing Stable Fuel
Response at 1X and 3X Reference Convective Heating
75% Ablated

100% Ablated

Figure 108. Cassini Mission LWRHU Fuel Results
Comparison of -50° Stable LWRHU Releasing Stable Fuel
Response at 1X and 3X Reference Convective Heating
75% Ablated

Figure 109. Cassini Mission LWRHU Fuel Results
Comparison of -70° Stable LWRHU Releasing Stable Fuel
Response at 1X and 3X Reference Convective Heating
75% Ablated

100% Ablated

— 7 @ 3X — 7 @ 1X

Figure 110. Cassini Mission LWRHU Fuel Results
Comparison of -90° Stable LWRHU Releasing Stable Fuel
Response at 1X and 3X Reference Convective Heating
75% Ablated

100% Ablated

Figure 111. Cassini Mission LWRHU Fuel Results
75% Ablated Side-on Stable LWRHU Releasing Spinning Fuel
-7° Reentry at Reference Convective Heating

-15° Reentry at Reference Convective Heating

-90° Reentry at Reference Convective Heating

Figure 112. Cassini Mission LWRHU Fuel Results
100% Ablated Side-on Stable LWRHU Releasing Spinning Fuel
-7° Reentry at Reference Convective Heating

-15° Reentry at Reference Convective Heating

-90° Reentry at 3X Reference Convective Heating

Figure 113. Cassini Mission LWRHU Fuel Results
75% Ablated Stable LWRHU Releasing Tumbling Fuel
-7° Reentry at Reference Convective Heating

-15° Reentry at Reference Convective Heating

-90° Reentry at Reference Convective Heating

Figure 114. Cassini Mission LWRHU Fuel Results
100% Ablated Stable LWRHU Releasing Tumbling Fuel
-7° Reentry at Reference Convective Heating

Figure 115. Cassini Mission LWRHU Fuel Results
Full Convective Heating
75% Ablated -5.2° Spinning LWRHU Releasing Stable Fuel

75% Ablated -5.2° Spinning LWRHU Releasing Spinning Fuel

75% Ablated -5.2° Spinning LWRHU Releasing Tumbling Fuel

c:\vetap\fuel\valish2.xls

— Node 1 — Node 15 - - - Node 4

Figure 116. Cassini Mission LWRHU Fuel Results
Full Convective Heating
75% Ablated -10° Tumbling LWRHU Releasing Stable Fuel

75% Ablated -7.0° Tumbling LWRHU Releasing Stable Fuel

75% Ablated -5.2° Tumbling LWRHU Releasing Stable Fuel

c:\retap\fuel\valsh2.xls

Figure 117. Cassini Mission LWRHU Fuel Results
Full Convective Heating
75% Ablated -10° Tumbling LWRHU Releasing Spinning Fuel

75% Ablated -7.0° Tumbling LWRHU Releasing Spinning Fuel

75% Ablated -5.2° Tumbling LWRHU Releasing Spinning Fuel

c:\retap\fuel\trallsh2.xls

— Node 1 - - - - - Node 28

Figure 118. Cassini Mission LWRHU Fuel Results
Full Convective Heating
75% Ablated -10° Tumbling LWRHU Releasing Tumbling Fuel

75% Ablated -7° Tumbling LWRHU Releasing Tumbling Fuel

75% Ablated -5.2° Tumbling LWRHU Releasing Tumbling Fuel

c:\retap\fuel\valsh2.xls

— Node 15 - - - Node 4

Figure 119
Thermostructural Model for the LWRHU

Figure 120
Temperature Loads on LWRHU Model
Cassini VVEJGA Reentry

Figure 121
Thermoplastic (realistic) Stress-Strain Material Properties of FWPF

Figure 122
Thermoelastic (approximate) Stress-Strain Material Properties of FWPF

Figure 123
Normal strains of a FWPF Unit Cell Model with Thermoelastic Material Properties Under
Hydrostatic Compressive Loads, at Different Temperatures

LWRHU Free-body Diagram

Figure 124

Y
Z X
Output Set: -90 Stable 2.35 Sec
Contour: STRAIN FS_X

Minimum FS_X=.78
@ Elem 3895

Y
Z X
Output Set: -90 Stable 2.35 Sec
Contour: STRAIN FS_Y

Minimum FS_Y=.79
@ Elem 3895

Y
Z X
Output Set: -90 Stable 2.35 Sec
Contour: STRAIN FS_Z

Minimum FS_Z=.61
@ Elem 3895

Figure 124
LWRHU Side-on Stable Gamma = -90°
Strain Factors of Safety

Figure 125
LWRHU Side-on Spinning Gamma = -90°
Strain Factors of Safety

Figure 126
LWRHU Side-on Spinning Gamma = -50°
Strain Factors of Safety

Figure 127
 LWRHU Side-on Spinning Gamma = -7°
 Strain Factors of Safety

Figure 128
LWRHU Random Tumbling Gamma = -90°
Strain Factors of Safety

Figure 129
 LWRHU Random Tumbling Gamma = -50°
 Strain Factors of Safety

Figure 130
 LWRHU Random Tumbling Gamma = -15°
 Strain Factors of Safety

**Initial Distribution External to the Applied Physics Laboratory
ANSP-M-24**

The Aerospace Corporation
P. O. Box 92957
Los Angeles, CA 90009

Haliburton NUS Corporation
910 Clopper Road
Gaithersburg, MD 20878

Lockheed Martin Missiles & Space
Astro-Space Division
Building B
720 Vandenberg Road
King of Prussia, PA 19406

Jet Propulsion Laboratory
California Institute of Technology
4800 Oak Grove Drive
Pasadena, CA 91103

Los Alamos National Laboratory
P. O. Box 1663
Los Alamos, NM 87545

LAI/EG&G Mound Applied Technologies
P. O. Box 3000
Miamisburg, OH 45342

NASA Headquarters
300 E. St. SW
Washington, DC 20546

Oak Ridge National Laboratory
P. O. Box 2008
Oak Ridge, TN 37831-6285

Orbital Sciences Corporation
20301 Century Blvd
Germantown, MD 20874

William H. Ailor
M1-023

B. W. Bartram
H. Firstenburg

L. E. DeFillipo, 29B12
R. J. Hemler, 29B12-KB
W. Tobery, 20B41

A. D. McDonald, MS 157-102
L. Reinhart
R. Wilcox, MS 264-450

T. George

E. W. Johnson

E. Huckins
Code S

J. P. Moore
Bldg 4508MS6080

Robert T. Carpenter
E. A. Skrabek

Initial Distribution External to the Applied Physics Laboratory
ANSP-M-24
(Continued)

U. S. Department of Energy
Office of Scientific and Technical Information (OSTI)
Special Assistant for Reproduction and Processing
P. O. Box 62
Oak Ridge, TN 37830

U. S. Department of Energy/GTN
Space and National Security Programs
Office of Nuclear Energy, Science and Technology
19901 Germantown Road
Germantown, MD 20874

U. S. Department of Energy
Office of Procurement Operations
1000 Independence Avenue, SW
Washington, DC 20585

W. J. Barnett, NE-50
B. A. Cook, NE-50
R. R. Furlong, NE-50
A. Mehner, NE-50
W. D. Owings, NE-50
L. L. Rutger, NE-50

Contracting Officer, MA-453.2

Applied Physics Laboratory
Laurel, Maryland 20723-6099

Internal Distribution
ANSP-M-24

The Johns Hopkins University
Applied Physics Laboratory
Johns Hopkins Road
Laurel, MD 20723

RW Constantine
WH Zinger
TR Betzer
DC Mitchell
RT Lundy
WJ Tropf
JA Krill
WG Bath
JE Whitely, Jr.
JJ Wozniak
PT Brenza
Y Chang
DW Conn
JA Ecker
LG Everhart
JK Frazer
EF Lucero
JS O'Connor
RC Sharbaugh
JT Stadter