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Volume II

Light-Weight Radioisotope Heater Unit Safety Analysis Report (LWRHU-SAR)

Volume II Accident Model Document

Ernest W. Johnson

October 1985

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MONSANTO RESEARCH CORPORATION
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VOLUME II

ACCIDENT MODEL DOCUMENT

1.0 INTRODUCTION

The purposes of this volume of the LWRHU SAR, the Accident Model Document (AMD), are to:

- A. Identify all malfunctions, both singular and multiple, which can occur during the complete mission profile that could lead to release outside the clad of the radioisotopic material contained therein;
- B. provide estimates of occurrence probabilities associated with these various accidents;
- C. evaluate the response of the LWRHU (or its components) to the resultant accident environments; and
- D. associate the potential event history with test data or analysis to determine the potential interaction of the released radionuclides with the biosphere.

The organization of this AMD follows the format developed in a January 23-24, 1985, meeting at Valley Forge, Pennsylvania (Reference 1). This structure is given in Table II-1.

There have been data supplied from a variety of sources which are used in the formulation of this document. Sources are identified in the specific locations, including appendixes and in the bibliography and are summarized below:

- A. Los Alamos National Laboratory (LANL) - In addition to being the design and fueling/assembly agency, LANL performed the bulk of the environmental safety tests on LWRHU hardware (including helium release);
- B. Applied Physics Laboratory - (APL) - This organization was responsible for the analyses of the various situations which must be addressed during reentry events: thermal stress, ablation, peak clad temperature, etc.;
- C. General Electric Company (GE) - They are the prime contractor for the radioisotope thermoelectric generator (RTG), including the FSAR for that system, and their methodology for the LWRHU SAR was extensively used, particularly the failure/abort sequence trees (FASTs) and many interpretations of the shuttle details during specific events;

TABLE II-1

VOLUME II: ACCIDENT MODEL DOCUMENT (AMD) FORMAT

1.0 Introduction

Purpose of AMD
Document Organization
Data Acknowledgements

1.1 Mission and Systems Description

- Mission Phases with Timeliness/Events
- LWRHU Design

2.0 Summary of Accident Evaluation

Flowchart
Centaur Domination of Accident Environments Described
Tabulation of Accidents/Consequences by Phase

3.0 Accident Evaluation and Failure Mode Analysis

3.1 Objectives and Approach
Sequence Tree Construction
3.2 Mission Accident Evaluation

- Each Phase Addressed Separately
- Each Accident in Each Phase Treated Separately in Entirety

3.2.1 Phase 0-Prelaunch

- o Top-Level Event Tree Showing Accidents with Probabilities
- o Accidents Defined and Characterized from Initiation to Identification of Source Terms Where Applicable

- Accident Description
- Accident Environment Definition
- Initial LWRHU Response to Explosions
- Synergistic Effects of Environments
- Intermediate Events Identified
- Final Disposition of LWRHU
- Source Term Characterized

TABLE II-1 (Continued)

All Inputs Positively Identified and Referenced
to Appendices

Minimal Analysis and/or Testing to Be Shown or
Discussed

- Results to Be Presented

- Reference to Details in Appendices

Repetitious Material Will Be Included Where
Applicable for Each Accident for Purposes of
Completeness and Ease of Readability and
Understanding

- o Complete Phase Event Tree

- Presented After All Accidents Are
Defined and Characterized

- Accidents and Events Identified by
Designators Referenced in Each
Accident Evaluation

3.2.2 Phase I - Above Sequence and Content
Repeated for Each Subsequent Phase

APPENDICES: Include all test and analytical data used (and its
justification) for all accidents, environments, and LWRHU
response modes addressed in the accident evaluations.

- A. Accident Definition
- B. Accident Environments
- C. LWRHU Response to Explosions
- D. LWRHU Response to Fragments/Projectiles
- E. LWRHU Response to Propellant Fires
- F. Spacecraft Reentry Breakup Analysis
- G. LWRHU Reentry Response
- H. Impact Test Program Results
- I. Burial Thermal Analysis
- J. Source Term Evaluation

- D. Johnson Space Center (JSC) - This NASA office was responsible for providing the shuttle and payload descriptions plus defining the accident environments and probabilities;
- E. Jet Propulsion Laboratory (JPL) - This organization provided spacecraft details plus some analyses (release altitude of LWRHUS, for example); and
- F. Monsanto Research Corporation (MRC) - In addition to manufacturing all nonradioactive components for the LWRHUS, MRC was responsible for issuing this SAR and for performing some tests and analyses in support of its issuance.

2.0 SUMMARY OF ACCIDENT EVALUATION

The flow chart sequence of mission phase as a function of success/failure branches is given in Figure 1. This flow chart (referred to as the Top-Level Tree) was provided to MRC by GE (Reference 2) by definition to ensure that the radiological safety input assessment was based on similar ground rules. These top-level trees are separated and addressed in much greater detail in Section 3.0.

As implied in the flow chart (Figure 1), most of the accidents are Centaur-dominated, either independently or in some lower-yield ET events, are triggered by this failure and become the major contributor to the accident environment. Appendix C addresses the explosion accident events which potentially could affect the LWRHU adversely. These cryogenic explosion probabilities and region within the mission are given in Table A-1. Although there were originally no explosions identified for Phase 4, the recently issued Reference 3 has defined a Centaur CBM potential.

A summary of the LWRHU clad failures that result in fuel release(s) is provided in Table II-2. As might be expected, the releases are highest in probability and quantity for explosion-released reentering clads during Phases 2, 3, and 4. Although some of the postulated earlier-phase accidents result in relatively more violent environments, the basic structural integrity of the LWRHU design precludes large releases, and the nature of the failure scenarios makes for relatively low probabilities.

3.0 ACCIDENT EVALUATION ON FAILURE MODE ANALYSIS

3.1 Objectives and Approach (Reference 3)

Heat sources containing plutonia are designed to be capable of controlling the radioactive materials so that, should the material ever reach Earth, the radiological risk would conform to recommended international limits. Because even the most reliable systems pose a finite failure probability, there is the requirement that the accident probability analyses, as well as population dose and health effect analyses, be completed prior to launch.

In general, each nuclear heat source is analyzed with regard to its application to a particular mission. For a given mission, the specific

FIGURE 1: The top-level FAST was defined to be the same as the RTG tree derived by GE. Note that triangles OA, 1C, and 2B include ET failure modes that wind up being Centaur CBGS-2D dominant. Each phase and branch is broken down into more detail in Figures 3 through 18.

Table II-2: SUMMARY OF FUEL RELEASES FOR GALILEO LWRHU

PHASE IDENTIFIER	ACCIDENT ENVIRONMENT	ALTITUDE (m)	QUANTITY		MAXIMUM PROBABILITY
			VAPOR, Ci (GBq)	PARTICULATE, Ci (TBq)	
1A OBM	Maximum Condition	60	3.6 (135)	92.4 (3.5)	6E-9
1A SBPWS		60	2.4 (90)	61.6 (2.3)	5E-9
1A IBM		60	3.6 (135)	92.4 (3.5)	3E-9
1A SCH		60	6.1 (225)	153.9 (5.8)	1.1E-9
1A DSE		60	21.9 (810)	554.1 (20.5)	5E-9
					Can Occur Together
					Cannot Occur If Above Happens
1B	ET	30	<1 (<40)	96 (3.6)	8E-9
1D OBM	CBGS-ID	60-10k	3.6 (135)	92.4 (3.5)	4.3E-8
		>10k	~0	96 (3.6)	4E-8
1D SBPWS		60-10k	2.4 (90)	61.6 (2.3)	3.2E-8
		>10k	~0	64 (2.4)	3E-8
1D SBPWS		60-10k	3.6 (135)	92.4 (3.5)	3.1E-8
		>10k	~0	96 (3.6)	3E-8
1D SCH		60-10k	6.1 (225)	153.9 (5.8)	6.6E-9
		>10k	~0	160 (5.9)	6E-9
1D DSE		60-10k	21.9 (810)	554.1 (20.5)	1.0E-8
		>10k	~0	576 (21.3)	1E-8
					Cannot Occur If Above Happens
2A SO+EO ΔEO	ET	~100k	0.377 (14)†	2144 (79.3) §	4E-8
		~100k	0.135 (5)†	768 (28.4) §	6E-8
2B SO+EO ΔEO	CBGS-2D	~100k	0.377 (14)†	2144 (79.3) §	1.2E-6
		~100k	0.242 (9) †	1376 (50.9) §	3.8E-6
2C SO+EO ΔEO	CBM	~100k	0.377 (14)†	2144 (79.3) §	1.0E-6
		~100k	0.242 (9) †	1376 (50.9) §	1.6E-6
3A SO+EO ΔEO	CBM	120k	0.377 (14)	2144 (79.3)	3.7E-5
		120k	0.242 (9)	1376 (50.9)	5.8E-5
4C SO+EO ΔEO	CBM	120k	0.377 (14)	2144 (79.3)	2.2E-5
		120k	0.242 (9)	1376 (50.9)	3.4E-5

†At End of Phase 2, T=534s

§After T=400s, or After Clad Melt Without Fuel Melt

OBM = Outboard Magnetometer
 SBPWS= Science Boom Plasma Wave Subsystem
 IBM = Inboard Magnetometer
 SCH = Science Cable Hinge
 DSE = Despun Electronics
 SO = Side-On LWRHU
 EO = End-on LWRHU
 Ci = Curie (1Ci = 37 GBq)
 TBq = Terabecquerel
 GBq = Gigabecquerel
 ΔEO = EO - SO

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phases (e.g., prelaunch transportation and handling, launch, ascent, and final operation) must be defined so that normal procedures and mission events may be systematically analyzed to determine the results of an abnormal event.

The systematic analysis of each phase begins with an analysis of abort or failure modes with the objective of identifying potential single or multiple malfunctions that can potentially affect the nuclear power source during the complete mission. An explanation of the failure and abort sequence tree, which is a logic diagram used to develop the analysis, is shown in Figure 2. In the case of the launch vehicle, the failure analysis includes the condition of the vehicle after failure and also the occurrence probability for that condition. For each of the vehicle conditions defined in the analysis, a sequence of adverse environments is defined, and this is followed by an evaluation of the response of the nuclear power source to each of the adverse environment sequences. If the analysis of an extreme environment shows that there is a potential for a fuel release, the occurrence probability can be determined from the interrelation of the failure analysis and sequence tree construction.

To evaluate the consequences of these events, the analyst must define the source terms. Within the context of space nuclear safety, a source term is the quantity of fuel which may be uncontrolled. In describing a source term, the analyst must consider its state (e.g., particle-size distribution, chemical form if changed from its original form, and degree of containment) and its location (e.g., at high altitude, on land, or in water; latitude and longitude; or random deposition during reentry from a specified orbit).

Information on the reasons that events occur leading up to the accident itself may be found in JSC 08116 (Reference 5). The accident environments and probabilities given below were excerpted from JSC 08116 summaries.

3.2 Mission Accident Evaluation

3.2.1 Phase 0 (Prelaunch/Launch) - Although separated in time as prelaunch (T-28,800 s to T-31 s or from when the cryogenic liquid propellant introduction into the various tanks begin until the launch sequence becomes automatic) and launch (T-31 s to T-0 or from the end of prelaunch, through SSME ignition, SRB ignition, and lift-off), these two mission segments are lumped together in this Phase 0 analysis. Figure 3 is the top-level FAST for Phase 0.

The two postulated conditions are:

3.2.1.1 Centaur Two-Diameter Confined-by-Ground Surface (CBGS-2D or simply 2D) explosion either independently generated or precipitated by a low-yield ET explosion - The environment in the area of the shuttle would be defined as shown in Figure A-2 in Appendix A. The sequence of events experienced by the various LWRHU categories and their responses are given in Subbranch OA, Figure 4. The result is that there are no gross clad failures as the geometry does not permit any high-velocity fixed structure impacts (Appendix D, Section 2.3.1), which is the only test condition which has exhibited release of fuel. There is a possible very low-level release [-5-25 nCi (~185-925 Bq)] resulting from sublimation of plutonia through the vent hole if a bare clad comes to rest adjacent to a burning SRB fuel segment

FIGURE 2: The methodology used in constructing the FASTs for this SAR.

FIGURE 3: The top-level FAST for Phase 0 of the Galileo mission.

FIGURE 4: The Centaur CBGS-2D explosion sequence with resultant LWRHU dispositions. The branch is identical to the 1C event in that there are no plutonia releases.

(discussed in Appendix E). This is in the order of normal contamination levels on a GPHS clad and is not listed as a release when risk assessments are made later.

3.2.1.2 Centaur Confined-by-Missile (CBM) Explosion - The CBM explosion originates in the intertank bulkhead flange area of the Centaur and would result in an environment as given in Figure A-4 in Appendix A. As in 3.2.1 above, the environmental levels are such as to not cause clad failures, and there are no geometrically possible high-velocity impacts with fixed or slow-moving hard surfaces (Appendix D). As in 3.2.1, the potential of a bare-clad exposure to a burning solid fuel block is there, but the fuel release would be in the same insignificant range (Appendix E, Section I-B). The sequence of conditions and LWRHU responses are shown in Subbranch OB, Figure 5.

3.2.2 Phase 1 (First-Stage Ascent) - Phase 1 for the FAST analysis begins at lift-off ($T = 0$) and ends at $T + 128$ s when the SRBs are separated from the ET. This is perhaps the most critical phase in terms of events that could result in accidents: clearing the launch tower, passing through the maximum dynamic pressure region, separation of the SRBs, and maintaining the course within the specified trajectory range as required by range safety. Because of this, the Phase 1 possible accidents can proceed with five possible end results as shown in the top-level FAST in Figure 6.

3.2.2.1 Maximum Condition - This one-time event can occur only from $T = 0$ to $T = 2$ s and if the left SRB fails with the STS lurching to the left into the Fixed-Service Structure (FSS) (Paragraph 2.4, Appendix D). This event results in a 13.8 MPa (2000 psi) overpressure with a correspondingly large static impulse of 34.5 kPa·s (5 psi·s). Flyer plate and LWRHU velocities are taken to be as for the Centaur CBGS-1D 1% environment (Appendix A, Figure A-3); LWRHU trajectories are assumed to be identical to that event also with the COE lying in the CBGS-1D envelope (Appendix D).

The sequence and results of exposing the 101 LWRHUs on the Galileo to this event are shown in Figure 7. In summary, this event can result in clad failures with significant fuel release. High velocity (~600 m/s) impact tests of bare clads on essentially unyielding steel surfaces have shown that failures with essentially 100% fuel release can occur (Appendixes D and H). The geometries and probabilities are discussed in Appendix D also. The highly pulverized fuel will be immediately exposed to the liquid propellant fireball with ~3.8% vaporization (Appendix E).

The fuel releases are summarized as follows (two independent cases):

- A. Despun Electronics LWRHUs: 576 Ci (20.7 TBq) could be released at a total probability of 5×10^{-9} per mission. About 3.8% would be as vapor and the balance as particulate plutonia.

NOTE: No HV = NO HIGH VELOCITY IMPACTS

FIGURE 5: Branch OB illustrates the LWRHU sequential response to the Centaur CBM explosion while on the launch pad. This branch is identical to the 1E branch in that there are no plutonia releases.

FIGURE 6: The top-level FAST for Phase 1 shows that all five defined cryogenic explosion accidents can occur in the 123-s length of the phase.

FIGURE 7: (Continued on next page)

FIGURE 7: The FAST for Branch 1A shows that LWRHUs in five different locations can be exposed to conditions that could release fuel.

B. Science Boom Units

	<u>SRB Impact</u>	<u>FSS Impact</u>
Maximum Release	416 Ci @ 1×10^{-9}	416 Ci @ 1×10^{-10}
Intermediate I	256 Ci @ 2×10^{-9}	—
Intermediate II	160 Ci @ 1×10^{-9}	—
Lowest Release	96 Ci @ 1×10^{-9}	256 Ci @ 1×10^{-9}

The released material would end up as 3.8% vapor and 96.2% particles.

NOTE: These cases are independent, as the COE envelopes discussed in Appendix D are not overlapping. The LWRHUs on the science boom axis can have coincident COEs; therefore, B., above, indicates the apportioning of these overlapping conditions to those LWRHUs with fuel releases and probabilities. (Multiply Ci by 0.037 to get TBq.)

3.2.2.2 ET Dominant - Should the intertank region between the upper tank (liquid oxygen) and lower tanks (liquid hydrogen) fail, the heavier liquid oxygen can stream into the low-density liquid hydrogen and provide conditions for an explosion. This explosion creates environments as shown in Figure A-1, Appendix A. The results of this event and ultimate disposition of the various clads are shown in Figure 3.

LWRHU clads will not generally fail because of these environments with one exception: The high-velocity impact of some LWRHUs with the flame trench, Rotating Service Structure (RSS) rail, or the pad itself further out (see Figure D-7, Appendix D). Those LWRHUs with unimpeded paths (the shuttle doors are assumed to be gone) are the two on each RTG boom and the two on the Plasma Wave Sensor (PWS) in the folded antenna area. All others would collide with slower-moving structures or be shielded from the blast wave and receive insufficient velocity for failure. Note that this event can occur in the first 5 s; after that, the probability of high-velocity structure impact becomes ~0.

Those six LWRHUs would be expected to fail at a 50% rate (Appendix H) at a frequency of 8×10^{-9} per mission. This would release 96 Ci (3.6 TBq) of plutonia as particles or vapor. (The release location would be inside the defined fireball radius of 150 m, but the released material may be caught up in the water which had been dousing the flame trench or be released too low to become effectively exposed to the fireball environment. Therefore, the release is given as vapor and particles.) Figure 8 provides the FAST for this event.

3.2.2.3 Centaur CBGS-2D - Subbranch 1C of Figure 6 shows that the Centaur 2D explosion is the most probable Phase 1 event with a total mission probability of 3.65×10^{-5} . This type event has been addressed already in Section 3.2.1.1, above. Although this accident in Phase 1 can occur at altitudes to 73 km, the accident conditions, geometries, and LWRHU responses do not result in fuel release.

FIGURE 8: Branch 1B indicates a potential for clad breach in the first 5 s of ascent as a result of high-velocity clad impact on flame trench concrete or the RSS rail.

3.2.2.4 Centaur CBGS-One Diameter (1D) - The Centaur CBGS-1D explosion can provide articles in the space shuttle bay with a set of severe environmental conditions over a range of probabilities, as may be noted in Appendix A, Figure A-3. The rather large volume in the bay in which the COE is located for the 1D event (see Figure D-1) permits some LWRHU trajectories to intersect with the SRBs or the FSS; this is discussed in detail in Sections 2.3.1 to 2.3.4 of Appendix D, and results are given in Table D-1. However, the explosion environment itself is not of a magnitude to breach the clad: Overpressures and the fragment/LWRHU ΔV s are not sufficient to breach the clad. Near-pad fires have been shown to not promote fuel release (Appendix E). After the STS has reached 10 km or above, the fuel is assumed to be released as particles and not subject to evaporation until sometime late in Phase 2. (This is about halfway through Phase 1.) Note also that even if the event occurs toward the end of the phase, the velocity and altitude are too low to result in ablative failure of a bare clad. The terminal velocity of ~120 m/s is not sufficient to cause rupture at impact (mainly on water in this case after the first 25 s).

The FAST diagram for Branch 1D is given in Figure 9. The summary of released plutonia for these various LWRHUs and condition-dependent probabilities are given as follows:

	First Half/Phase 1 (Vapor+Particles, SRB+FSS)	Second Half/Phase 1 (Particles, SRB)
A. Despun Electronics	576 Ci @ 1.1×10^{-8}	576 Ci @ 1×10^{-8}
B. Science Boom Units	416 Ci @ 6.6×10^{-9} (maximum release) 96 Ci @ 4.3×10^{-8} (minimum release)	416 Ci @ 6×10^{-9} 96 Ci @ 4×10^{-8}

NOTE: Despun Electronics and Science Boom Units lie on different axes. Therefore, the COE cannot cause both interactions to occur simultaneously. (See Appendix D for geometrical discussions. Multiply Ci by 0.037 to get TBq.)

3.2.2.5 Centaur CBM - Phase 1 can be afflicted with the Centaur CBM explosion event at a probability of 5×10^{-6} per mission. This event, labeled 1E in Figure 6, is virtually the same as the Branch OB shown in Figure 5.

Although the event has a much wider range of altitudes over which it can occur, neither the velocity nor altitude are sufficient to result in aerodynamic heating to failure of bare clads. The intact clad would then incur (mainly) water impact at a maximum velocity of ~120 m/s; no failures have been identified in impact tests performed at this level. Overall, no clad failures and no fuel releases are expected for this branch.

FIGURE 9: (Continued on next page)

FIGURE 9: The Centaur CBGS-1D explosion can result in a wide range of fuel release quantities and probabilities for Phase 1, first-stage ascent.

3.2.3 Phase 2 (Second-Stage Ascent) - Figure 10 provides the first-level FAST for Phase 2, T + 128 s to T + 534 s. As the SRBs are no longer attached to the ET and there are no Centaur CBGS-1D explosions defined, clad failure caused by high-velocity SRB impact does not occur during this phase. The accidents associated with these three branches to this phase are discussed below.

3.2.3.1 ET Failure - The least-likely failure of those identified for Phase 2 is the ET explosion with a projected mission incidence of 5×10^{-7} . This branch, No. 2A, is provided in Figure 11.

Although one might assume that the ET environmental conditions would diminish as the fuel is expended from the tanks, such is not the case for the model used (Reference 6). Therefore, the FAST for this situation indicates a significant potential for plutonia release after 400 s into the mission (Appendix G, Section 7). The release form is addressed in 3.2.3.2 (following). The summary of releases for this type of incident is:

Maximum Release: 2144 Ci (79.3 TBq) @ 4.0×10^{-8} probability

Most Probable Release: 1376 Ci (50.9 TBq) @ 6.0×10^{-8} probability

3.2.3.2 Centaur CBGS-2D - The highest probability Phase 2 explosion accident is the Centaur CBGS-2D event with a frequency of 5.36×10^{-5} per mission. Figure 12 provides the event sequence expected for this event (identified as Branch 2B).

The full fuel inventory in the Centaur results in the full range of explosion environments identified in Figure A-2 in Appendix A as being probable. Therefore, stripping of the graphite reentry protection can occur in the overpressure environment, no adverse effects are expected with the low V fragments, but some reentry failures (clad melts) are expected at T > 400 s. (Appendix G, Section 7.)

Unmelted clads would fall to the earth's surface at ~ 120 m/s, impact, and not release fuel; see Appendix H. At T > 400 s, clads can experience sufficient aerodynamic heating to melt the Pt-30Rh (Appendix G, Section 7). At times just over T + 400 s, the fuel will reenter with little or no burnup (vaporization) and drift down as particulates with an expected size and weight fraction distribution identified in Appendix J (Figure J-1) for flyer plate/shuttle floor impacts. The fraction of this released fuel that is vaporized increases over the remaining 134 s until the fraction vaporized becomes 0.000176 of the released inventory. Reentry assessments discussed above are documented in Appendix G.

In summary, a maximum expected release would be 2144 Ci (79.3 TBq) at a mission probability of 1.2×10^{-6} and a more probable value 1376 Ci (50.9 TBq) at a mission probability of 3.8×10^{-6} . [The first release value is for side-on plus end-on overpressure-failed LWRHUs, whereas the lower value represents the end-on failures which occur at lower threshold values.] The released fuel is dispersed initially as particulates and, toward the end of Phase 2, the release would include a small (0.000176) fraction as vapor as well.

FIGURE 10: The top-level FAST for Phase 2 with its three potential branches is given above.

FIGURE 11: The Branch 2A, ET failure between $T = 128$ and $T = 534$ s, indicates fuel release as fines or particles, depending upon when the explosion occurs.

FIGURE 12: Branch 2B also indicates a fuel release probability as particles or particles and vapor, depending on when the Centaur CBGS-2D explosion occurs.

3.2.3.3 Centaur CBM - Branch 2C of Phase 2, identified as as Centaur CBM explosion (see Figure A-4 for the environment), occurs at a mission probability of 1.4×10^{-5} . Except for different overpressure aeroshell removal fractioning, the tree (Figure 13) is the same as for the Centaur CBGS-2D event discussed previously. This extends throughout the FAST, and the final summary values are:

Maximum Release: 2144 Ci (79.3 TBq) @ 1.0×10^{-6} probability

Most Probable Release: 1376 Ci (50.9 TBq) @ 1.6×10^{-6} probability.

The comments concerning particulate and vapor dispersion presented for the 2B branch are true here also.

3.2.4 Phase 3 (On-Orbit) - The orbital segment of the mission extends over the period $T + 534$ s to $T + 24,084$ s. The only variety of cryogenic explosion identified for Phase 3 is the Centaur CBM event. The top-level FAST, Figure 14, shows that cases for payload doors open or closed are lumped into the one branch, 3A.

The 3A branch, with a mission probability of 1.69×10^{-4} occurrence frequency, results in the highest release probabilities and quantities as shown in Figure 15. The survivability of intact LWRHUs in general is governed by the pass/fail lines on Figure A-4 of Appendix A and lies under the "OVERPRESSURE" column in Figure 15. If the aeroshell is stripped from the clad, clad melt is a certainty and the fuel, already comminuted as Figure J-1, Appendix J, will undergo vaporization to an extent of 0.000176.

In summary, these Phase 3 releases are identified as follows:

2144 Ci (79.3 TBq) as particles and 0.38 Ci (14 GBq) as vapor @

3.7×10^{-5} probability (maximum release), and

1376 Ci (50.9 TBq) as particles and 0.24 Ci (9 GBq) as vapor @

5.8×10^{-5} probability for the most probable release accident.

3.2.5 Phase 4 (Insertion) - There have been various malfunctions defined that could occur after the Centaur/Galileo has been deployed from the shuttle bay and that could cause the spacecraft (and thus LWRHUs) to reenter the earth's atmosphere with subsequent surface impact. The Phase 4 FAST (Figure 16) identifies the particular failure modes that are applicable to GPHS reentry scenarios. As all normal (unfailed aeroshell) reentry analyses applicable to LWRHU are for worst-case conditions (Appendix G) and no cryogenic propellant explosions except for 4C (which is informally defined) are defined for this phase; the 4A and 4B Branches are combined for LWRHU purposes as shown in Figure 17.

FIGURE 13: Branch 2C yields a probability for fuel release after $T = 400 \text{ s}$.

FIGURE 14: The only on-orbit cryogenic explosion is the Centaur CBM at a mission frequency of 169 E-6.

FIGURE 15: Branch 3A, the only on-orbit cryogenic propellant explosion defined (Centaur CBM), can strip the aeroshell from the clads and result in fuel burnup at high altitudes.

FIGURE 16: Top-level FAST for the final phase identifies one branch, 4C, that involves a cryogenic propellant explosion environment.

FIGURE 17: Branches 4A and 4B for the Top FASTs can be lumped together for the LWRHU reentry case, as the γ^* or maximum clad temperature trajectory does not result in clad failure nor aeroshell thermal stress failure.

Branch 4C, although not defined in the GPHS FASTs (Reference 1) nor in JSC 08116 (Reference 4), was identified, and its inclusion was informally recommended in Reference 5. The FAST structure (Figure 18) and releases are the same as for the Phase 3A event, but the release probabilities are lower (2.2×10^{-5} and 3.4×10^{-5} , respectively).

The information on anticipated LWRHU response to this event is included for the reader's information. As it will remain a separated branch in Volume III, one may easily not employ this analysis in future assessments.

4.0 REFERENCES

1. Verbal Presentation, C. T. Bradshaw, Valley Forge, Pennsylvania (January 23, 1985).
2. Private Communication, C. T. Bradshaw to E. W. Johnson (May 28, 1985).
3. Bennett, G. L., "Overview of the U. S. Flight Safety Process for Space Nuclear Power," Nuclear Safety, 22-4 (July-August 1981).
4. Space Shuttle Data for Planetary Mission Radioisotope Thermoelectric Generator (RTG) Safety Analysis, JSC-08116, Johnson Space Center (February 15, 1985).
5. Schaefer, G. J., to Lombardo, J. J., Telecommunication (July 12, 1985.)

FIGURE 18: The recently defined Branch 4C results in high altitude burnup of the released fuel similar to Branch 3A except for probabilities.

APPENDIX A: ACCIDENT DEFINITION
APPENDIX B: ACCIDENT ENVIRONMENTS

(These two required appendixes have been combined
to provide continuity in this SAR.)

1.0 INTRODUCTION

With the sizable quantity of cryogenic propellant contained in the ET and Centaur, there exists the potential for device failure(s) which in turn can result in explosions of varying severity. Table A-1 summarizes accidents that could expose the LWRHUs to explosion environments which could result in the release of contained plutonia. Prelaunch at T-8 hr is the start time for consideration, as this is when the cryogenic propellant loading begins. (There may be accidents before and after the time segment encompassed in Table A-1, but these do not result in release of plutonia from the LWRHUs.)

2.0 EXPLOSION ENVIRONMENTS

The probabilistic environments generated by the explosions are summarized as follows (pass/fail lines are related to LWRHU aeroshell's ability to withstand the shock overpressure event):

- A. Maximum Environment - This is a unique event caused by the left SRB malfunctioning in the 0-2 sec time frame. This results in the maximum environment of 13.8 MPa (2000 psi) shock pressure with its corresponding large (~34.5 kPa·s or 5 psi·s) static impulse. It also would result in a high-velocity fragment environment. The mission probability is 0.4×10^{-6} .
- B. ET Bulkhead Failure - Figure A-1 displays the variation of environment with respect to its probability of severity; the total probability of occurrence from Table A-1 is 2.2×10^{-6} over the Centaur mission.
- C. Two-Diameter (2D) Centaur Explosion Failure - The probabilistic variations of environments for this event are given in Figure A-2. This sort of environment is anticipated to occur at a mission frequency of 102.2×10^{-6} .
- D. One-Diameter (1D) Centaur Explosion Failure - Figure A-3 provides the relationship of various environmental parameters as a probability of their occurrence for this rather severe event. Accidents leading to this sort of environmental conditions occur only during the first stage (0 to 134 sec) and at a frequency of 9.5×10^{-6} per mission.

TABLE A-1: Summary of Probabilities for various Cryogenic Explosions is provided below (from JSC 08116, Table 3.5, Reference 1; the column headed Insertion is from TWX, G. J. Schaefer/J. J. Lombardo, July 12, 1985).

Environment/Accident	10 ⁻⁶ Failure Probability/Mission Phase* (Timeline in Seconds)					
	Prelaunch -28800 to -31	Launch -31 to 0	1st Stage 0 to 128	2nd Stage 128 to 534	On-Orbit 534 to 24084	Insertion >24084
Maximum Environment	--	--	0.4	--	--	--
ET Bulkhead Curve - ET Failure	--	--	1.7	0.5	--	--
2D Centaur**						
-ET Low Yield	1.4	--	7.8	2.5	--	--
-STS Origin	2.5	6.5	15.7	13.3		
-Centaur Ext.	5	1	13	38		
10 Centaur*** Range Destruct	--	--	9.5	--	--	--
Centaur CBM	12	--	5	14	169	101
FAST Phase (X1)	0	0	1	2	3	4

*The probabilities of STS failure are to be treated as events that could occur at any one time during a defined mission phase. If the event occurs during a subphase, it has happened and should not be repeated (or added in a subsequent subphase). Centaur probabilities are distributed over the mission phase equally. If subphases are defined, the probability for each subphase is equal to: $\frac{\text{Probability} \times \text{Subphase Time}}{\text{Phase Time}}$

**ET low-yield event does not add to accident severity but results in a 2D Centaur explosion.

***Includes spill conditions without positive acceleration.

FIGURE A-1: The ET Explosion Mode results in these curves; the abscissa is the percentage of time that variable will exceed value selected.

FIGURE A-2: Parameters associated with the Centaur 2D Spill Mode. The abscissa is percent probability that the variable will exceed the corresponding value.

FIGURE A-3: Parameters associated with the Centaur 1D Spill Mode. Probability (in percent) is time that the parameter will exceed that value.

- E. Centaur-Confined-by-Mission (CBM) Failure - The most frequently anticipated accident environment is the Centaur CBM event, which may occur throughout the various phases on Table A-1 and totals 299×10^{-6} per mission. The probability of the various environmental parameters being realized is given in Figure A-4.

The curves in Figures A-1 and A-4 labeled Shock Overpressure, Static Impulse, and Flyer Plate Velocity have been excerpted directly (with appropriate unit conversions) from JSC 08116 (Reference 1). The shock wave velocity curves were calculated from the expression (GESF-1786, Reference 2, p. A-14):

$$V = 340 \left[\frac{6 P_s}{7 P_o} + 1 \right]^{1/2} \text{ m/s.}$$

where P_s = Static Overpressure

P_o = Atmosphere Pressure

V = Velocity.

The LWRHU velocities were obtained by numerically integrating the basic force = mass x acceleration equation. The force in this case is the aerodynamic drag produced by the blast wind behind the incident shock; i.e., $F = q/AC_D$ where q , the dynamic pressure, is $1/2 \rho_p (\mu_p - \mu)^2$. The terms μ_p and ρ_p are the local particle velocity and density, and are obtained by assuming a triangular blast pressure pulse; μ is the LWRHU velocity. The ballistic coefficient, $W/C_D \cdot A$, was taken to be the average of the end-on and cylinder broadside values, 42.7 kg/m^2 .

Although the aeroshell gets stripped from the clad at the pass/fail overpressure values, it is assumed that it remains intact long enough to transfer the theoretical velocity to the clad. This has some experimental verification in the one flash x-ray taken by LANL after a 12.8 MPa (1850 psi) shock at an impulse value showed the LWRHU moving at a velocity in the order of 1300 m/s.

The explosion environments which impart to a clad a sufficiently high velocity and proper direction which can result in a fuel release upon impact with an essentially unyielding surface with subsequent fuel form release alteration are addressed in Appendix E. Similarly, some explosions at near or on-orbit conditions which remove the aeroshell reentry protection could result in clad melt with subsequent fuel dispersion. Appendix G addresses this accident scenario.

Reference 3, which defines an insertion Centaur CBM probability, was received by MRC on July 19, 1985, and has been included as an accident condition. The environment had already been defined in Reference 1.

FIGURE A-4: Parameters associated with the Centaur CBM Mode are given as a function of "greater than" probability percentage.

3.0 REFERENCES

1. Space Shuttle Data for Planetary Mission Radioisotope Thermoelectric Generator (RTG) Safety Analysis, JSC-08116, Johnson Space Center (February 15, 1985).
2. Updated Safety Analysis Report for the Galileo Mission and the International Solar-Polar Mission, Corporate Author, GESP-7186 (April 1984).
3. Schaefer, G. J., to Lombardo, J. J., Teletype Communication (July 12, 1985).

APPENDIX C

LWRHU RESPONSE TO EXPLOSIONS

1.0 LWRHU

The LWRHU response to the overpressure is that, in general, the aeroshell will be stripped from the clad at overpressures >3.9 MPa (570 psi) for end-on and >5.5 MPa (800 psi) for side-on orientation of the assembly with respect to overpressure direction (Reference 1) with the clad incurring velocities shown in Figures A-1 through A-4 (Appendix A). The overpressure explosion per se does not fail the clad; some slight deformation was noted on clads from assemblies tested to 12.75 MPa (1850 psi), however (Reference 2). This test, although slightly below the NASA-defined maximum of 13.8 MPa (2000 psi), is near enough to it to justify not requiring added tests to the 13.8 MPa level (Meeting Agreement, INSRP Presentation, June 4-5, 1985, Germantown, Maryland).

Responses of the LWRHUs to fragments and subsequent impact interactions are addressed in Appendix D (following).

The method used to calculate these two estimated failure thresholds is given in Teledyne Energy Systems Report No. TES-3203, F. A. Schumann, June 3, 1985 (Reference 1). Dr. Schumann employed the following methodology:

1. Define pressure-time characteristics on the aeroshell on the two orientations.
2. Determine the response amplification or maximum dynamic load factor (a function of pulse shape and duration and aeroshell period).
3. Compare the pressure-stress relationship with material capability and thus the initiation of fractures.
4. Associate this with the static overpressure that would result in failure initiation.

The two values were 3.9 MPa for a shock wave impinging upon the closed end of the LWRHU aeroshell and 5.5 MPa for the aeroshell being struck side-on with the shock.

After this analysis was performed, the LWRHU test assemblies were subjected to the low-level (429 psi/2.96 MPa) overpressure test performed by LANL. The results (Reference 2) verify that this analysis has credence (even though slightly lower than the desired overpressure level) in that damage to the two LWRHUs in the test was minimal. Figure C-1 illustrates the conditions of the "end-on" exposed assembly (LRF-131, on the left-hand side of the three photomicrographs in Figure C-1) and the "side-on" item (LRF-167, to the right of LRF-131 in the three pictures). Although some pyrolytic graphite insulation breakup is noted (especially on the inner sleeve in LRF-167), the material did not move physically from its intended location during the test exposure.

As-tested cans,
side view.

1.3X

As-removed aeroshells

1.3X

Disassembled internals

0.9X

FIGURE C-1: Disassembly stages of LRF-131 (end-on) and LRF-167 (side-on) 2.96 MPa overpressure test analyses.

The significantly greater inner sleeve damage in LRF-167 is quite likely due to the hits incurred sometime during the test; these are evident on the can in the top photograph. The values cited in Reference 1 are those used as pass/fail lines in the figures which define the environmental variables.

2.0 PROBE RESPONSE CONSIDERATIONS

The probe, which contains 34 LWRHUs is approached in a somewhat different fashion, because of its inherently sturdy structure (defined earlier in Volume IB,, Section 2.4.1.2). For explosions in the payload bay, the large mass of 339 kg and 1.26-m diameter cross section would result in a probe velocity somewhat less than 300 m/s based upon other payload bay structure velocities. This is not severe enough to cause any LWRHU clad failures regardless of environments. For on-orbit events, the Centaur CBM maximum environment in all likelihood would not cause even the probe reentry body itself to fail or the aeroshell to be stripped from the clad, although it might fracture the PGs. The Centaur CBGS-2D is only slightly more severe than the CBM condition. This event should still result in intact LWRHU aeroshells with ability to reenter satisfactorily in later portions of Phase 2 (second-stage ascent). For ET explosions in the launch pad areas, LWRHUs in the probe would not receive a velocity exceeding the impact failure threshold for bare clads as the cross-sectional area is even lower in this direction.

It is, in summary, evident that the heavy probe structure will result in highly attenuated environments to the 34 LWRHUs contained in the probe. Consequently, FAST diagrams for these LWRHUs invariably indicate no plutonia release.

3.0 REFERENCE

1. Schumann, F. A., Study of the Blast Overpressure Capability for the RHU Heat Shield, TES-3203, Teledyne Energy Systems (June 3, 1985).
2. Tate, R. E., and Land, C. C., Environmental Safety Analysis Tests on the Light-Weight Radioisotope Heater Unit, LA-10352-MS, Los Alamos National Laboratory (May 1985).

APPENDIX D

LWRHU RESPONSE TO FRAGMENTS/PROJECTILES

1.0 INTRODUCTION

As a result of liquid propellant explosions (see Appendix C), there can be generated a significant quantity of high-velocity fragments emanating from the structures within the shuttle bay following a Centaur-based explosion or from the ET/Bay interfering structures in case of the ET explosion event. The four defined probabilistic scenarios have already been given in Figures A-1 through A-4 (Appendix A). The "worst-case" event would not result in fragment velocities greater than the Centaur 1D 1% event; the static impulse is actually lower than some of the defined 1D events. As noted in Appendix A, an LWRHU clad, with or without the aeroshell, can receive a relatively high velocity and act as a fragment itself. This appendix presents methodology and conclusions for these various potential interactions.

2.0 VELOCITIES

2.1 LWRHU

The LWRHU can receive energy (and therefore velocity) from the shock overpressure as was shown in Appendix A. After passage of this pressure front, the LWRHU will continue until it encounters another fragment traveling in the same direction but at a slower velocity, strike a stationary object with the high velocity, or continue unimpeded in a trajectory which will result in ground-level impact at a greatly reduced (approximately terminal) velocity.

Tests have been performed on bare LWRHU clads to determine their ability to withstand high-velocity impacts with various structures.

- A. LANL performed flat-on impact tests of bare LWRHU clads on a flat steel surface. Although significant distortions were noted, impacts at 48, 105, and 128 m/s did not result in clad failure or fuel release (Reference 1).
- B. MRC performed flat-on and 45° impacts of bare LWRHU clads with 6061 aluminum flyer plates 3.7 mm thick at 1100 m/s. No failures were noted in the three specimens thus tested (presentation by E. W. Johnson at NUS Corporation, Germantown, Maryland, on June 5, 1985).
- C. These tests (Section B above) included secondary impacts on a heavy (11 mm thick) aluminum plate, which was the shuttle floor flyer plate reference. These three impacts at ~330 m/s and at various angles resulted in significant added distortion to the clads but with no discernable failures or release of the UO₂ simulant fuel.
- D. MRC also performed higher velocity impacts of bare clads on 12-mm thick structural steel plates that were designed to determine if expected maximum velocities would result in failures or fuel release (Reference 3):

1. An end-on impact onto the plate, oriented perpendicular to the trajectory, resulted in the LWRHU clad being imbedded in the plate with about 2 mm protruding above the plane of the plate after a 607 m/s impact. No loose urania contamination was noted, although the clad appeared to have failed.
2. An impact on such a steel plate oriented at 45° to the flight path of the LWRHU clad ($V = 593$ m/s) resulted in total release of the urania simulant. This was the fifth high-velocity encounter with other materials for this test unit, however.

It appears that a 100% release 50% of the time or 100% release for 50% of the clads where velocities are greater than 330 m/s would be a logical release conclusion for structure impacts.

2.2 Flyer Plates

The interaction of flyer plates with LWRHUs can be at a differential velocity as high as about 200 m/s (see Figure A-3) for the Centaur 1D explosion event. From the previous Section 2.1, it is noted that reference flyer plate velocities considerably higher than this have not resulted in clad failure.

2.3 Immovable Objects

There can be high-velocity impacts of LWRHU clads with stationary solid objects in the launch pad vicinity and on the heavy steel SRB cases. (The LWRHUs should bounce off the aluminum ET tank wall or shuttle floor, depending on floor failure scenario, without failure, as they have demonstrated good survivability in the aforementioned tests.) Section 2.1.D. presents test data for this sort of event on steel. Concrete surfaces in the launch pad area can also be struck, generally at low angles, by high-velocity LWRHU clads expelled from the shuttle bay.

The probability of a "hit" with a LWRHU on one of these more-or-less stationary structures is assessed as a function of Center of Explosion (COE) location. It is assumed that the LWRHU(s) in question receive an impulse which results in a movement along the COE-LWRHU line of sight regardless of intervening structure.

2.3.1 Centaur 1D LWRHU/SRB Hit Fractions - The Centaur 1D-CBGS COE lies within a volume as shown in Figure D-1. [The geometry of the other two Centaur COEs (2D and CBM) would not permit SRB/LWRHU interaction.] When viewed from above, the geometrical layout appears as Figure D-2. If one cuts along the two bounding lines, side views of the possible SRB/LWRHU lines which pass through the COE volume are shown in Figure D-3. As the COE location is taken to be random, the probability of its causing a LWRHU to impinge on an SRB is simply a ratio of the volume defined by the lines shown in Figure D-1, D-2, and D-3 divided by the total COE volume from Figure D-1. Table D-1 gives these probabilities (total SRB hit is twice the single SRB hit per LWRHU). Note that only the steel-cased portion of the SRBs is considered to be a potential failure target.

FIGURE D-1: The COEs for the various defined cryogenic explosions are given in the above illustrations.

FIGURE D-2: Geometrical layout of possible COE/LWRHU/SRB lines looking down the STS axis.

FIGURE D-3: Direct line geometry layout of SRB/LWRHU/COE paths show cross sections in which possible LWRHU/SRB interaction can occur.

TABLE D-1: Statistics of Centaur 1D-CBGS LWRHU hits on various structures are presented below.

LWRHU		STS in Vertical Position		Maximum Condition	
<u>Location</u>	<u>Quantity</u>	<u>SRB Probability</u>	<u>FSS Probability</u>	<u>SRB Probability</u>	<u>FSS Probability</u>
OBM	3	0.027	0.024	0.027	0.0064
SB PWS	2	0.021	0.018	0.021	0.0064
IBM	3	0.017	0.013	0.017	0.0064
SCH	5	0.004	0.006	0.004	0.0017
DSE	36	0.003	0.003	0.003	0.010

OBM = Outboard Magnetometer
 SBPWS = Science Boom Plasma Wave Subsystem
 IBM = Inboard Magnetometer
 SCH = Science Cable Hinge
 DSE = Despun Electronics
 CBGS = Confined by Ground Surface
 SRB = Solid Rocket Booster
 FSS = Fixed Service Structure
 1D = One-Diameter (defined)

2.3.2 Centaur 1D LWRHU/FSS Hit Fractions - Techniques similar to those employed in 2.3.1 were used to determine the hit probabilities of LWRHUs on the FSS. Those values are given in Table D-1.

2.3.3 Centaur 1D LWRHU/RSS and Other Structure Hit Fractions - There are no high-velocity impacts geometrically possible with the RSS from explosions occurring in the normal (vertical STS) position. The geometry is such that all high-velocity LWRHUs pass over the RSS. The same is true for fixed steel structures in the distance; the range is such that the velocity would be well under the 330 m/s threshold value.

2.3.4 Centaur 1D LWRHU/Concrete Hit Fractions - There are no high-velocity concrete impacts identified for the COE/LWRHU/concrete line-of-sight trajectories.

2.4. Worst-Case Event

The "worst-case" or "maximum condition" liquid propellant explosion would result if, during the first 2 s of Phase 1 Ascent, the left SRB failed and the STS collided with the FSS. The assumptions generated by GE (verbal presentation by C. T. Bradshaw to INSRP at NUS Corporation, June 5, 1985) were used to calculate the physical position at explosion as shown side-on in Figure D-4.

The geometrical bounding of trajectories by the COE (the event is assumed to be Centaur CBGS-1D dominant) is provided in two views, Figures D-5 and D-6, for the items that could impact the various structures. These hit probabilities are also summarized in Table D-1. Note that the SRB hit probabilities have not changed; the FSS hit probabilities are lower except for the DSE items. Similar to the vertical STS orientation explosion, no RSS or other fixed structures would be struck by high-velocity LWRHU clads as the directional vector elevates rapidly as the horizontal component rotates toward the RSS.

2.5 ET Explosion

The ET explosion can provide an environment as defined in Figure A-1. It is evident that the ΔV between flyer plates and LWRHUs would result in LWRHUs outrunning the defined flyer plates. If the LWRHU clad overtakes debris, the maximum interaction ΔV is about 450 m/s. It can be noted that a LWRHU clad can attain a theoretical velocity in the order of 950 m/s.

There are six LWRHUs which could have unimpeded flight paths (other than the shuttle doors): Two PWS and two each on the RTG booms. [One can see by viewing Figure D-7 that all other LWRHUs that could be ejected in a downward angle $\geq 22.5^\circ$ (100 m range) would encounter the probe, tanks, and other intervening structures. Bay E has a "straight-shot" out the doors but is shielded from the potential COEs by the fuel tanks, so it is assumed that the LWRHUs in this area would not receive sufficient energy to exceed the threshold failure value.]

From Figure D-6, all surfaces within 100 m of the COE line are assumed to be candidates for fuel release upon bare clad impact. The graphite failure

FIGURE D-4: The "Maximum Condition" liquid propellant explosion results when the left SRB fails during the first 2 s of the ascent phase. The STS is about 10 m off the MLP tilted at 30° into the FSS when the CBGS-1D Centaur-dominated explosion occurs.

FIGURE D-5: With the STS in the orientation shown in Figure D-4, the Centaur 1D CBGS COE would tend to expel LWRHUs along trajectories (as illustrated above) into the Fixed Service Structure (FSS).

FIGURE D-6: The "Maximum Condition" geometry would result in LWRHU possible paths for FSS interception as shown above (side view similar to Figure D-4 orientation).

FIGURE D-7: The six LWRHUs which could be ejected from the shuttle doors with a downward high-velocity trajectory would force the ET to lie in the upper third of the COE line.

threshold is an average of the side-on/end-on values: 40% of the time, the graphites will be stripped from the clads as a result of the ET shock wave. These are the clads which would be exposed to failure environments; the maximum intact LWRHU velocity is about 330 m/s on an area where bare clads have been noted to survive the impact event. For the six clads impacting on the pad surface, the response is taken to be the same as the tests performed on structural steel surfaces.

As to fuel release size fractions upon impact, the clads which impact with a high angle (in the flame trench, or 86% of the failures) will release the fuel as particulates, and those which hit the pad beyond the flame trench edge will have a release distribution similar to the 330 m/s impacts (Reference 3).

2.6 Bullet Tests - LANL has reported (in Reference 1) the results of some high-velocity fragment (bullet) tests on LWRHU test items:

In the test, 0.50-caliber bullets, machined from the special aluminum alloy (2219-T87) used in the space shuttle external tank, were fired at LWRHU assemblies containing simulated fuel to evaluate the resistance of the heat source to fragments generated in a postulated launch-pad detonation event. The length of the bullet/fragment was adjusted by machining so that it weighed 18 g. These projectiles were fired at various velocities ranging from about 305 to 914 m/s (1000 to 3000 ft/s). Heat source units containing simulated fuel were installed singly on a magnetometer ring; the gun used to fire the projectiles is a thick-walled 0.50-caliber barrel mounted on a heavy pedestal. Velocity traps measured the projectile velocity, and flash x-ray equipment recorded the position of the bullet just before it impacted the target.

Seven tests were conducted; the conditions and results are summarized in Table D-2. At velocities from 289 to 757 m/s (948 to 2483 ft/s), capsules were deformed but not breached. In the two tests at the highest velocities, 908 and 940 m/s (2979 and 3083 ft/s), no physical remnants of the target capsules were found, but a significant amount of uranium was detected in the graphite debris collected from the catch area. Uranium in the post-test debris is interpreted as failure of the containment capability of the capsule. In the test of unit LRF 008, the bullet struck the holder off-center and destroyed the graphite, but did not strike the capsule. In the test of unit LRF 018, no fragments were recovered nor was uranium detected in the post-test debris.

Based on the results from five of the seven fragment tests conducted, it was concluded that the LWRHU assemblies mounted on a magnetometer ring can survive impact by an 18-g, 0.50-caliber aluminum bullet at velocities greater than 750 m/s (2460 ft/s) but not as great as 900 m/s (2950 ft/s).

TABLE D-2: The summary of bullet impact test results on LWRHUs indicate fuel release conditions occur at bullet velocities somewhere above 775 m/s (Reference 5).

Unit ID	Bullet Velocities		Results
	(m/s)	(ft/s)	
009	289	948	Capsule deformed/not breached
005	661	2170	Capsule deformed/not breached
008	773	2535	Capsule not hit
018	775	2542	Nothing recovered
169	757	2483	Capsule deformed/not breached
003	940	3083	Fragmented, U by chemistry
013	908	2979	Fragmented, U by chemistry

3.0 REFERENCES

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APPENDIX E

LWRHU RESPONSE TO PROPELLANT FIRES

1. SRB PROPELLANT FIRES

1.1 On-Pad Events

The two SRBs can receive a static impulse loading from one of the two events cited Appendix C with the result that they would be expelled outward in two pie-shaped wedges emanating from the center of the 39B Pad. These are bound by two lines $\theta + 25^\circ$ and $+ 49^\circ$ from north as shown in Figure E-1. A general isometric is given in Figure E-2.

Although the defined Centaur cryogenic explosions can result in a large energy release, it is expected that the massive SRBs would receive only a few tens of meters per second velocity as a result of such an event. As the SRB components will not attain a very high velocity in these explosion scenarios, it is expected that the residual solid fuel fire will be within 100 to 200 m of the original location.

Figure E-1 demonstrates the fate of the SRBs after such an event. The possible resting places of SRB components are:

1. Any explosion probability could result in SRB constituents falling directly into the flame trench through the holes in the MLP.
2. Tip-overs would result in most of the SRB components remaining on the MLP with the possibility of some segments or pieces rolling off the edge onto the concrete pad.
3. Higher energy events may result in sufficient momentum being gained by the SRBs (or portions thereof), such that they could roll down the slope onto sand/grass.

Note also from the geometry that Centaur propellant COEs lie just above the lowest SRB casting segment junction. Explosions of these types would likely collapse the SRBs at that point; the upper portions would not necessarily be propelled very far away but would likely remain on the MLP.

1.2 On-Pad Event Results

From section 1.1, the following scenarios would result:

FIGURE E-1: Centaur liquid propellant explosions would result in causing the SRBs to disperse in cone areas as shown above.

FIGURE E-2: The general isometric view of the launch pad (looking toward the southwest) shows the relationships among the MLP, planar pad area, flame trench, and sloping pad areas.

1.2.1 Burning SRB Fuel with LWRHU or MLP

- a. With an integral LWRHU, experimental evidence has shown that ~5 nCi/clad could be released per LWRHU in the immediate proximity of burning SRB fuel.*
- b. As the melting point of iron is 1808K, if the bare clad comes to rest near the burning SRB component, the resultant good Fe/Pt-30 Rh contact would prevent the clad from melting. Limited Pt-Rh-Fe alloying might occur; but based on the Pt-Fe binary phase diagram, melting failure of the clad would not be expected.

Therefore, plutonium-238 release would be insignificant for an integral bare clad which comes to rest near burning SRB fuel.

1.2.2 Burning SRB Fuel with LWRHU on Concrete Pad

- a. Same as 1.2.1a., above.
- b. A bare clad coming to rest on concrete next to a portion of burning SRB fuel should not suffer significantly more damage than were it in the graphites (the thermal response will be much quicker, of course). The concrete would not melt (Ca_2SiO_4 has a melting point in the order of 2400K) significantly, but the 600-s exposure in the test cited in 1.2.1a., above, should have been sufficiently extended for the clad to have reached a temperature steady state. The inherent small size and low emissivity of the clad would tend to keep it in a cooler mode also. Catastrophic alloy degradation due to this exposure may occur in this short (600 s) time, but the fuel release should be low (<100 μCi).

1.2.3. Burning SRB Fuel with LWRHU in the Flame Trench - The analysis would be as 1.2.2., above. If there is water on this side at the time of the accident, the probability and amount of release would be essentially zero.

*Conditions: $2000\text{K} < T < 2183\text{K}$ ** (based on clad condition)
 $t = 600 \text{ s}$
Orifice = 2.37 mm
 $\log P = 7.381 - 28890/T$ (assume $T = 2100\text{K}$) (Ref. 1)

Results: As $Q = C_o (Dt/\pi)^{1/2}$ (infinite reservoir assumption)
(Ref. 2)
Plutonia Vapor = 4.8 nCi/clad

As there is no motion after exposure begins and no ΔP , no fines would be released.

**CMB-5-C-81-8 gives flame temperature of ~2333K at ~0.7 m above the ground surface (Ref. 3).

1.2.4. Other SRB Fuel with LWRHU Scenarios - All integral LWRHUs would behave as 1.2.1a., above. Should the SRB and LWRHU roll down the ramped sides of the platform, the sand disposition would be inherently safe; the melting point of silica (1980K) would act to protect the LWRHU clad and prevent fuel release.

There might be interactions with water in any of the above. Water would cool the clad and reduce any quantity of plutonium effusate. No significant adverse chemical reactions should occur that would promote the plutonia release.

1.3 SRB Fires After ET Explosion

Because the dispersion of LWRHUs is at essentially a right angle to the SRB eject paths, there would be no exposure of LWRHUs to burning SRB propellant after an ET explosion.

1.4 SRB Fire Exposure After Clad Failure

The Centaur CBGS-1D event has the potential for a clad failure due to a high-velocity SRB impact followed by an SRB fire. This fuel release would occur toward the forward end of the SRB and would be dominated by the liquid propellant fireball. The same would be true if the LWRHU struck the FSS and failed. A similar interaction scenario would follow for the maximum condition event. Therefore, failed clad events that release fuel at the steel surface impact points will be considered as releasing plutonia to the liquid propellant fireball and not to the burning SRB fuel.

1.5 Probabilities

Most clads would receive energy sufficient to propel them well away from the near-ground-zero area. It is possible for LWRHU clads to go essentially straight up and return to the pad area. The estimated areal hit probability per clad would be (assuming equal density) $A \text{ (SRB fuel)} / A \text{ (LWRHU clad impact area)}$, or about 0.00032 for CBM and CBGS-2D and 0.00015 for CBGS-1D.* As mentioned previously, this probability is zero for ET explosions.

2. LIQUID PROPELLANT FIRES

The large quantities of liquid cryogenic propellant inventory on the STS at launch could result in the generation of a fireball. The document JSC 08116 (Reference 4) provides data that define the character of the fireball; these data plus plutonia weight loss and LWRHU clad temperature are plotted as a function of time in Figure E-3.

*Based on dispersion radii of 350 m and 500 m for the two cases.

FIGURE E-3: Variables associated with a liquid propellant explosion fireball are provided as a function of time above.

From Figure E-3, it is evident that the liquid propellant fireball in itself will not initiate fuel release from the LWRHU either intact or with the carbons removed from the clad. The fireball environment will not contribute sequentially to failure of deformed clads remaining in the environment. In the cases where fuel is released (see Appendix D), the fireball will vaporize a 0.038 fraction of the released inventory (see upper line in Figure E-3) with the vapor immediately agglomerating or condensing into small particulates in the post-fireball residue upon cooling. These will be treated in the normal fireball release scenarios in Volume III.

NOTE: Calculations for clad and LWRHU responses were made as follows:

$$C_p (\text{clad}) = [(5.9 \text{ g}) (0.038 \text{ cal g}^{-1} \text{ K}^{-1} + (\text{Pt-30Rh}) \\ (2.5 \text{ g}) (0.08 \text{ cal g}^{-1} \text{ K}^{-1}))] 4.18 \text{ J cal}^{-1} (\text{PuO}_2) \\ C_p = 1.773 \text{ J/K} \\ A = 460 \text{ mm}^2 (\text{bare clad}).$$

Therefore:

$$\frac{Q (\text{W mm}^{-2}) \times A (\text{mm}^2) \times \epsilon}{C_p (\text{J K}^{-1})} = \Delta T \text{ K/s} = \frac{460 \times 0.2}{1.773} = 52 Q (\text{W mm}^{-2})$$

The values were taken from Figure 7.2 in JSC 08116 for Q over the first 10 s, and the bare clad values plotted as shown.

For the clad inside integral graphites, the clad response to similar reentry heat pulses were used as reasonable approximations.

In order to estimate the quantity of fuel evaporated in the liquid propellant fireball in the case of high-velocity SRB or FSS impact, the size spectrum of impacted fuel from LWRHU Clad 043 (see Figure J-1 in Appendix J) was employed (Reference 5). This UO_2 fuel was assumed to be representative of PuO_2 as to particulates generation; bare-clad GPHS tests at 54 m/s validate that choice (Figure E-4) (Reference 6). The fireball will cause the evaporation of 5 g/m² over the 10-s lifetime defined by JSC 08116. (NOTE: Even if the total 30-s increment is assumed, the quantity of fuel evaporated in the last 20 s is only about 1% of that lost in the first 10 s, so this may be ignored for this analysis as it is well under other variables uncertainties.)

This 10-s evaporation amounts to $W = 0.0050 \text{ kg m}^{-2}$. Recognizing that $dr/dt = -W/\rho$ (dr/dt = change in radius with time and ρ = density), then $dr = 0.44 \text{ }\mu\text{m}$ in the 10-s defined fireball lifetime. Also, as $V = 4 \pi r^3/3$ and $dV = 4 \pi r^2 dr$, then $dV/V = 3dr/r$. Using the expression

FIGURE E-4: Plutonia-urania total impact fines size fraction percentages appear to be fairly close based upon ~ 54 m/s impacts performed by LANL. The three BCI impacts show released fuel size distributions. Data source: LANL Memorandum, D. Pavone/Distribution, July 26, 1985.

$$\left(\frac{dV}{dV_T}\right) = \sum_{i=1}^n \left[\left(\frac{dV}{dV_i}\right) \cdot W_i \right],$$

where T = Total

i = Ith size fraction

W_i = Weight fraction of size fraction i

n = Total number of size populations

V = Particle volume

it was calculated that the quantity of fuel vaporized in the liquid fireball was 3.8% of the released inventory.

[NOTE: The radius for each size fraction was taken to be at the midpoint of that size fraction range.]

3. REACTION OF PLATINUM WITH OTHER METALS

Molten metals such as iron or aluminum can react with platinum (Reference 6), but the reaction times would be too abbreviated to result in total wall breach (References 7 and 8). Reactions with ceramic material (principally oxides) should not adversely affect the clad. Noxious chemicals, mainly propellants and oxidizers, would not remain in the fires long enough to inflict significant damage upon the bare clad. The reaction products from a burning SRB fuel chunk should not react significantly with the Pt-30 Rh material.

In summary, there appear to be no catastrophic materials interaction scenarios that would result in loss of the clad in launch pad area fires which would subsequently expose fuel to the environment.

4. REFERENCES

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APPENDIX F

SPACECRAFT REENTRY BREAKUP ANALYSIS*

1. INTRODUCTION

This appendix reports the result of a JPL study of release of the LWRHUs (Light-Weight Radioisotope Heater Units) carried on the the Galileo spacecraft during accidental Earth reentry. The study has two parts: (1) to identify the LWRHU (out of over 100 on board) most likely to be released first during a "minimum gamma" reentry, and (2) to evaluate the release point (altitude, speed, and flight path angle).

The LWRHUs have been designed with ablative heat shield and impact absorbing features appropriate for surviving Earth reentry. The early release trajectory determined here will be used in subsequent analyses, by others, of the entry ablation and ground impact.

2. CHOICE OF TRAJECTORY

The minimum gamma reentry trajectory is the case where the spacecraft enters the atmosphere at parabolic speed at a path angle such that it will later skip up to the entry altitude before again descending. It is known from prior experience that this trajectory gives the largest time-integrated aero-heating and thus the greatest ablation of heat shield during the entry. Thus, the LWRHU which is released first on a minimum gamma trajectory is to be considered as incurring the greatest ablation.

3. RELEASE: BREAKUP CASE 2

The entry conditions for the Galileo spacecraft on the minimum gamma trajectory have been described in References 2 and 3 (called Case 2). In this entry case, considered to result from a misdirected Centaur burn, the fully deployed spacecraft enters the Earth's atmosphere at 400 kft altitude at parabolic speed (36 kft/s). An entry angle of 5° was adopted as approximating that for skip-up. Two subcases were considered: (1) a nonspinning spacecraft in the aerodynamic trim condition, in which the magnetometer boom trails and the spacecraft axis makes an angle of attack of about 70° ; and (2) a spinning spacecraft (3 rpm) with axis almost vertical; i.e., at an angle of attack of about 90° . It was noted that Subcase (2) is more likely than (1), since it requires only a single malfunction (misdirected Centaur burn), whereas Subcase (1) requires a second failure (absence of spin).

A similar situation arises in the present LWRHU analysis: one can see a particular nonspin fixed attitude that favors the very early release of a particular LWRHU, and a more likely spinning subcase giving a later release.

*Reference 1, A. D. McDonald

4. CHOICE OF LWRHU FOR EARLY RELEASE

The first step in the LWRHU analysis was to identify LWRHUs that, from their location and method of mounting, would likely be released from the spacecraft early in the entry, essentially by aeroheating. The minimum gamma trajectory is characterized by a substantial level of aeroheating (up to tens of Btu/ft²/s for the spacecraft) over a period of tens of seconds in the entry heat pulse, combined with the relatively low aerodynamic force (stagnation pressure of a few pounds per square foot).

One difficulty in identifying an LWRHU likely to experience early release is the large number of LWRHUs carried; the spacecraft has 101 of these, distributed over about 12 locations (see Figure F-1). Of these, 34 are inside the Jovian probe and are assumed to remain so during the entry. Of the remaining 71 on the rest of the spacecraft, 48 are mounted, typically in groups of three, in aluminum cans secured by mounting brackets on the outside of two large outrigger electronic units (boxes): 12 are located on three faces of Bay E, and 36 are on two opposite faces of the Despun Electronics. Figure F-1 shows a schematic of the spacecraft. Because these 52 LWRHUs are mounted close to the outside face of a relatively large unit (and below an outer multilayer thermal blanket, as all are), the heating rate is relatively low (varies as the inverse square root of body size); and they are unlikely to be released early.

The choice of the first release is then narrowed to five items: (1) inboard magnetometer; (2) outboard magnetometer; (3) PWS (Plasma Wave Subsystem); (4) LBA (Linear Boom Actuator), and (5) Science Boom Hinge Cable. After detailed consideration of each location, manner of mounting, thermal insulation, etc., it became evident that the most likely candidate for early release was Item (2), the group of three LWRHUs mounted in individual aluminum cylindrical cans attached via brackets to a thick aluminum cross plate at the outboard end of the magnetometer boom. The three cans are grouped around the central magnetometer, which is encased in a thermal blanket. An outer blanket is fitted over the whole assembly and kept in place by means of the stand-off isolation loops.

5. RELEASE OF THE LWRHUs

Following a similar approach to that taken in analyzing the RTG release (References 1 and 2), two subcases were analyzed: (1) with the spacecraft fixed in an attitude giving maximum aeroheating of the outboard magnetometer RHUs, and (2) with the spacecraft spinning with its axis at 90° to the flow. Subcase (1) represents the earliest possible release, and Subcase (2) a more realistic early release.

The aeroheating at the LWRHU site was evaluated for both subcases. There is first free-molecular heating of the "top hat" thermal blanket covering all three LWRHUs and the magnetometer sensor. At about 15 s in Subcase (1) and 17 s in Subcase (2), the blanket fails and heating of the LWRHU cans begins. At about 25 s, the conditions become continuum. In Subcase (1), the tops of the LWRHU cans are heated, while in Subcase (2), the heating is cyclic, due to

PWS = Plasma Wave Subsystem
LBA = Linear Boom Actuator

FIGURE F-1: Galileo spacecraft, showing locations of LWRHUs.

the spacecraft spin (period 19 s). At about 32 s in Subcase (1), the top of the LWRHU can begins to melt, and this represents the earliest time for release of any of the LWRHUs. The corresponding point in Subcase (2) occurs at 44 sec. We note that ejection of the LWRHU capsule is more positive in Subcase (2), due to centrifugal force imparted by the spin. As has been mentioned, the spin case is more likely on the single-point failure basis and, additionally, gives more positive ejection of the capsule.

The corresponding altitude Z, inertial velocity V and inertial flight path angle values at LWRHU release for the two subcases are:

- (1) earliest: Z = 315 kft; V = 36069 ft/s; $\gamma = -3.481^\circ$;
- (2) early probable: Z = 290 kft; V = 36072 ft/s; $\gamma = -2.909^\circ$.

6. FAILURE OF THE MAG BOOM

It is appropriate to check that the magnetometer boom will stay intact at least until the LWRHUs on the outboard end are released. The boom is of light fiberglass rod construction, covered with MLI. In Subcase (1), the hypothesis is that the end plate faces the flow, and thus the boom runners are seen at a glancing angle. Calculations indicate that the boom blanket will fail before 32 sec but that the fiberglass longerons will be intact at this time (LWRHU release).

In Subcase (2), the spacecraft rotates with its axis at 90° to the flow, so that the magnetometer boom is exposed cyclically to the flow. It is calculated that the boom blanket and the fiberglass longerons will fail by about 40 s, but the electrical wires will be intact, and the outboard unit will continue to rotate for the moment as if the boom structure were there. Thus, in both subcases, the thermal response of the boom will not affect the LWRHU release times stated above.

7. SUMMARY AND CONCLUSIONS

This analysis has identified a group of three LWRHUs, mounted in individual aluminum cans on the outboard magnetometer boom of the Galileo spacecraft, as likely to be released first during accidental Earth reentry of the spacecraft on the minimum gamma trajectory.

Thermal response calculations of the aeroheating absorbed first by the thermal blanket and then by the LWRHU mounting cans give the following release points:

- (1) earliest (spacecraft in fixed attitude most favorable to early release): release at 315 kft altitude, velocity 36069 ft/s, path angle -3.481° ;
- (2) probable early (spinning spacecraft, axis 90° to flow): release at 290 kft altitude, velocity 36072 ft/s, path angle -2.909° .

With regard to initial conditions or entry ablation studies, it is recommended that appropriate assumptions are: at release, the LWRHUs have incurred no

significant prior aeroheating, have no significant body rotation rate, and have no preferred initial attitude. However, one cannot exclude the possibility of small initial rotation rates and of various attitudes; and appropriate assumptions should be made where relevant.

8. REFERENCES

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APPENDIX G

LWRHU REENTRY RESPONSE

1. INTRODUCTION

The LWRHU has been designed to survive unplanned reentry incidents, should abort condition(s) be encountered during phases of the mission which would result in these reentry events. The principal concerns based on the design are:

- A. Ensure that the most severe reentry condition would result in the maintaining of an integral clad.
- B. Ensure that excessive ablation of the aeroshell does not occur which could adversely affect the overall thermal distribution and subsequent clad response.
- C. Ensure that even with "worst-case" thermal input, the aeroshell does not incur thermal stress failure which could compromise the clad integrity.
- D. Should on-orbit events occur which result in the release of the bare clad, an assessment must be made as to released fuel size distribution and altitude.

These considerations have been addressed in analyses peculiar to the LWRHU system and are addressed below. Acknowledgement is given to Dr. J. C. Hagan of APL-JHU who provided the draft of this appendix (ANSP-L-829, RL-85-045).

2. THERMAL RESPONSES OF THE Pt-30Rh

One of the potential reentry failure modes for the LWRHU is overheating of the Pt-30Rh clad to the extent that the material reaches its carbon eutectic. The carbon eutectic of Pt-30Rh is 1730°C. Because of the uncertainty of the flight attitude of the cylinder, the reentry performance was evaluated assuming, in one case, end-stable and, in a second case, side-stable hypersonic flight. The analysis of two different flight attitudes was accommodated through the use of two separate multidimensional thermal models.

2.1 End-Stable Thermal Analysis of Maximum Clad Temperature

The thermal analysis of the LWRHU in the end-on attitude concentrated on the Y^* (maximum thermal response) trajectory. The initial conditions for the trajectory are $\gamma = -4.75^\circ$, $V = 11$ km/s, and $h = 122$ km. It was assumed for the analysis that helium was released from the fuel at the time estimated by LANL, and that it first filled the gap between the fuel and the clad and later filled the gaps outside the fuel clad. The thermal model that was used for the end-on thermal response calculations used 762 nodes: the nodal locations are sketched in Figure G-1.

FIGURE G-1: Sketch of the end-on LWRHU thermal model which shows the 762 nodal points. Dimensions are in inches in this particular drawing.

The internal thermal contact between adjacent parts was specified in accordance with the following table:

Contact Conductance $G=1000 \text{ Btu/ft}^2 \text{ hrR}$ ($5680 \text{ W/m}^2 \cdot \text{K}$)
plus radiation

aeroshell/outer sleeve standoffs - radial
aeroshell/insulator plugs - radial
aeroshell standoff/insulation plug - axial
aeroshell end cap standoff/insulation plug - axial

Contact Conductance, $G=500 \text{ Btu/ft}^2 \text{ hrR}$ ($2840 \text{ W/m}^2 \cdot \text{K}$)
plus radiation

outer sleeve/middle sleeve standoffs - radial
middle sleeve/inner sleeve standoffs - radial
outer sleeve (lower segment)/forward insulation plugs - axial
middle sleeve/forward and aft insulation plugs - axial
inner sleeve/clad standoffs - radial
clad weld bead/forward insulation plug - axial
fuel/clad - radial
fuel/shim - axial

Contact Conductance, $G=2000 \text{ Btu/ft}^2 \text{ hrR}$ ($11360 \text{ W/m}^2 \cdot \text{K}$)
plus radiation

shim/clad (force fit) - radial

The helium was assumed to release from the fuel when the clad temperature reached 860°C . At this time, the open fuel/clad interfaces were assumed to fill with helium instantaneously and thereby supplement interface radiation with gaseous conduction. When the clad temperature reached 1150°C , the helium was assumed to be released from the clad and into the gaps between the clad and graphite parts. Here again, gaseous conduction at all open interface interior to the aeroshell was assumed to occur instantaneously.

The convective heating boundary conditions over the windward-end face and side surface are described by Figure G-2. The side heating distribution was taken to be the mid-range values defined by the bounds shown in this figure. The heating rate level over the leeward end face was a uniform distribution defined at 5% of the stagnation level.

The results of the end-on reentry analysis are summarized by the clad response shown in Figure G-3. This figure shows the results of two calculations. For the calculation denoted by the solid line, it was assumed that vacuum was maintained within the gaps throughout the flight period, thereby restricting the heat transfer at this interface to radiation only. The dashed lines show the change in the temperature that results when helium is released from the fuel and flows into the gaps as described above. The helium release to the full assembly is an important event, resulting in a peak clad temperature slightly greater than that predicted, should the gaps remain evacuated. The

FIGURE G-2: The plots above describe the heating boundary conditions used in the APL analyses.

FIGURE G-3: LWRHU standoff design clad response to γ^* reentry (40.3 g) in an end-on stable attitude.

peak clad temperature is 1400°C , substantially below the clad eutectic of 1730°C . More details of these calculations are available in Reference 1.

2.2 Side-Stable Thermal Analysis of Maximum Clad Temperature

The thermal analysis of the LWRHU in the side-stable attitude also concentrated on the trajectory that produces maximum thermal response of the clad. The trajectory initial conditions for the side-stable γ^* are slightly different from those for the end-stable case. For the side-stable situation, the inertial flight path angle is $\gamma = -4.80^{\circ}$, the velocity is 11 km/s, and the initial altitude is 122 km. As was the case with the end-stable analysis, it was assumed that helium was released from the fuel and filled the gap between the fuel and the clad when the clad temperature reached 860°C . The helium was assumed to be released into the remaining gaps in the assembly when the clad temperature reached 1150° .

The thermal model that was used for the side-stable thermal response calculations used 460 nodes. The nodal locations are sketched in Figure G-4. It was assumed that the thermal contact conductance between the Fine-Weave Pierced fabric and the pyrolytic graphite insulators had a value of $1000 \text{ Btu/ft}^2 \text{ hrR}$ ($5680 \text{ W/m}^2 \text{ K}$) and that the thermal contact conductance between the pyrolytic graphite insulators had a value of $500 \text{ Btu/ft}^2 \text{ hrR}$ ($2840 \text{ W/m}^2 \text{ K}$). The hypersonic convective heat transfer distribution around the circumference of the cylinder is described by Figure G-5. It is assumed that the heat transfer coefficient on the end of the RHU is 10%.

3. CLAD IMPACT TEMPERATURE

The temperature of the clad at the time of impact with the earth can be an important factor in determining the survivability of the clad. Owing to the porous nature of the Fine-Weave Pierced fabric aeroshell, a proper estimate of the impact temperature must account for the passage of ambient gases into and out of the gaps. The gases that need to be considered are the helium that has been generated by the fuel decay and the ambient air. The amount of these gases in the gaps and the degree of rarefaction of the gases dictate the amount of heat conduction across the gaps and, therefore, the thermal response. The computation of the diffusion of the gases adds significantly to the computational time within the thermal response program and so a two-dimensional thermal model was used to provide the estimate of the impact temperature. The details of the calculation are provided in Reference 2. The results of the calculation are described in Figure G-6. This figure shows both the helium mass fraction in the gaps and the thermal response of the RHU. At the beginning of reentry, it is assumed that there is a small quantity of helium present in the gaps; this helium diffuses through the Fine-Weave Pierced Fabric aeroshell and escapes to space early in the reentry. Later, as the fuel is heated, the helium is released from the lattice, so that by about 150 s into the reentry, the helium concentration in the gaps has peaked, and the helium mass fraction in the gaps has reached nearly 100%. As time increases, the helium escapes and is replaced by air. The temperature at the time of impact is not much different from that which would have been predicted had air been present in the gaps at a continuum pressure level throughout the reentry period. The clad temperature at the time of impact is estimated to be 220°C , a value sufficiently low that LANL expects the impact characteristics to remain similar to those that have been tested at room temperature.

FIGURE G-4: Sketch of the LWRHU side-stable 3D configuration showing some of the nodal locations.

FIGURE G-5: Heat transfer distribution around a circular cylinder.

FIGURE G-6: Helium mass fraction in gaps and clad thermal response.

4. ABLATION OF THE FINE-WEAVE PIERCED FABRIC (FWPF) AEROSHELL

The ablation of the LWRHU aeroshell was estimated for both side-stable and end-stable reentry trajectories. Each of the two cases was evaluated based on the appropriate Y^* trajectory with the conservative assumption that the LWRHU aeroshell was exposed to the reentry environment at a 122-km altitude. In fact, the RHUs are either enclosed in aluminum housings or protected for some period of time by the probe.

It is estimated that the recession will total 40 to 45% of the wall thickness for a side-stable reentry. A profile of the LWRHU aeroshell with an outline of the predicted recession is sketched in Figure G-7.

5. THERMAL STRESS OF THE FINE-WEAVE PIERCED FABRIC AEROSHELL

The aeroshell of the Light-Weight Radioisotope Heater Unit is constructed from Fine-Weave Pierced Fabric, a 3-D carbon-carbon composite. The material was developed by the Air Force as a thermal stress resistant material suitable for use as a reentry body nose tip. Techniques for analyzing the structural behavior of composite materials subjected to thermal load are only now evolving; until better analysis techniques are developed, it is necessary to analyze structures that use this material by using the same analysis techniques that were developed for bulk materials. The analysis program used to evaluate the stress in the LWRHU aeroshell is SAAS III. Of several stress-strain material models available in SAAS III, three were finally chosen for use with FWPF:

1. Orthotropic - elastic properties
2. Orthotropic - elastic/plastic properties
3. Orthotropic - elastic/plastic, different properties in tension and compression.

These material models are listed in order of increasing complexity and were correspondingly applied as more refined analyses were undertaken.

It was assumed for the stress analysis that the inertial flight path angle was -90° , the initial velocity was 11 km/s and the release altitude was 122 km. Calculations were performed for both an end-stable and a side-stable flight attitude of the cylinder. The initial temperature of the LWRHU was assumed to be 90°C (200°F) for the end-stable trajectories and 540°C (1000°F) for the side-stable trajectories. The lower of the two temperatures more nearly approximates the steady-state temperature, but the side-stable stress computations were completed before the steady-state values were available. It was assumed that the RHUs were released from the spacecraft either at the time of initial entry into the atmosphere (122 km) or at the time of the peak convective heat pulse. For all side stable reentry situations, plane stress and zero stress resultant boundary conditions using elastic material properties were applied. Axisymmetric boundary conditions with elastic material properties were applied to the end-stable reentry conditions. In both the side- and the end-stable orientation, more refined calculations were subsequently made by assuming that plastic yielding in the aeroshell can occur, and that the

FIGURE G-7: LWRHU recession profiles γ^* trajectory - nominal heating.

Prandtl-Reuss flow rules incorporated into the SAAS III finite element routine accurately represent this behavior. The elastic-plastic option, combined with defining different material properties in tension and compression, provided the most comprehensive model of each reentry situation. For the end-stable reentry profile, it was unsure whether gap closure in the threaded connection between aeroshell barrel and end cap was maintained. Because of this, a gap solution was obtained by using the special program modification to SAAS III, SAAS GAPS.

The end-stable solutions utilize a single quarter section barrel/end cap finite element grid assuming axisymmetry. The boundary conditions are shown in Figure G-8. The threaded region between the aeroshell barrel wall and the end cap was modeled in two ways: (a) the barrel wall and end cap were considered to be monolithic structure, or (b) gaps will form between the two pieces. The first assumption represents the structure most accurately if the graphite glue that seals the barrel and the end cap maintains its integrity, while the second assumption suggests that the glue will have structurally failed. The results are tabulated in Tables G-1 and G-2.

The minimum margin of safety in tension is 2.1 and in compression is 1.4, where the compressive margin is based on the stress at 1% strain. In fact, the material will strain to at least 5%, and perhaps more; and so the compressive margin is even greater than the value reported.

The side-stable solutions were determined by using a coarse-grid, plane-stress solution and noting the time and position of maximum equivalent stress. Final solutions were then obtained by applying the various planar options to the fine-mesh model. The results of the side-stable stress analysis are shown in Tables G-3 and G-4. The most realistic of the stress models is the one using the stress resultant boundary condition with elastic/plastic material properties that differ in tension and compression. Other boundary conditions and material models (which are less expensive to use) were used for preliminary calculations. The minimum margin in tension is 1.5 for the stress resultant boundary conditions with elastic/plastic material properties that differ in tension and compression. For the same assumptions on boundary conditions, the minimum compressive margin is 1.3. For the reasons described above, the compressive margin is conservatively stated based on the stress corresponding to a 1% strain. Additional details of the stress analysis are available in Reference 3.

6. AEROSHELL INTACT/PG BROKEN REENTRY CASE

One of the consequences of a Centaur explosion in the parking orbit phase of the Galileo mission is assumed to be an orbital decay reentry of an LWRHU with damaged (compacted) pyrolytic insulators. Appendix C, Section 4.0, addressed the damage one would expect in such a CBM explosion environment. In view of the uncertainty surrounding the LWRHU's degree of compaction, prediction of the assembly's reentry thermal response was executed by an approximate technique rather than an elaborate 3-D simulation. The LWRHU's state of compaction was represented by the severe condition of all the assembly's interfaces being closed in perfect thermal contact.

FIGURE G-8: Boundary conditions - end-stable models.

Table G-1: LWRHU End-On Summary Table - Zero Heat Pulse Release

Release @ time = 0.0 s
Calculations @ time = 7.29 s

Boundary Condition - Material Model		<u>IN-PLANE</u>							<u>AXIAL</u>						
		Ele. #	R (in)	Z (in)	Temp. (°F)	σ_{Max} (σ_T or σ_R)	σ_{ULT} (psi)	S.F.	Ele #	R (in)	Z (in)	Temp. (°F)	σ_{max} (σ_z)	σ_{ULT} (psi)	S.F.
Max. Tens.	Axisymmetric-Elastic/T	49*	.3346	.2186	3508	11670 (σ_T)	25000	2.1	37*	.3346	.2859	3045	8177	24300	3.0
	Axisymmetric-EP/TC	49*	.3346	.2186	3508	11666 (σ_T)	25000	2.1	37*	.3346	.2859	3045	8194	24300	3.0
	Axisymmetric-Elastic/GAPS	43*	.3346	.2522	3177	9401 (σ_T)	26000	2.8	37*	.3346	.2859	3045	6264	24300	3.9
Max. Comp.	Axisymmetric-Elastic/T	6**	.5018	.5997	2615	-6122 (σ_T)	22500	3.7	42**	.5018	.2859	3351	-11338	20500	1.8
	Axisymmetric-EP/TC	6**	.5018	.5997	2615	-6076 (σ_T)	22500	3.7	42**	.5018	.2859	3351	-11048	20500	1.8
	Axisymmetric-Elastic/GAPS	6**	.5018	.5997	2615	-5348 (σ_T)	22500	4.2	42**	.5018	.2859	3351	-8106	20500	2.5

* extrapolated values to inner surface of aeroshell

** extrapolated values to outer surface of aeroshell

Table G-2: LWRHU End-On Summary Table - Peak Heat Pulse Release

Release @ time - 7.0 s
 Calculations @ time - 7.11 s

IN-PLANE								AXIAL						
Boundary Condition - Material Model	Ele. #	R (in)	Z (in)	Temp. (°F)	$\sigma_{\max}$ (σ_T or σ_R)	σ_{ULT} (psi)	S.F.	Ele. #	R (in)	Z (in)	Temp. (°F)	$\sigma_{\max}$ (σ_Z)	σ_{ULT} (psi)	S.F.
Axisymmetric-Elastic/T	141	.027	.086	1204	6063 (σ_R)	27400	4.5	49*	.3346	.2186	398	4951	23200	4.7
Max. Axisymmetric-EP/TC	141	.027	.086	1204	6062 (σ_R)	27400	4.5	49*	.3346	.2186	398	4965	23200	4.7
Tens. Axisymmetric-Elastic/GAPS			NO GAP CLOSURE								NO GAP CLOSURE			
Axisymmetric-Elastic/T	90**	.5018	.018	3864	-20159 (σ_T)	28000	1.4	72**	.5018	.118	1296	-7998	16000	2.0
Max. Axisymmetric-EP/TC	90**	.5018	.018	3864	-19615 (σ_T)	28000	1.4	72**	.5018	.118	1296	-7834	16000	2.0
Comp. Axisymmetric-Elastic/GAPS			NO GAP CLOSURE								NO GAP CLOSURE			

* extrapolated values to inner surface of aeroshell

** extrapolated values to outer surface of aeroshell

Table G-3: LWRHU Side-On Summary Table - Zero Heat Pulse Release

Release @ time = 0.0 sec.
Calculations @ time = 7.4 sec.

		IN-PLANE								AXIAL						
Boundary Conditions - Material Model	Model	Ele. #	R (in)	θ (deg)	Temp. (°F)	σ HOOP (psi)	σ ULT (psi)	S.F.		Ele. #	R (in)	θ (deg)	Temp. (°F)	σ T (psi)	σ ULT (psi)	S.F.
Max. Tension	Plane Stress-Elastic/T	1	86*	.3346	175	1963	6016	28800	4.8							
	SRBC-Elastic/T	2	351*	.3346	177.5	1954	7639	28700	3.8	171*	.3346	87.5	3258	17692	24000	1.4
	SRBC-EP/TC	2	351*	.3346	177.5	1954	7365	28700	3.9	181*	.3346	92.5	3082	15908	24000	1.5
Max. Comp.	Plane Stress-Elastic/T	1	75**	.5015	145	2313	-3341	21000	6.3							
	SRBC-Elastic/T	2	290**	.5015	142.5	2354	-3578	21500	6.0	350**	.5016	172.5	2156	-17789	18500	1.04
	SRBC-EP/TC	2	290**	.5015	142.5	2354	-3168	21500	6.8	350**	.5016	172.5	2156	-12167	18500	1.5

* extrapolated to inner surfaces of aeroshell
** extrapolated to outer surfaces of aeroshell

Table G-4: LWRHU Side-On Summary Table - Peak Heat Pulse Release

Release @ time = 6.96 s
 Calculations @ time = 7.31 s

		IN-PLANE								AXIAL						
Boundary Conditions -		Ele.	R	θ	Temp.	σ _{HOOP}	σ _{ULT}		Ele.	R	θ	Temp.	σ _T	σ _{ULT}		
Material	Model	#	(in.)	(deg)	(°F)	(psi)	(psi)	S.F.	#	(in.)	(deg)	(°F)	(psi)	(psi)	S.F.	
Max. Tens.	Plane Stress-Elastic/T	1	1*	.3346	2.5	1926	5342	28700	5.4							
	SRBC-Elastic/T	2	21*	.3346	12.5	1985	4428	28900	6.8	1*	.3346	2.5	1954	11842	24300	2.0
	SRBC-Elastic/TC	2	151*	.3346	77.5	1423	5224	27800	5.3	1*	.3346	2.5	1954	10616	24300	2.3
	SRBC-EP/TC	2	151*	.3346	77.5	1423	4851	27000	5.7	1*	.3346	2.5	1954	9946	24300	2.4
Max. Comp.	Plane Stress-Elastic/T	1	5**	.5097	5	4893	-9600	-22800	2.4							
	SRBC-Elastic/T	2	30**	.5098	12.5	4883	-8555	-22700	2.6	30**	.5098	12.5	4883	-27040	-20101	.74
	SRBC-Elastic/TC	2	30**	.5098	12.5	4883	-12240	-22700	1.8	30**	.5098	12.5	4883	-24264	-20100	.83
	SRBC-EP/TC	2	30**	.5098	12.5	4883	-10074	-22700	2.2	50**	.5099	22.5	4589	-17937	-23500	1.3

* extrapolated values to inner surface of aeroshell

** extrapolated values to outer surface of aeroshell

The approximate technique is a 1-D thermal analog which is based on the rationale shown in Figure G-9. The equivalent heating distribution is hallmarked by the heating conversion factors developed in Figure G-10 for the free-molecular and continuum density regimes. The analog showed excellent performance in correlating prior 2-D and 3-D design studies as well as current 2-D studies involving changes in interface heat transfer conditions and reentry reference heating profiles.

Clad melt is the reentry failure mode of concern for the in-orbit explosion scenario. The 1-D analog's prediction of clad thermal response for an orbital decay reentry, given by Figure G-11, indicates a melt temperature margin of 370°F (164°C). This margin, in conjunction with the severe representation of the interfaces' thermal state, indicates violation of the clad melt failure mode is very unlikely for an orbital decay return (Reference 4).

7. BARE CLAD REENTRY CASE

One consequence postulated for the Centaur explosion accident scenario during the parking orbit phase of the Galileo mission is an orbital decay reentry for an unprotected clad assembly. The safety issue of concern for this situation is the release and disposition of the fuel subsequent to the clad melt event during reentry. As a result of the preceding explosive overpressure, the fuel will be fragmented into a finely granulated form with a 1000- μ m diameter sphere encompassing 90% of the particle distribution.

The clad assembly was assumed to travel an orbital decay reentry in a random tumbling orientation rather than a fixed side-on or end-on attitude to provide greater atmospheric penetration prior to clad melt. Based on current estimates for transitional heating for a tumbling motion and a clad emittance of 0.2 in determining surface radiation, the clad melt event (or correspondingly, the granulated fuel release condition) was predicted to occur at an altitude of 270.5 kft and a relative velocity of 22,975 ft/s.

For the above release condition, trajectories were determined for stable PuO₂ spheres ranging in size from 500 μ m to 1000 μ m in diameter. The small size of these spheres results in very low ballistic coefficient reentries with rapid decelerations and, like the prior clad assembly, heat pulses that reside principally in the transitional gas dynamic regime. Based on Matting's bridging equation, the transitional stagnation (cold wall) heating rates for the various particle sizes are shown in Figure G-12. In all cases, maximum reentry heating occurs at the time of initial release and decays rapidly thereafter.

As a preliminary screening device, it is noted that the fuel melt event can occur only if the transitional heating rates are equal or greater than the PuO₂ sphere's surface radiation rate evaluated at the melting point. For a melting point of 4812°R, it is clear from Figure G-12 that this condition is not met and thereby eliminates fuel melt as a potential ablation mechanism. A second screening device that serves in estimating vaporization losses for PuO₂ from its solid state is the equilibrium condition where the transitional heating rate is equal to surface radiation. This provides an upper

FIGURE G-9: Rationale for 1-D thermal analog.

FIGURE G-10: Development of heating rate factors for 1-D thermal analog (correlation of clad peak temperatures - prior design studies).

FIGURE G-11: Approximate production of clad maximum temperature; compacted LWRHU - orbital decay reentry; 1-D thermal analog predictor with Case 1 factors.

FIGURE G-12: Stagnation heating rates and corresponding surface equilibrium temperatures (500 to 1000 μm diameter sphere - stable orbital decay reentry).

bound on surface temperature and therefore vaporization rate for the fuel spheres during the course of reentry. The equilibrium surface temperatures are also shown in Figure G-12. Using the vapor pressure equation determined for PuO_2 (Reference 5) and a Knudsen-Langmuir vaporization model, it can be demonstrated that solid-state vaporization is negligible as an ablation mechanism for the subject reentry conditions. To further support this observation, two-dimensional thermal models were developed for the 500, 750, and 1000 μm diameter spherical particles. The stagnation surface temperature response for the 1000 μm diameter particles is shown in Figure G-13 and is typical in behavior for all the particle sizes investigated. The response shows a slight increase upon initial release followed quickly by a monotonic decay thereafter with surface temperatures significantly below the equilibrium temperatures previously calculated. The temperature data should be considered as an estimation since the results suggest large internal conduction heat transfer from the hot windward to the cooler leeward regions of the sphere. Although the sphere's thermal response will likely be altered through use of a finer computational grid, the point to be made from Figure G-13 is that the general magnitude and highly transient nature of the response equates to negligible vaporization losses during reentry.

It is noted that the heating methodology and the results of this study are consistent with the results of an earlier Sandia Laboratories investigation (Reference 6) that considered PuO_2 microsphere reentries in the 50 μm to 250 μm diameter range. In that study, a threshold was established for microsphere release conditions (i.e., velocity and altitude) that identified incipient melting during subsequent reentry. This boundary is reproduced in Figure G-14. This figure also shows the velocity/altitude track of the clad assembly during its orbital decay descent and represents the locus of fuel release conditions for this study. It shows that the predicted clad melt occurrence is far removed from the fuel release boundary required for melting. In fact, passage of the clad assembly through a major portion of its heat pulse (including maximum heating) is required to obtain sufficient fuel release conditions to anticipate incipient melting.

Taking the APL-generated temperature profiles, one can show that, assuming unmelted spherical particles, that

$$\left[\frac{\Delta M}{M} \right]_i = \frac{6}{\rho} \cdot \frac{W_i}{d_i}$$

where ΔM = Evaporated plutonia (kg)

M = Mass of particles (kg)

W_i = Specific weight loss (kg/m^2)

d_i = Diameter

i = Ith size range

ρ = Plutonia density.

FIGURE G-13: Stagnation surface temperature response during the early reentry flight period (1016 μm diameter sphere - stable orbital decay reentry)

FIGURE G-14: Comparison of LWRHU bare clad assembly reentry track with Sandia's fuel release melt boundary.

As only the leading central portion achieves sufficiently high temperature to evaporate insignificant quantities of fuel, one-fourth of the surface is taken to reach the value such that

$$\left[\frac{\Delta M}{M} \right]_i = \frac{3}{2\rho} \cdot \frac{W_i}{d_i} = 1.31 \times 10^{-4} \cdot \frac{W_i}{d_i} \quad (\rho = 11.4 \times 10^3 \text{ kg/m}^3)$$

From Figure G-15, the 1000- μm case indicates that $W_i = 1.64 \times 10^{-4} \text{ kg/m}^2$; for the 500 μm case, $W_i \sim 1.2 \times 10^{-4} \text{ kg/m}^2$. It was taken that for lower size fractions, $W_i = 1 \times 10^{-4} \text{ kg/m}^2$. (These smaller ones would spend much less time at the peak temperature than the larger particles.) Taking the mid-range value as the diameter of each range, M_i was calculated and summed over the spectrum. This yielded a vapor fraction of 176×10^{-6} weight fraction of the material contained in the originally reentering bare clads.

8. PHASE TWO ASCENT CLAD MELTING

The companion scenario to the parking orbit accident is one where a certain explosion occurs during the ascent phase of the mission and yields a bare clad assembly return. The same approach applies to this scenario with the exception that the explosion event can now occur over a multiple of flight conditions comprising the shuttle ascent trajectory. This necessitated a screening of the trajectory in defining a post-explosion clad melt zone rather than a solitary event as previously demonstrated with the parking orbit scenario.

In screening the mission's ascent trajectory, it was assumed the explosion imparts the instantaneous values of velocity, altitude, and flight path angle of the shuttle to the clad assembly as initial conditions for its ensuing ballistic trajectory. As before, the assembly was assumed to possess a random tumbling motion in defining the aeroheating environment. From this procedure, a clad melt zone was defined to occur shortly after 384 s from lift-off through to injection as indicated in Figure G-15. From this zone, four cases as indicated were chosen for further in-depth analysis regarding granulated fuel release and subsequent disposition. The fuel release conditions for these cases are located relative to the Sandia melt envelope (for a 250- μm sphere) in Figure G-16. This comparison clearly indicates that fuel microspheres of 250 μm or less will not experience melting and likely extends to the 1000- μm particle size as well. However, subsequent screening of the stagnation heating rates of the 1000- μm spheres, which again reside in the transitional gas dynamic regime, indicated the potential for melting in the stagnation region during initial release. At the very least, these release conditions are in closer proximity to the melt boundary than determined for the previous orbital decay release and therefore should yield higher surface temperatures. This could result in a vaporization loss that bears significance from a radiological viewpoint.

FIGURE G-15: Region of LWRHU clad melt ascent phase of Galileo mission.

FIGURE G-16: Comparison of LWRHU fuel release conditions for ascent phase explosion scenario with Sandia's PuO₂ melt boundary.

Stable sphere reentry simulations were conducted for the four cases using the 2-D thermal model previously developed for the 1016- μm diameter particle size. The previous orbital decay reentry study indicated this size particle produced the highest surface temperatures over the considered range of 500 to 1016 μm . The estimated stagnation surface temperature response for each of the four cases is shown in Figure G-17. The response behavior is similar to that indicated for the orbital decay scenario (Figure G-13) but yields higher peak temperatures due to the effect of the lower release altitudes on initial particle heating rates. The rapid thermal decay displayed for each of these cases relates to the high decelerations experienced by a body of such minute size. Comparison of the thermal responses indicated maximum stagnation surface temperatures are experienced in the clad melt zone bounded by Cases A and B. However, it is likely that maximum vaporization losses will occur later in this zone where surface temperatures are somewhat lower but decay at a slower rate.

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FIGURE G-17: Stagnation surface temperature response for a 1016 μm PuO₂ sphere - selected cases from the Ascent Phase of the Galileo mission.

APPENDIX H

IMPACT TEST PROGRAM RESULTS

1. LWRHU REENTRY IMPACT TEST PROGRAM

A series of tests was conducted at LANL to evaluate the normal response to the ablated LWRHU upon some reference earth surface as well as some bare clad impacts. Following is an excerpt from Reference 1, which summarizes this endeavor:

Four units, LRF 021 through 024, were impacted "as built" shortly after their assembly. Two units, LRF 011 and 020, were stored at ambient temperature ($\sim 45^{\circ}\text{C}$) for about 2.5 yr and then impacted. The nominal impact velocity for all tests was 49 m/s (161 ft/s), which is 110% of the predicted reentry impact velocity at sea level, and the nominal temperature of the units just before impact was in the range of 25 to 50°C . The units were impacted in various orientations with respect to the vent end of the capsule. By convention, the angle is specified as the angle the flight trajectory makes with the cylindrical axis of the heat source; that is, the angle for a unit impacted on the vent end is 0° , on the side is 90° , and on the closure end is 180° . Before the actual impact test, each fueled capsule was removed from its graphite components and heated in an electron-beam furnace through a short duration thermal pulse to simulate the heating in a reentry event. The reentry impact conditions and results are summarized in Table H-1.

The graphite components were significantly damaged, as might be expected. There was little or no damage or distortion to the fuel capsules because the graphite provides considerable protection. A small crack was observed in the interior of the closure weld zone of LRF 011, aged 2.5 yr before impact, but the unit was not breached. No conclusion has been reached as to the cause of this small crack. During the engineering development of the LWRHU (Reference 1), capsules were impacted without graphite at 48 m/s (157 ft/s) in the 0° , 45° , and 90° orientations. They were also impacted in the 90° orientation as successively higher velocities (68, 88, 105, and 128 m/s) with substantial deformation but without failure. The development tests on the bare capsules and the safety analysis tests on capsules with graphite protection demonstrate that the ductile Pt-30 Rh alloy capsule provides excellent fuel containment capability under postulated impact conditions.

2.0 HIGH-VELOCITY STRUCTURE IMPACTS

When it became apparent that there would be some probability of a LWRHU encountering fixed structures (SRBs and the FSS were the two identified) after a Centaur CBGS-1D explosion or concrete or the RSS rail in the case of the on-pad ET explosion, a high-velocity impact test with two remaining bare clads was performed (Reference 2). A summary of the two tests is given as follows:

TABLE H-1: Los Alamos National Laboratory-performed Reentry
Impacts^a

<u>Unit ID</u>	<u>Test Conditions</u>			<u>Results</u>
<u>As Built</u>	<u>Angle</u>	<u>Velocity (m/s)</u>	<u>Temperature (°C)</u>	
023	45°	49.3	47	Minimal capsule deformation
021	90°	49.3	30	Minimal capsule deformation
022	135°	49	51	Minimal capsule deformation
024	180°	49.6	52	Minimal capsule deformation
<u>Aged 2.5 yr</u>				
011	135°	49.9	24	Cracked weld/not breached
020	90°	49.2	26	Minimal capsule deformation

^aDocumented per Reference 1.

- A. Test 1 - The virgin urania-fueled Clad 043 was fired into a steel plate that was oriented perpendicularly to the flight path. The clad axis was parallel to the flight path with the vent end forward. At a velocity of 609 m/s (1993 ft/s), the clad buried itself into the 1/2-in. thick cold-rolled steel (75 HRB), the vent failed, and a crack developed around the outer edge, but there was no detectable urania release.
- B. Test 2 - The previously-impacted (with flyer plate and shuttle floor models) Clad 039 was fired onto a similar steel plate that was oriented 45° to the flight path. The clad "flew" as a result of its previously incurred deformation, going through two 1-in. (25 mm) thick plywood structural components before striking the target. The measured impact velocity was 593 m/s (1944 ft/s) after passing through one of the plywood pieces. The clad failed catastrophically. The fuel released appeared very fine; the estimate is that the majority was <100 µm in size. (For purposes of calculating the fraction which would be vaporized in a fireball, Appendix E used the average distribution as shown in Figure J-1.)

From these tests, it appears that fuel release would occur in 50% of the cases where there are high-velocity (>330 m/s) impacts of bare clads on essentially unyielding structures such as structural steel. This rationale was employed in Phase 1 FASTs where such events could occur.

3.0 REFERENCES

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2. Johnson, E. W., Cryogenic Explosion Environment Modeling and Testing of Space Shuttle and Light-Weight Radioisotope Heater Unit Interactions (to be published as a Mound report).

APPENDIX I

BURIAL THERMAL ANALYSIS

After certain abort situations, there is the potential that LWRHUS could become imbedded in earth media with the potential for release of plutonia to the soil. Earlier, it was noted that no earth impacts would result in clad breaching. Therefore, what must be assessed is the ability of the clad to withstand the conditions of earth burial.

The low quantity of heat emanating from a buried LWRHU would result in a modest temperature increase over normal ambient. The least favorable reported soil thermal conductivity was considered (Reference 1 cites $0.0346 \text{ W m}^{-1} \text{ K}^{-1}$ for diatomaceous earth). If a LWRHU clad is imbedded within an infinite diatomaceous earth medium, the temperature gradient would be:

$$\Delta T = \frac{Q}{4 \pi k r} = \frac{1 \text{ W}}{4 \pi (0.0346 \text{ W m}^{-1} \text{ K}^{-1}) (0.005 \text{ m})} = 460 \text{ K},$$

or the clad would be in the order of 775K (502°C) maximum. This assumes an average soil temperature of 315K (108°F). It would be less severe for any other burial media.

Platinum at this temperature* should last virtually forever, assuming these initial conditions. Vaporization of fuel through the vent would be insignificant; the vapor pressure of plutonia at this temperature is about 10^{-25} Pa . As all real conditions will be significantly less severe, soil burial will result in no release ($<1 \text{ aCi}$ or $\sim 1 \text{ nBq/yr}$) of plutonia to the environment. This is significantly less than the allowable alpha residue after the decontamination process for most heat sources of $<2000 \text{ dpm}$ (33 Bq).

REFERENCES

1. Updated Safety Analysis Report for the Galileo Mission and the International Solar-Polar Mission, General Electric Co., GESP-7186, (April 1984).
2. Alcock, C. B., and Hooper, G. W., Proc. Royal Soc. A, 254, 551 (1960).

*Data from Alcock and Hooper (Reference 2) indicate an extrapolated oxidation rate of platinum at 500°C of about $1.3 \text{ fg/s}\cdot\text{m}^2$. This corresponds to 0.2 nm/yr erosion. Rhodium is better by about an order of magnitude. As the temperature difference drops linearly with decreasing thermal output, an insignificant fraction of the LWRHU clad wall will be lost during soil burial.

APPENDIX J
SOURCE TERM EVALUATION

1.0 INTRODUCTION

Up to this point, for each of the vehicle conditions defined in the analysis, a sequence of adverse environments was defined and followed by an evaluation of the response of the LWRHU to each of the adverse environment sequences. As analyses of these extreme environments show that there is a potential for a fuel release, the occurrence probability was determined from the interrelation of the failure analysis and sequence tree construction.

To evaluate the consequences of these events, the analysis must define the source terms. Within the context of space nuclear safety, a source term is the quantity of fuel which may be uncontrolled and hence subject to dispersion into the environment. In describing a source term, one must consider its state (e.g., particle-size distribution, chemical form if changed from its original form, and degree of containment) and its location (e.g., at high altitude, on land, or in water; latitude and longitude; or random deposition during reentry from a specified orbit).

When the first step of the risk analysis is completed, the analyst develops a series of specific nonnominal events that are postulated, with an associated probability of occurrence, to generate a known source term. The next step is to evaluate the consequences of the source terms. This will be addressed in Volume III, Nuclear Risk Analysis Document.

2.0 PLUTONIA PARTICLE SIZES RELEASED BY LWRHUS

To address the effect of fuel particle size on the source terms identified, selected available data on fines generation were assessed. These included:

- A. Fines reported for impacted LWRHU (plutonia fueled) test assemblies: The two chosen were impacted at about 49 m/s at orientation angles of 45° (No. 023) and 90° (No. 021). The particle size data as shown on Figure J-1 were taken from Table III, Reference 1.
- B. Some urania-fueled GPHS clads were subjected to overpressure environments only as reported in Reference 2. One case is shown plotted in Figure J-1 for the CST-1 unit.
- C. LWRHU clads which had been struck by 1100 m/s flyer plates and then impacted the shuttle aluminum floor model were opened, and the fuel size distribution was characterized. The two analyses are also shown in Figure J-1 (data from Reference 3).
- D. A high-velocity (~600 m/s) impact of a clad containing a urania pellet fuel simulant resulted in severe fuel breakup. These data are provided on the log-probability plot, Figure J-1.

FIGURE J-1: Particle size distributions for various test cases are shown above. For the LWRHU cases in this document, the average released distribution is given by the dashed line. This is NUS "Code B" for size distribution (see Volume III).

These two conditions where fuel is released would tend to follow the curves defined in C. and D. above and shown in Figure J-1. Releases that have been identified in Phases 2 through 4 would exhibit a size partitioning shown by the dashed line (average) curve. For particulates shown below 10 μm diameter, the dashed line starting at 10 μm , 0.5% was used. For cryogenic propellant explosions during Phase 1, the average curve in Figure J-1 was employed also.

3.0 SOURCE TERM SUMMARY

Table J-1 provides a summary of the various plutonia releases by phase, probability, and type for the Galileo LWRHU Mission. Tables J-2 through J-4 provide source term assessments for each phase when considered from most-probable, worst-case and expected aspects. The methodology that NUS used to generate these data is provided in Volume III.

4.0 REFERENCES

1. Tate, R. E., and Land, C. C., Environmental Safety Analysis Tests on the Light-Weight Radioisotope Heater Unit, LA-10352-MS, Los Alamos National Laboratory (May 1985).
2. Zocher, R. W., to Bradshaw, C. T., Telecommunication Message (April 29, 1985).
3. Johnson, E. W., Cryogenic Explosion Environment Modeling and Testing of Space Shuttle and Light-Weight Radioisotope Heater Unit Interactions (to be published as a Mound report).

Table J-1: SUMMARY OF FUEL RELEASES FOR GALILEO LWRHU

PHASE IDENTIFIER	ACCIDENT ENVIRONMENT	ALTITUDE (m)	VAPOR, Ci (GBq)	QUANTITY PARTICULATE, Ci (TBq)	MAXIMUM PROBABILITY
1A OBM	Maximum Condition	60	3.6 (135)	92.4 (3.5)	6E-9
1A SBPWS		60	2.4 (90)	61.6 (2.3)	5E-9
1A IBM		60	3.6 (135)	92.4 (3.5)	3E-9
1A SCH		60	6.1 (225)	153.9 (5.8)	1.1E-9
1A DSE		60	21.9 (810)	554.1 (20.5)	5E-9
Can Occur Together					
Cannot Occur If Above Happens					
1B	ET	30	<1 (<40)	96 (3.6)	8E-9
1D OBM	CBGS-ID	60-10k	3.6 (135)	92.4 (3.5)	4.3E-8
		>10k	~0	96 (3.6)	4E-8
1D SBPWS		60-10k	2.4 (90)	61.6 (2.3)	3.2E-8
		>10k	~0	64 (2.4)	3E-8
1D SBPWS		60-10k	3.6 (135)	92.4 (3.5)	3.1E-8
		>10k	~0	96 (3.6)	3E-8
1D SCH		60-10k	6.1 (225)	153.9 (5.8)	6.6E-9
		>10k	~0	160 (5.9)	6E-9
1D DSE		60-10k	21.9 (810)	554.1 (20.5)	1.06E-8
		>10k	~0	576 (21.3)	1E-8
Can Occur Together					
Cannot Occur If Above Happens					
2A SO+EO ΔEO	ET	~100k	0.377 (14)†	2144 (79.3)‡	4E-8
		~100k	0.135 (5)†	768 (28.4)‡	6E-8
2B SO+EO ΔEO	CBGS-2D	~100k	0.377 (14)†	2144 (79.3)‡	1.2E-6
		~100k	0.242 (9)†	1376 (50.9)‡	3.8E-6
2C SO+EO ΔEO	CBM	~100k	0.377 (14)†	2144 (79.3)‡	1.0E-6
		~100k	0.242 (9)†	1376 (50.9)‡	1.6E-6
3A SO+EO ΔEO	CBM	120k	0.377 (14)	2144 (79.3)	3.7E-5
		120k	0.242 (9)	1376 (50.9)	5.8E-5
4C SO+EO ΔEO	CBM	120k	0.377 (14)	2144 (79.3)	2.2E-5
		120k	0.242 (9)	1376 (50.9)	3.4E-5

†At End of Phase 2, T=534s

‡After T=400s, or After Clad Melt Without Fuel Melt

OBM = Outboard Magnetometer
 SBPWS = Science Boom Plasma Wave Subsystem
 IBM = Inboard Magnetometer
 SCH = Science Cable Hinge
 DSE = Despun Electronics
 SO = Side-On LWRHU
 EO = End-on LWRHU
 Ci = Curie (1Ci = 37 GBq)
 TBq = Terabecquerel
 GBq = Gigabecquerel
 ΔEO = EO - SO

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Table J-2: Maximum Release Cases for LWRHUs on the Galileo Mission

Mission Phase	Accident Branch	Release Branch	Accident Probability	Conditional Fuel Release Probability	Total Fuel Release Probability	Source Term, Ci		Release Location
						Vapor	Particulates	
0		(No Releases)						
1	1D	SRB Impact of DSE RHUs	9.5E-06	1.1E-03	1.0E-08	21.9 ^a	554 ^b	Pad
2	2B	Side-on clads End-on clads	5.36E-05	2.2E-02	1.2E-06	0.377 ^a	2144 ^b	10 km above ocean
3	3A	Side-on clads End-on clads	1.69E-04	2.2E-01	3.7E-05	0.377 ^a	2144 ^b	High altitude, 28° N latitude
4	4C	Side-on clads End-on clads	1.01E-04	2.2E-01	2.2E-05	0.377 ^a	2144 ^b	High altitude, 28° N latitude

a = 0.02 μ m particle sizeb = 50 μ m particle size

Table J-3: Most Probable Release Cases for LWRHUS on the Galileo Mission

Mission Phase	Accident Branch	Release Branch	Accident Probability	Conditional Fuel Release Probability	Total Fuel Release Probability	Source Term, Ci		Release Location
						Vapor	Particulates	
0		(No Releases)						
1	1D	SRB Impact @ 10 km of OBM RHUS	9.5E-06	4.2E-03	4.0E-08	--	96 ^b	10 km above ocean
2	2B	End-on clads	5.36E-05	9.3E-02	5.0E-06	0.242 ^a	1376 ^b	10 km above ocean
3	3A	End-on clads	1.69E-04	5.6E-01	9.5E-05	0.242 ^a	1376 ^b	High altitude, 0° lat
4	4C	End-on clads	1.01E-04	5.6E-01	5.7E-05	0.242 ^a	1376 ^b	High altitude, 0° lat

a = 0.02 µm particle size

b = 50 µm particle size

Table J-4: Release Expectation Cases for LWRHUS on the Galileo Mission

Mission Phase	Accident Branch	Release Branch	Accident Probability	Source Term, Ci		Release Location
				Vapor	Particulates	
0		(No Releases)				
1	1A	SRB/FSS Impacts	4.0E-07	4.0E-01 ^a	10.2 ^b	Pad
	1B	Flame Trench/RRS Impact	1.7E-06	--	4.5E-01 ^b	Pad
	1D	SRB/FSS Impacts SRB Impacts	9.5E-06	6.5E-02 ^a	1.65 ^b 1.62 ^b	Pad 10 km above ocean
	Phase	SRB/FSS/Flame Trench/ RSS Impacts SRB Impacts	5.31E-05	1.46E-02 ^a	3.86E-01 ^b 2.90E-01 ^b	Pad 10 km above ocean
2	2A	End-On/Side-On	5.0E-07	4.64E-02 ^a	2.64E+02 ^b	Mid-trajectory
	2B	End-On/Side-On	5.36E-05	2.56E-02 ^a	1.46E+02 ^b	Mid-trajectory
	2C	End-On/Side-On	1.4E-05	5.46E-02 ^a	3.10E+02 ^b	Mid-trajectory
	Phase	End-On/Side-On	6.81E-05	3.18E-02 ^a	1.81E+02 ^b	Mid-trajectory
3	3A (Phase)	End-On/Side-On	1.69E-04	1.65E-01 ^a	9.40E+02 ^b	High Altitude, 0° Latitude
4	4C	End-On/Side-On	1.01E-04	1.65E-01 ^a	9.40E+02 ^b	High Altitude, 0° Latitude
	Phase	End-On/Side-On	2.08E-02	8.03E-04 ^a	4.56 ^b	High Altitude, 0° Latitude

a = 0.02 μ m particle sizeb = 50 μ m particle size

APPENDIX K

TABLE OF ABBREVIATIONS AND ACRONYMS FOR VOLUME II

A - Area
AMD - Accident Model Document
APL-JHU - Applied Physics Laboratory - Johns Hopkins University
CBGS-1D - Confined-by-Ground Surface - One Diameter
CBGS-2D - Confined-by-Ground Surface - Two Diameter
CBM - Confined by Missile
 C_0 - Initial Concentration
COE - Center of Explosion
 C_p - Specific Heat
D - Diffusion Coefficient
DOE - Department of Energy
DSE - Despun Electronics
 ϵ - Emissivity
ET - External Tank
FAST - Failure/Abort Sequence Tree
FSAR - Final Safety Analysis Report
FSS - Fixed-Service Structure
FWPF - Fine-Weave Pierced Fabric
G - Contact Conductance
 γ - Flight Path Angle
 γ^* - Maximum Clad Thermal Response Trajectory
GE - General Electric
GLI - Galileo Mission
GPHS - General Purpose Heat Source
h - Height
IBM - Inboard Magnetometer
INSRP - Interagency Nuclear Safety Review Board
JPL - Jet Propulsion Laboratory
JSC - Johnson Space Center
k - Thermal Conductivity
KSC - Kennedy Space Center
LANL - Los Alamos National Laboratory
LBA - Linear Boom Actuator
LRF - Los Alamos Test Unit Designator
LWRHU - Light-Weight Radioisotope Heater Unit
MLP - Mobil Launch Pad
MRC - Monsanto Research Corporation
NASA - National Aeronautics and Space Administration
NRAD - Nuclear Risk Analysis Document
OBM - Outboard Magnetometer
OSNP - Office of Special Nuclear Projects (now Division of Special Applications)
 P_0 - Ambient Pressure
 P_s - Peak Shock Overpressure
PG - Pyrolytic Graphite
PWS - Plasma Wave Subsystem
Q - Heat Per Unit Area or Flux
r - Radius

RHU - Radioisotope Heater Unit
rpm - Revolutions per Minute
RSS - Rotating Service Structure
RTG - Radioisotope Thermoelectric Generator
S/C - Spacecraft
SAR - Safety Analysis Report
SBPWS - Science Boom Plasma Wave Subsystem
SCH - Science Cable Hinge
SRB - Solid Rocket Booster
STS - Space Transportation System (Shuttle)
T - Temperature
3DCC - Three Dimensional Carbon/Carbon
v, V - Velocity and/or Volume
w - Specific Weight Loss Rate
Z - Altitude

NOTE: Standard abbreviations for chemical symbols, English, and International System of Units (SI) are not included.