0423-5
MLM-3540

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

Volume I: A. Introduction and Executive Summary
B. Reference Design Document (RDD)

Ernest W. Johnson

October 1988

REPRODUCED FROM
BEST AVAILABLE COPY

MOUND

operated by
EG&G MOUND APPLIED TECHNOLOGIES
P.O. Box 3000, Miamisburg, Ohio 45343-0987

for the
U. S. DEPARTMENT OF ENERGY
Contract No. DE-AC04-88DP43495

MASTER

DISTRIBUTION OF THIS DOCUMENT IS UNLIMITED

DISCLAIMER

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

Printed in the United States of America
Available from
National Technical Information Service
U. S. Department of Commerce
5285 Port Royal Road
Springfield, VA 22161

NTIS price codes
Printed Copy: A14
Microfiche copy: A01

DO NOT MICROFILM
COVER

DISCLAIMER

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

DISCLAIMER

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

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

Volume I: A. Introduction and Executive Summary
B. Reference Design Document (RDD)

Ernest W. Johnson

October 1988

DISCLAIMER

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

MOUND

operated by
EG&G MOUND APPLIED TECHNOLOGIES
P.O. Box 3000, Miamisburg, Ohio 45343-0987

for the
U. S. DEPARTMENT OF ENERGY
Contract No. DE-AC04-88DP43495

ACKNOWLEDGMENTS

The author would like to acknowledge the contributions from the following
Mound persons:

M. L. Hurst - Typing/Word Processing
M. B. England - Artistry/Computer Graphics
P. A. Fitzharris - Technical Editing
D. A. Sohn - Photography

Other agency persons contributing included:

APL Staff - Reentry Analyses

J. C. Hagan - Program Manager
E. F. Lucero - Assistant Program Manager
D. W. Conn - Reentry Analyses
C. C. Chan - Thermal Analyses
P. T. Brenza - Thermal Analyses
J. A. Ecker - Thermal Stress Analyses
S. A. Lutz - Test Program

B. W. Bartram, NUS - Volume III/NRAD
C. T. Bradshaw, GE - FASTs and Helpful Comments
R. W. Zocher, LANL - Test Activities

TABLE OF CONTENTS

LIST OF TABLES	4
LIST OF FIGURES.	5
ABSTRACT	6
A. INTRODUCTION AND EXECUTIVE SUMMARY	
1.0 Introduction.	7
2.0 Mission and Flight System Summary	12
3.0 Accident Summary.	16
4.0 Executive Summary References.	21
B. REFERENCE DESIGN DOCUMENT	
1.0 Nuclear System.	22
2.0 Galileo Spacecraft.	45
3.0 Launch Vehicle.	61
4.0 Inertial Upper Stage.	72
5.0 Trajectory and Flight Characteristics	79
6.0 Launch Site	79
APPENDIX B-1 - LWRHU Drawings.	88
APPENDIX B-2 - Abbreviations and Acronyms.	97
APPENDIX B-3 - References.	101
Definitions of SI Units.	102

LIST OF TABLES

A-1:	The LWRHU-FSAR Defined	8
A-2:	Accident Initiating Systems.	17
A-3:	Maximum, Most Probable and Expectation Release Cases	20
B-1:	LWRHU Components Description	24
B-2:	At-Launch Inventories of Radionuclides	33
B-3:	Galileo Orbiter Science Objectives	46
B-4:	Galileo Probe Science Objectives	47
B-5:	Galileo Mission On-Orbit Activities.	50
B-6:	Galileo Abort Plans.	52
B-7:	LWRHU Quantity Summary	58
B-8:	SRM Parameters	77

LIST OF FIGURES

A-1:	LWRHU Schematic	.13
A-2:	Galileo Launch Configuration	.14
A-3:	LWRHU Location on the Galileo Spacecraft	.15
A-4:	LWRHU top Failure Abort Sequence Tree.	.19
B-1	LWRHU.	.23
B-2	Specified LWRHU Dimensions	.26
B-3	Specified LWRHU Test Configuration	.29
B-4	Specified LWRHU Random Vibration	.30
B-5	Specified LWRHU Sinusoidal Vibration	.31
B-6	Pt-30Rh Tensile Properties	.35
B-7	PG Physical Properties	.36
B-8	FWPF Emissivity and Thermal Conductivity	.39
B-9	LWRHU Dose Rates	.40
B-10	Plutonia Gamma Spectrum.	.41
B-11	Plutonia Neutron Spectrum.	.42
B-12	LWRHU Shipping Container	.43
B-13	Galileo Spacecraft Interplanetary Trajectory	.49
B-14	LWRHU Locations (Spacecraft Stowed).	.54
B-15	Shuttle with Galileo at Launch Configuration	.55
B-16	LWRHU Locations (Spacecraft Deployed).	.56
B-17	Major Spacecraft Components.	.57
B-18	Probe Components	.59
B-19	Probe Deceleration Module.	.60
B-20	Shuttle Side View.	.62
B-21	Shuttle Top View	.63
B-22	Shuttle Vehicle Front and Back Views	.64
B-23	Basic Mission Cycle for Shuttle.	.65
B-24	SSME Details	.66
B-25	SRB Details.	.68
B-26	SRB Configuration.	.69
B-27	OMS Detail	.70
B-28	ET Overview.	.71
B-29	IUS Vehicle.	.73
B-30	SRM-1.	.74
B-31	SRM-2.	.75
B-32	IUS Propulsion Subsystem	.76
B-33	Shuttle Trajectory - Altitude versus Time.	.80
B-34	Shuttle Trajectory - Velocity versus Time.	.81
B-35	Shuttle Trajectory - Acceleration versus Time.	.82
B-36	Shuttle Trajectory - Range versus Time	.83
B-37	Shuttle Trajectory - Impact Range versus Time.	.84
B-38	Launch and VAB Areas at KSC.	.85
B-39	Launch Pad 39A	.86
B-40	Launch Pad 39B	.87

ABSTRACT

The orbiter and probe portions of the National Aeronautics and Space Administration (NASA) Galileo spacecraft contain components which require auxiliary heat during the mission. To meet these needs, the Department of Energy's (DOE's) Office of Special Applications (OSA) has sponsored the design, fabrication, and testing of a one-watt encapsulated plutonium dioxide-fueled thermal heater named the Light-Weight Radioisotope Heater Unit (LWRHU). This report, prepared by Monsanto Research Corporation (MRC), addresses the radiological risks which might be encountered by people both at the launch area and worldwide should postulated mission failures or malfunctions occur, resulting in the release of the LWRHUs to the environment. Included are data from the design, mission descriptions, postulated accidents with their consequences, test data, and the derived source terms and personnel exposures for the various events.

A. INTRODUCTION AND EXECUTIVE SUMMARY

1.0 INTRODUCTION

The Light-Weight Radioisotope Heater Unit (LWRHU)* is planned to be used on the NASA Galileo Mission to provide thermal energy to the various systems on the orbiter and probe, which are adversely affected by the low temperature a spacecraft encounters during an interplanetary mission such as the Galileo to Jupiter. Using these plutonia-fueled sources in l-W increments permits employment of a single design and provides the spacecraft user the option of how many to use and where to position them to satisfy the proper thermal environment for components requiring such consideration. The use of the radioisotope ²³⁸Pu in these devices necessitates the assessment of postulated radiological risks which might be experienced in case of accidents or malfunctions of the shuttle (space transportation system or STS) or the spacecraft during phases of the mission in the vicinity of the earth.

1.1 Purpose of SAR

This Final Safety Analysis Report (Final SAR or FSAR) presents the analyses and results of the evaluation of the nuclear safety properties of the 129 LWRHUs to be employed on the Galileo Mission. Many analyses and tests have already been documented in the SAR issued for the originally-planned Galileo Mission (Reference 1). In addition, the analyses performed by the radioisotope thermoelectric generator (RTG) systems contractor on accident scenarios, probabilities, etc. were used to avoid duplication of effort. Therefore, considerable use was made of the General Electric documents generated for the General Purpose Heat Source (GPHS) RTG FSAR (Reference 2).

1.2 Document Organization

The format of this document conforms to the requirements defined in the Overall Safety Manual (Reference 3). Details of this format are provided in Table A-1 (References 4 and 5).

*All abbreviations and acronyms are defined in Appendix B-2.

Table A-1: The LWRHU-FSAR Format Defined

VOLUME I

A. INTRODUCTION AND EXECUTIVE SUMMARY

1.0 Introduction

Purpose of FSAR
Document Organization
Data Acknowledgments

2.0 Missions and Flight Systems Summary

Nuclear Description
Space Shuttle/IUS
Mission Phase Definition

3.0 Accident Summary

Flowchart of Accidents and Probabilities by Phase
Tabulation of Accidents/Consequences by Phase
 Accidents
 Fuel Release Mechanisms
 Locations Affected
Source Terms
 Expected - Most Probable
 Worst Case
 Causative conditions
 Probabilities

Summary Discussions of Significant Accidents

B. REFERENCE DESIGN DOCUMENT (RDD)

- 1.0 Nuclear Power System
- 2.0 Spacecraft
- 3.0 Launch Vehicle
- 4.0 Centaur
- 5.0 Trajectory and Flight Characteristics
- 6.0 Launch Site

Table A-1 (Continued)

VOLUME II: ACCIDENT MODEL DOCUMENT (AMD)

1.0 Introduction

Purpose of AMD
Document Organization
Data Acknowledgments

1.1 Missions and Systems Description

- Mission Phases with Timelines/Events
- LWRHU Design

2.0 Summary of Accident Evaluation

Flowchart
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
Mission Accident Evaluation

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

3.3.1 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
 - Initial LWRHU Response to Explosions
 - Synergistic Effects of Environments
 - Intermediate Events Identified
 - Final Disposition of LWRHU
 - Source Term Characterized

TABLE A-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 Purpose 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

Table A-1 (Continued)

LWRHU FSAR NUCLEAR RISK ANALYSIS DOCUMENT (NRAD) (VOLUME III) OUTLINE

1.0 EXECUTIVE SUMMARY

2.0 MAJOR ACCIDENT SCENARIOS AND CONSEQUENCES

Launch
Ascent
Reentry
Mission Aborts to Landing

3.0 INTEGRATED MISSION RISK ANALYSIS

4.0 RELATED ASPECTS OF RADIOLOGICAL IMPACT

Effect of Emergency Countermeasures
Effect of Meteorological Launch Restraints
Land Contamination
Water Contamination

APPENDIXES

A. KSC Meteorology

B. Population Distribution

Night Launch Spectators*
Occupational - Kennedy Space Center (KSC)
Resident Population

C. Radiological Assessment Methodology

Source Term Characterization
Plume Rise/Cloud Size
Dispersion Analyses
Atmospheric
Ocean
Radiation Dose Models

D. Uncertainty analysis

E. Biomedical Considerations of $^{238}\text{PuO}_2$

F. Parametric Radiological Analysis

*Actually day launch

2.0 MISSION AND FLIGHT SYSTEM SUMMARY

2.1 Nuclear System (LWRHU)

The LWRHU is a radioisotope-fueled system consisting of a 1-W pellet of plutonium-238 dioxide, a clad of platinum-30 rhodium (Pt-30Rh), an insulation system of pyrolytic graphite (PG), and an aeroshell/impact body of Fine-Weave Pierced Fabric (FWPF).^{*} The exterior dimensions are 26 mm diameter by 32 mm long; each LWRHU weighs about 40 g. The detailed description of the LWRHU is in Section B, RDD. A cutaway drawing of the LWRHU is shown in Figure A-1.

2.2 Galileo Mission Description

The NASA Galileo spacecraft is scheduled for launching during November 1989 by the Space Shuttle to attain a temporary Earth parking orbit; the IUS vehicle will be used to propel the spacecraft from the parking orbit into the trajectory toward Venus. This will initiate the Venus-Earth-Earth Gravity Assist (VEEGA) interplanetary trajectory which will allow the Galileo spacecraft to acquire sufficient energy to get to Jupiter. The spacecraft should arrive in the vicinity of Jupiter after an interplanetary transit of a little more than six years. Plans are for a probe to be deployed from the spacecraft 150 days before arrival at Jupiter and to descend into the Jovian atmosphere. The scientific objectives of the mission are to conduct comprehensive investigations of the Jovian system, including the planet, its satellites, and the vast expanse of the Jovian magnetosphere.

2.3 Space Transportation System (Shuttle)

The Galileo spacecraft is scheduled for launching from Pad A or B of Launch Complex 39 at the KSC, Cape Canaveral, Florida. The current launch configuration is shown in Figure A-2. Figure A-3 provides a more detailed drawing of the Galileo spacecraft with LWRHU locations indicated.

2.4 Mission Phase Definition

To provide a logical approach to the safety analysis, the reference mission for Galileo is divided into six distinct phases for purposes of the safety analysis. These phases cover all mission-related operations beginning with loading the liquid propellants into the Shuttle external tank (ET) after the spacecraft has been installed in the cargo bay and ending with the attainment of the Earth escape trajectory. At this point, with a successful burn of the IUS having been accomplished, escape of the spacecraft from the Earth's gravitational pull will be effected, and the LWRHUs will present a potential risk to the Earth's populace only during the two VEEGA Earth fly-bys. Definitions of the phases** are as follows:

^{*}Manufactured by AVCO Systems Division

^{**}Prelaunch and launch are grouped together in the FASTs as Phase 0.

LIGHTWEIGHT RADIOISOTOPE HEATER UNIT

FIGURE A-1: The principal features of the Light-Weight Radioisotope Heater Unit.

Figure A-2: Galileo launch configuration showing the spacecraft/IUS in the shuttle bay.

FIGURE A-3: The cruise configuration of the Galileo spacecraft showing the location of the 129 LWRHUs.

Phase 0 - Prelaunch - The applicable portions of this phase begin with the initiation of loading the liquid propellants into the ET and end with the initiation of the Group Launch Sequencer. The duration of this portion of Phase 0 is from T - 30600 s to T -31 s.

Phase 0 - Launch - This phase begins the automatic launch sequence at T - 31 s, continues with the ignition of the space shuttle main engines (SSMEs) at T - 6.6 s, and continues until the solid rocket booster (SRB) ignition command is given at T = 0. It might be noted that there are no fuel releases expected for accidents during the Phase 0 launch/prelaunch.

Phase 1 - First-Stage Ascent - Phase 2 begins at T = 0 s and lasts until the SRBs are jettisoned at T + 128 s. No plutonia fuel releases are predicted during this phase.

Phase 2 - Second-Stage Ascent - This phase includes the period from SRB separation (T + 128 s) until main engine cutoff (MECO) at T + 532 s. No LWRHU plutonia fuel would be released as a result of accidents in this phase.

Phase 3 - On-Orbit - Phase 4 starts at T + 532 s and includes IUS/spacecraft deployment from the orbiter at T + 24,084 s. The significant events that occur during this phase include the first and second burns of the orbital maneuver system (OMS, OMS-1 and OMS-2) for orbit attainment and circulation, the release of the IUS and spacecraft, and the starting of the orbiter RCS (Reaction Control System) to move away from the IUS. No fuel releases are predicted to occur as a result of accidents experienced during Phase 3.

Phase 4 - Insertion - Phase 5 starts at T + 24,084 s and ends when the IUS has attained Earth escape velocity even though the spacecraft has not yet been deployed. Phase 4 has no fuel releases identified due to the LWRHU failures.

Phase 5 - VEEGA - For the purposes of this analysis, there are two Earth fly-bys: December 1990 and December 1992. A targeting error could result in the Galileo spacecraft entering the Earth's atmosphere although the chances are quite remote (less than one part per million). Should this superorbital reentry become a reality, there is a chance for a release of plutonia from some of the LWRHUs depending upon the reentry angle, orientation and stability. In one instance, pellets of uncladded fuel can impact upon the Earth's surface.

3.0 ACCIDENT SUMMARY

3.1 Accident Definitions

The Shuttle Data Book (Reference 6) provides detailed summaries of accidents which could be encountered by the shuttle/Galileo spacecraft during the various mission phases. Table A-2 provides a summary of those accidents by Mission Phase along with the identifications of the systems which could precipitate the subsequent accident environment to which the LWRHUs would be exposed.

TABLE A-2: The potential initiating system(s) which result in the various FAST branches.

<u>Phase- Branch</u>	<u>Event or Consequence</u>	<u>Possible Initiating System</u>
0'	On-Pad RSS Destruct	Range Safety System (RSS)
0"	Fire/Explosion	Launch Support Equipment, Orbiter, ET, SRB, or SSME
1S	Explosion/Fire/Breakup	SRB Failure
1E	Aft Compartment Explosions	Payload, Orbiter, ET, SRB, or SSME
1V	Vehicle Breakup	Payload, Orbiter, ET, SRB, or SSME
1C	Crash Land/Ocean Ditch	Payload or Orbiter
1R	RSS Destruct	Payload, Orbiter, ET, SRB, SSME, or RSS
2V	In-Flight Breakup	Payload, Orbiter, ET, or SSME
2C	Crash Land/Ocean Ditch	Payload, Orbiter, ET, or SSME
3	Orbiter Reentry	Payload or Orbiter
4	Spacecraft Reentry	Payload
5	VEEGA Reentry	Spacecraft

3.2 Accident Probabilities

The incorporation of the accidents and probabilities together results in a Failure Abort Sequence Tree (FAST) as shown in Figure A-4. The generation of this analytical tool is discussed in detail in Volume II of this analysis.

In general, the Galileo Mission has greater than a 98% chance of success. The only phase that has been identified as having a probability for plutonia release is Phase 5. The incidence of the suborbital reentry in the VEEGA Earth fly-bys is small: $<1 \times 10^{-6}$ per mission.

3.3 Fuel Release Mechanisms

Although the LWRHUS aboard the Galileo Spacecraft are subjected to a wide variety of hostile environments, a thorough systematic assessment of the response of LWRHUS to these environments shows that fuel release would occur only in certain instances during the VEEGA superorbital reentry. The release mechanism is a 50% erosion (ablation) of the protective LWRHU aeroshell which is considered to be the failure point. At this point, the clad fuel is subjected to aerothermal heating and the heat pulse is sufficient to melt and ablate away the clad. This results in a bare fuel pellet as the final reentering and subsequent impacting body. In low γ (reentry angle) conditions ($4^\circ < \gamma < 20^\circ$), the pulse is more benign and causes only partial (8.5%) evaporation of the fuel at the high reentry altitude. The partially-ablated (91.5% remaining) pellet now falls to the earth surface where it can hit on water (no added fracturing), soil-type land (no added fracturing) or on rock-type land (break up into particulates).

3.4 Source Terms

The source terms which result as a consequence of Earth fly-by reentries during the VEEGA phase of the Galileo Mission are summarized as follows:

<u>Branch</u>	<u>Ci(TBq)</u>	<u>Form</u>	<u>Locale</u>	<u>Probability</u>
5A	2935 (109)	Vapor	Upper Atmosphere	5×10^{-9}
5A	155 (5.74)	Particles	Land Surface	5×10^{-9}
5B	250 (9.25)	Vapor	Upper Atmosphere	1×10^{-8}
5B	1906 (70.5)	Pellets	Ocean Bed	1×10^{-8}
5B	644 (23.8)	Pellets	Land Surface	1×10^{-8}
5B	135 (5.00)	Particles	Land Surface	1×10^{-8}

Table A-3 provides the source term assessments for these releases when considered from maximum, most probable and expectation aspects. The methodology used to generate these data is provided in Volume III.

FIGURE A-4: The top-level LWRHU FAST was defined to be the same as the FAST for the GPHS RTG.

Table A-3: Maximum, Most Probable and Expectation Release Cases are Provided below for the Galileo Mission Phase 5 accidents. Phases 0 through 4 have no LRRHU fuel releases identified and are thus not shown

Phase	Accident Type	Release Probability	Source Term, Ci (TBq)	Release Category	Description
<u>Most Probable Release Case</u>					
5	Zone B VEEGA Reentry	1.00E-08	250 (9.3)	High Altitude	Vapor 0° Latitude
			135 (5.0)	Ground Level	0° Latitude
<u>Maximum Release Level</u>					
5	Zone A VEEGA Reentry	5.00E-09	2935 (109)	High Altitude	Vapor 33° N Latitude
			155 (5.7)	Ground Level	Rock Impact of Bare Fuel Pellets 33° N Latitude
<u>Expectation Release Case</u>					
5	VEEGA Reentry	1.50E-08	1145 (42.4)	High Altitude	Vapor 0° Latitude
			142 (5.3)	Ground Level	Rock Impact of Bare Fuel Pellets 0° Latitude

Note: 1 E-6 = 1×10^{-6} , etc.

4.0 EXECUTIVE SUMMARY REFERENCES

1. Johnson, E. W., Light-Weight Radioisotope Heater Unit Safety Analysis Report (LWRHU-SAR), MLM-3293, Monsanto Research Corporation (October 1985).
2. Final Safety Analysis Report II for the Galileo Mission, Document No. 87SDS4213, GE (May 1988).
3. Overall Safety Manual, NUS Corporation (1974).
4. Bradshaw, C. T., Verbal Presentation, Valley Forge, PA (January 23, 1985)
5. Englehart, R. W., Verbal Presentation, Valley Forge, PA (January 23, 1985).
6. Space Shuttle Data for Planetary Mission Radioisotope Thermoelectric Generator (RTG) Safety Analysis, NSTS-08116.

B. REFERENCE DESIGN DOCUMENT

1.0 NUCLEAR SYSTEM (LIGHT-WEIGHT RADIOISOTOPE HEATER UNIT OR LWRHU)

1.1 General Description

The LWRHU is to be used on the NASA Galileo Mission to provide heat to various systems on the orbiter and probe. Many areas of the spacecraft are adversely affected by temperatures to which it would be exposed during an interplanetary mission such as Galileo. A singular design, in which auxiliary heat is provided in increments of 1 W, can fulfill the many requirements by proper distribution to those areas needing thermal input. This significantly cuts the spacecraft electrical energy drain, compared to the drain had these items been resistance heaters and, consequently, reduces the launched quantity of plutonium-238 for the same power consumption requirement.

The LWRHU is a heat source that contains sufficient plutonium-238 dioxide to provide slightly over 1 W of heat at the time of fabrication. MRC was responsible for fabrication of the nonradioactive components and for issuing this document. Los Alamos National Laboratory was responsible for design, assembly and testing activities with analytical support from other DOE-authorized participants, such as the Applied Physics Laboratory and Fairchild Space Company. The overall configuration is shown in Figure B-1. External dimensions are a diameter of 26 mm and a length of 32 mm. Drawings of the parts are provided in Appendix B-1.

A general summary of the components with typical weights is given in Table B-1. In addition to the control documents cited in this table, the following process controls were employed:*

1. MD-70384, Light-Weight Radioisotopic Heater Unit (LWRHU) Program Sub-assembly Manufacture. This document contains the procedures and in-process acceptance criteria employed for manufacturing the clad components and subassembly.
2. SPA-780244, "Specification for Marking of Parts and/or Assemblies." This document provides requirements for maintaining identification of parts.

*NOTE: MRC's documents may be obtained by contacting MRC's Drawing Control at Telephone (513)-865-3160.

LIGHTWEIGHT RADIOISOTOPE HEATER UNIT

FIGURE B-1: The principal features of the Light-Weight Radioisotope Heater Unit. External dimensions are 26 mm diameter by 32 mm long; it weighs slightly less than 40 g.

TABLE B-1: General Description of the LWRHU Components

Component	Material ^a	Size, mm Length x Diameter	Material Specification	Drawing Number	Typical Weight, g
Fuel Pellet	PuO ₂	9.4 x 6.0	--	AYC-790106	2.664
Frit Vent	Pt	0.05 x 3.15	SPA-790605	AYC-790098	
Clad Cap, Vent End	Pt-30Rh	1.0 x 7.1	SPA-790139	AYC-790099	
Clad Cap, Closure End	Pt-30Rh	1.0 x 7.1	SPA-790139	AYC-790105	5.702
Clad Body	Pt-30Rh	12 x 8.6	SPA-790139	AYC-790100	
Shim	Pt-30Rh	0.6 x 6.5	SPA-790139	AYC-790101	
Insulator Cap ^b	PG	4.15 x 16.8	SPA-790171	AYC-790381	2.532
Outer Insulator Body	PG	20 x 16.8	SPA-790171	AYC-790382	3.166
Inner Insulator Body	PG	14.1 x 10.4	SPA-790171	AYC-790383	1.486
Aeroshell End Cap	FWPF	5.3 x 19	SPA-790053	AYC-790385	2.543
Aeroshell Body	FWPF	32 x 26	SPA-790053	AYC-790380	<u>21.070</u>

TOTAL WEIGHT = 39.787

^aFWPF = Fine Weave-Perced Fabric;
PG = Pyrolytic

^bTwo Required

3. SPA-790616 "Marking Parts." Laser marking requirements are identified in this general manual for both FWPF and metallic components.
4. SPA-790617, "LWRHU Subassembly." This document defines the acceptance of the clad assembly, including frit vent flow rate.
5. 26Y318614, "Light-Weight Radioisotope Heater Unit (LWRHU) Product Index," (LANL). This document lists the drawings, procedures, documents, and flow charts applicable to the LWRHU activities at LANL.
6. 26Y318189, "Light-Weight Radioisotope Heater Unit (LWRHU) Product Specification," (LANL). This specification defines the physical and chemical requirements of the plutonium oxide pellet, welding, vent activation, and graphite assembly requisites for the LWRHU.
7. Drawings: 26Y318190, "LWRHU Assembly"
(LANL) 26Y318191, "LWRHU Fueled Capsule"
26Y318192, "LWRHU Fuel Pellet"
26Y200174, "Packaging Container - Shipping Fixture -
LWRHU Assembly."

1.2 Design Requirements

The design requirements as excerpted from the Jet Propulsion Laboratory's (JPL's) Spec No. ES513279, Revision A (ca. October 1984) are as listed below.

1.2.1 Function - The function of the LWRHU is to provide 1 W(th) by means of radioactive decay of its plutonium fuel. The unit is used to obtain a local desirable temperature in the Galileo orbiter and the Galileo probe.

1.2.2 Components - The LWRHU consists of the following:

- a. Aeroshell and end cap (Fine Weave-Pierced Fabric Graphite*).
- b. Insulator body (pyrolytic graphite).
- c. Fuel clad (Pt-30Rh).
- d. Fuel pellet (PuO_2).

1.2.3 Power - The thermal power of the unit shall be 1.1 plus or minus 0.03 W, when back decayed to the date of pellet pressing.

1.2.4 Dimensions - The unit shall be a right circular cylinder with dimensions as shown in Figure B-2.

1.2.5 Weight - The unit shall have a maximum weight of 42 g.

*A product of AVCO Systems Division, 201 Lowell Street, Wilmington, MA, 018870

1 END CAP TO BE FLUSH TO 0.025 BELOW END BODY SURFACE ONE SIDE ONLY

NOTE: THE DIMENSIONS ARE IN MILLIMETERS UNLESS OTHERWISE SPECIFIED.

FIGURE B-2: LWRHU dimensions.

1.2.6 Compressive Load - The unit shall withstand the following compressive load applied by the enclosure during the mission:

a. Radial compressive load of 890 N maximum uniformly applied on a 120° minimum arc by a 0.5-in. wide band.

b. End compressive load of 445 N maximum, uniformly distributed.

1.2.7 Surface Temperature - The unit shall have operational capability with surface temperatures between -130 and +180°C*.

1.2.8 Magnetic - The unit shall contain no significant amount of ferromagnetic material. For the purpose of this specification, impurity amounts (a few hundred ppm) of Fe, Cr, and Ni in the fuel and in the clad shall not be considered to be significant ferromagnetic material.

1.2.9 Radiation - The unit shall be packed with plutonium dioxide fuel with a maximum neutron (n) emission of 6,000 n/s-g ²³⁸Pu. The concentration of plutonium-236, when decayed to the date of fuel production, shall not exceed 2 parts per million (ppm) of total plutonium.

1.2.10 Tests

1.2.10.1 Acceptance Tests - Each unit shall be subjected to the following measurements to verify compliance with the requirements of this document.

1.2.10.1.1 Mass - The mass of each unit shall be measured with an accuracy of plus or minus 0.01 g.

1.2.10.1.2 Power - Each unit shall be subjected to thermal power measurements with an accuracy of 3%.

1.2.10.1.3 Radiation - The neutron emission rate of each unit shall be measured with an accuracy of 5%.

1.2.10.1.4 Geometry - Each unit shall be measured to ensure that it falls within the envelope dimensions defined by Figure B-2.

1.2.10.2 Qualification Test - One unit shall be subjected to random vibration (1.2.10.2.1) sinusoidal vibration (1.2.10.2.2), and acceleration tests (1.2.10.2.3). In order to successfully complete the qualification test, the unit under test shall maintain its mechanical integrity during and after the qualification testing.

*In practice, the upper temperature attained by the LWRHU is 105°C. However, the addition of the six units on the photocalibration mirror has resulted in six LWRHUs operating at 300°C. This is well within their design capability.

The unit selected for the qualification testing shall be a development unit with a depleted uranium dioxide fuel pellet, which is mechanically identical to the flight units. The qualification of the unit shall be based upon demonstrating that it is mechanically intact and meets the requirements of this and other applicable documents.

1.2.10.2.1 Random Vibration - The unit shall be vibrated along each of the two perpendicular axes while mounted in both Orbiter and Probe configuration as illustrated in Figure B-3. The random vibration levels shall be in accordance with Figure B-4.

1.2.10.2.2 Sinusoidal Vibration - The unit shall be subjected to the sinusoidal vibration along its perpendicular axis while mounted in the Orbiter and Probe configuration as shown in Figure B-3. The sinusoidal test level will be in accordance with Figure B-5.

1.2.10.2.3 Acceleration Test - The acceleration test is performed to determine the response of the unit to forces that will occur when the Galileo Probe descends into the Jovian atmosphere. The g loading force shall be perpendicular to the mounting plate and in a direction to stress the mounting strap and fasteners. The unit shall be subjected to a load of 4.25 g for 15 s and a load of 300 g for 30 s.

1.2.10.3 Quality Assurance Provisions

1.2.10.3.1 Quality Assurance Program - The DOE shall establish and implement a quality assurance program, which essentially conforms to the requirements of OSNP-2, Quality Assurance Program Requirements for Space and Terrestrial Nuclear Power Systems.

1.2.10.4 Safety Requirements

1.2.10.4.1 Safety Policies - The LWRHU shall meet the provisions of NASA NHB 1700.7A, Safety Policy Requirements for Payloads Using the Space Transportation System. Overall spacecraft safety data for the LWRHUS will be delivered by JPL.

1.3 Materials and Their Properties

Material description and properties are being addressed in this section from an inside-to-outside basis.

1.3.1 Plutonium Dioxide (Plutonia) Fuel - The 1.1-W plutonia fuel pellets were hot pressed from Savannah River Plant feed that contained isotopic percentages (based upon total) and actinide concentrations (in weight ppm) as follows (Reference 9):

²³⁶ Pu:	0.00007
²³⁸ Pu:	83.62
²³⁹ Pu:	13.98
²⁴⁰ Pu:	1.96
²⁴¹ Pu:	0.41
²⁴² Pu:	0.14
²⁴¹ Am:	254
²³⁷ Np:	203
²³² Th:	232
²³⁴ U:	6,191

FIGURE B-3: LWRHU test configuration.

FIGURE B-4: Random vibration test levels.

FIGURE B-5: Sinusoidal vibration test levels.

The above fuel data were accumulated in the early-1980 time frame. As there will be a 9- to 11-year delay in the launch of these units, at-launch inventories were calculated, along with the radioactive daughters. These values are given in Table B-2.

These pellets weighed 2.664 ± 0.002 g with a density of $87.4 \pm 0.7\%$ of theoretical. The neutron emission was measured at 5190 ± 103 n/s-g Pu-238 with an average power of 1.106 ± 0.005 W per pellet (this works out to be 33.6 Ci or 1.24 TBq per pellet) (Reference 1).

The FSAR II Reference Design Document for the GPHS RTG Galileo Mission (Reference 2) provides an excellent summary of general physical properties data for PuO_2 . The only properties employed in these analyses are the following:

Vapor Pressure: $\log P (\text{total}) = 7.381 - 28,890/T$ where $P = \text{atm}$ and $1900 \text{ K} < T < 2200 \text{ K}$,

and Heat Capacity:

T	=	300	500	700	900	1100
C_p	=	256	314	335	338	342

where $T = \text{kelvins}$ and $C_p = \text{J/kg K}$.

1.3.2 Pt-30 Rh Clad - The platinum-30 wt% rhodium material was obtained from the Matthey-Bishop Company of Malvern, Pennsylvania. This material has been demonstrated to exhibit excellent compatibility with stoichiometric plutonia (Reference 1).

Relevant tensile properties as measured by the Oak Ridge National Laboratory and cited in Reference 1 are shown in Figure B-6, A and B. The thermal expansion coefficient is about $13 \times 10^{-6} \text{ K}^{-1}$.

Physical properties of interest to this document include (Reference 3). The following

Melting Point = 2183 K
Pt-30 Rh/C eutectic = 2033 K
Emissivity = 0.2 (total normal)
Heat Capacity = 158 178 194 207 (J/kg K)
@ Temperature = 400 900 1300 1700 K.

The vent is composed of sintered platinum powder. This item is an insignificant contributor to most thermal analyses, but the melting point of platinum (2043 K, Reference 4) is important in assessing some accident scenarios.

1.3.3 Pyrolytic Graphite Insulators - The insulation package that surrounds the clad and is immediately inside the aeroshell consists of pyrolytic graphite (PG) manufactured by Pfizer Company, Easton, Pennsylvania. The components are formed such that the c-axis is in the direction of heat flow (the AB plane normal to the heat flow direction). The properties of PG as they relate to this FSAR are provided in Figure B-7 (Reference 5). The emissivity is given as 0.845 at 1590 K (Reference 5) and increases linearly from 0.41 at 256 K to 0.87 at 2200 K (Reference 3).

Activities on----->		15-Oct-89 from----->		129 LWRHU units											
Nuclide----->	Pu-236	U-232	Th-228	Ra-224	Pn-220	Po-216	Pb-212	Bi-212	Tl-208	Po-212					
T(1/2) yr.-->	2.851	71.7	1.91313	1.003E-02	1.762E-06	4.59E-09	1.2141E-03	1.1522E-04	5.8042E-06	9.38E-15					
curies----->	1.10E-02	3.59E-03	3.08E-03	3.07E-03	3.07E-03	3.07E-03	3.07E-03	3.07E-03	1.11E-03	1.97E-03					
Nuclide----->	Pu-238	U-234	Th-230	Ra-226	Rn-222	Po-218	Pb-214	Bi-214	Po-214	Pb-210	Bi-210	Po-210			
T(1/2) yr.-->	87.74	2.446E+05	8.0E+04	1599	1.04684E-02	5.80E-06	5.10E-05	3.75E-05	5.187E-12	22.26	1.373E-02	0.3788544			
curies----->	3.99E+03	1.10E-01	4.52E-06	6.16E-09	6.13E-09	6.13E-09	6.13E-09	6.13E-09	6.13E-09	4.23E-10	4.20E-10	3.38E-10			
Nuclide----->	Pu-239	U-235	Th-231	Pa-231	Ac-227	Th-227	Ra-223	Rn-219	Po-215	Pb-211	Bi-211	Tl-207			
T(1/2) yr.-->	24119	7.039E+08	2.911E-03	3.276E+04	21.7720	5.12471E-02	3.13069E-02	1.25E-07	5.634E-11	6.86E-05	4.09E-06	9.11E-06			
curies----->	2.60E+00	2.40E-08	2.40E-08	2.38E-12	2.20E-13	2.15E-13	2.12E-13	2.12E-13	2.12E-13	2.12E-13	2.12E-13	2.12E-13			
Nuclide----->	Pu-240	U-236	Th-232	Ra-228	Ac-228	Th-228	Ra-224	Rn-220	Po-216	Pb-212	Bi-212	Tl-208	Po-212		
T(1/2) yr.-->	6564	2.3415E+07	1.410E+10	5.77	6.99E-04	1.91313	1.003E-02	1.76E-06	4.59E-09	1.2141E-03	1.1522E-04	5.8042E-06	9.38E-15		
curies----->	1.35E+00	3.73E-07	8.60E-17	2.49E-17	2.49E-17	1.26E-17	1.25E-17	1.25E-17	1.25E-17	1.25E-17	1.25E-17	4.50E-18	8.00E-18		
Nuclide----->	Pu-241	Ra-241	Np-237	Pa-233	U-233	Th-229	Ra-225	Ac-225	Fr-221	At-217	Bi-213	Po-213	Tl-209	Pb-209	
T(1/2) yr.-->	14.348	433.6	2.14E+06	7.379E-02	1.5911E+05	7340	4.05E-02	2.74E-02	9.1E-06	1.02E-09	8.668E-05	1.3E-13	4.18E-06	3.711E-04	
curies----->	8.48E+01	1.59E+00	2.61E-06	2.55E-06	3.57E-11	7.98E-15	7.79E-15	7.66E-15	7.66E-15	7.66E-15	7.66E-15	7.49E-15	1.65E-16	7.660E-15	
Nuclide----->	Pu-242	U-238	Th-234	Pa-234m	U-234	Th-230	Ra-226	Rn-222	Po-218	Pb-214	Bi-214	Po-214	Pb-210	Bi-210	Po-210
T(1/2) yr.-->	3.763E+05	4.4683E+09	6.5996E-02	2.23E-06	2.446E+05	8.0E+04	1599	1.04684E-02	5.80E-06	5.10E-05	3.75E-05	5.187E-12	22.26	1.373E-02	0.3788544
curies----->	1.52E-03	2.21E-12	2.19E-12	2.19E-12	2.87E-17	7.95E-22	<7.9E-22	<7.9E-22	<7.9E-22	<7.9E-22	<7.9E-22	<7.9E-22	<7.9E-22	<7.9E-22	<7.9E-22
Nuclide----->	Ra-241	Np-237	Pa-233	U-233	Th-229	Ra-225	Ac-225	Fr-221	At-217	Bi-213	Po-213	Tl-209	Pb-209		
T(1/2) yr.-->	433.6	2.14E+06	7.379E-02	1.5911E+05	7340	4.05E-02	2.74E-02	9.1E-06	1.02E-09	8.668E-05	1.3E-13	4.18E-06	3.711E-04		
curies----->	2.57E-01	7.85E-07	7.76E-07	1.57E-11	4.58E-15	4.50E-15	4.44E-15	4.44E-15	4.44E-15	4.44E-15	4.35E-15	9.59E-17	4.44E-15		
Nuclide----->	Np-237	Pa-233	U-233	Th-229	Pa-225	Ac-225	Fr-221	At-217	Bi-213	Po-213	Tl-209	Pb-209			
T(1/2) yr.-->	2.14E+06	7.379E-02	1.5911E+05	7340	4.05E-02	2.74E-02	9.1E-06	1.02E-09	8.668E-05	1.3E-13	4.18E-06	3.711E-04			
curies----->	4.30E-05	4.30E-05	1.74E-09	7.59E-13	7.50E-13	7.44E-13	7.44E-13	7.44E-13	7.44E-13	7.27E-13	1.60E-14	7.44E-13			
Nuclide----->	U-234	Th-230	Ra-226	Pn-222	Po-218	Pb-214	Bi-214	Po-214	Pb-210	Bi-210	Po-210				
T(1/2) yr.-->	2.446E+05	8.0E+04	1599	1.04684E-02	5.80E-06	5.10E-05	3.75E-05	5.187E-12	22.26	1.373E-02	0.3788544				
curies----->	1.16E-02	9.44E-07	1.92E-09	1.91E-09	1.91E-09	1.91E-09	1.91E-09	1.91E-09	1.73E-10	1.72E-10	2.02E-11				
Nuclide----->	Th-232	Ra-228	Ac-228	Th-228	Pa-224	Pn-220	Po-216	Pb-212	Bi-212	Tl-208	Po-212				
T(1/2) yr.-->	1.41E+10	5.77	6.99E-04	1.91313	1.003E-02	1.762E-06	4.59E-09	1.2141E-03	1.1522E-04	5.8042E-06	9.38E-15				
curies----->	7.61E-09	5.14E-09	5.14E-09	4.05E-09	4.04E-09	4.04E-09	4.04E-09	4.04E-09	4.04E-09	1.45E-09	2.59E-09				

TABLE B-2: Isotopic analyses performed on LWRHU fuel at the time of pellet fabrication were used to calculate inventories.

A. October, 1989 Launch

Activities on----->		15-Jul-91 from----->		134 LMBU units											
Nuclide----->	Pu-236	U-232	Th-228	Ra-224	Pn-220	Po-216	Pb-212	Bi-212	Tl-208	Po-212					
T(1/2) yr.-->	2.851	71.7	1.91313	1.003E-02	1.762E-06	4.59E-09	1.2141E-03	1.1522E-04	5.8042E-06	9.38E-15					
curies----->	7.44E-03	3.82E-03	3.47E-03	3.47E-03	3.47E-03	3.47E-03	3.47E-03	3.47E-03	1.25E-03	2.22E-03					
Nuclide----->	Pu-238	U-234	Th-230	Ra-226	Pn-222	Po-218	Pb-214	Bi-214	Po-214	Pb-210	Bi-210	Po-210			
T(1/2) yr.-->	87.74	2.446E+05	8.0E+04	1599	1.04684E-02	5.80E-06	5.10E-05	3.75E-05	5.187E-12	22.26	1.373E-02	0.3788544			
curies----->	4.09E+03	1.35E-01	6.59E-06	1.06E-08	1.06E-08	1.06E-08	1.06E-08	1.06E-08	1.06E-08	8.60E-10	8.54E-10	7.11E-10			
Nuclide----->	Pu-239	U-235	Th-231	Pa-231	Ac-227	Th-227	Ra-223	Rn-219	Po-215	Pb-211	Bi-211	Tl-207			
T(1/2) yr.-->	24119	7.038E+08	2.911E-03	3.276E+04	21.7728	5.12471E-02	3.1306E-02	1.25E-07	5.634E-11	6.06E-05	4.00E-06	9.11E-06			
curies----->	2.70E+00	2.96E-08	2.96E-08	3.48E-12	3.76E-13	3.69E-13	3.65E-13	3.65E-13	3.65E-13	3.65E-13	3.65E-13	3.65E-13			
Nuclide----->	Pu-240	U-236	Th-232	Ra-228	Ac-228	Th-228	Pa-224	Rn-220	Po-216	Pb-212	Bi-212	Tl-208	Po-212		
T(1/2) yr.-->	6564	2.3415E+07	1.410E+10	5.77	6.99E-04	1.91313	1.003E-02	1.762E-06	4.59E-09	1.2141E-03	1.1522E-04	5.8042E-06	9.38E-15		
curies----->	1.41E+00	4.64E-07	1.27E-16	4.17E-17	4.17E-17	2.31E-17	2.30E-17	2.30E-17	2.30E-17	2.30E-17	2.30E-17	8.28E-18	1.47E-17		
Nuclide----->	Pu-241	Ra-241	Np-237	Pa-233	U-233	Th-229	Pa-225	Ac-225	Fr-221	At-217	Bi-213	Po-213	Tl-209	Pb-209	
T(1/2) yr.-->	14.348	433.6	2.14E+06	7.379E-02	1.5911E+05	7340	4.05E-02	2.74E-02	9.1E-06	1.02E-09	8.660E-05	1.3E-13	4.18E-06	3.711E-04	
curies----->	8.10E+01	1.89E+00	3.71E-06	3.65E-06	6.10E-11	1.63E-14	1.59E-14	1.57E-14	1.57E-14	1.57E-14	1.57E-14	1.54E-14	3.39E-16	1.57E-14	
Nuclide----->	Pu-242	U-238	Th-234	Pa-234m	U-234	Th-230	Ra-226	Rn-222	Po-218	Pb-214	Bi-214	Po-214	Pb-210	Bi-210	Po-210
T(1/2) yr.-->	3.763E+05	4.4683E+09	6.5986E-02	2.23E-06	2.446E+05	8.0E+04	1599	1.04684E-02	5.80E-06	5.10E-05	3.75E-05	5.187E-12	22.26	1.373E-02	0.3788544
curies----->	1.58E-03	2.72E-12	2.70E-12	2.70E-12	4.22E-17	1.37E-21	<1.3e-21	<1.3e-21	<1.3e-21	<1.3e-21	<1.3e-21	<1.3e-21	<1.3e-21	<1.3e-21	<1.3e-21
Nuclide----->	Am-241	Np-237	Pa-233	U-233	Th-229	Pa-225	Ac-225	Fr-221	At-217	Bi-213	Po-213	Tl-209	Pb-209		
T(1/2) yr.-->	433.6	2.14E+06	7.379E-02	1.5911E+05	7340	4.05E-02	2.74E-02	9.1E-06	1.02E-09	8.660E-05	1.3E-13	4.18E-06	3.711E-04		
curies----->	2.66E-01	9.66E-07	9.56E-07	2.30E-11	7.99E-15	7.86E-15	7.78E-15	7.78E-15	7.78E-15	7.78E-15	7.61E-15	1.68E-16	7.78E-15		
Nuclide----->	Np-237	Pa-233	U-233	Th-229	Pa-225	Ac-225	Fr-221	At-217	Bi-213	Po-213	Tl-209	Pb-209			
T(1/2) yr.-->	2.14E+06	7.379E-02	1.5911E+05	7340	4.05E-02	2.74E-02	9.1E-06	1.02E-09	8.660E-05	1.3E-13	4.18E-06	3.711E-04			
curies----->	4.47E-05	4.47E-05	2.14E-09	1.11E-12	1.10E-12	1.09E-12	1.09E-12	1.09E-12	1.09E-12	1.07E-12	2.35E-14	1.09E-12			
Nuclide----->	U-234	Th-230	Ra-226	Pn-222	Po-210	Pb-214	Bi-214	Po-214	Pb-210	Bi-210	Po-210				
T(1/2) yr.-->	2.446E+05	8.0E+04	1599	1.04684E-02	5.80E-06	5.10E-05	3.75E-05	5.187E-12	22.26	1.373E-02	0.3788544				
curies----->	1.21E-02	1.16E-06	2.80E-09	2.79E-09	2.79E-09	2.79E-09	2.79E-09	2.79E-09	2.96E-10	2.94E-10	3.56E-11				
Nuclide----->	Th-232	Ra-228	Ac-228	Th-228	Pa-224	Pn-220	Po-216	Pb-212	Bi-212	Tl-208	Po-212				
T(1/2) yr.-->	1.41E+10	5.77	6.99E-04	1.91313	1.003E-02	1.762E-06	4.59E-09	1.2141E-03	1.1522E-04	5.8042E-06	9.38E-15				
curies----->	7.61E-09	5.14E-09	5.14E-09	4.05E-09	4.04E-09	4.04E-09	4.04E-09	4.04E-09	4.04E-09	1.45E-09	2.59E-09				

Table B-2: Continued

B. July, 1991 Launch

A. Elongation of Pt-30 Rh at temperature (Oak Ridge)

B. Strength of Pt-30 Rh at temperature (Oak Ridge)

FIGURE B-6: Measured tensile properties of Pt-30 Rh.

FIGURE B-7: The thermal conductivity, k , of pyrolytic graphite is plotted for both A (parallel to basal plane) and C (perpendicular to basal plane) directions as a function of absolute temperature (Aerojet General, Vol. 2, NERVA Program, Report No. 2275). (Continued)

FIGURE B-7 (continued): Thermal expansion and heat capacity values for pyrolytic graphite are given as a function of absolute temperature (Aerojet General, Vol. 2, NERVA Program, Report No. 2275).

1.3.4 FWPF Aeroshell - The LWRHU aeroshell not only affords the required orbital decay reentry protection but also provides added impact resistance and fragmentation survivability to the fueled clad, should unplanned events be encountered resulting in perturbations of those sorts. The material used to fabricate the aeroshell is FWPF (Fine Weave-Pierced Fabric[®]), a product of AVCO Systems Division, Wilmington, Massachusetts. This material consists of layers of fine-weave graphite fabric (x-y plane) that is pierced by stiffened graphite yarn bundles in the z axis. The bulk density is $>1.95 \text{ g cm}^{-3}$. The minimum room temperature tensile requirements are shown below (Reference 6):

	Tensile Strength MPa	Tensile Modules MPa
x-y direction	125	58.6
z direction	114	6.55

Thermal conductivity and emissivity behavior for FWPF as a function of temperature is provided in Figure B-8. The GPHS FSAR II (Reference 2), provides a more comprehensive compilation of mechanical properties for this material.

1.4 Radiation Properties

1.4.1 Gamma - The intensity and energy distribution of gamma radiation emanating from the LWRHU is not a specification. Representative gamma dose rates on LWRHU Fueled Clad No. 033 are shown in Figure B-9 (Reference 7).

The gamma spectrum for the LWRHU would not be significantly different from the GPHS Qual RTG measurement, which is shown in Figure B-10 (Reference 8). These data were taken by an Ortec GMX-25195-S high-purity germanium gamma-ray detector.

1.4.2 Neutron - The measured neutron emission from LWRHU clads has been reported as $5190 \pm 103 \text{ n/s-g}^{238}\text{Pu}$ (Reference 1).

The anticipated neutron dose rate as a function of distance is provided in Figure B-9 (Reference 7). The neutron spectrum for the Qual GPHS RTG is given in Figure B-11 (Reference 9). The LWRHU neutron spectrum would be slightly different, due to fewer neutron-induced fission neutrons because of the smaller fuel pellet.

1.5 Ground Support Equipment (GSE)

Other than tooling and fixturing required to produce the LWRHU, the only GSE required is the 5790 Shipping Container that is described in Reference 10. The 12-gallon drum outer envelope is 0.37 m (14.6 in.) diameter by 0.54 m (21.1 in.) high. The maximum gross weight is 41 kg or 90 lb. Figure B-12 provides a general overview and identification of the materials of construction of the Model AL-M3 USA/5790/BLF(DOE/AL) configuration.

FIGURE B-8: Thermal conductivity and emissivity as a function of absolute temperature for FWPF.

FIGURE B-9: Dose rates as a function of distance for gamma and neutrons from two representative LWRHU fueled clads.

FIGURE B-10: The gamma spectrum of the Qual GPHS RTG. It is expected that the LWRHU spectrum would resemble this.

FIGURE B-11: The measured Qual GPHS neutron spectrum. The LWRHU neutron spectrum would be only slightly different in appearance.

Figure B-12: Twelve-gallon drum shipping container
Model AL-M3 USA/5790/BLF (DOE-AL).

The inner container is designed to accept a maximum of 30 W of heat (910 Ci or 34 TBq) of plutonium-238. This material must be in a "special form" or enclosed in primary containers placed inside the inner container of a shipping container. The 30-W loading will result in the inner container attaining a temperature of 150°C (300°F) at a drum surface temperature of 44°C (112°F). The DOE hypothetical fire would result in an inner container temperature of 225°C (437°F). These temperatures are readily accommodated by the LWRHU design.

2.0 GALILEO SPACECRAFT

2.1 Mission Objectives

The overall scientific objectives of the Galileo Mission are to conduct comprehensive investigations of the Jupiter planetary system by making in situ and remote measurements of the planet, its environment, and its satellites. Investigations of the Galilean satellites of Jupiter will constitute a major objective of the mission. A close-up study of the planet and its principal satellites will greatly extend our knowledge of the role of the Jovian system in the complex and analogous relationships between the Sun and its planetary system.

The Galileo spacecraft consists of both a Jovian orbiter and a Jovian atmospheric entry probe. The orbiter mission encompasses an equatorial tour of the planet system and multiple encounters with the Galilean satellites Europa, Ganymede, and Callisto. An Io encounter is possible before orbit insertion. The orbiter will conduct a synoptic study of the Jovian atmosphere,, determine the distribution and stability of trapped radiation, and define the topology and dynamics of the outer magnetosphere, magnetosheath, and bowshock.

The probe will seek to determine the physical structure and chemical composition of the Jovian atmosphere to a pressure depth of at least 10 bars, the location and structure of the Jovian clouds in the troposphere, and the thermal balance of the planet. It will also characterize the upper atmosphere and the nature and extent of the cloud particles.

Tables B-3 and B-4 provide a more detailed list of the experiments and objectives of the orbiter and probe portions of the Galileo Mission.

2.2 Nominal Prelaunch Sequence of Events

The overall launch period begins with the transporting of the spacecraft (with many LWRHUs already installed) to KSC, extends through lift-off, and terminates with a successful Deep-Space Network acquisition. The nominal prelaunch (prior to lift-off) sequence of events begins when the Galileo spacecraft is transported from JPL to KSC by truck. After being unpacked in the Spacecraft Assembly and Encapsulation Facility, the spacecraft is inspected to determine whether any damage was sustained during transit.

At the conclusion of the propulsion loading and pyrotechnics installation, the spacecraft will again be activated for further testing and will be prepared for transfer to the Vertical Processing Facility (VPF). At the VPF, the spacecraft will be mated to the upper-stage vehicle. Tests will be conducted to verify Space Shuttle end-to-end communications. A series of operational tests will also be conducted. Upon satisfactory completion of these tests, the spacecraft will be placed in the storage mode to await shipment to the launch pad.

TABLE B-3

THE GALILEO ORBITER WILL STUDY THE
AREA SURROUNDING JUPITER, INCLUDING ITS SATELLITES

Instrument Name	Objectives
REMOTE SENSING INSTRUMENTS	
Solid state imaging	Image Jupiter and its satellites for studies of atmospheric dynamics and physical geology.
Near infrared mapping spectrometer	Study mineralogy of satellite surfaces, as well as morphology and structure of Jovian clouds.
Photopolarimeter radiometer	Study photometric and thermal properties of satellite surfaces as well as cloud and haze properties in Jovian atmosphere.
Ultraviolet spectrometer	Study composition and structure of high neutral atmosphere of Jupiter and Galilean satellites
FIELDS AND PARTICLES INSTRUMENTS	
Magnetometer	Study magnetic field of Jupiter and search for magnetic fields associated with the satellites.
Plasma	Study Jovian plasma.
Plasma Wave	Study time-varying electric and magnetic waves in the Jovian plasma.
Energetic particles detector	Measure detailed energy and angular distribution of protons, electrons, and ions.
Dust detector	Study physical and dynamical properties of small dust particles in the Jovian environment.
RADIO SCIENCE	
Celestial mechanics	Study gravity fields of Jupiter and its satellites, as well as the space environment.
Radio propagation	Study structure of atmospheres of Jupiter and satellites by use of radio signals from orbiter and probe.

TABLE B-4

THE GALILEO PROBE WILL ENTER JUPITER'S
ATMOSPHERE AND PERFORM NUMEROUS
MEASUREMENTS

Instrument Name	Objectives
Atmospheric Structure Instrument	Determine properties (temperature, pressure, density, and molecular weight) of Jovian atmosphere.
Neutral Mass Spectrometer	Determine chemical and isotopic composition of Jovian atmosphere.
Helium Abundance Detector	Perform precision determination of helium abundance in Jovian atmosphere.
Nephelometer	Determine microphysical characteristics (particle size distribution, number, density, and physical structure) of Jovian clouds.
Net Flux Radiometer	Measure vertical distribution of net flux of solar energy and planetary emissions.
Lightning and Radio Emission/ Energetic Particle Detector	Study lightning in the Jovian atmosphere and energetic particles near Jupiter.
Radio Science	Study composition and structure of Jovian atmosphere.

About 30 days before launch, the spacecraft will be removed from storage and transported to the launch pad, preceding the arrival of the shuttle by two days. After cargo preparations are completed, the spacecraft will be installed in the Shuttle orbiter bay. About four days before launch, the RTGs will be reinstalled onto the spacecraft. Final communication tests will then be conducted. These tests should last about two days. At their conclusion, the launch countdown will commence.

2.3 From Launch to Jupiter Arrival

The Shuttle launch which initiates the Galileo Mission is scheduled to occur in October/November 1989. The interplanetary trajectory to be described is illustrated in Figure B-13. The IUS vehicle will be used to boost the spacecraft from the low-altitude Earth orbit attained by the shuttle. In the case of a delay from the 1989 launch, a July 1991 launch would be a possibility.

After the attaining of Earth orbit, the IUS-spacecraft is to separate from the Shuttle orbiter, nominally on the sixth orbit. Forty-five minutes after this separation, the first and second stages of the IUS will fire (about five minutes total) and the spacecraft will begin deployment of the RTGs and science and magnetometer booms. After achieving the proper orientation and rotation, the IUS will separate from the Galileo spacecraft, whereupon the spacecraft will be independently in communication with Earth. Table B-5 (from Table 12.1 in NSTS-08116) provides the expected chronology of events for these operations (Reference 11).

The overall mission after launch is detailed as follows:

- Shuttle launch with IUS injection (October/November 1989)
- Venus flyby (February 1990)
- First Earth flyby (December 1990)
- Second Earth flyby (December 1992)
- Jupiter arrival (1995-1996)
- Ten-orbit Jupiter tour.

In the event of problems while in orbit, it is possible to abort the Galileo Mission and still have the Shuttle return with the spacecraft in the payload bay. Table B-6 gives an overview of operations anticipated in case of this deviation from planned sequences.

Should an IUS failure prior to firing occur, the IUS would separate from the spacecraft. As the spacecraft would then be in low Earth orbit, the on-board propellant would be used to boost the spacecraft into a 2000-km circular orbit, which would have a lifetime on the order of thousands of years.

FIGURE B-13: Interplanetary trajectory for November 1989 VEEGA.

Table B-5: Galileo Spacecraft On-Orbit Activities

Nominal Time ^a	On-Orbit Events ^b
1. 001:23:00 MET.	Open Payload Bay Doors.
2. 001:45:30 MET.	Send IUS Discrete Command Set A to start spacecraft thermal control sequence. This will: Enable select fault protection algorithms for temperature control. Turn on selected heaters to maintain thermal control and prevent instrument contamination after cargo bay doors open. Nominal 3 min 36 s duration.
3. 009:00:00 MET.	Send IUS Discrete Command Set B to start spacecraft power sharing sequence. This will turn off selected heaters to meet RTG power constraints as the RTG coolant pump is turned off and the RTG power decreases. (Nominal 14 s duration).
4. 009:00:00 MET.	JPL Go/No-Go for separation.
5. 009:05:00 MET.	Stop RTG cooling pump and start purge of RTG cooling lines. RTG power output will decrease to a minimum within 25 min. After that, RTG power output will increase gradually.
6. 009:15:00 MET.	Spacecraft/IUS tilt-up.
7. 009:30:00 MET.	Fire Super-Zip. Spacecraft IUS payload separates from Shuttle orbiter.

^aTimes are approximate and representative, awaiting more detailed sequence planning.

^bReference: Taken from Table 12.1, NSTS-08116 (Reference 11).

(Table Continued Next Page)

Table B-5: Galileo Spacecraft On-Orbit Activities - (Continued)

Nominal Time ^a	On-Orbit Events ^b
8. 010:15:00 MET.	ARM and UNSHORT Spacecraft Power Switching Units 1 and 2. These two independent safety inhibits, are removed 45 min. after separation. IUS-1 Main Engine is also enabled at this time.
9. 010:20:00 MET.	IUS-1 Main Engine start (Nominal burn of TBS seconds).
10. TBS MET.	IUS-1 MECO.
11. TBS MET.	Send IUS Discrete Command Set C to start Spacecraft deployment Phase 1 Sequence (nominal 24 min 30 s duration).
12. MECO + 000:03:08.	Deploy RTG and science booms.
13. MECO + 000:08:00. TBS MET.	Deploy magnetometer booms.
14. MECO + 000:21:00.	S-Band Traveling Wave Tube Amplifier on.
15. MECO + 000:26:00.	IUS turn to Sun and spin up to 2.9 rpm.
16. MECO + 000:26:00.	Begin acquisition spacecraft Deep Space Network S-Band downlink (nominal).
17. MECO + 000:29:00.	Send IUS Discrete Command Set D to start spacecraft deployment Phase 2 sequence.
18. MECO + 000:29:00.	Spacecraft-IUS separation.
19. MECO + 000:54:00.	Pressurize RPM.
20. MECO + 001:19:00.	Spacecraft back-up Sun acquisition.

^aTimes are approximate and representative, awaiting more detailed sequence planning.

^bTaken from Table 12.1, NSTS08116 (Reference 11).

Note: TBS = to be supplied
RPM = Retropropulsion Module

Table B-6: Post-Landing Activities Galileo Spacecraft Abort

Step 1: Spacecraft in Shuttle Bay (doors closed):

- A. Verify condition of RTGs and radiation levels around orbiter bay.
- B. Monitor propulsion condition for evidence of leaks.
- C. Monitor temperature and humidity levels in orbiter bay.
- D. Monitor RPM.

Note: RTGs are shorted in abort case.

Step 2: Spacecraft in Shuttle (doors open):

- A. Inspect spacecraft for evidence of physical damage.
- B. Safe pyrotechnics super-zip.
- C. Remove RTGs and place in shipping container.
- D. Move RTGs to storage area, away from all personnel.

Note: Capability must exist to remove RTGs (KSC stands).

Step 3: IUS/Spacecraft removed and placed on Payload Special Handling Stand:

- A. Vent propulsion helium tanks.
- B. Initiate science purge and probe cooling.
- C. Safe pyrotechnics (Galileo orbiter).
- D. Remove spacecraft from IUS and place on transporter.
- E. Remove S-Band and X-Band antennae from spacecraft.
- F. Remove lower adapter from spacecraft.
- G. Depressurize and defuel RPM.
- H. Prepare to transport spacecraft and equipment.
- I. Transport to KSC.

2.4 Galileo Payload Description

2.4.1 Launch Configuration - The stowed configuration of the spacecraft is shown in Figure B-14. Locations of the LWRHU heat sources are indicated. The location of the spacecraft/IUS within the Shuttle at launch is shown in Figure B-15.

2.4.2 Galileo Jovian Orbiter - The Galileo orbiter is designed to release the probe as it approaches the planet Jupiter and provide radio relay/link/power functions prior to the probe-orbiter separation with data receipt/transmission after separation. As the orbiter circles Jupiter, it will accomplish a number of scientific investigations of the planet, its satellites, and its environment (See Table B-3).

The deployed orbiter (with probe) is illustrated in Figure B-16. Figure B-17 separates the orbiter into its major components. The Galileo orbiter is a dual-spin spacecraft. Part of the spacecraft will be three-axis stabilized to provide a steady base for the remote-sensing instruments. These instruments must be precisely pointed. The despun section carries its related electronics. The main portion of the orbiter will spin at 3 rpm to provide stability and to allow its instruments to continuously "sweep" the sky to make their measurements. The spun section contains both the high- and low-gain antennae, the retropulsion module (RPM) for all propulsive and attitude maneuvers, the nuclear power sources (RTGs), most of the electronics, most of the command and data equipment, and the instruments to study fields and particles.

The RPM has one 400-N engine and two clusters of 10-N thrusters that are used for attitude control and the smaller propulsive maneuvers. Because of minimum burn size and the total wetted lifetime constraints, the 400-N engine will be used only for the deflection maneuver after probe release, orbit insertion, and the perijove raise maneuver. The 10-N thrusters will be used for all other maneuvers.

As Jupiter is too far from the Sun for solar cells to be practical as a source of electrical power, Galileo will use two RTGs similar to those flown on the two NASA Voyager spacecraft. To conserve electrical power, 95 LWRHUs are dispersed about the orbiter as shown in Figure B-16. Table B-7 summarizes the quantities and locations of LWRHUs and compares the original configuration to those anticipated for 1989 and 1991 launches. Other than the two GPHS RTGs, the LWRHUs are the only major source of radioactivity and radiation aboard the Galileo spacecraft, although they contain only about 1/70 the plutonium of the RTGs.

2.4.3 Galileo Probe Description - The general appearance and dimensions of the probe are shown in Figure B-18. A more detailed depiction of the protective housings (aeroshell and aft cover) which would provide additional protection for the 34 LWRHUs contained within the probe during accident situations, is given in Figure B-19. Within the probe itself is the series of battery power supplies that are to be activated just prior to the probe's entering the Jovian atmosphere.

FIGURE B-14: Stowed Galileo LWRHU locations for a 1989 launch.

Figure B-15: Galileo launch configuration showing the spacecraft/IUS in the shuttle bay.

FIGURE B-16: The cruise configuration of the Galileo spacecraft showing the location of the 129 LWRHU's.

Figure B-17: Exploded view of the Galileo spacecraft showing major components for both spun and despun sections.

Table B-7: Proposed LWRHU usage for the 1989 and 1991
Galileo Mission options is provided below

LOCATION	1986 Direct Mission (Obsolete)	1989 VEEGA Mission (Proposed)	1991 VEEGA Mission (Proposed)	COMMENTS
MAG (outboard	3	3	3	No Change
MAG (inboard)	3	3	3	No Change
PWS Pre-amp (elec. field)	2	2	2	No Change
PWS Pre-amp (mag. field)	1	1	1	No Change
PWS Search Coils	1	1	1	No Change
SCI Boom Hinge Cable	5	5	5	No Change
Bay E	12	12	12	No Change
+X LBA	2	2	2	No Change
-X LBA	2	2	2	No Change
Despun Electronics	36	40	40	4 add'l. units in bay B
Probe Aeroshell	26	27	28	Offset reduced thermal output with age
Probe Aft Cover	7	7	7	No change
PCM	0	6	6	Decontamination strategy
+X Thruster Cluster	0	8	8	MBB assessing 6&8 unit options
-X Thruster Cluster	0	8	8	MBB assessing 6&8 unit options
LGA-2 Motor	0	2	2	Preliminary
Bay 5 Mounted Battery	0	0	2	Preliminary
Bay 8 Mounted Battery	0	0	2	Preliminary
Total Used	100	129	134	
Spares	35	6	1

FIGURE B-18: The major components of the GLL probe are illustrated above.

FIGURE B-19: The 34 LWRHUs inside the probe are quite well protected by the deceleration module (shaded area) structure.

3.0 LAUNCH VEHICLE

3.1 General Description

The launch vehicle for the Galileo Mission consists of two main components, the Space Shuttle and the IUS, designed to boost the spacecraft into an Earth-escape trajectory. The Space Shuttle, the tracking and communications relay satellites, the Kennedy Space Center and Johnson Space Center control centers, the Goddard Space Flight Center, and the worldwide space tracking and data network form the Space Transportation System.

3.2 Space Shuttle

The basic mission of the Space Shuttle is to be a space transport carrying payloads into space and returning to Earth for another load. The shuttle consists of the orbiter, ET, and the SRBs. The arrangement of these components is shown in Figures B-15, B-20, B-21 and B-22.

Figure B-23 illustrates the basic mission cycle for the Space Shuttle. It starts with the launch of the shuttle vehicle (with SRBs and orbiter main engines firing). After approximately 125 s at an altitude of about 37 km, the SRBs are jettisoned and fall back to Earth for recovery. After approximately 525 s of flight (before the orbiter attains orbit), the main engines are shut down, the ET is separated, and it falls back to Earth. The orbital maneuvering engines thrust the orbiter into orbit. For these missions, the orbital operations would include ejecting the IUS/spacecraft from the orbiter. The orbiter would subsequently return to Earth to be made ready for its next flight.

3.2.1 Main Engines - The main propulsion subsystem of the orbiter consists of three Space Shuttle Main Engines (SSME) (Figure B-24) which burn for approximately 525 s from just before lift-off until slightly before attaining orbit. The SSMEs are reusable, high-performance, liquid-propellant rocket engines with variable thrust. The propellants, LH_2 (liquid hydrogen fuel) and LOX (liquid oxygen oxidizer), are carried in the ET. Each engine weighs about 2860 kg (6300 lb) and has a rated thrust of $1.67 \times 10^6 \text{ N}$ (375,000 lb) at sea level and $2.09 \times 10^6 \text{ N}$ (470,000 lb) in vacuum. The nozzle is gimbled with hydraulic actuators for steering.

3.2.2 Solid-Rocket Boosters The signals to light the two SRBs will be sent 40 ms prior to lift-off. The initiation of these signals is dependent upon normal operation of the SSMEs with at least 90% of rated thrust. The simultaneous operation of the SRBs and the main engines, which are started in sequence about 6.6 s before lift-off, will cause lift-off to occur.

FIGURE B-20: Shuttle vehicle, side view.

FIGURE B-21: Shuttle vehicle, top view.

FIGURE B-22: Shuttle vehicle, front and back views.

Figure B-23: Basic mission cycle for shuttle.

Figure B-24: Space Shuttle Main Engine Schematic

Each SRB provides 12.9×10^6 N (2.9×10^6 lb) of thrust at sea level and contains 505,000 kg (1.11×10^6 lb) of propellant. The propellant is a composite-type solid propellant formulated of polybutadiene acrylic and acrylonitrile terpolymer binder, ammonium perchlorate, and aluminum powder with a small amount of iron oxide added as a burning rate catalyst. The nozzle of the SRB is gimballed with hydraulic actuators for steering.

Figures B-25 and B-26 show the SRB components and overall construction.

3.2.3 Orbital Maneuvering Subsystem (OMS) - The OMS includes two engines, located in pods at the top of the aft fuselage on either side of the vertical tail. The arrangement of these OMS pods is shown in Figure B-27.

These engines provide thrust for carrying the orbiter into orbit after the main engines are shut down, for maneuvering while in orbit, and for providing retrothrust to retard the orbiter out of orbit for reentry. The rated (vacuum) thrust of each engine is 26,700 N (6000 lb). The fuel is monomethylhydrazine (MMH), and the oxidizer is nitrogen tetroxide (N_2O_4). The nozzles are gimballed for steering with electromechanical actuators.

3.2.4 Orbiter Reaction Control System (RCS) - The RCS includes 44 thrusters (38 primary, 6 vernier) for altitude control and for three-axis translation during orbit insertion, on-orbit, and entry phase of the orbiter flight. The RCS propellants are MMH and N_2O_4 . The thrust (in vacuum) is 3870 N (870 lb) for each primary thruster and 107 N (24 lb) for each vernier thruster.

3.2.5 External Tank - The ET supplies the orbiter main propulsion system with LH_2 and LOX. The ET contains 703,000 kg (1.55×10^6 lb) of usable propellant for main engines at lift-off. At MECO, the ET is separated from the orbiter before orbital velocity is achieved. The ET then proceeds on a ballistic reentry for a safe impact in the ocean. Figure B-28 shows the ET construction.

FIGURE B-25: Solid-rocket booster parts.

FIGURE B-26: Shuttle solid-rocket booster.

FIGURE B- 27: Orbital maneuvering subsystem engine pod.

FIGURE B-28: Shuttle external tank.

4.0 INERTIAL UPPER STAGE

The IUS vehicle, shown in Figure B-29, is 5.0 m (16.4 ft) long, and 5.4 m (7.6 ft) diameter in the cylindrical end, flaring to 2.9 m (9.5 ft) diameter at the forward end. The vehicle consists of two stages. The first stage includes the interstage structure, the large solid rocket motor (SRM), and avionics that are required only prior to staging. The second stage has a smaller solid rocket motor and the equipment support section that houses the majority of the vehicle avionics.

4.1 Propulsion Subsystem

All IUS solid rocket motors are of similar construction and materials but are provided in two sizes: large or small. The motors can be loaded with varying quantities of propellant to satisfy specific mission requirements. The large rocket motor (SRM-1) (Figure B-30) is 2.3 m (92 in.) in diameter and is equipped with a vectorable nozzle. The small rocket motor (SRM-2) (Figure B-31) is 1.6 m (63 in.) in diameter and has a vectorable nozzle with extendible exit cones (EECs). Each SRM consists of an igniter, a loaded motor case, and a vectorable nozzle assembly. The IUS propulsion subsystem is shown in Figure B-32. Table B-8 provides data regarding physical and performance characteristics relevant to these items.

4.2 Reaction Control Subsystem (RCS)

The RCS includes the propellant tank assemblies, RCS manifold assembly, and the rocket engine module. The RCS performs the thrust functions required for coast attitude control, SRM powered flight roll control, vehicle maneuvers, velocity vernier for SRM impulse dispersions, and spacecraft collision avoidance maneuvers. The RCS propellant (hydrazine) remains sealed in the RCS tank until after the IUS has been deployed and is a safe distance from the shuttle orbiter; this is usually 600 s after separation or at a separation distance of 60 m (200 ft).

The Galileo Mission will employ only one RCS propellant tank loaded with 14.5 kg (32 lb) of propellant. The tank is made of a titanium alloy (Ti-6Al-4V), is 0.53 m (21 in.) in diameter, and is equipped with an internal elastomeric diaphragm for positive propellant expulsion. After the propellant has been placed in the tank, a gas pressurized to 2.8 MPa (400 to 405 psi) is introduced into the driver side of the bladder. The tank rated operating pressure is 3.0 MPa (430 psi) with a design burst pressure of 11.9 MPa (1720 psi).

The general location of the RCS tank and thrusters can be noted in Figure B-29.

Figure B-29: Two-Stage IUS Vehicle

ALL DIMENSIONS ARE
IN INCHES

Figure B-30: Solid Rocket Motor SRM-1

ALL DIMENSIONS ARE
IN INCHES

EXTENDIBLE EXIT CONE DEPLOYMENT
MECHANISM NOT SHOWN

Figure B-31: Solid Rocket Motor SRM-2

Figure B-32: IUS Propulsion Subsystem

Table B-8: SRM Loading Particulars

<u>SRM DESCRIPTION AND PERFORMANCE^a</u>	<u>SRM-1</u>	<u>WITH EEC</u>	<u>WITHOUT EEC</u>
Motor Description			
Overall length, in.	24	77.98 (Stowed) 117.85 (Extended)	74.2
Case diameter, in.	92.0	63.3	63.3
Total loaded weight, lb. m.	22,907	6689	6598
Propellant weight, lb. m.			
Onload motor ^b	21,580	6059	6059
Full load motor	21,400	6000	6000
Offload motor (max. offload)	10,700	3000	3000
Igniter propellant weight, lb.	3.8	1.8	1.8
Nozzle length, in.	59.3	36.68 (Stowed)	32.9
TVC capability, degrees	4° Max	7° Max	7° Max
Motor Performance (16°C):			
Duration time ^c , s	149.2	109.3	109.3
Average pressure, psia	621.8	564.3	564.3
Maximum pressure, psia	836.6	797.1	797.1
Average thrust, lb. f.	42190.7	16742.3	15945.8
Maximum thrust, lb. f.	57483.6	23664.3	22538.3
Average expansion ratio	57.53	161.63	44.02
Average effective ISP, s	293.3	301.2	286.9
Total Impulse, lb. s	6292237	1829868	1742811

^aTotal loaded weight, nozzle throat diameter and motor performance data are applicable to motors with the following baseline propellant load configuration.

SRM-1 - Full load (100%) propellant

SRM-2 - Onload (101%) propellant

^b"Onload" motors are motors machined with a "skin cut" which removes the minimum amount of propellant necessary to ensure ignition. These motors, in contrast to the other motors, are machined to a dimension instead of a weight and the propellant weight shown is a nominal weight. This propellant load provides maximum motor performance and is the baseline load for SRM-2 motors and is an option available on certain SRM-1 motors. Onload motors will be used for planetary missions.

^cDuration time is defined as the time from the ignition signal until the burn area equals zero.

4.3 Weight Summary

The estimated weight for the IUS with the Galileo spacecraft is as follows:

<u>Component</u>	<u>kg</u>	<u>lb</u>
Spacecraft Separated Weight	2,501	5,509
Airborne Support Equipment	683	1,504
Boeing Airborne Support Equipment	2,596	5,717
IUS Vehicle (Stages 1 and 2)	14,703	32,387
Galileo Adapter	155	341
Totals	20,638	45,458

5.0 TRAJECTORY AND FLIGHT CHARACTERISTICS

The General Electric Company in Document Number 87DS4213, August 1987 (Reference 2), reports typical flight parameters for a Space Shuttle launch. The selected graphs included in this document are the following: altitude as a function of time (Figure B-33); relative velocity as a function of time (Figure B-34); relative acceleration as a function of time (Figure B-35); range as a function of time (Figure B-36); and range of instantaneous impact point as a function of time (Figure B-37).

The interplanetary trajectory for the Galileo Mission was presented earlier in Figure B-13.

6.0 LAUNCH SITE

The Space Shuttle will be launched from either Launch Pad 39A or 39B at the KSC, Cape Canaveral, Florida. Figure B-38 is a map of KSC, which shows the relationships among the launch pads, Vehicle Assembly Building (VAB on the map), and the Shuttle Landing Facility. Figures B-39 and B-40 provide details of the two potential launch pads for the Galileo launch.

Figure B-33: STS Trajectory - Altitude as a Function of Time

Figure B-34: Shuttle Trajectory - Shuttle Relative Velocity Versus Time

Figure B-35: STS Trajectory - Shuttle Relative Acceleration

Figure B-36: Shuttle Trajectory - Shuttle Range as a Function of Time

Figure B-37: Shuttle Trajectory - Range of Instantaneous Impact as a Function of Time

FIGURE B-38: The overall layout of Launch Complexes 39 and 39B with respect to the VAB and Shuttle Landing Facility is shown above.

26

APPENDIX B-1

LWRHU DRAWINGS

The following are MRC's fabrication drawings for the LWRHU components:

AYC-790095, "Radioisotopic Heater Unit"

AYC-790096, "Clad Body Assy"

AYC-790097, "Clad Cap, Vent End Assy"

AYC-790098, "Frit"

AYC-790099, "Clad Cap, Vent End"

AYC-790100, "Clad Body"

AYC-790101, "Shim"

AYC-790105, "Clad Cap, Closure End"

AYC-790106, "Pellet, Fuel"

AYD-790379, "Aeroshell Assembly"

AYD-790380, "Aeroshell Body"

AYC-790381, "Insulator Cap"

AYC-790382, "Outer Insulator Body"

AYC-790383, "Middle Insulator Body"

AYC-790384, "Inner Insulator Body"

AYC-790385, "Aeroshell End Cap"

[illegible]

48 C.061.741

-SI METRIC-

CLASS. BY: 1000 000 000 000

DESCRIPTION: 1000 000 000 000

DATE: 1000 000 000 000

REV. 1

REV. 2

REV. 3

REV. 4

REV. 5

REV. 6

REV. 7

REV. 8

REV. 9

REV. 10

REV. 11

REV. 12

REV. 13

REV. 14

REV. 15

REV. 16

REV. 17

REV. 18

REV. 19

REV. 20

REV. 21

REV. 22

REV. 23

REV. 24

REV. 25

REV. 26

REV. 27

REV. 28

REV. 29

REV. 30

REV. 31

REV. 32

REV. 33

REV. 34

REV. 35

REV. 36

REV. 37

REV. 38

REV. 39

REV. 40

REV. 41

REV. 42

REV. 43

REV. 44

REV. 45

REV. 46

REV. 47

REV. 48

REV. 49

REV. 50

REV. 51

REV. 52

REV. 53

REV. 54

REV. 55

REV. 56

REV. 57

REV. 58

REV. 59

REV. 60

REV. 61

REV. 62

REV. 63

REV. 64

REV. 65

REV. 66

REV. 67

REV. 68

REV. 69

REV. 70

REV. 71

REV. 72

REV. 73

REV. 74

REV. 75

REV. 76

REV. 77

REV. 78

REV. 79

REV. 80

REV. 81

REV. 82

REV. 83

REV. 84

REV. 85

REV. 86

REV. 87

REV. 88

REV. 89

REV. 90

REV. 91

REV. 92

REV. 93

REV. 94

REV. 95

REV. 96

REV. 97

REV. 98

REV. 99

REV. 100

REV. 101

REV. 102

REV. 103

REV. 104

REV. 105

REV. 106

REV. 107

REV. 108

REV. 109

REV. 110

REV. 111

REV. 112

REV. 113

REV. 114

REV. 115

REV. 116

REV. 117

REV. 118

REV. 119

REV. 120

REV. 121

REV. 122

REV. 123

REV. 124

REV. 125

REV. 126

REV. 127

REV. 128

REV. 129

REV. 130

REV. 131

REV. 132

REV. 133

REV. 134

REV. 135

REV. 136

REV. 137

REV. 138

REV. 139

REV. 140

REV. 141

REV. 142

REV. 143

REV. 144

REV. 145

REV. 146

REV. 147

REV. 148

REV. 149

REV. 150

REV. 151

REV. 152

REV. 153

REV. 154

REV. 155

REV. 156

REV. 157

REV. 158

REV. 159

REV. 160

REV. 161

REV. 162

REV. 163

REV. 164

REV. 165

REV. 166

REV. 167

REV. 168

REV. 169

REV. 170

REV. 171

REV. 172

REV. 173

REV. 174

REV. 175

REV. 176

REV. 177

REV. 178

REV. 179

REV. 180

REV. 181

REV. 182

REV. 183

REV. 184

REV. 185

REV. 186

REV. 187

REV. 188

REV. 189

REV. 190

REV. 191

REV. 192

REV. 193

REV. 194

REV. 195

REV. 196

REV. 197

REV. 198

REV. 199

REV. 200

REV. 201

REV. 202

REV. 203

REV. 204

REV. 205

REV. 206

REV. 207

REV. 208

REV. 209

REV. 210

REV. 211

REV. 212

REV. 213

REV. 214

REV. 215

REV. 216

REV. 217

REV. 218

REV. 219

REV. 220

REV. 221

REV. 222

REV. 223

REV. 224

REV. 225

REV. 226

REV. 227

REV. 228

REV. 229

REV. 230

REV. 231

REV. 232

REV. 233

REV. 234

REV. 235

REV. 236

REV. 237

REV. 238

REV. 239

REV. 240

REV. 241

REV. 242

REV. 243

REV. 244

REV. 245

REV. 246

REV. 247

REV. 248

REV. 249

REV. 250

REV. 251

REV. 252

REV. 253

REV. 2

APPENDIX B-2

ABBREVIATIONS AND ACRONYMS FOR VOLUME IA AND IB

<u>Abbreviation</u>	<u>Definition</u>	<u>Where Referenced</u>
AMD	Accident Model Document	Table A-1
V	Change in Velocity	Figure B-13
DOE	Department of Energy	Abstract
EEC	Extendible Exit Cone	B.4.1
EG&G-MAT	EG&G Mound Applied Technologies	Cover
ET	External Tank	A.2.4
FAST	Failure Abort Sequence Tree	A.3.2
FSAR	Final Safety Analysis Report	A.1.1
FWPF	Fine Weave-Pierced Fabric	A.2.1
γ	Reentry Angle	A.3.3
g, G	Gravity	B.1.2.10.2.3
GPHS	General Purpose Heat Source	A.1.1
GSE	Ground Support Equipment	B.1.5
IIP	Instantaneous Impact Point	Figure B-37
IUS	Inertial Upper Stage	Table A-1
ISP	Specific Impulse	Table B-8
JPL	Jet Propulsion Laboratory	B.1.2
keV	Kilo Electron Volts	Figure B-10
KSC	Kennedy Space Center	Table A-1

Continued.....

APPENDIX B-2 - Continued

ABBREVIATIONS AND ACRONYMS FOR VOLUME 1A AND 1B

<u>Abbreviation</u>	<u>Definition</u>	<u>Where Referenced</u>
LANL	Los Alamos National Laboratory	B.1.1
LH ₂	Liquid Hydrogen	B.3.2.1
LO ₂	Liquid Oxygen	Figure B-24
LOX	Liquid Oxygen	B.3.2.1
LWRHU	Light-Weight Radioisotope Heater Unit	Abstract
MECO	Main Engine Cut Off	A.2.4
MET	Mission Elapsed Time	A.2.4
MEV	Million Electron Volts	Table B-11
MMH	Monomethylhydrazine	B.3.2.3
MRC	Monsanto Research Corporation	Abstract
n	Neutron(s)	B.1.2.9
NASA	National Aeronautics and Space Administration	Abstract
NRAD	Nuclear Risk Analysis Document	Table A-1
OMS	Orbital Maneuvering System	A.2.4
PCM	Photocalibration Mirror	Table B-7

Continued.....

APPENDIX B-2 - Continued

ABBREVIATIONS AND ACRONYMS FOR VOLUME IA AND IB

<u>Abbreviation</u>	<u>Definition</u>	<u>Where Referenced</u>
PG	Pyrolytic Graphite	A.2.1
ppm	Parts per Million	B.1.2.9
PWS	Plasma Wave Subsystem	Table B-7
RCS	Reaction Control System	A.2.4
RDD	Reference Design Document	Table A-1
RHU	Radioisotope Heater Unit (JPL)	Figure B-3
rpm	Rotations per Minute	8.2.4.2
RPM	Retropropulsion Module	Table B-5
RSS	Range Safety System	Table A-2
RTG	Radioisotope Thermoelectric Generator	A.1.1
S&A	Safe and Arm	Figure B-32
SAR	Safety Analysis Report	A.1.1
SRB	Solid Rocket Booster	A.2.4
SRM	Solid Rocket Motor	B.4.0
SSMEs	Space Shuttle Main Engines	A.1.0
T	Time	A.2.4
TBS	To be Supplied	Table B-5

APPENDIX B-2 - Continued

ABBREVIATIONS AND ACRONYMS
FOR VOLUME IA AND IB

<u>Abbreviation</u>	<u>Definition</u>	<u>Where Referenced</u>
TVC	Thrust Vector Control	Figure B-30
VAB	Vehicle Assembly Building	B.6.0
VEEGA	Venus-Earth-Earth Gravity Assist	A.2.2
VPF	Vertical Processing Facility	B.2.2

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

APPENDIX B

REFERENCES

1. Tate, R. E., The Light-Weight Radioisotope Heater Unit (LWRHU): A Technical Description of the Reference Design, LA-9078-MS, Los Alamos National Laboratory, (January 1982).
2. FSAR II: Reference Design Document for the Galileo Mission, 87SD54213, General Electric Company, (August 1987).
3. Uzzell, Jr., J. C., Handbook of Thermal Properties for Nuclear Power System Reentry Analysis, ANSP-169, Johns Hopkins University-Applied Physics Laboratory, (1979).
4. Bockris, J. O'M., et al., "Physicochemical Measurements at High Temperatures", Butterworths Scientific Publications, (1959).
5. NERVA Program, Report No. 2275, Volume 2, Aerojet General, (1966).
6. "Acceptance Specification for FWPF Graphite", NS0060-01-02, General Electric Company, (1982).
7. Johnson, E. W. and Rinehart, G. H., Private Communicate, (November 12, 1984).
8. Campbell, A. R. and Hawley, E. A., Internal MRC memorandum, (October 16, 1984).
9. Anderson, M. E., "Neutron Flux, Spectrum and Dose Equivalent Measurements for a 4500-W (Th) PuO General Purpose Heat Source", MLM-3248, Monsnato Research Corporation, (May 9, 1985).
10. "Safety Analysis Report for Packing (SARP) USA/5790/BLF (DOE-AL) and USA/5791/BLF (DOE-AL)" MLM-2242, Monsnato Research Corporation, (January 25, 1980).
11. "Space Shuttle Data for Planetary Mission Radioisotope Thermoelectric Generator (RTG) Safety Analysis", NSTS08116, Johnson Space Center, (1987).

NOTICE TO READER

Throughout the volumes comprising the LWRHU SAR, use is made as much as practicable of the SI (International System of Units) nomenclature for units. The four tables below are copied from ASTM E380-84, "Standard for Metric Practice."

TABLE 7 Units in Use with SI Temporarily

Quantity	Unit	Symbol	Definition
energy	kilowatthour	kWh	1 kWh = 3.6 MJ
cross section	barn	b	1 b = 10^{-28} m ²
pressure	bar	bar	1 bar = 10^5 Pa
activity (of a radionuclide)	curie	Ci	1 Ci = 3.7×10^{10} Bq
exposure (X and gamma rays)	roentgen	R	1 R = 2.58×10^{-4} C/kg
absorbed dose	rad	rd	1 rd = 0.01 Gy

TABLE 1 Base SI Units

Quantity	Unit	Symbol
length	metre	m
mass	kilogram	kg
time	second	s
electric current	ampere	A
thermodynamic temperature	kelvin	K
amount of substance	mole	mol
luminous intensity	candela	cd

TABLE 3 Derived SI Units with Special Names

Quantity	Unit	Sym- bol	Formula
frequency (of a periodic phenomenon)	hertz	Hz	1/s
force	newton	N	kg·m/s ²
pressure, stress	pascal	Pa	N/m ²
energy, work, quantity of heat	joule	J	N·m
power, radiant flux	watt	W	J/s
quantity of electricity, electric charge	coulomb	C	A·s
electric potential, potential difference, electromotive force	volt	V	W/A
electric capacitance	farad	F	C/V
electric resistance	ohm	Ω	V/A
electric conductance	siemens	S	A/V
magnetic flux	weber	Wb	V·s
magnetic flux density	tesla	T	Wb/m ²
inductance	henry	H	Wb/A
Celsius temperature	degree Celsius	°C	K-273.15
luminous flux	lumen	lm	cd·sr
illuminance	lux	lx	lm/m ²
activity (of a radionuclide)	becquerel	Bq	1/s
absorbed dose	gray	Gy	J/kg
dose equivalent	sievert	Sv	J/kg

TABLE 4 Some Common Derived Units of SI

Quantity ¹	Unit	Symbol
absorbed dose rate	gray per second	Gy/s
acceleration	metre per second squared	m/s ²
angular acceleration	radian per second squared	rad/s ²
angular velocity	radian per second	rad/s
area	square metre	m ²
concentration (of amount of substance)	mole per cubic metre	mol/m ³
current density	ampere per square metre	A/m ²
density, mass	kilogram per cubic metre	kg/m ³
electric charge density	coulomb per cubic metre	C/m ³
electric field strength	volt per metre	V/m
electric flux density	coulomb per square metre	C/m ²
energy density	joule per cubic metre	J/m ³
entropy	joule per kelvin	J/K
exposure (X and gamma rays)	coulomb per kilogram	C/kg
heat capacity	joule per kelvin	J/K
heat flux density	watt per square metre	W/m ²
irradiance		
luminance	candela per square metre	cd/m ²
magnetic field strength	ampere per metre	A/m
molar energy	joule per mole	J/mol
molar entropy	joule per mole kelvin	J/(mol·K)
molar heat capacity	joule per mole kelvin	J/(mol·K)
moment of force	newton metre	N·m
permeability (magnetic)	henry per metre	H/m
permittivity	farad per metre	F/m
power density	watt per square metre	W/m ²
radiance	watt per square metre steradian	W/(m ² ·sr)
radiant intensity	watt per steradian	W/sr
specific heat capacity	joule per kilogram kelvin	J/(kg·K)
specific energy	joule per kilogram	J/kg
specific entropy	joule per kilogram kelvin	J/(kg·K)
specific volume	cubic metre per kilogram	m ³ /kg
surface tension	newton per metre	N/m
thermal conductivity	watt per metre kelvin	W/(m·K)
velocity	metre per second	m/s
viscosity, dynamic	pascal second	Pa·s
viscosity, kinematic	square metre per second	m ² /s
volume	cubic metre	m ³
wave number	1 per metre	1/m

TABLE 5 SI Prefixes

Multiplication Factor	Prefix	Symbol
1 000 000 000 000 000 000 = 10 ¹⁸	exa	E
1 000 000 000 000 000 = 10 ¹⁵	peta	P
1 000 000 000 000 = 10 ¹²	tera	T
1 000 000 000 = 10 ⁹	giga	G
1 000 000 = 10 ⁶	mega	M
1 000 = 10 ³	kilo	k
100 = 10 ²	hecto ⁴	h
10 = 10 ¹	deka ⁴	da
0.1 = 10 ⁻¹	deci ⁴	d
0.01 = 10 ⁻²	centi ⁴	c
0.001 = 10 ⁻³	milli	m
0.000 001 = 10 ⁻⁶	micro	μ
0.000 000 001 = 10 ⁻⁹	nano	n
0.000 000 000 001 = 10 ⁻¹²	pico	p
0.000 000 000 000 001 = 10 ⁻¹⁵	femto	f
0.000 000 000 000 000 001 = 10 ⁻¹⁸	atto	a

⁴ To be avoided where practical

DISTRIBUTION LIST - LWRHU FSAR

DOE

W. Forster
R. J. Grandfield
R. T. Kratzke (2)
J. Merrick
A. L. Mowery, Jr. (10)
C. B. Quinn
P. Saxman
D. J. Skinner
J. A. Turi

OSTI

UC-744 (82)

EG&G MAT

W. R. Amos
R. A. Fischbein
C. W. Huntington
D. E. Michel
W. H. Smith
R. E. Vallée
Library (3)
Publications

LANL

S. E. Bronisz
C. M. Seabourn
H. Sullivan
T. C. Wallace
R. W. Zoicher

NUS

B. W. Bartram
R. W. Englehart
R. W. Juback

FSC

R. T. Carpenter
M. B. Eck
E. Skrabek

JPL

R. W. Campbell
R. M. Clayton
M. J. Cork
S. Dawson (20)
R. G. Ivanoff
P. Jaffe
A. D. McDonald
W. G. Meeks
L. C. Montgomery
L. T. Shaw
R. J. Spehalski

JSC

H. Battaglia
R. H. Brown
R. F. Fletcher
R. H. Kohrs
H. O. Pohl

OTHER NASA

J. Anderson
G. L. Bennett
F. Benz
D. B. Channell
W. Fletcher
L. B. Gray
J. A. Lovingood
G. M. Marmaro
D. McConnell
R. Murray
J. R. Reynolds
R. W. Schaupp

DOD

Lt. D. Blaylock
B. F. Boyd
Maj. G. Buckner
Capt. J. F. Burke
Lt. Col. J. G. Burr
Capt. N. J. Clemens
Lt. Col. W. Gornall
Lt. B. Haswell
K. Hill
F. Jankowski
Col. J. P. Joyce (2)
K. L. Kaisler
Capt. J. A. Leonowich
Capt. J. Lund
J. W. Marshall
Maj. T. Meyers
Lt. Col. W. A. Neighbors
Lt. Col. R. C. Nelson
Lt. Col. J. Rice
Lt. Col. J. A. Sholtis
Lt. Col. D. G. Woods

OTHER

W. Ailor
D. C. Anderson
T. M. Beasley
C. T. Bradshaw
C. R. Chappel
J. Coleman
R. J. Cuddihy
E. Goldberg
M. Goldman
J. C. Hagan
D. Hayes
E. W. Johnson (10)
R. J. Kurzeja
J. A. Leary
W. H. McColloch
J. F. Park
L. C. Parker
C. R. Phillips
W. Riehl
L. J. Ullian