81
7/16/89
(RB)

(4)

DR # 0423-5

MLM-3540
NUS-5153

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

Volume III: NUCLEAR RISK ANALYSIS DOCUMENT

November 30, 1988

Prepared for

U.S. Department of Energy
Contract No. DE-AC01-87NE134

By

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

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.

TABLE OF CONTENTS

<u>Section</u>		<u>Page</u>
1.0 INTRODUCTION		1-1
2.0 SUMMARY	MLM--3540-Vol.3	2-1
2.1 Methodology	DE89 005496	2-1
2.2 Source Term Characteristics		2-1
2.3 Results		2-3
3.0 ACCIDENT SCENARIOS AND CONSEQUENCES		3-1
4.0 INTEGRATED MISSION RISK ANALYSIS		4-1
5.0 REFERENCES		5-1
III-B CHANGES TO VOLUMES I AND II DUE TO VEEGA PROBABILITY		6-1

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.

LIST OF FIGURES

<u>Figure</u>		<u>Page</u>
2-1	Integrated Risk Assessment Methodology	2-2
2-2	Radiological Consequence Summary	2-6
3-1	FAST for Phase 5 (All Zones)	3-2
3-2	FAST for Phase 5 (Zone A)	3-3
3-3	FAST for Phase 5 (Zone B)	3-4

LIST OF TABLES

<u>Table</u>		<u>Page</u>
2-1	Light-Weight Radioisotope Heater Units, Most Probable, Maximum, and Expectation Cases	2-4
2-2	Particle Size Distribution for Release Cases	2-5
2-3	Light Weight Radioisotope Heater Units, Summary of Radiological Consequences	2-7
2-4	Light-Weight Radioisotope Heater Units, Mission Risk Summary	2-8
2-5	Individual Risk from Various Causes	2-9
3-1	Radiological Consequences (Phase 5, Most Probable)	3-7
3-2	Radiological Consequences (Phase 5, Maximum)	3-8
4-2	Radiological Consequences (Phase 5, Expectation)	4-2

1.0 INTRODUCTION

The Light-Weight Radioisotope Heater Unit (LWRHU) Final Safety Analysis Report (FSAR), Volume II, Accident Model Document (AMD) describes potential accident scenarios during the Galileo mission and evaluates the response of the LWRHUs to the associated accident environments. Any resulting source terms, consisting of PuO₂ (with Pu-238 the dominant radionuclide), are then described in terms of curies released, particle size distribution, release location, and probabilities. This volume (LWRHU-FSAR, Volume III, Nuclear Risk Analysis Document (NRAD)) contains the radiological analyses which estimate the consequences of the accident scenarios described in the AMD. It also contains the quantification of mission risks resulting from the LWRHUs based on consideration of all accident scenarios and their probabilities. Estimates of source terms and their characteristics derived in the AMD are used as inputs to the analyses in the NRAD.

The Failure Abort Sequence Trees (FASTs) presented in the AMD define events for which source terms occur and quantify them. Based on this information, three types of source term cases (most probable, maximum, and expectation) for each mission phase were developed for use in evaluating the radiological consequences and mission risks. The three release cases are defined as follows:

1. Most Probable Case

The FASTs for each mission phase are examined and the single release having the highest probability is selected. All associated releases within the FAST sub-branch (e.g. vapor release at high altitude and bare fuel pellet impact on rock) comprise the source term.

2. Maximum Case

Within a mission phase, the single fuel release that maximizes radiological consequences is selected. This release and all related releases comprise the source term.

3. Expectation Case

The expectation case uses all of the predicted releases and their probabilities to define a probability-weighted source term, considering all of the scenarios postulated in a mission phase. The purpose of the expectation case is to develop the components of a risk analysis considering the entire mission phase. It represents a probabilistic combination of all accident scenarios considered. In this context, risk is defined as the product of accident probability and consequence, summed over all accidents.

The radiological consequences analyzed for each of the cases described above include the following:

1. The "short-term" dose which results from the initial exposure during plume passage. The doses are 70 year dose commitments resulting from the extended retention of material in the body.
2. The "long-term" dose which would result from continuing exposure to materials in the environment over an extended period following release. Long-term dose include those due to inhalation of resuspended material and ingestion of contaminated food over a 70 year period.
3. Estimates of land- and water-surface areas contaminated. This contamination results from deposition of materials from a passing plume from ground-level and/or elevated releases.

The information on radiological consequences reported in the NRAD includes the following:

1. Numbers of persons estimated to be subject to greater than specified levels of short-term and long-term doses. The reported doses are in terms of "committed effective dose equivalents" as defined in ICRP-30 (Reference 1) with the dose commitment period extended from

50 to 70 years, formerly called "effective whole body dose" in some analyses.

2. Total short-term and long-term population doses. In calculating population doses, the concept of de minimis has been used, meaning a dose level below concern and below which no health effects are assumed. For the purpose of the NRAD, the de minimis dose was taken to be 1 mrem/year and 50 mrem total individual dose commitment. Total population doses are reported both with and without de minimis.
3. The maximum short-term and long-term doses to individuals
4. Estimates of land and surface water areas contaminated above specified levels. The guidance level of $0.2 \mu\text{Ci}/\text{m}^2$ established by EPA, above which consideration should be given to cleanup, has been used as a reference level.

The remaining sections of this volume present the results of the NRAD analyses. Section 2.0 summarizes the overall methodology used and the NRAD results. Section 3.0 describes the accident scenarios and radiological consequences in terms of the most probable and maximum cases. Section 4.0 presents the overall mission risks determined based on the expectation cases. References are presented in Section 5.0.

The methodology used in the NRAD analyses is briefly addressed in Sections 2.0 and 3.0 where appropriate. Details on the methodology are contained in Reference 2 as a series of appendices.

2.0 SUMMARY

2.1 METHODOLOGY

For each mission phase having postulated accident scenarios leading to source terms, the radiological consequences resulting from the most probable, maximum, and expectation cases were calculated using the process shown in Figure 2-1.

The FSAR-EMERGE model is used to perform atmospheric transport and dispersion calculations for releases within the troposphere (less than approximately 10 kilometers altitude) and within 100 kilometers horizontal distance from the release location. FSAR-EMERGE, described in Reference 2, is a Gaussian puff-trajectory model which treats meteorology that varies in time and altitude and accounts for vertical plume configuration; particle-size-dependent transport, deposition; and plume depletion, and sea-breeze recirculation.

Releases at high altitude are treated by a particle trajectory model (HIPAR) in the case of large particles (greater than 10 microns) and by an empirical model (LOPAR) derived from atmospheric weapons test data in the case of small particulates or vapor (less than or equal to 10 microns). These models and their application are discussed further in Reference 2.

Radiation doses to populations are determined by calculating exposure of population distributions in the region of release to time-integrated airborne and deposited concentrations of PuO_2 , accounting for variations over meteorological conditions. The population distributions, meteorology, exposure pathway parameters, and internal dosimetry models used in the analysis are presented in Reference 2.

2.2 SOURCE TERM CHARACTERISTICS

Based on the analyses presented in the AMD, source terms occur only in mission phase 5, VEEGA reentry. These source terms result from melting of the LWRHU cladding, partial vaporization of PuO_2 fuel at high altitude,

Figure 2-1
INTEGRATED RISK ASSESSMENT METHODOLOGY

and/or subsequent rock impacts of bare pellets. The resulting source terms for the most probable, maximum, and expectation cases are summarized in Table 2-1. The particle size distribution of particulates following rock impact of bare pellets is presented in Table 2-2, as developed in the AMD.

2.3 RESULTS

The radiological consequences for the most probable, maximum, and expectation cases in phase 5 are summarized in Table 2-3 in terms of population dose and environmental contamination. Population versus dose distribution curves corresponding to these cases are presented in Figure 2-2.

The expectation cases for the mission are used to quantify risk. The risk of a mission phase is defined as the product of the total release probability and the radiological consequences for the expectation case. The risk from a mission phase considers all the accidents in that phase as represented by the expectation case source term. Similarly, the mission risk is the sum of the risk of all mission phases.

The results of the risk analysis are presented in Table 2-4. The health effects reported are in terms of excess cancer fatalities estimated by multiplying the population dose above de minimis by a health effects estimator of 185 excess cancer fatalities per million person-rem. The basis of this health effects estimator is discussed in Reference 2. The results have also been put in terms of individual lifetime risk of cancer fatality resulting from the accident. These risks can be compared to the approximate annual risk of fatality to an individual from various accidental causes, as summarized in Table 2-5.

Table 2-1

Light Weight Radioisotope Heater Units
Most Probable, Maximum, and expectation Release Cases

<u>Phase</u>	<u>Accident Type</u>	<u>Release Probability</u>	<u>Source Term (Ci)</u>	<u>Release Category</u>	<u>Description</u>
<u>Most Probable Release Case</u>					
5	Zone B* VEEGA Reentry	5.00E-09	250	High altitude	<ul style="list-style-type: none">• Vapor• 0° latitude
			135	Ground-level	<ul style="list-style-type: none">• Rock impact of bare fuel pellets• 0° latitude
<u>Maximum Release Case</u>					
5	Zone A* VEEGA Reentry	2.50E-09	155	Ground-level	<ul style="list-style-type: none">• Rock impact of bare fuel pellets• 33° N latitude
<u>Expectation Release Case</u>					
5	VEEGA Reentry	7.50E-09	1145	High altitude	<ul style="list-style-type: none">• Vapor• 0° N latitude
			142	Ground-level	<ul style="list-style-type: none">• Rock impact of bare fuel pellets• 0° N latitude

*Zone A includes reentry angles greater than 4 degrees and less than or equal to 7.5 degrees.

Zone B includes reentry angles greater than 7.5 degrees and less than or equal to 20 degrees.

TABLE 2-2

Particle-Size Distribution for Release Cases

<u>Particle Size Range, μ</u>	<u>Fraction in Size Range^{a, b}</u>
+850	0.087
420-840	0.147
149-420	0.304
105-149	0.075
63-105	0.045
44-63	0.139
30-44	0.121
20-30	0.044
10-20	0.034
9-10	0.0003
8-9	0.0004
7-8	0.0003
6-7	0.0004
5-6	0.0005
4-5	0.0004
3-4	0.0004
2-3	0.0004
1-2	0.0005
0-1	0.0004

a. Average of particle size distributions for Clads-035
043, and 046.

b. Particle size for vapor releases is 0.02 μm .

Table 2-3

Light Weight Radioactive Heater Units
Summary of Radiological Consequences

<u>Case^a</u>	<u>Release Probability</u>	<u>Population Dose, Person-Rem</u>		<u>Area Contaminated Above 0.2 μCi/m², km²</u>			
		<u>Total^b</u>	<u>Above DeMinimis^c</u>	<u>Dry Land</u>	<u>Swamp</u>	<u>Inland Water</u>	<u>Ocean</u>
Most Probable	5.00E-09	2.66E+05	8.80	4.80E-01	0.00	1.08E-02	0.00
Maximum	2.50E-09	-	5.87E+01	1.20	0.00	1.72E-01	0.00
Expectation	7.50E-09	2.18E+06	9.28	4.80E-01	0.00	1.08E-02	0.00

^aMission Phase 5

^bDue primarily to high altitude vapor releases

^cDue entirely to ground level releases

Figure 2-2 RADIOLOGICAL CONSEQUENCES SUMMARY

Table 2-4

Light Weight Radioisotope Heater Units
Mission Risk Summary

<u>Release^a Probability</u>	<u>Population Dose, Person-Rem Above De Minimis</u>	<u>Excess Health^b Effects</u>	<u>Population^b Affected</u>	<u>Average Individual Risk</u>
7.50E-09	9.28	1.72E-03	4.68E+01	2.76E-13

^aMission Phase 5.

^bHealth effects based on 1.85E-04 excess cancer fatalities per person-rem.

^cApplicable to persons receiving dose above de minimis.

^dAverage individual risk equals probability times health effects, divided by population affected.

TABLE 2-4

TABLE 2-5

Individual Risk from Various Causes^a

<u>Accident Type</u>	<u>Total Number for 1969</u>	<u>Approximate Individual Risk Early Fatality Probability/yr^a</u>
Motor Vehicle	55,791	3×10^{-4}
Falls	17,827	9×10^{-5}
Fires and Hot Substance	7,451	4×10^{-5}
Drowning	6,181	3×10^{-5}
Poison	4,516	2×10^{-5}
Firearms	2,309	1×10^{-5}
Machinery (1968)	2,054	1×10^{-5}
Water Transport	1,743	9×10^{-6}
Air Travel	1,778	9×10^{-6}
Falling Objects	1,271	6×10^{-6}
Electrocution	1,148	6×10^{-6}
Railway	884	4×10^{-6}
Lightning	160	5×10^{-7}
Tornadoes	118 ^b	4×10^{-7}
Hurricanes	90 ^c	4×10^{-7}
All Others	8,695	4×10^{-5}
All Accidents	115,000	6×10^{-4}
Diseases	1,750,000	8×10^{-3}

a. Based on total 1969 U.S. population, except as noted.

b. (1953-1971 avg.)

c. (1901-1972 avg.)

3.0 ACCIDENT SCENARIOS AND CONSEQUENCES

This section presents descriptions of the accident scenarios leading to PuO₂ releases from LWRHUs and resulting radiological consequences based on the most probable and maximum cases.

3.1 ACCIDENT SCENARIOS

Based on the analyses in the AMD, the accident environments postulated in Phases 0 through 4 are not severe enough to result in PuO₂ releases from LWRHUs, and cladding integrity is retained. Source terms are predicted to occur only as a result of VEEGA reentry (Phase 5). In the AMD, LWRHU response to VEEGA reentry heating was modeled in terms of four reentry angle ranges, identified as Zones A through D, respectively. These reentry zones are defined as follows:

- Zone A: $4^{\circ} < \gamma < 7.5^{\circ}$
- Zone B: $7.5^{\circ} < \gamma < 20^{\circ}$
- Zone C: $20^{\circ} < \gamma < 40^{\circ}$
- Zone D: $\gamma > 40^{\circ}$.

The shallow reentry angle associated with Zone A maximizes thermal heating, resulting in aeroshell burn-through and extensive clad melting. Zone B reentry leads to partial aeroshell burn-through and partial clad melting. The LWRHUs are predicted to survive reentry intact for zones C and D. These reentry scenarios and LWRHU response for VEEGA reentry are summarized in FASTs presented in Figures 3-1 through 3-3. The overall FAST covering reentry in all four zones is presented in Figure 3-1. The more detail FASTs for Zones A and B are presented in Figure 3-2 and 3-3, respectively.

3.2 RADIOLOGICAL CONSEQUENCES

The source terms resulting from Zone A and B reentries include both vaporization of PuO₂ at high altitude during reentry and/or rock impact of bare fuel pellets. For a Zone A or B reentry, it is likely that the footprint of impact locations is so large that world wide fractions of

Figure 3-1
FAST FOR PHASE 5 (ALL ZONES)

Figure 3-2
FAST FOR PHASE 5 (ZONE A)

Figure 3-3
FAST FOR PHASE 5 (ZONE B)

water, land, and rock surfaces can be used to partition the impact types. The radiological consequences associated with the most probable and maximum cases are presented in the following sections.

3.2.1 Phase 5, Most Probable Case

The most probable case consists of a Zone B reentry with an initiating probability of $5.00\text{E-}08$. The 34 LWRHUs in the probe survive intact due to the reentry protection provided by the probe. The remaining 95 LWRHUs in the Galileo spacecraft would experience aeroshell burn-through, clad melting and reentry of bare fuel pellets with a conditional probability of 0.1, resulting in a total fuel release probability of $5.00\text{E-}09$. Reentry heating of the bare fuel pellets in Zone B results in a release of 250 Ci vapor at high altitude. Of the 95 bare fuel pellets, 67 impact the ocean and 23 impact soil intact. The remaining five fuel pellets would independently impact rock in separate locations, resulting in a release of 27 Ci each (135 Ci total) in particulate form with a particle size distribution presented previously in Table 2-2.

Due to the intact nature of fuel pellets impacting water and soil, no radiological consequences would be expected to occur. The low solubility of PuO_2 and the potential for encrustation on the ocean floor would effectively prevent the fuel pellets impacting water from being a hazard. Bare fuel pellets impacting soil (either buried or on the surface) could not biologically interact with persons in the vicinity of the impact unless they were physically picked up, which would be unlikely due to the small size of LWRHU fuel pellets.

The 250 Ci vapor released at high altitude would be dispersed worldwide and would take years to filter downward through the atmosphere to ground level. The radiological consequences the vapor release were calculated using the LOPAR methodology described in Section 2.0. A release latitude of 0 degrees was assumed. The vapor was assumed to have a particle size of 0.02 microns.

The radiological consequences of bare fuel pellets hitting rock have been estimated using the KSC-EMERGE model as described in Section 2.1 with the

following additional considerations. The initial source configuration of the 27 Ci from each of the 5 impacting pellets was taken to be a spherical Gaussian puff centered at a 5 m height and 10 m in diameter. A worldwide average population density of 31.8 persons/km² and an average meteorological condition of a D atmospheric stability class with a wind speed of 5.4 m/s were used based on information contained in Reference 3.

Table 3-1 presents a summary of the radiological consequences. Although the total population dose is 2.66E+05 person-rem due primarily to the vapor release, the population dose above de minimis is only 8.80 person-rem due entirely to the ground-level release. The dose to any person is less than one mrem over a lifetime, which is regarded as below concern for the individual and for population health effects estimates. The land area contaminated above 0.2 μ Ci/m² is estimated to be 0.48 km² or about 0.1 km² per fuel pellet due to the ground level release.

3.2.2 Phase 5, Maximum Case

The maximum case consists of a Zone A reentry with an initiating probability of 5.00E-09. The 34 LWRHUSs in the probe survive reentry intact. There is a 0.5 probability of total burnup of the LWRHUs, resulting in 2935 Ci as vapor, and a 0.5 probability of reentry heating resulting in a clad-carbon eutectic. The latter scenario would result in 5 LWRHUs hitting rock independently releasing 31 Ci each (155 Ci total). The maximum case consists of that release which maximizes the radiological consequences. Although the vapor release results in high-population doses, none are above de minimis. Therefore, the second scenario was selected as the maximum case, with a total fuel release probability of 2.50E-09. (Note: The clad-carbon eutectic material prevents fuel vaporization at altitude, and fuel pellets impact rock with higher radioactive inventories (15 percent) than in the most probable case).

The radiological consequences for the maximum case were calculated in a manner similar to that for the bare fuel pellets impacting rock in the most probable case with the following exceptions. The maximum case uses a maximum latitude band population density on a worldwide basis of

Table 3-1

Radiological Consequences
(Phase 5, Most Probable)

Population Exposure

<u>Dose Level, rem</u>	<u>Number of Persons Exceeding Dose Level</u>	
	<u>Short Term</u>	<u>Long Term^a</u>
1.0E+00	0.00E+00	0.00E+00
5.0E-01	0.00E+00	3.12E+00
2.5E-01	0.00E+00	1.25E+01
1.0E-01	9.40E+00	1.88E+01
5.0E-02	1.56E+01	3.12E+01
2.5E-02	3.12E+01	5.95E+01
1.0E-02	7.90E+01	1.80E+02
5.0E-03	1.46E+02	3.06E+02
2.5E-03	2.90E+02	5.10E+02
1.0E-03	7.00E+02	1.01E+03
Maximum Individual Dose, rem:	<u>Short-Term</u> 1.24E-01	<u>Long-Term</u> 5.29E-05 ^a
Population Dose, Person-rem	<u>Short-Term</u>	<u>Long-Term</u>
Without De Minimis:	1.05E+01	2.66E+05 ^a
With De Minimis:	1.40	7.40E+00
Initial Surface Concentration		
<u>Concentration Level μCi/m²</u>	<u>Area Exceeding Level, km²</u>	
	<u>Land</u>	<u>Inland Water</u>
6.0E-01	0.00E+00	0.00E+00
2.0E-01	4.80E-01	1.08E-02
6.0E-02	2.57E+00	5.80E-02
2.0E-02	9.35E+00	2.10E-01
6.0E-03	2.63E+01	5.90E-01
2.0E-03	6.70E+01	1.51E+00

- a. High altitude vapor release results in worldwide individual doses less than 1.0E-04 rem and a long-term population dose without de minimis of 2.66E+05 person-rem.

90.1 persons/km². A more restrictive meteorological condition was selected consisting of an F atmospheric stability condition and a wind speed of 1.2 m/s.

The radiological consequences for the maximum case are summarized in Table 3-2. The population dose above de minimis is 58.7 person-rem, and the area of land contaminated above 0.2 $\mu\text{Ci}/\text{m}^2$ is 1.2 km² or about 0.25 km² per fuel pellet.

Table 3-2

Radiological Consequences
(Phase 5, Maximum)

Population Exposure

<u>Dose Level, rem</u>	<u>Number of Persons Exceeding Dose Level</u>	
	<u>Short Term</u>	<u>Long Term^a</u>
1.0E+00	0.00E+00	0.00E+00
5.0E-01	1.76E+01	8.85E+00
2.5E-01	3.55E+01	2.66E+01
1.0E-01	1.06E+02	4.44E+01
5.0E-02	2.64E+02	8.00E+01
2.5E-02	7.25E+02	1.24E+02
1.0E-02	2.46E+03	3.36E+02
5.0E-03	6.75E+03	5.55E+02
2.5E-03	1.62E+04	1.25E+03
1.0E-03	4.66E+04	3.45E+03
Maximum Individual Dose, rem:	<u>Short-Term</u> 8.12E-01	<u>Long-Term</u> 6.51E-01
Population Dose, Person-rem	<u>Short-Term</u>	<u>Long-Term</u>
Without De Minimis:	2.14E+02	4.54E+01
With De Minimis:	4.07E+01	1.80E+01
Initial Surface Concentration		
<u>Concentration Level μCi/m²</u>	<u>Area Exceeding Level, km²</u>	
	<u>Land</u>	<u>Inland Water</u>
6.0E-01	0.00E+00	0.00E+00
2.0E-01	1.20E+00	1.72E-01
6.0E-02	1.92E+00	3.44E-01
2.0E-02	2.65E+00	6.85E-01
6.0E-03	5.10E+00	1.09E+00
2.0E-03	9.35E+00	1.73E+00

4.0 INTEGRATED MISSION RISK ANALYSIS

The nuclear risk associated with the utilization of the LWRHUs on the Galileo mission has been assessed based only on the expectation case for mission phase 5, presented previously in Table 2-1, since no releases occur in phases 0 through 4. The expectation case for phase 5 uses all of the predicted releases and their probabilities to define a probability-weighted source term, considering all of the scenarios postulated for phase 5. The risk is then defined as the product of the total release probability times the radiological consequences for the expectation case. The total mission risk is then the sum of all mission phase risks. The radiological consequences for the expectation case in phase 5 are summarized in Table 4-1. An overall summary of the radiological consequences of the expectation cases was presented previously in Table 2-2 and Figure 2-2 of Section 2.0. The overall mission risk was summarized previously in Table 2-3 of Section 2.0.

Table 4-1

Radiological Consequences
(Phase 5, Expectation)

Population Exposure

<u>Dose Level, rem</u>	<u>Number of Persons Exceeding Dose Level</u>	
	<u>Short Term</u>	<u>Long Term^a</u>
1.0E+00	0.00E+00	0.00E+00
5.0E-01	0.00E+00	3.12E+00
2.5E-01	0.00E+00	1.56E+01
1.0E-01	9.40E+00	2.19E+01
5.0E-02	1.56E+01	3.12E+01
2.5E-02	3.12E+01	6.25E+01
1.0E-02	7.90E+01	1.96E+02
5.0E-03	1.82E+02	3.10E+02
2.5E-03	2.90E+02	5.10E+02
1.0E-03	7.05E+02	1.07E+03 ^a
Maximum Individual Dose, rem:	<u>Short-Term</u> 1.31E-01	<u>Long-Term</u> 5.58E-05 ^a
Population Dose, Person-rem	<u>Short-Term</u>	<u>Long-Term</u>
Without De Minimis:	1.10E+01	2.18E+06 ^a
With De Minimis:	1.48E+00	7.80E+00

Initial Surface Concentration

<u>Concentration Level μCi/m²</u>	<u>Area Exceeding Level, km²</u>	
	<u>Land</u>	<u>Inland Water</u>
6.0E-01	0.00E+00	0.00E+00
2.0E-01	4.80E-01	1.08E-02
6.0E-02	3.58E+00	8.05E-02
2.0E-02	9.85E+00	2.22E-01
6.0E-03	3.05E+01	6.85E-01
2.0E-03	7.20E+01	1.62E+00

- a. High altitude vapor release results in worldwide individual doses less than 5.0E-04 rem and a long-term population dose without de minimis of 2.18E+06 person-rem.

5.0 REFERENCES

1. International Commission on Radiological Protection, Limits on Intakes by Workers, ICRP-30 (1979 and Supplements).
2. NUS Corporation, Final Safety Analysis Report for the Galileo Mission, Volume III (Book 2), Nuclear Risk Analysis Document, Appendices, Prepared for U.S. Department of Energy, NUS-5126 (November 1988).
3. NUS Corporation, Overall Safety Manual, Prepared for U.S. Department of Energy (1982).

III-B: CHANGES TO VOLUMES I AND II DUE TO VEEGA PROBABILITY

1.0 INTRODUCTION

After Volumes I and II of MD-3540 were printed, it was learned that the VEEGA (Venus-Earth-Earth Gravity Assist) reentry probability had been lowered by a factor of 2 to 5×10^{-7} per mission (Reference 1). This change has already been incorporated into this Volume III NRAD rationale. However, changes to the already-issued Volumes I and II (Reference 2) should be made by the recipient of this document.

2.0 VEEGA PROBABILITY CHANGES

The pages affected by this guidance change are listed below. The pages themselves that incur changes follow. Line(s) on the margin indicate(s) the general area of the change(s).

2.1 Volume IA

Page 17	No changes
Page 18	Changes in 3.2 and 3.4
Page 19	Changes in Phase 5 probabilities
Page 20	Changes in Release Probability column

2.2 Volume II

Page 9	Changes in 2.0, Probability Column
Page 10	Phase 5 Probabilities are changed
Page 35	Phase 5 probabilities are changed
Page 36	Changes to 5A probabilities
Page 37	Changes to 5B probabilities
Page 38	No changes
Page 173	Probability changes in 4.0
Page 174	No changes
Page 175	Changes in Release Probability column
Page 176	No changes

3.0 REFERENCES

1. Informal Memorandum, M. J. Cork/R. J. Hemler, C. T. Bradshaw, November 16, 1988.
2. Letter, W. R. Amos/Distribution, November 17, 1988.

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

Phase- Branch	Event or Consequence	Possible Initiating System
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

*ET = External Tank

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: 5×10^{-7} 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	2.5×10^{-9}
5A	155 (5.74)	Particles	Land Surface	2.5×10^{-9}
5B	250 (9.25)	Vapor	Upper Atmosphere	5×10^{-8}
5B	1906 (70.5)	Pellets	Ocean Bed	5×10^{-8}
5B	644 (23.8)	Pellets	Land Surface	5×10^{-8}
5B	135 (5.00)	Particles	Land Surface	5×10^{-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 LWRHU 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	5.0E-9	250 (9.3)	High Altitude	Vapor 0° Latitude
			135 (5.0)	Ground Level	0° Latitude
<u>Maximum Release Level</u>					
5	Zone A	2.5E-9	155 (5.7)	Ground Level	Rock Impact of Bare Fuel Pellets 33° N Latitude
<u>Expectation Release Case</u>					
5	VEEGA Reentry	7.5E-9	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.

- 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.
- G. EG&G - Mound Applied Technologies (EG&G-MAT) - Effective October 1, 1988, the Mound Plant operations were taken over by EG&G-MAT from MRC. The references in this document are indicative of the time-frame of responsibility.

2.0 SUMMARY OF ACCIDENT EVALUATION

The flowchart sequence of mission phase as a function of success/failure branches is given in Figure 1. This flowchart (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.

The release of plutonia to the environment occurs only in the Phase 5 VEEGA (Venus-Earth-Earth Gravity Assist) encounter with earth during a fly-by as given below:

Branch	Ci(TBq)	Form	Locale	Probability
5A	2935 (109)	Vapor	Upper Atmosphere	2.5×10^{-9}
5A	155 (5.74)	Particles	Land Surface	2.5×10^{-9}
5B	250 (9.25)	Vapor	Upper Atmosphere	5×10^{-9}
5B	1906 (70.5)	Pellets	Ocean Bed	5×10^{-9}
5B	644 (23.8)	Pellets	Land Surface	5×10^{-9}
5B	135 (5.00)	Particles	Land Surface	5×10^{-9}

No fuel releases from accidents other than the VEEGA reentries have been identified for LWRHUs.

FIGURE 1: The top-level FAST was defined to be the same as the GE-derived FAST for the GPHS RTG. Each phase and branch is delineated in more detail in Figures 3 through 19.

FIGURE 18: A misdirected VEEGA maneuver could result in the exposed (as well as those in the probe) LWRHUs entering Earth's atmospheres in four zones. Zones A and B subbranches are given in Figure 19 and 20 and identify plutonia fuel releases.

FIGURE 19: The shallow-angle VEEGA reentry (Zone A) indicates a 50% probability of complete burnup of the 95 LWRHUs not in the probe. As the clad-carbon eutectic temperature is approached in the other 50% of the time, a hard surface impact may result in the release of plutonia.

FIGURE 20: The uncertainty split for Zone 5B indicates that there is a 10% probability that bare fuel pellets would reenter, partially evaporate, and impact upon the Earth's surface.

As in previous assessments, the 34 LWRHUs within the probe are considered to be protected; the probe aeroshell is designed to enter Jupiter's atmosphere at a considerably higher velocity so it should withstand Earth's environment even though the chemistries of the environments are different. Appendix F addresses spacecraft breakup (which should be very rapid here) so the LWRHUs are released early in the aerothermal realm. The LWRHUs would assume a side-on stable (tilted at 40°) configuration to provide the maximum cross sectional area (Reference 4) regardless of orientation or spin state upon entering Earth's upper atmosphere. All 95 LWRHUs not in the probe are assumed to acquire this altitude for all four zones analyzed.

Appendix G addresses the VEEGA zonal responses of the LWRHUs. These zonal responses are a function of the reentry angle (γ) and are summarized as follows:

- A. Zone A - This zone is for very shallow reentry angles - 4 to 7.5 degrees. This prolonged high heat pulse will fail the aeroshell 50% of the time and the released fuel pellet will completely vaporize at high altitudes. For the other 50% of the time, the aeroshell will ablate less than 100% through and the integral unit will incur Earth impact. The clad has undergone some eutectic formation with the inner PG sleeve and the vent might have melted (it is pure platinum rather than Pt-40% Rh). The FAST for Phase 5A is shown in Figure 19.
- B. Zone B - At somewhat steeper angles bracketed by 7.5 to 20 degrees, the aeroshell will fail 10% of the time but remains integral with only minor clad-PG reaction the rest of the time (See Figure 20). As outlined in Appendix G, approximately 8.5% of the plutonia will be deposited as a gas in the upper atmosphere with the pellet (now 91.5% of its original mass) impacting Earth's surface in those that do fail.

Figure 20 also details the pellet impact fate. Ocean and soil impacts by the fuel pellets would result in no further comminution of the pellets. In the 0.05 time fraction where the impact involves rocks or other hard surfaces, generation of particles upon impact would result. As no studies of bare LWRHU fuel impacts have been performed, it was assumed that the particulate spectrum is identical to other similar velocity impacts (Appendix H).

It should be pointed out that the chance of five fuel pellets striking a surface which would comminute those pellets is the most probable assuming random partitioning. Other values are possible, of course. The probability of all 95 randomly striking a rock surface would be $(0.05)^{95}$ or in the order of 10^{-124} .

- C. Zone C - At reentry angles from 20 to 40 degrees, the aeroshell 100% ablation value is reached so late in the heat pulse that the clad does not receive sufficient energy to melt. Therefore, the un-failed clad impacts the Earth's surface at a velocity of 49 m/s but only 2% of the time. This velocity is insufficient to cause clad failure and release of plutonia (see Appendix H).

- 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 (approximately 600 m/s) impact of a clad containing a urania pellet fuel simulant resulted in severe fuel break-up. These data are provided on the log-probability plot, Figure J-1.

3.0 PLUTONIA VAPOR AND PELLETS

These forms are straight-forward. Appendix G addressed the partial or complete "burn-up" or vaporization of the side-on stable pellets in VEEGA Reentry Zones A and B. After a small ablation (8.4%), the still integral pellet would impact the Earth's surface. Thermal stressing was performed on fuel pellets during helium release studies up to about 17 K/s (Reference 4) with no reported breakup; APL reentry data for the bare LWRHU fuel pellet show up to 150 K/s heating rates in some locales, however. As no data exist which would indicate that LWRHU pellets fracture during normal or thermal stressed environments, for these analyses (other than evaporation loss of material from the liquid face of a reentering fuel pellet), the impacting item would be the integral fuel pellet.

4.0 SOURCE TERM SUMMARY

From Figures 19 and 20, which show the Phase 5A and 5B FASTs, the only plutonia releases from LWRHUs aboard the Galileo spacecraft are identified. These are:

<u>Branch</u>	<u>Ci(TBq)</u>	<u>Form</u>	<u>Locale</u>	<u>Probability</u>
5A	2935 (109)	Vapor	Upper Atmosphere	2.5×10^{-9}
5A	155 (5.74)	Particles	Land Surface	2.5×10^{-9}
5B	250 (9.25)	Vapor	Upper Atmosphere	5×10^{-8}
5B	1906 (70.5)	Pellets	Ocean Bed	5×10^{-8}
5B	644 (23.8)	Pellets	Land Surface	5×10^{-8}
5B	135 (5.00)	Particles	Land Surface	5×10^{-8}

Table J-1 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 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).

Table J-1: Maximum, Most Probable and Expectation Release Cases are Provided below for the Galileo Mission Phase 5 accidents. Phases 0 through 4 have no LWRHU 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	5.0E-9	250 (9.3)	High Altitude	Vapor 0° Latitude
			135 (5.0)	Ground Level	0° Latitude
<u>Maximum Release Level</u>					
5	Zone A	2.5E-9	155 (5.7)	Ground Level	Rock Impact of Bare Fuel Pellets 33° N Latitude
<u>Expectation Release Case</u>					
5	VEEGA Reentry	7.5E-9	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.

5.0 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, MLM-3303, Monsanto Research Corporation (October 1985).
4. Peterson, D. E., and Starzynski, J. S., Reentry Thermal Testing of Light-Weight Radioisotope Heater Units, LA-9226 (March 1982).