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GE Astro Space

FINAL SAFETY ANALYSIS REPORT FOR THE GALILEO MISSION

VOLUME II (BOOK 1) ACCIDENT MODEL DOCUMENT

GENERAL PURPOSE HEAT SOURCE
RADIOISOTOPE THERMOELECTRIC GENERATOR
PROGRAM
CONTRACT DE-AC01-79ET32043

PREPARED FOR
U.S. DEPARTMENT OF ENERGY

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PREPARED FOR
U.S. DEPARTMENT OF ENERGY

ASTRO-SPACE DIVISION
SPACECRAFT OPERATIONS
Valley Forge Space Center
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This technical report has been approved for publication.

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LIST OF ACRONYMS

ACS	Attitude Control System
AMD	Accident Model Document
BCI	Bare Clad Impact
Ci	Curie (Radioisotope Activity Level)
DIT	Design Iteration Test
DOE	Department of Energy
ET	External Tank
FAST	Failure/Abort Sequence Tree
FB	Fireball
FC	Fueled Clad
FFT	Fuselage/Fragment Test
FGT	Fragment Gun Test
FSAR	Final Safety Analysis Report
FSS	Fixed Service Structure
FWPF	Fine Weave Pierced Fabric
GE	General Electric
GIS	Graphite Impact Shell
GPHS	General Purpose Heat Source
ID	Inside Diameter
IFIT	Isotope Fuels Impact Tester
INSRP	Interagency Nuclear Safety Review Panel
IUS	Inertial Upper Stage

ACRONYMS (Cont'd)

JPL	Jet Propulsion Laboratory
JSC	Johnson Space Center
LASEP	Launch Accident Scenario Evaluation Program
LFT	Large Fragment Test
LH ₂	Liquid Hydrogen
LOx	Liquid Oxygen
LSC	Linear Shaped Charge
LSE	Launch Support Equipment
MC	Monte Carlo
MECO	Main Engine Cut-Off
MET	Mission Elapsed Time
MLP	Mobile Launch Platform
MSFC	Marshall Space Flight Center
NASA	National Aeronautics and Space Administration
NUS	NUS Corporation
OMS	Orbital Maneuvering System
OSA	Office of Special Applications
PAM-S	Payload Assist Motor - Special
PL	Payload
PuO ₂	Plutonium Dioxide
RCS	Reaction Control System
RSO	Range Safety Officer
RSS	Range Safety System
RTG	Radioisotope Thermoelectric Generator

ACRONYMS (Cont'd)

SRB	Solid Rocket Booster (used with Space Shuttle)
SRM	Solid Rocket Motor (used with IUS)
SSME	Space Shuttle Main Engine
SVT	Safety Verification Test
TVC	Thrust Vector Control
VEEGA	Venus-Earth-Earth Gravity Assist
$\gamma_{\min}$	Minimum Gamma Flight Path Angle (Reentry)

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SECTION 1.0
INTRODUCTION

The Accident Model Document (AMD) is the second volume of the three volume Final Safety Analysis Report (FSAR) for the Galileo outer planetary space science mission. This mission employs Radioisotope Thermoelectric Generators (RTGs) as the prime electrical power sources for the spacecraft. Galileo will be launched into Earth orbit using the Space Shuttle and will use the Inertial Upper Stage (IUS) booster to place the spacecraft into an Earth escape trajectory. The RTG's employ silicon-germanium thermoelectric couples to produce electricity from the heat energy that results from the decay of the radioisotope fuel, Plutonium-238, used in the RTG heat source. The heat source configuration used in the RTG's is termed General Purpose Heat Source (GPHS), and the RTG's are designated GPHS-RTGs. The use of radioactive material in these missions necessitates evaluations of the radiological risks that may be encountered by launch complex personnel as well as by the Earth's general population resulting from postulated malfunctions or failures occurring in the mission operations. The FSAR presents the results of a rigorous safety assessment, including substantial analyses and testing, of the launch and deployment of the RTGs for the Galileo mission.

This AMD is a summary of the potential accident and failure sequences which might result in fuel release, the analysis and testing methods employed, and the predicted source terms. Each source term consists of a quantity of fuel released, the location of release and the physical characteristics of the fuel released. Each source term has an associated probability of occurrence.

The purposes or objectives of the AMD are:

1. Identify all potential single or multiple malfunctions during the complete mission profile which can possibly affect nuclear safety.
2. Provide estimates of probabilities of occurrence associated with each type of accident.

3. Define the environments to which the nuclear heat source can be subjected as a result of the accidents.
4. Evaluate the response of the RTG's to the accident-induced environments.
5. Determine the event history for the RTGs relative to their possible return to Earth and to potential interaction of the radioactive fuel with the biosphere.

The AMD is divided into three sections: 1.0 Introduction, 2.0 Accident Evaluation Summary, and 3.0 Accident Evaluation and Failure Mode Analysis. Details supporting the various analyses and calculations presented in Section 3.0 are included as Appendices A through G.

Section 3.0 includes a chronological summary of the possible accidents considered and their evaluation with respect to the RTGs. The overall missions consist of several phases, and the accidents are presented individually according to the phase in which they occur. The possible accidents evaluated have been defined by NASA in the Space Shuttle Data Book, NSTS 08116, References 1-1 and 1-2. The same document provides Space Shuttle and IUS booster configurational and hazard definitions required for the safety analysis. Sequential events leading from specified accidents to various types of damage to the RTG's and possible fuel release are presented schematically in the form of Failure/Abort Sequence Trees (FASTs). The FASTs identify the instances, their locations and associated probabilities for which source terms (fuel release) can potentially occur and constitute a primary guide and tool for quantitative safety analysis and assessment. The analysis methods and assumptions employed in conjunction with the FASTs to calculate the source terms and probabilities are also described in this section.

This Accident Model Document (AMD), Volume II of the FSAR, provides the source terms and probabilities required for the radiological risk assessment presented in Volume III. Volume I of the FSAR is the Reference Design Document (RDD) for the GPHS-RTGs, and presents information about the missions, spacecraft and launches.

The FSAR has been prepared for use by DOE and is provided to the Interagency Nuclear Safety Review Panel (INSRP) to support their assessment of the degree of radiological risk associated with the use of the GPHS-RTGs for the Galileo mission. The FSAR is based upon accident, mission and environmental conditions provided by NASA in the Shuttle Data Book NSTS-08116 in accordance with agreements with the Department of Energy. The response characteristics of the RTG to postulated accident environments are based on data from a continuing series of safety test programs conducted by the Los Alamos National Laboratory. The FSAR analysis includes data, evaluations, and analyses from DOE contracts and others in the nuclear safety community.

1.1 MISSION AND SYSTEM DESCRIPTION

The Galileo spacecraft will be launched from Kennedy Space Center in November of 1989, using the Space Shuttle. The IUS will place the spacecraft on an Earth escape trajectory. Figure 1-1 illustrates the Galileo launch configuration, with the IUS and the Galileo spacecraft located in the Shuttle Bay.

The Galileo spacecraft is designed to accomplish a scientific investigation of the planet Jupiter and its satellites. This spacecraft includes an atmospheric probe which will separate from the spacecraft as it approaches Jupiter and descend into the Jovian atmosphere. The Orbiter portion of the spacecraft will continue to orbit the planet, investigating the Jovian environment and moons. The Galileo spacecraft employs two GPHS-RTGs. Figure 1-2 depicts the Galileo spacecraft in its stowed or launch configuration showing the RTGs.

For purposes of safety evaluation, a reference mission has been developed and broken into six distinct phases, beginning with loading of the liquid propellants into the Shuttle External Tank (ET), after the spacecraft with RTG(s) has been installed in the cargo bay, and ending with the attainment of the hyperbolic Earth escape trajectory. At this point, with a successful and correct burn of the IUS, escape of the spacecraft from the Earth's gravitational pull will be effected. A subsequent successful VEEGA maneuver will place the spacecraft on the orbit to Jupiter, and the RTGs will no longer

Figure 1-1. Galileo Launch Configuration

Figure 1-2. Galileo Spacecraft: Stowed Configuration

present a potential risk to the Earth's population. Definitions of the phases are as follows:

Phase 0 - Prelaunch-Launch

Begins with the initiation of loading the liquid propellants into the ET (T-8 hours) and ends with lift-off.

Phase 1 - Ascent

Begins with liftoff of the Space Shuttle/IUS vehicle from the launch pad at T-0 and continues until the Solid Rocket Boosters (SRB's) are jettisoned at T+128 seconds.

Phase 2 - Second Stage

Begins at T+128, includes Shuttle main engine cutoff (MECO) and ET release and ends at T+532 seconds when the Orbital Maneuvering System (OMS) engines begin first burn.

Phase 3 - On Orbit

Begins at T+532 seconds with the first burn of the OMS (OMS-1), includes the first and second burns of the OMS (OMS-1 and OMS-2) for orbit attainment and circularization, opening of cargo bay doors, the release of the IUS with spacecraft, and the firing of the Orbiter Reaction Control System (RCS) to move away from the IUS and ends when the IUS with spacecraft is deployed from the Orbiter at T+24084 seconds (6 hours, 41 minutes, 24 seconds).

Phase 4 - Payload Deploy

Begins at T+24084 seconds and ends when the IUS has attained Earth escape velocity even though the spacecraft has not yet been deployed.

Phase 5 - VEEGA Maneuver

Begins when the IUS attains Earth escape velocity, includes the Venus flyby and two Earth flybys, and ends with attainment of the correct trajectory to Jupiter.

1.2 RADIOISOTOPE THERMOELECTRIC GENERATOR DESCRIPTION

The GPHS-RTG is a radioisotope fueled, thermoelectric generator comprised of two major functional components: the thermoelectric converter and the isotope heat source. The power system is designed to provide 285 watts of electrical power under initial space operational conditions for a thermal fuel loading of 4410 watts. The GPHS-RTG system, shown in Figure 1-3, has a weight of 123.3 pounds.

The converter is approximately 44.9 inches long and 16.6 inches in diameter. It contains 572 silicon germanium (SiGe) thermoelectric couples (Unicouples) surrounded by multifoil insulation to reduce thermal losses. Each Unicouple assembly is attached to an aluminum outer case (radiator) by sealing screws inserted through the case wall.

The General Purpose Heat Source (GPHS), (Figure 1-4) supplies the thermal energy to the thermoelectric converter. It is comprised of rectangular parallelepiped modules, each having dimensions approximately 3.7 by 3.8 by 2.1 inches, a weight of about 3.2 pounds, and a thermal output at launch of approximately 245 watts. Each module contains four (4) plutonium dioxide fuel pellets, each clad in iridium post impact containment shells. Two of these fueled clads are encased in each of two graphite impact shells (GIS), each of which is surrounded by a thermally insulative graphitic sleeve. The two GISs are inserted into a graphitic reentry aeroshell. Eighteen (18) of these modules constitute the heat source stack for the GPHS-RTG and provide a nominal total thermal output of 4197 watts at beginning-of-mission.

Additional detail describing the mission, launch vehicles and GPHS-RTG can be found in Volume I, the Reference Design Description of this Final Safety Analysis Report.

Figure 1-3. GPHS-RTG

Figure 1-4. General Purpose Heat Source

1.3 REFERENCES

- 1-1 Space Shuttle Data for Planetary Mission Radioisotope Thermoelectric Generator Safety Analysis, NSTS 08116, Draft Revision A, June 2, 1987.
- 1-2 Letter from M. Joseph Cork, NASA/JPL, to Robert H. Brown, NASA/JSC, Subject: Corrections to NSTS 08116, 1 October 1987 Release, and Replacements to Section 5.2 and Section 6.

SECTION 2.0
SUMMARY OF ACCIDENT EVALUATION

2.1 ACCIDENT AND FAILURE MECHANISMS SUMMARY

The accident and failure mode analysis presented in the following paragraphs is based upon the reference mission, the accidents, and the failure environments specified by NASA in the Shuttle Data Book (Ref 1.1) and supplemental transmittals. Figure 2-1 presents the specific accident probabilities by mission phase. The accident probabilities represent only those failures that can lead to RTG damage and possible fuel release. These accident probabilities have been supplied by NASA for the purpose of this FSAR. Those shown on Figure 2-1 represent the geometric mean of the range of values provided.

In phase 0 of the mission (Prelaunch/Launch) the accidents that have been defined by NASA include the very low probability (6×10^{-9}) inadvertent Range Safety System (RSS) destruct and fire/explosion.

The Phase 1 (Ascent) accidents defined by NASA include:

- 1) SRB failures
- 2) RSS destruct
- 3) Aft compartment explosion
- 4) Vehicle breakup
- 5) Crash landing
- 6) Ocean ditch

Included in the SRB failures are:

- 1) Case rupture
- 2) Tower impact caused by a failure in the left SRB
- 3) Loss of thrust by the right SRB
- 4) Loss of thrust by the left SRB after two seconds
- 5) no ignition of the right SRB

PHASE 0 PRE-LAUNCH/LAUNCH	PHASE 1 ASCENT	PHASE 2 SECOND STAGE	PHASE 3 ON-ORBIT	PHASE 4 PAYLOAD DEPLOY	PHASE 5 VEEGA MANEUVER
RSS DESTRUCT 6.32×10^{-9}	SRB FAILURES 3.80×10^{-3}	ORBITER FAILURES 2.37×10^{-4}	ORBITER FAILURE & REENTRY 1.58×10^{-4}	IUS SRM CASE BURST 3.28×10^{-4}	HIGH VELOCITY REENTRY 5.00×10^{-7}
FIRE/EXPLOSION 1.79×10^{-4}	RSS DESTRUCT 1.51×10^{-6}	ET FAILURES 1.9×10^{-5}		OTHER IUS FAILURES & REENTRY 9.63×10^{-3}	
	AFT COMPARTMENT EXPLOSION 3.95×10^{-4}	SSME FAILURES 1.23×10^{-3}			
		PAYLOAD FAILURES 2.40×10^{-5}			
	VEHICLE BREAK-UP 8.95×10^{-5}	RSS DESTRUCT 1.58×10^{-6}			
	CRASH LANDING 3.79×10^{-6}	CRASH LANDING 8.85×10^{-6}			
	OCEAN DITCH 7.21×10^{-5}	OCEAN DITCH 1.68×10^{-4}			

Figure 2-1. Mission Success and Accident Probabilities

Failure in the left SRB can be caused either by no ignition or by loss of thrust within the first two (2) seconds MET. RSS destruct is an intentional abort action by the Range Safety Office arising from other failures in the Shuttle vehicle that could result in endangering populated land areas. The crash landing and ocean ditch accidents can occur from intact and contingency abort modes of the Orbiter arising from other malfunctions in the Shuttle.

Accidents in Phase 2 (Second Stage) can arise from malfunctions in:

- 1) Orbiter
- 2) External tank (ET)
- 3) Space Shuttle Main Engines (SSME)
- 4) The payload
- 5) RSS destruct
- 6) Crash landing
- 7) Ocean ditch

Since these accidents occur at altitudes exceeding 150,000 feet, explosion and fragment environments are no longer a threat to the RTG's. Ballistic re-entry of the spacecraft will result in breakup of the vehicle and release of the RTGs. The impact shells of the RTGs would be damaged, possibly releasing small amounts of fuel, only if they impact on rock or similarly hard surface during the African overfly.

Phase 3 (On-Orbit) accidents may result in an uncontrolled orbital decay re-entry of the Orbiter and payload with speed less than 26,000 ft/sec at a shallow angle. Again, only if the RTGs impact on a hard surface can the impact shell be damaged and small amounts of fuel possibly be released.

In Phase 4 (Payload Deploy) the accidents defined by NASA are:

- 1) Burst of the IUS solid rocket motors (SRM)
- 2) No ignition
- 3) Low impulse
- 4) Tumbling from faulty separation or recontact

- 5) Misaligned burns due to guidance failures
- 6) Erratic burns

Re-entry conditions can range from speeds of 14,000 to 36,000 ft/sec (4.3 - 11.1 Km/sec) at angles of -0.5 to -36.0 degrees. The case burst accidents typically involve chunks of the hard rubber-like propellant being ejected that can potentially interact with the RTGs.

A failure in Phase 5 (VEEGA Maneuver) of the mission can result in a very high speed (45,600 - 49,300 ft./sec.) re-entry of the spacecraft containing the RTGs at angles essentially from 0 to -90 degrees. The resulting thermal and dynamic environment can be very severe with peak heating rates around 11,000 Btu/ft²-sec. and peak dynamic loads of 17,700 lb./ft.² at decelerations of approximately 600 g's.

Consistent with the accident modes and the associated environments specified by NASA, the mechanisms that can result in damage to fuel containment and release of fuel can be summarized as follows:

- 1) Explosion of ET propellants on or near the launch pad, with the subsequent implosion of the Orbiter payload bay walls around the RTGs, does not result in breach of the fuel clads. Distortions of the clads generally are less than 10% which is well below the 30% threshold for breach.
- 2) In a small percent of cases, ET propellant explosions could result in release of fueled clads (FC) from the RTGs and GPHS aeroshells as free bodies. The secondary impact of the FCs on the concrete and steel surfaces around the launch pad could then result in breach of some clads. A root - sum - square combination of distortions is used in the LASEP program to arrive at the release resulting from the secondary impacts.

- 3) Based on tests simulating Range destruct or SRB case rupture, SRB fragments at velocities up to 695 ft/sec (212 m/s) in the face-on impact attitude will not breach the FCs when struck in the full RTG configuration.
- 4) The results of recent mockup tests simulating SRB fragment interaction with the Orbiter structure indicate that attenuation by passage through the wing and payload bay wall can reduce fragment velocity up to 46% and spin rate up to essentially 100%. Passage through only the payload bay wall can reduce velocity up to 20%. These data coupled with the results of the large SRB fragment tests indicate that SRB fragments in the face-on attitude at impact during the first 105 seconds MET will not cause a breach of the FCs. A Range destruct of the vehicle during the 105-128 second MET will not breach the FCs by a face-on SRB fragment impact. At least 95% of the fragments from a SRB case rupture during the 105-128 second MET are of the face-on impact type.
- 5) SRB fragments impacting in an edge-on attitude can breach the FC at velocities in the range of 130-370 ft/sec (40-113 m/sec) depending on the fuel properties used and the location of impact with respect to the clads as well as the FC position in the stack of modules.
- 6) If re-entry occurs as a result of spacecraft failures during the VEEGA Maneuver phase, the aeroshells of the GPHS modules are expected to fail and release the GIS with FCs. The iridium clad can fail from eutectic formation with the graphite in the GIS. Impact on a hard ground surface is then assumed to release all the fuel in the GIS.
- 7) Both intact and damaged GPHS fueled clads and modules may have some residence time in the fireball from liquid propellant explosions. The effects of the fireball will not result in breach of the clads; the fireball, however, will modify the particle size distribution or location of any fuel released by SRB fragment damage.

- 8) Modules released during On-Orbit or Payload Deploy phase accidents may release small amounts of fuel upon impact on a rock or other hard surface for cases involving land impact following reentry.

2.2 SUMMARY OF SOURCE TERMS

The detailed FASTs presented and discussed in Section 3.0 of this document identify the several points at which fuel release can occur with the source terms defined for each. For each of these release cases, two source terms are presented with their associated probabilities. The two source terms given are the average and the largest or maximum for a specific instance of release. The two values are a result of the Monte Carlo calculational technique used to sample values from the range of variables and conditions applicable to each failure mode and accident scenario. As an example, for a SRB case rupture failure mode, the SRB fragment sizes, velocities, spin rates, heading or azimuth angles, and elevation angles are specified over a range of values with most of these variables being interdependent. In the Launch Accident Scenario Evaluation Program (LASEP) used for the overall analysis of these accidents, all of the above quantities are randomly sampled as is the point along the trajectory (i.e., MET) at which the accident occurs.

Probabilistic risk assessment methods are used to determine the level of safety provided to the public through engineering design and operational controls. The analyst using this method faces the question of how to treat

those events of low probability, which, although possible, are so remote from occurring that they are insignificant when considered as contributors to the actual risk to an individual or population group.

It is an accepted safety analysis practice to disregard predicted releases of radioactive material under accidental conditions with probabilities of release less than one in a million (i.e., $<1 \times 10^{-6}$). In this document, the reporting of potential releases of the fuel from the radioisotope thermoelectric generators uses a cutoff value of 1×10^{-7} probability for the maximum releases. Events of a lower probability are not included because their contribution to risk does not influence the expectation value. The cutoff value, although arbitrary, results in the estimated risk falling below established norms for other hazardous activities.

For example, the US Nuclear Regulatory Commission has estimated the risk to the public from one hundred operating nuclear power plants to be well below other risks nominally considered acceptable by the public at large. Such risks include fatalities from such causes as lightning strike, airplane crash, or release of toxic chemicals. (See the Commission's Reactor Safety Study, WASH-1400, October, 1975, Executive Summary, p.2.)

Similarly for RTGs on the Galileo mission, based on the analysis reported in this volume and the analysis in Volume III of this FSAR, the risk to the public falls well below these other examples. Sufficient analysis of all of the potential accidents has been performed to show that the relation between the magnitude of the release and its associated probability does not exhibit any significant discontinuities at lower probabilities. Thus, no event that could affect the overall risk assessment is concealed by using the 1×10^{-7} probability cutoff.

The average source term defined for purposes of this AMD is the arithmetic mean value of all the trials in a Monte Carlo sampling run that result in a fuel release. In other words, given that a fuel release has occurred, the average is based only on those trials that produce a release. It is not the average over all trials. The maximum source term is simply the one trial or several trials that result in the largest release (within the tolerance of the

bin size) occurring in all Monte Carlo trials for a given failure mode. If only one trial within a given bin (e.g., 10 - 20 gm release) occurs as a maximum, the magnitude of that maximum is used. If the LASEP printout shows more than one trial in the bin size containing the maximum release, the median value of the bin size (e.g., 15 gm, as related to the 10 - 20 gm bin) is used as the maximum. This approach is used since there is no way of determining how closely the release magnitudes in that bin are related. This definition of the maximum includes the combination of variables that result in the largest release and does not necessarily occur with the maximum value of a given accident environment. Table 3-4 in Section 3.0 of the AMD is a complete listing of all individual source terms.

The assessment of radiological consequences and risk arising from the release of the radioactive fuel material into the environment uses the maximum source terms, the most probable and the expectation source terms. The latter two are both related to consequences and risk on a mission phase basis.

The most probable source term, as associated with a mission phase, is the magnitude of the average release that has the highest probability, taking into account all accidents possible in the phase. It includes any associated or sequential related source terms.

The other source term that is used in risk assessment is the expectation value, sometimes called release expectation. The expectation for an event (given that it occurs) is the sum of the products of the individual source terms and their probabilities of occurrence divided by the probability for the initiating accident causing the event. The expectation value is, therefore, a probability weighted average that can be used to estimate the relative contribution of the various accidents and/or mission phases to the damage or fuel release potential for the RTG's.

Tables 2-1 and 2-2 present the most probable and maximum source terms, respectively, for each mission phase. Table 2-3 is a summary of source term expectations calculated for the mission by phase with the contributions from each accident mode shown.

Table 2-1. Most Probable Source Terms for Radiological Consequence Analysis

<u>Phase</u>	<u>Accident Mode</u>	<u>Source Term (Curies)</u>	<u>Release Probability</u>	<u>Release Location</u>
0	Fire/Explosion	44.3	5.01×10^{-7}	ground (FB)*
1	SRB Loss of Thrust (w/Vehicle Breakup)	796	3.30×10^{-4}	ground (FB)
2	Vehicle Breakup	0.0016	1.21×10^{-3}	ground
3	Uncontrolled Orbiter Re-entry	0.17	1.58×10^{-4}	ground
4	IUS Failure	0.17	8.54×10^{-3}	ground
5	Guidance Failure & Re-entry	12900	5.0×10^{-7}	ground

*FB indicates the release occurs within the area engulfed by the fireball

Table 2-2. Maximum Source Terms for Radiological Consequence Analysis

<u>Phase</u>	<u>Accident Mode</u>	<u>Source Term (Curies)</u>	<u>Release Probability</u>	<u>Release Location</u>
0	Pad Fire/Explosion	44.3	5.01×10^{-7}	ground
1	Loss of Thrust	1860	1.39×10^{-4}	air - 147,800
2	Vehicle Breakup	0.136	3.32×10^{-7}	ground
3	Uncontrolled Orbiter Re-entry	1.19	3.33×10^{-7}	ground
4	IUS Failure & Re-entry	1.78	1.49×10^{-7}	ground
5	Guidance Failure & Re-entry	12900	5.0×10^{-7}	ground

Table 2-3. Mission Source Term Expectations by Phase & Accident

PHASE	PHASE ACCIDENT PROBABILITY	PHASE TOTAL	Expectations in Curies			AFT. COMP. EXPLOSION	VEHICLE BREAKUP	REENTRY
			FIRE & EXPLOSION	RSS DESTRUCT	SRB FAILURES			
0	1.79×10^{-4}	2.22×10^{-5}	2.22×10^{-5}		---	---	---	---
1	4.36×10^{-3}	3.25×10^{-1}	---	2.40×10^{-6}	3.14×10^{-1}	9.39×10^{-3}	1.69×10^{-3}	---
2	1.69×10^{-3}	1.97×10^{-6}	---	---	---	---	1.97×10^{-6}	---
3	1.58×10^{-4}	2.69×10^{-5}	---	---	---	---	---	2.69×10^{-5}
4	9.96×10^{-3}	1.45×10^{-3}	---	---	---	---	---	1.45×10^{-3}
5	5.0×10^{-7}	6.45×10^{-3}	---	---	---	---	---	6.45×10^{-3}

SECTION 3.0
ACCIDENT EVALUATION AND FAILURE MODE ANALYSIS

3.1 INTRODUCTION

This section of the Accident Model Document (AMD) addresses the detailed evaluation of the potential accident scenarios that can be initiated by failures occurring in the Space Shuttle/IUS vehicle and of the resulting consequences involving the RTGs. These scenarios and consequences are evaluated for each of several phases defined for the Galileo mission. The potential mission accidents are presented for each mission phase. In order to present the RTG response to the various accident scenarios in a logical sequence of cause and effect, detailed failure/abort sequence trees (FASTs) are constructed for each mission phase and for each type of accident to aid in evaluating those situations that could result in release of radioisotope fuel. The assessment of the risks resulting from any potential plutonium dioxide (PuO_2) fuel release (Volume III of the FSAR) is based on the probabilities of occurrence for each event in the sequences, including the probabilities of the accident occurring.

3.2 SEQUENCE TREE CONSTRUCTION

Failure/Abort Sequence Trees (FASTs) are generated for each of the six (6) mission phases for the Galileo mission, which are defined by mission time-lines, key vehicle operational events, and environmental conditions. The six mission phases for FAST construction and analysis include:

Phase 0 - Prelaunch/Launch

Phase 1 - Ascent

Phase 2 - 2nd Stage

Phase 3 - On Orbit

Phase 4 – Payload Deploy

Phase 5 – VEEGA Maneuver

Each FAST is a graphical representation of potential causal sequences for imposing physically severe environments on the RTGs. Each FAST begins with the phase identification and divides into decision branches representing mission phase success and failure. The success branch indicates that the mission phase objective is achieved and leads directly to the next mission phase. The failure branch is subdivided, as conditions require, into various primary initiating situations or events. From each of these initiating events, a sequence of intermediate events and conditions progresses to a terminal event which either results in 1) a significant fuel release, 2) a fuel release of little or no consequence, or 3) no fuel release. In this manner, the FASTs are constructed based on the accident scenarios identified for each of the six mission phases in a logical sequence of occurrence.

In order to apply the FASTs to a mission failure evaluation, they must indicate how the individual events and their relative probabilities of occurrence affect the source terms, which are a characterization of a fuel release. A source term includes the quantity of fuel released, the release location and the particle size distribution of the released fuel. The probability of a given accident occurring in any phase of the mission has been provided by NASA from specific vehicle failure modes and effects analysis and from supporting data as they apply to the particular accident scenarios.

An explanation of the graphical symbols and notations used in the FASTs is presented in Figure 3-1. A conditional probability is defined as the probability of a particular event occurring, given a defined set of precursor events. The cumulative or absolute probability (sometimes referred to as mission probability) of an event is the overall probability of the sequence of events leading to and including the event of interest as related to the entire mission. The conditional probability of a particular event occurring is shown inside the oval or other symbol as shown in Figure 3-1. The sum of the conditional probabilities of parallel events is one, and the sum of parallel accident probabilities is the value defined by NASA for the total accident

LEGEND

Pentagon	-	start of a mission phase sequence
Oval	-	indicates initiating, intermediate, and terminal events
Triangle	-	indicates where a sequence branch is continued
Diamond	-	indicates a terminal event in which fuel release occurs, producing source term.

Figure 3-1. Explanation of Sequence Tree Construction/Features

probability for that phase or accident. Probabilities given on the trees are rounded off to three significant places except for success probability through each phase. Probabilities for intermediate and final events may not be shown if the final event does not result in a fuel release.

Another feature of the FAST construction or arrangement is that an event oval is generally followed by one or more effect ovals (these are actually events also). For example, the initiating event may be an explosion of the launch vehicle. Subsequent parallel events (or effects) ovals may be 1) GPHS module intact, or 2) Fueled Clad (FC) intact. These states, or events, are the potential direct consequence or condition of the RTG and/or Heat Source leading into the subsequent event. The subsequent event (e.g., impact in launch pad area) would, in turn, be followed by effect ovals. In some instances, an event oval may be followed by one or more qualifying event ovals before the state or effect oval is given. An example of this would be the impact of the GPHS (say, following reentry) with qualifying event ovals stating whether the impact is on land or in the ocean. The land oval may, in turn, be followed by other qualifying ovals stating whether rock, soil, or inland water is to be considered. In the event a fuel release is identified, qualifying ovals may be included to indicate differing conditions that affect the release and associated source terms used in the risk analysis presented in the Nuclear Risk Analysis Document, Volume III of the FSAR.

3.3 ACCIDENT SCENARIOS/ENVIRONMENTS

3.3.1 INTRODUCTION

In the Shuttle Data Book (NSTS-08116), NASA defines the accident conditions for the failures that can potentially occur both in the Space Shuttle and the IUS vehicles. The probabilities for the failures leading to these accidents have been provided separately by NASA.

The NASA approach to define the potential accident scenarios was first to identify the potential failures that might present a threat to the RTGs that could occur in each of seven major elements of the Space Shuttle system:

- a) Launch Support Equipment (LSE)
- b) Payload (PL)
- c) Orbiter
- d) External Tank (ET)
- e) Solid Rocket Boosters (SRB)
- f) Space Shuttle Main Engines (SSME)
- g) Range Safety System (RSS)

Each element was further divided into its major failure components which were then subdivided until all known failures were identified. All of the failure modes identified were reviewed for credibility, and those that were not considered credible because of equipment and subsystem redundancy or because of the necessary condition of multiple failures were eliminated. The next step involved dividing the mission into six phases with each of the phases subdivided further as necessary. Then fault trees were developed for each of the mission phases with the contribution to each of the failures from the seven major Shuttle systems previously given being determined. Finally, and because many of the scenarios looked similar subsequent to some point in the sequence of an accident, representative accident scenarios were developed for each of the mission phases.

3.3.2 ACCIDENT SCENARIOS

The representative accident scenarios developed in the Shuttle Data Book (NSTS 08116, with corrections to the 1 October 1987 release given in letter from Cork to Brown, dated March 14, 1988, Ref. 230-MJC-88-023) are summarized briefly in the following paragraphs. The correspondence of these scenarios to the system failures and accidents shown on Figure 2-1 is given in Table 3-1.

3.3.2.1 On Pad Accidents

Three accidents are given for on pad events during Phase 0: Pad Fire, Pad Explosion, and Inadvertent Range Destruct.

SYSTEM FAILURE/ACCIDENT WITH PROBABILITY	PHASE 0		PHASE 1						PHASE 2						PHASE 3	PHASE 4	PHASE 5		
	RSS DESTRUCT 6.32 X 10 ⁻⁹	FIRE EXPLOSION 1.79 X 10 ⁻⁴	SRB FAILURE 3.8 X 10 ⁻³	RSS DESTRUCT 1.51 X 10 ⁻⁶	AFT COMPARTMENT EXPLOSION 3.95 X 10 ⁻⁴	VEHICLE BREAKUP 8.95 X 10 ⁻⁵	CRASH LANDING 3.79 X 10 ⁻⁶	OCEAN DITCH 7.21 X 10 ⁻⁵	ORBITER FAILURE 2.37 X 10 ⁻⁴	ET FAILURE 1.9 X 10 ⁻⁵	SSME FAILURE 1.23 X 10 ⁻³	PAYLOAD FAILURE 2.4 X 10 ⁻⁵	RSS DESTRUCT 1.58 X 10 ⁻⁵	CRASH LANDING 8.85 X 10 ⁻⁵	OCEAN DITCH 1.68 X 10 ⁻⁴	ORBITER FAILURE/REENTRY 1.58 X 10 ⁻⁴	SRB CASE BURST 3.28 X 10 ⁻⁴	OTHER IUS FAILURE/REENTRY 9.63 X 10 ⁻³	HIGH VELOCITY REENTRY 5.0 X 10 ⁻⁷
ACCIDENT SCENARIO																			
PAD FIRE/EXPLOSION - 8HR TO T-O		○																	
INADVERTENT RANGE DESTRUCT	○																		
TOWER IMPACT SCENARIO 0-2 SEC			○																
AFT COMPARTMENT EXPLOSION 0-10 SEC					○														
SRB CASE RUPTURE 0-10 SEC 10-128 SEC			○ ○																
RANGE DESTRUCT 0-10 SEC 10-128 SEC				○ ○															
INFLIGHT BREAKUP 10-30 SEC 30-128 SEC 128S TO MECO						○ ○ ○			○ ○ ○	○ ○ ○	○ ○ ○	○ ○ ○							
UNCONTROLLED REENTRY																○	○	○	
HIGH VELOCITY REENTRY																			○
CRASH LANDING							○								○				
OCEAN DITCH								○							○				

Table 3-1. Relation of Accident Scenario to System Failure/Accident

3.3.2.1.1 Pad Fire Scenario, - 8 Hours To 0 Seconds MET

For the Pad Fire Scenario, an uncontrolled pad fire can develop as a result of an initial leak of LOX/LH₂, wherein the fire control system is unable to attenuate the fire. The pad fire, fed by the remaining LH₂ made available by the failure of the LH₂ ET tank due to thermal effects, develops into a fireball. Tanks containing onboard propellants burst as the propellants vaporize, and/or decompose from the heat input. LOX and LH₂ from at least one set of burst PRSDS tanks pool on the aft bulkhead of the Orbiter and explode. The RTGs, in proximity to these tanks, are subjected to the blast and fragment environment from these tanks.

Since the pad fire scenario was not defined until the development of the Launch Accident Scenario Development Program was nearly completed for the analysis of the RTG response to the accidents, this scenario was not included as a separate scenario for purposes of this FSAR. Instead, this scenario was combined along with the pad explosion scenario (as presented in the October 1, 1987 release of NSTS-08116) and treated according to the environment for the latter scenario. This treatment is considered to be conservative since the effects of the pad fire scenario are expected to be less severe than the pad explosion scenario. Also, it is expected that a fire in the Shuttle which could not be controlled by the pad fire control system would ultimately lead to structural failure of the ET, massive dump of propellants, and an ensuing pool explosion, or the equivalent of the pad explosion scenario.

3.3.2.1.2 Pad Explosion, - 8 Hours to 0 Seconds MET

For this scenario, blast effects and fragments from initiating sources in the Orbiter or LSE are assumed to be sufficiently severe to rupture the 18-inch diameter (ID) LOX and LH₂ lines. These fragments may puncture the ET LH₂ tank. However, the blast effects and fragments from an aft compartment explosion are not expected to affect the RTG environment due to the separating bulkhead between the aft compartment and payload bay and due to the shielding afforded by the IUS.

If the LOX and LH₂ feed lines rupture, significant propellant flow rates are expected due to the combination of the line size and head of liquid propellant. The liquids ignite as they flow toward the ground. However, a significant portion is expected to remain unburned due to the relatively poor mixing. These unburned propellants will pool in the trench and horizontal surfaces of the MLP. Impact with these surfaces will produce turbulence and mixing and thus promote the formation of an explosive mixture. At some point, an explosive reaction will take place. The blast wave, propagating from the origin of the explosion, travels up along the Orbiter. Due to the blast's intensity (pressure and impulse), the Orbiter's structural capability will be exceeded, particularly for elements such as the payload bay doors. Structure torn loose by the blast may fly clear and impact the ground. Additional smaller explosions and fire fed by the remaining propellants will continue.

3.3.2.1.3 Inadvertent Range Destruct

This scenario assumes that the Linear Shaped Charges (LSC) on both SRBs and the ET inadvertently detonate.

NOTE: This scenario is not actually listed in Section 3.4 of the Shuttle Data Book as a representative accident scenario, but it is listed in Section 3.3.1.5 as a potential scenario, and a probability for its occurrence is given in Table A-3, Appendix A, Volume II (Book 2) of this FSAR, as supplied by NASA.

3.3.2.2 Near-Pad Accident Scenarios.

Near-Pad accident scenarios which might occur at (or shortly after) SRB ignition and concurrent tiedown release are more diverse than the previously discussed on-pad scenarios. The near-pad scenarios include Tower Impact, Aft Compartment Explosion, SRB Case Rupture, and Inadvertent Range Destruct as discussed in the following sections.

3.3.2.2.1 Tower Impact Scenario, After Failure During 0 to 2 s MET.

Shuttle trajectory simulations were utilized to study the consequences of SRB failures. In the event of an SRB Thrust Vector Control (TVC) actuator failure, adequate control is maintained by the remaining actuators to avoid a tower collision or ground impact for approximately 30 seconds, with adequate time for RSO destruct before impact. For right SRB nozzle burnthroughs, the simulations indicate that these failures will result in vehicle breakup during early ascent (see Section 3.3.2.2.2). For a left SRB loss of thrust or nozzle burnthrough prior to a MET of 2 seconds, the Orbiter stack will subsequently impact the launch tower within a MET of 7 seconds.

Tower impact would cause the ET to rupture. After the impact, the system may be configured with the Orbiter and ET connected and the right SRB breaking free. (It is more probable that all structural connections between the elements of the stack will fail.)

The rupture of the ET allows propellant to flow toward the ground. As with the on-pad explosion scenario, a significant portion is expected to remain unburned due to poor mixing. Pooling of the unburned propellants after impacting horizontal surfaces promotes the formation of an explosive mixture.

3.3.2.2.2 Aft Compartment Explosion Scenario, 0 to 10 s MET.

Rupture of 17-inch ID LOX and LH₂ lines, plus a possible puncture of the ET, can be anticipated as a result of an SSME propulsion system failure and ensuing aft compartment explosion. The details of this scenario continue to parallel those for the on-pad event, except that:

- a) The Orbiter stack continues its ascent due to SRB thrust until the blast wave from the explosion originating in the pool formed on the ground breaks up the Orbiter.
- b) Both SRBs continue ascent until RSS destruct if the flight duration after the initiating event is long enough (estimated at 10 s).

Flight dynamics analyses by MSFC have indicated that total loss of flight control due to SRB thrust disruption during the early mission phases will result in Orbiter breakup due to aerodynamic and/or dynamic forces. It is expected that this breakup will cause failure of the Orbiter/ET MPS interface, thereby releasing LOX and LH₂ through the 17-inch feed lines. The rate of propellant released should be comparable to the aft compartment explosion. Therefore, the aft compartment explosion scenario is also used for vehicle breakup for 0 to 10 seconds MET.

3.3.2.2.3 SRB Case Rupture Scenario, 0 to 10 s MET.

If a SRB case ruptures, fragments of the rocket motor can impact the adjacent ET and Shuttle structure, causing their complete failure. These impacts induce motions perpendicular to the vehicle flight path, resulting in a dispersal of Orbiter elements with a lateral component.

A massive dump of LOX and LH₂ occurs, with the unburned cryogenics pooling in the trench and on other horizontal surfaces. The turbulence which results from impacting these surfaces promotes mixing, finally leading to an explosive reaction. As the blast wave propagates from the origin of the explosion, intact structures are subjected to the blast's intensity. Orbiter elements (including the payload) impacting in the launch pad area can experience small secondary explosions, fire fed by the remaining liquid propellants, and chunks of solid rocket propellant.

Fragments from the rupturing SRB are not expected to damage the opposite SRB severely due to the shielding by the ET and its propellants. Therefore, the remaining SRB will continue to fly until extinction or range destruct action is taken.

3.3.2.2.4 Inadvertent Range Destruct Scenario, 0 to 10 s MET.

This scenario assumes that the linear shaped charges (LSC) on both SRBs and the ET inadvertently detonate. This causes fragmentation of the upper segments of both SRBs as well as the ET. The aft segments (that have no LSC) of both SRBs will fall back to the ground.

A massive dump of LOX and LH₂ might occur, with the unburned cryogenics pooling in the trench and on other horizontal surfaces. The turbulence which results from impacting these surfaces promotes mixing, finally leading to an explosive reaction. Structure which had survived after the fragmentation of the upper segments of both SRBs is now subjected to the blast's intensity. Orbiter elements (including the payload) impacting in the launch pad area can experience small secondary explosions, fire fed by the remaining liquid propellants, and chunks of solid rocket propellant.

3.3.2.3 In-Flight Representative Scenarios.

Many of the failures which can initiate near-pad accident scenarios are also sources for in-flight events. Even so, the sequence and primary energy releasing phenomena associated with the in-flight case may differ significantly from its near-pad counterpart.

3.3.2.3.1 SRB Case Rupture Scenario, 10 To 128 s MET.

If an SRB case ruptures, fragments of the rocket motor can impact the adjacent ET and Shuttle structure, causing their complete failure. Fragments from the rupturing SRB are not expected to severely damage the opposite SRB due to the shielding by the ET's intervening structure and propellants. Therefore, the remaining SRB will continue to fly until extinction or range destruct action is taken. The impact of the SRB fragments induces motions perpendicular to the nominal flight motion and consequently causes a lateral dispersal of Orbiter elements. Likewise, this promotes dispersal of the LOX and LH₂ and thus minimizes any vapor cloud explosion. Because the propellants tend to be so spread out, a trailing fire is more probable.

3.3.2.3.2 Range Destruct Scenario, 10 to 128 s MET.

Range Safety destruct would fire the linear shaped charges on both SRBs and the ET. This results in complete failure of the Orbiter by fragments from the upper SRB segments and the ET. The aft SRB segments (containing no LSC) remain intact, impacting within the land mass bounds for a MET less than around 17 seconds, otherwise on water, with an impact velocity on the order of

300 to 500 ft/s. As with the SRB case rupture, the fragment impacts induce lateral dispersal of Orbiter elements as well as LOX and LH₂. This minimizes the potential for a vapor cloud explosion. Since the propellants have been so dispersed, a trailing fire is more probable. This scenario is also applicable to an inadvertent range destruct.

3.3.2.3.3 In-Flight Breakup Scenario, 10 to 30 s MET.

Although the possible initial structural failure of the ET may be relatively small, catastrophic structural failure of the ET may quickly ensue due to small local explosions and aerodynamic loads. The massive dump of LOX and LH₂ during this portion of the flight regime will most probably result in a hydrogen/air vapor cloud explosion since the reactants can adequately mix to form a continuum which can propagate an explosive reaction, as contrasted with the dispersed situation in the SRB case rupture scenario. As the blast wave propagates from the origin of the explosion, the Orbiter's structure is subjected to the blast's intensity, causing breakup and subsequent ground impact.

3.3.2.3.4 In-Flight Breakup Scenario, 30 to 128 s MET.

Although this scenario could be initiated in the same manner as the 10 to 30 seconds scenario, the massive dump of LOX and LH₂ would result in a trailing fire with small, local explosions as in the 51-L accident. Structural breakup of the Orbiter does occur as a result of both hydrodynamic interaction with the LOX and LH₂ and aerodynamic effects during this flight regime. The impact point is on water.

3.3.2.3.5 In-Flight Breakup Scenario, 128 s to MECO MET.

Although initiated in the same manner as the 10 to 30 seconds scenario, and characterized by a trailing fire with small local explosions as a consequence of the propellant dump as with the 30 to 128 seconds scenario, the Orbiter's structural response may take three forms in this case:

- a) Immediate breakup followed by reentry with aerodynamic heating of structural elements.
- b) Out-of-control reentry at conditions which vary depending on time of event.
- c) Minimal failure which allows controlled reentry, but which could result in an Orbiter ditch or crash landing.

Two important parameters differ for this in-flight case compared to earlier ones:

- a) Shock wave intensities are non-existent at these altitudes.
- b) Aerodynamic loads are small in this flight regime, although an out-of-control Orbiter would be subjected to severe aerodynamic loading upon reentry to the atmosphere.

Based on a reentry breakup study conducted by JPL for the purpose of determining the potential configurations possible at impact on the Earth's surface and presented in Section 6.1 of NSTS 08116, the following conclusions were reached (for a fault occurring on the nominal Orbiter ascent from 128 to 510 seconds):

- a) The Orbiter and IUS will always break up during reentry and will not reach the surface intact.
- b) For a failure between 128 and 155 seconds, the RTGs reach the surface intact.
- c) Between 155 and 210 seconds, the RTGs may reach the surface without the outer case melting, or the GPHS modules may be released prior to reaching the surface.
- d) After 210 seconds, the GPHS modules are released from the RTG prior to impact.

3.3.2.4 On-Orbit Scenarios

Uncontrolled Orbiter reentry is the potential accident scenario given for the On-Orbit Phase.

3.3.2.5 Payload Deploy Scenarios

Upper stage and/or spacecraft reentry is representative of the potential accident scenarios that might occur during the IUS free-flight phase of the mission. Also the potential exists for pressure rupture of the IUS solid rocket motor (SRM) casings due either to a case defect with a lower pressure rupture or to a propellant defect with a higher pressure case rupture.

3.3.2.6 VEEGA Maneuver Scenario

The only scenario that potentially can occur that might present a severe environment to the RTGs is a very high-velocity reentry of the spacecraft. This scenario is not included in the Shuttle Data Book (NSTS 08116), but it is presented in References 3-1 and 3-2.

3.3.3 FAILURE PROBABILITIES

Appendix A of this Galileo FSAR presents the accident probabilities provided by NASA for the purpose of the safety analysis presented in this document. The NASA accident probabilities are given by phase and by each Space Shuttle major element. As shown in Appendix A, the failure probabilities for the Space Shuttle are given as decade ranges. The IUS failure probabilities are given as point values.

In consideration of the method by which to treat these ranges for purposes of this FSAR, an agreement was reached in a teleconference between DOE/OSA, JPL, NASA/EL, GE, and NUS (Reference 3-3). The agreement was as follows:

- 1) GE will develop the Failure/Abort Sequence Tree (FAST) probabilities using the geometric mean accident probabilities determined from the ranges provided by NASA.
- 2) NUS will calculate the mission phase risks (accident probability times hazard summed over all accidents) based on the geometric mean probabilities.

- 3) NUS will perform sensitivity analysis on risks by transport/pathway parameters affecting risk and by probability variations. Each factor affecting the calculated risks, including probabilities will be characterized by a mean (i.e., geometric mean), a range, and a distribution characterized by a log-normal with the probability range end points treated as the 5 and 95 percentile values, when no other information is available.

Based on this agreement and the accident probability ranges provided by NASA, the following mean probabilities are derived for use in this accident model document (AMD). For reference, the geometric mean of a range given with end points specified is:

$$P_{GM} = \sqrt{P_U \times P_L}$$

P_{GM} = geometric mean probability
 P_U = upper end point probability
 P_L = lower end point probability

Phase 0: Prelaunch/Launch

From Table A-1 of Appendix A, the probability for pad fire/explosion for the periods T-8 hr to T-6s and T-6s to T+128s (this is really T+0 since the pad fire and explosion is only applicable up to T+0) is:

$$\begin{aligned} & (0.5 + 0.067) \times 10^{-4} \text{ to } (5.0 + 0.67) \times 10^{-4} = \\ & \quad 0.567 \times 10^{-4} \text{ to } 5.67 \times 10^{-4} \\ & P_{GM} = 1.79 \times 10^{-4} \end{aligned}$$

The probability for Range Safety System inadvertent destruct during this period is seen from Table A-3 to be:

$$\begin{aligned} & 2 \times 10^{-9} \text{ to } 2 \times 10^{-8} \\ & P_{GM} = 6.32 \times 10^{-9} \end{aligned}$$

The total Phase 0: Prelaunch/Launch accident probability is the sum of these two values, namely 1.79×10^{-4} .

Phase 1: Ascent

From Table A-2 for SRB failures:

	P_U	P_L	P_{GM}
	<hr/>	<hr/>	<hr/>
Case Rupture	32.4×10^{-4}	3.24×10^{-4}	1.02×10^{-3}
Tower Impact	6.5×10^{-4}	0.65×10^{-4}	2.06×10^{-4}
(Left SRB Failures)***			
Loss of Thrust*	78.8×10^{-4}	7.88×10^{-4}	2.49×10^{-3}
No Ignition**	2.4×10^{-4}	0.24×10^{-4}	7.59×10^{-5}
			<hr/>
			3.80×10^{-3}

* Results in Vehicle Breakup

** Only for Right SRB since Left SRB No Ignition is categorized as Tower Impact

*** No Ignition and Loss of Thrust within 0-2 sec.

From Table A-3, RSS Destruct for the 0-10 seconds and 10-128 seconds periods are:

$$\begin{aligned}
 & (.00037 + .0044) \times 10^{-4} \text{ to } (.0037 + .044) \times 10^{-4} = \\
 & .00477 \times 10^{-4} \text{ to } .0477 \times 10^{-4} \\
 & P_{GM} = 1.51 \times 10^{-6}
 \end{aligned}$$

From Table A-2, Aft Compartment Explosion probability is:

$$1.248 \times 10^{-4} \text{ to } 12.48 \times 10^{-4}$$

$$P_{GM} = 3.95 \times 10^{-4}$$

Vehicle Breakup, excluding those failures initiated by the Aft Compartment (SSME) Explosion and the SRB Loss of Thrust and No Ignition, is made up of Orbiter, External Tank, and Payload failures. From Table A-2:

	P_U	P_L	P_{GM}
Orbiter Failures	2.4×10^{-4}	0.24×10^{-4}	7.59×10^{-5}
ET Failures	0.2×10^{-4}	$.02 \times 10^{-4}$	6.32×10^{-6}
Payload Failures	0.24×10^{-4}	$.024 \times 10^{-4}$	7.59×10^{-6}
			8.98×10^{-5}

The Shuttle Data Book treats Crash Landing and Ocean Ditch accidents differently in different situations. It lists these as a separate phase (Phase 5) in Sections 3.3 and 3.4 of NSTS 08116, but in the probabilities provided (see Tables A-2 and A-6 in Appendix A), they are listed in the phase in which they can occur. Since these can not be treated independently as a separate phase (mainly because they occur in two different phases) in the FSAR, they are treated as separate accidents in the phases where they can occur. For these accidents in Phase 1 (Ascent) (see Table A-2 in Appendix A), the following values are determined:

	P_U	P_L	P_{GM}
Crash Landing	0.12×10^{-4}	$.012 \times 10^{-4}$	3.79×10^{-6}
Ocean Ditch	2.28×10^{-4}	0.228×10^{-4}	7.21×10^{-5}

Phase 2: Second Stage

From Table A-6 of Appendix A:

	<u>P_U</u>	<u>P_L</u>	<u>P_{GM}</u>
Vehicle Breakup			
Orbiter Failure	7.5×10^{-4}	0.75×10^{-4}	2.37×10^{-4}
ET Failure	0.6×10^{-4}	$.06 \times 10^{-4}$	1.90×10^{-5}
SSME Failure	38.95×10^{-4}	3.895×10^{-4}	1.23×10^{-3}
Payload Failure	0.76×10^{-4}	$.076 \times 10^{-4}$	2.40×10^{-5}
RSS Destruct	0.5×10^{-4}	$.005 \times 10^{-4}$	1.58×10^{-6}
			1.51×10^{-3}
Crash Landing	0.28×10^{-4}	$.028 \times 10^{-4}$	8.85×10^{-6}
Ocean Ditch	5.32×10^{-4}	0.532×10^{-4}	1.68×10^{-4}
			1.69×10^{-3}

Phase 3: On Orbit

From Table A-1, On-Orbit Failure Probability is:

$$0.5 \times 10^{-4} \text{ to } 5.0 \times 10^{-4} \quad P_{GM} = 1.58 \times 10^{-4}$$

Phase 4: Payload Deploy

The failure probabilities for this phase arise only from failures in the IUS. The probabilities given in Section 11.0 (Tables 11.1 and 11.3) of the Shuttle Data Book are as follows:

SRM Case Burst	328×10^{-6}
Other Failures	
No Ignition	610×10^{-6}
Low Impulse	1447×10^{-6}
Tumbling	2078×10^{-6}
Erratic Burns	3367×10^{-6}
Misaligned Burns	2127×10^{-6}
	9629×10^{-6}
	<hr/>
	9957×10^{-6} or 9.96×10^{-3}

Phase 5: VEEGA Maneuver

The probability given in Reference 3-1 for the potential failures leading to the high velocity reentry is 5.0×10^{-7} .

3.3.4 TOP LEVEL FASTs

In Section 3.3.2, the accident scenarios have been presented, and Section 3.3.3 has given the accident probabilities with the geometric mean probability derived for each of the mission phases as defined in this document. These probabilities and the accident scenarios are combined into the top level failure sequence trees shown on Figures 3-2 through 3-7 for each of the six (6) mission phases.

Figure 3-2. Phase 0: Prelaunch/Launch Top Level Fast

Figure 3-3. Phase 1: Ascent Top Level FAST

Figure 3-4. Phase 2: Second Stage Top Level FAST

Figure 3-5. Phase 3: On Orbit Top Level FAST

Figure 3-6. Phase 4: Payload Deploy Top Level FAST

Figure 3-7. Phase 5: VEEGA Maneuver Top Level FAST

3.3.5 ACCIDENT ENVIRONMENTS

Appendix B of this document presents the detailed accident environments as given in the Shuttle Data Book. A brief summary of those environments is presented in this section. The values given generally represent the ranges of the environment as given in the Shuttle Data Book (NSTS 08116). Table 3-2 is a cross reference between the accident scenarios presented in Section 3.3.2 and the environments included herein.

3.3.5.1 Explosion Environments for Shuttle Failures

3.3.5.1.1 ET Propellant Near-Pad Explosions

From Vehicle Breakup or Tower Impact:⁽¹⁾

a. On-Pad Explosions

<u>Dist.(2)</u> <u>ft</u>	<u>Percent(3)</u> <u>Occurrence</u>	<u>PSTAT(4)</u> <u>psi</u>	<u>PDYN(4)</u> <u>psi</u>	<u>PREFL(4)</u> <u>psi</u>	<u>ISTAT(4)</u> <u>psi-s</u>	<u>IDYN(4)</u> <u>psi-s</u>
20	0.1 50	349 41	524 36	2407 167	1.83 0.25	0.60 .076
200	0.1 50	48 Nil	55 Nil	202 Nil	1.24 Nil	0.82 Nil

1) For these accidents, the Shuttle Data Book indicates that the on-pad and in-trench explosions can occur with equal probability.

2) Distance is from surface of pooled propellants vertically to point of interest.

3) Percent occurrence indicates that the values given (i.e., pressure and impulse) will not occur with a probability greater than the value indicated.

(4) PSTAT peak static overpressure of explosive shock
 PDYN peak dynamic pressure of explosive shock
 PREFL peak instantaneous reflected pressure of explosive shock
 ISTAT specific impulse of static overpressure pulse
 IDYN specific impulse of dynamic pressure pulse

Table 3-2. Relation of Accident Environments to Accident Scenarios

SCENARIO	SECTION	ENVIRONMENT											SECTION
		ON-PAD EXPLOSION	IN-TRENCH EXPLOSION	AFT COMPARTMENT EXPLOSION	IN-FLIGHT EXPLOSION (VAPOR CLOUD)	AUXILIARY PROPELLANT EXPLOSION	SRB FRAGMENTS RSS DESTRUCT	SRB FRAGMENTS RANDOM FAILURE	ET - FRAGMENTS ON-PAD EXPLOSION	IN-TRENCH EXPLOSION	AFT COMP. EXPLOSION	IN-FLIGHT EXPLOSION (VAPOR CLOUD)	3.3.5.1.1
PAD FIRE/EXPLOSION - 8HR TO T-O	3.3.2.1.1/.2	O	O			O			O	O			3.3.5.1.1
INADVERTENT RANGE DESTRUCT < T-O	3.3.2.1.3	O	O				O						3.3.5.1.1
TOWER IMPACT 0-2 SEC	3.3.2.2.1	O	O						O	O			3.3.5.1.1
AFT COMPARTMENT EXPLOSION 0-10 SEC	3.3.2.2.2			O							O		3.3.5.1.2
SRB CASE RUPTURE 0-10 SEC	3.3.2.2.3	O	O					O					3.3.5.1.3
10-128 SEC	3.3.2.3.1							O					3.3.5.2
RANGE DESTRUCT 0-10 SEC	3.3.2.2.4	O	O				O						3.3.5.2
10-128 SEC	3.3.2.3.2						O						3.3.5.2
INFLIGHT BREAKUP 10-30 SEC	3.3.2.3.3				O							O	3.3.5.3.1
30-128 SEC	3.3.2.3.4												3.3.5.3.1
128S TO MECO	3.3.2.3.5												3.3.5.3.2
UNCONTROLLED REENTRY	3.3.2.4/.5												3.3.5.4
HIGH VELOCITY REENTRY	3.3.2.6												3.3.5.5.1
CRASH LANDING						O						O	3.3.5.5.2
OCEAN DITCH						O						O	3.3.5.6
													3.3.2.3.5

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b. In-Trench Explosions

<u>Dist.</u> <u>ft</u>	<u>Percent</u> <u>Occurrence</u>	<u>P_{STAT}</u> <u>psi</u>	<u>P_{DYN}</u> <u>psi</u>	<u>P_{REFL}</u> <u>psi</u>	<u>I_{STAT}</u> <u>psi-s</u>	<u>I_{DYN}</u> <u>psi-s</u>
110	0.1	163	236	953	4.19	1.55
	50	22	18	82	0.66	0.24
290	0.1	87	110	429	3.94	2.17
	50	3	5	7	0.40	0.20

From Aft Compartment Initiated Explosions:

<u>Dist.</u> <u>ft</u>	<u>Percent</u> <u>Occurrence</u>	<u>P_{STAT}</u> <u>psi</u>	<u>P_{DYN}</u> <u>psi</u>	<u>P_{REFL}</u> <u>psi</u>	<u>I_{STAT}</u> <u>psi-s</u>	<u>I_{DYN}</u> <u>psi-s</u>
20	0.1	175	297	1040	0.67	0.29
	50	18	15	67	.093	.037
200	0.1	14	15	53	0.25	0.26
	50	N11	N11	N11	N11	N11

3.3.5.1.2 ET Propellant In-Flight Explosions

From Vehicle Breakup MET:10 T < 30 sec (i.e., Vapor Cloud Explosions):

<u>Dist.*</u> <u>ft</u>	<u>P_{STAT}</u> <u>psi</u>	<u>P_{DYN}</u> <u>psi</u>	<u>P_{REFL}</u> <u>psi</u>	<u>I_{STAT}</u> <u>psi-s</u>	<u>I_{DYN}</u> <u>psi-s</u>
263	298	122	1991	3.23	1.60
1056	8	2	34	1.19	0.22

From Vehicle Breakup MET: $30 < T < \text{MECO}$ the explosion environment is nil.

* Distance for in-flight explosions refers to the distance from the center of the vapor cloud to the point of interest (i.e., RTG).

3.3.5.1.3 Auxiliary Propellant Explosions

Caused by fire:

	P_{STAT} <u>psi</u>	V_{FRAG^*} <u>fps</u>
MMH Tanks (OMS, ARCS, RPM)	3-4.5	174-367
N_2H_4 Tanks (APU, IUS RCS)	Nil-5.3	207-226
He Tank (RPM)	14.2	1050
PRSDS Tanks	138	-

* Indicates velocity of fragments from given tanks.

These pressures and fragment velocities are predicated on failure of all pressure relief devices for the tanks. Also, especially for the MMH and N_2H_4 , Revision A of the earlier Shuttle Data Book (JSC 08116, March 1987) stated that the time to burst is on the order of 2 to 20 hours.

Caused by Crash:

Typical crash velocities estimated for these tanks are 30-130 fps (See Table B-8 in Appendix B).

3.3.5.2 SRB Fragment Environments

RSS Destruct:

Summary of High Speed Cutline Octant and Quadrant Sized Fragments¹

<u>MET Range</u> <u>sec</u>	<u>Fragment</u> <u>Size</u>	<u>Vel. Range</u> <u>ft/sec</u>	<u>AZ Range</u> ⁽²⁾ <u>deg.</u>	<u>Spin Rate Range</u> ⁽⁴⁾ <u>rev/sec</u>
0-20	Octant	273-344	84-102	9.6-12.5
	Quadrant	181-227	96-104	6.6- 8.5
20-70	Octant	233-319	82-104	8.0-11.5
	Quadrant	158-206	93-113	5.7- 7.7
70-105	Octant	240-339	92-106	7.7-11.2
	Quadrant	193-261	106-117	5.4- 7.8
105-120(H) ⁽³⁾	Octant	413-450	69- 82	8.6-11.0
	Quadrant	326-339	83- 92	5.8- 8.4
105-120(L) ⁽³⁾	Octant	650-717	72- 89	10.9-19.8
	Quadrant	514-537	83- 95	7.9-14.1

(1) A large range of SRB fragment size was analyzed by hydrocode to determine the relationship between velocity azimuth, and spin rate with size. This table shows the representative ranges of these variables for only two of the size categories studied - octants and quadrants.

(2) Azimuth refers to the angle between the initial flight path of the fragment and the SRB radial through the destruct charge.

(3) H & L refer to heavy and light fragments based upon which half SRB segment the fragments originate from due to the differences in propellant loading and burn characteristics.

(4) About an axis parallel to the SRB longitudinal axis.

Velocity and spin rate reduction factors for intervening structure of the Orbiter payload bay walls and wings have been observed from the current test program (no reports yet available) to be as large as 25% for the wing and 20% for the sidewall for velocity. Up to 100% reduction in spin rate was observed for fragments going through the wing only. Spin reduction factors for fragments going only through the sidewall have not yet been determined.

SRB Random Failure (Case Burst)

Typical velocity ranges for fragments from the SRB segment in which the failure occurs are as follows:

<u>MET (sec)*</u>	<u>Velocity Range (ft/sec)</u>
0-20	134-369
20-70	134-342
70-105	182-364
105-120 H	267-481
105-120 L	407-765

* H&L refer to heavy and light fragments based upon which half SRB segment the fragments originate from due to the difference in propellant loading and burn characteristics.

For the sixth segment away from the segment experiencing the initial failure, the fragment velocities would be only 47% of the values given for the failed segment. Azimuth ranges are as follows:

1

Failed segment	0 ± 110 deg.
Other segments	0 ± 130 deg.

Spin rates are related to fragment velocity, size, and azimuth with maximum values for octant sized fragments from the failed segment as follows:

<u>MET (sec)*</u>	<u>Spin Rate (max.) rev/sec</u>
0-20	11.2
20-70	10.2
70-105	12.4
105-120(H)	11.5
105-120(L)	19.5

* H Heavy
L Light See previous explanation

Clevis pins and segment joint fragments have mass characteristics similar to RSS destruct fragments, but the velocity can be higher by 35% than that for the larger fragments. Azimuth and spin rate are treated in the same way as for the large fragments in the random failure model.

3.3.5.3 ET Propellant Explosion - Fragments

External Tank (ET) explosions are postulated to result in the Orbiter payload bay walls and doors being collapsed or imploded around the payload. The walls and door panels are referred to as flyer plates in the definition of the environments. These flyer plates are typically thin, relatively light weight, aluminum fragments that cause relatively little damage even though the velocities can be appreciable. Flyer plate velocity is generally dependent upon areal density; the values given in the Shuttle Data Book are 0.024 lb/in^2 for the payload bay doors and 0.01 to 0.04 lb/in^2 for the sidewall.

3.3.5.3.1 Near-Pad Explosions

From Vehicle Breakup or Tower Impact:

a) On-Pad Explosions

<u>Dist.</u> <u>ft</u>	<u>Percent</u> <u>Occurrence</u>	<u>Flyer Plate Velocity - ft/sec</u> [*]	
		<u>0° Angle</u>	<u>90° Angle</u>
20	0.1	888	2054
	50	186	544
200	0.1	388	727
	50	nil	nil

b) In-Trench Explosions

<u>Dist.</u> <u>ft</u>	<u>Percent</u> <u>Occurrence</u>	<u>Flyer Plate Velocity - ft/sec</u> [*]	
		<u>0° Angle</u>	<u>90° Angle</u>
110	0.1	781	1497
	50	226	388
290	0.1	591	1084
	50	57	114

* Angle refers to the angle between the Shuttle vertical longitudinal axis and the local vertical when the flyer plates are generated by the explosive shock wave, with the trajectory of the shock wave front approaching the vehicle at this angle.

See previous explanations of Distance and Percent Occurrence.

From Aft Compartment Initial Explosions*

<u>Dist.</u> <u>ft</u>	<u>Percent</u> <u>Occurrence</u>	<u>Flyer Plate Velocity - ft/sec</u>	
		<u>0° Angle</u>	<u>90°Angle</u>
20	0.1	477	1449
	50	82	261
200	0.1	124	266
	50	nil	nil

3.3.5.3.2 In-Flight Explosions (Vapor-Cloud Explosions)*

<u>Dist.</u> <u>ft</u>	<u>Flyer Plate Velocity - ft/sec</u>	
	<u>0° Angle</u>	<u>90°Angle</u>
263	958	1949
1056	141	180

* See previous explanations of distance, percent occurrence, and angle.

3.3.5.4 Orbiter Crash Environment

Typical crash velocities for the RTGs upon landing accidents in the Orbiter are predicted to be in the range of 50-125 ft/sec. (15-38 m/s). These velocities are the equivalent velocities experienced by the RTGs considering deceleration of the Orbiter when breaking up and crushing.

3.3.5.5 Upper Stage (IUS) Environments

3.3.5.5.1 Fragment Environment

a. SRM-1

Av. Weight		Areal Density <u>Range-lb/in²</u>	Velocity Range at RTG* (ft/sec)	
<u>MET(sec)</u>	<u>Range - lb</u>		<u>Level 1</u>	<u>Level 2</u>
0-49	4-79	.26-.68	98-278	159-450
49-98	2-47	.22-.58	164-458	212-594
98-147	0.8-16	.15-.40	180-498	278-767

*Based on no intervening structure

b. SRM-2

Av. Weight		Areal Density <u>Range-lb/in²</u>	Velocity Range at RTG* (ft/sec)	
<u>MET(sec)</u>	<u>Range - lb</u>		<u>Level 1</u>	<u>Level 2</u>
0-34	2-40	.20-.54	92-265	150-428
34-68	1-24	.17-.46	152-432	196-558
68-102	0.4-7.9	.12-.32	161-457	256-728

3.3.5.5.2 IUS Errant Reentry

The reentry configuration for a majority of potential failure modes is a separated spacecraft. The only credible failure modes that can cause the spacecraft and some part of the upper stage to reenter intact are those that preclude IUS ignition or result in either a prompt elliptic or a powered reentry. Typical reentry velocities for any of the IUS failure modes are in the range of 14,400 to 36,400 ft/sec (4.4 to 11.1 km/sec) at flight path angles in the range of -0.5 to -32°.

3.3.5.6 VEEGA Reentry Environment

Table E-6 of Appendix E, Volume II (Book 2) of this FSAR shows that the ranges of velocity and flight path angle that can occur in the potential reentries arising from spacecraft and mission failures during the VEEGA maneuver are 13.9 to 15 km/sec (45.6 to 49.2 kft/sec) and 7° to 90° down from the local horizontal, respectively. The reentry configuration is the deployed Galileo spacecraft.

3.3.5.7 Liquid Propellant Fireball/Afterfire

All accidents that occur on or in the immediate vicinity of the launch pad (i.e., for METs of 0 - 10 sec) that involve explosion and spillage of the liquid propellants from the ET will include a fireball and an afterfire from the burning propellants. Based on the information given in Section 7 of the Shuttle Data Book (NSTS-08116), the total propellant load in the ET will result in the following fireball/afterfire characteristics:

Max. diameter	=	1000 $\pm$ 300 ft
Total duration	=	30 $\pm$ 25 sec
Time to lift-off	=	6 - 7 sec
Time to stem lift-off	=	9 - 10 sec
Peak heat flux (experimental model)	=	2000 Kw/m ² (176 Btu/sec/ft ²) (~2163°C black body temp.)
Afterfire heat flux	$\approx$	230 Kw/m ² (20 Btu/sec/ft ²) (~1141°C black body temp.)

The effects of the fireball/afterfire on the thermal response of the RTG and/or GPHS heat source are not determined, in this FSAR, however. Previous tests (Refer to Appendix G, Section G.2.3) have demonstrated the ability of the GPHS module to withstand the thermal environment from exposure to a full web thickness of burning solid propellant typical of the Shuttle SRBs. In these tests, even the bare fueled clads withstood the higher temperature (estimated to be around 2360°C) of the burning solid propellant, as compared with that of the liquid propellants (2163°C), without breaking. The Shuttle Data Book does not include a specification for the solid propellant fire for that reason. In this FSAR, the liquid propellant fire model is used only to

determine the degree of vaporization that the PuO_2 fuel will undergo in the event that a fuel release occurs within the region affected by the fireball. This is explained in Section 3.4.3.2 for the Fire/Explosion branch (Branch 0') of the Prelaunch/Launch phase, Phase 0.

3.4 RTG RESPONSE TO ACCIDENTS

This section of the AMD presents the detailed FASTs and source terms for each mission phase and each accident scenario defined by NASA in the Shuttle Data Book. Previous sections have summarized the accident scenarios and environments and the accident probabilities with the resulting top level failure sequence trees for each mission phase. Included in this section are the details of the response of the RTG to the accidents. The development of the details in the FAST branches are presented as well as the source term analyses.

3.4.1 ACCIDENT ENVIRONMENTS TEST PROGRAM

Much of the previous testing performed in the GPHS-RTG program was specific to the launch vehicle and to the mission configuration. As a result of the analyses following the Challenger accident, subsequent cancellation of the Centaur as the upper stage, and the reconfiguration of the mission profile, additional mission/vehicle-specific safety tests were deemed necessary. In these tests, primary emphasis has been placed on accidents in which the Shuttle SRB motor case fragments have become the major threat; air shock from explosive events has become negligible because of the relatively low levels currently predicted. Additional testing has been performed to obtain basic response data of the heat source components for use in calibration of analytical models used in the GPHS response analysis for the accident environments. These recent tests are summarized in the following paragraphs. Details of all applicable tests are given in Appendix G.

3.4.1.1 Bare Fueled Clad Impact Tests (BCI)

These tests were conducted to extend and augment the previous data base and to get a better comparison between the fuel and the fuel simulant. Also, these tests were performed at increased impact velocities in an attempt to get larger fuel releases for the purpose of characterizing release versus crack size and versus particle size distribution. The results of these tests have indicated that the PuO_2 fuel generally tends to deform to a greater extent than does the fuel simulant at a given velocity and for a given impact surface. There are several ways in which the test results have been used. First, they have been used to provide a calibration for the analytical models for the hydrocode analysis of the RTG response to the SRB fragment environment (along with data from the previous SVT impact series). The details of this analysis are presented in Appendix C, and the use of this analysis is described in Appendix D, which also presents the details of the Launch Accident Scenario Evaluation Program (LASEP) computer program developed to analyze the overall response of the GPHS-RTG in the various on-pad and near-pad launch accidents. The test data have also provided a basis for estimating fuel release as a function of clad deformation.

3.4.1.2 SRB Fragment Tests In Gas Gun (FGT)

These tests used the turn-around technique in which a GPHS module (either with fuel or fuel simulant - both have been tested) and a simulated flat plate RTG converter section (with uncouples and multifoil insulation) were propelled into a stationary SRB case fragment. The tests were conducted in the Los Alamos completely contained Isotope Fuels Impact Test (IFIT) Facility, a 178mm cannon using a pneumatically propelled sabot in an upward firing arrangement. Tests were run with fuel simulant and with actual fuel in the velocity range of 100-120 m/s (328-394 ft/sec). For this test configuration, 120m/s was the upper limit of the facility. A comparison between the fuel and simulant response was obtained. The load attenuation, as seen by the GPHS module, due to the intervening converter structure was determined. These results were used in the hydrocode analysis of the RTG response to SRB fragments. There was no breaching of the fueled clads in any of these tests.

3.4.1.3 Large SRB Fragment Impact Tests (LFT)

In these tests, a 142 cm (56 inch) square, 1.27 cm (0.5 inch) thick SRB case fragment was propelled by rocket sled into a flight configuration RTG housing of one-half length containing two (2) simulant fueled test modules and six (6) mass simulant modules. The purpose of these tests was to determine the response of the GPHS modules in the RTG configuration and with representative full size SRB fragments. The tests were conducted on the Sandia Laboratories rocket sled test facility. Because the facility was exposed to the atmosphere with no absolute containment capability, the actual live fuel could not be used in these tests. Depleted uranium simulant was used instead. Two tests were run with the SRB fragment impacting in the face-on attitude at 115 and 212 m/s (377 and 695 ft/sec, respectively). A third test was conducted with the SRB fragment oriented in an edge-on attitude at a velocity of 95.4 m/s (313 ft/sec). There was no breaching in either of the face-on tests from the initial fragment impact. Because of the way in which the test fixturing and catch tube caused the SRB fragment to breakup in the 212 m/s test, secondary impact (after the clads were arrested in the catch tube) caused minor breaches in one of the fueled clads.

In the edge-on test, the two leading clads (one in each test module) that were struck directly by the SRB fragment were breached with gram quantity releases of the fuel simulant. The other two leading clads and all trailing clads had minimal distortions.

3.4.1.4 Fragment/Fuselage Tests

SRB case fragments 61 cm (24 in) square were explosively propelled through sections of the actual Orbiter wing and/or payload bay wall structures at velocities in the range of 180-183 m/s (590-600 ft/sec) and with rotation rates of 6.6 to 10.7 rev/sec. The purpose of these tests was to determine the velocity attenuation and alteration of rotational motion due to the interaction with the Orbiter structure. In the three tests conducted to date, wing structure attenuation has varied from 25 to 46% in velocity and from 80 to 100% reduction in rotation rate. In a combined test, the overall attenuation through both the wing and Orbiter bay sidewall has been observed to be 40%.

3.4.2 LAUNCH ACCIDENT SCENARIO EVALUATION PROGRAM (LASEP)

3.4.2.1 Description

A computer program has been developed to analyze the overall response of the RTG/GPHS modules in the accidents that can occur in the Space Shuttle vehicle on and near the launch pad and during the early ascent of the Shuttle up to jetison of the SRBs. This program is called the Launch Accident Scenario Evaluation Program, or LASEP. Details of the program are presented in Appendix D of this AMD. LASEP determines the sequential response of the GPHS modules (in whatever configuration) from the initial insult through their subsequent pathways of predicted damage until either they no longer receive additional damage or the fueled clads experience a breach and release of fuel, thus constituting a source term. LASEP also calculates the source terms, should they occur, and the particle size distribution of the released fuel. Incorporated into LASEP are the results of the detailed hydrocode analyses that have been conducted by Fairchild Space Company of the RTG/GPHS response to flyer plates and Shuttle SRB fragments as well as the results of the tests conducted in the current safety test program. Details of the hydrocode analysis program are presented in appendix C of the AMD. A summary description of LASEP is given in the following paragraphs. As the detailed FASTs and source terms for the mission phases are developed in subsequent sections, the use of the results from LASEP are described in more detail.

The LASEP has the capability of analyzing one or more of the following accident/environment scenarios:

- 1) Left SRB Failure/Tower Impact (0-2 sec MET)
- 2) SRB Random Case Rupture
- 3) Range Safety System (RSS) Destruct
- 4) Mobile Launch Platform (MLP) Pool Explosion
- 5) Flame Trench Explosion
- 6) Aft Compartment Explosion
- 7) Vapor Cloud Explosion

After the initial interaction with the RTG by SRB fragments or Orbiter payload bay wall fragments and by any accompanying shock wave, the remaining configuration of the RTG, (or GPHS modules or free fueled clads) is then propelled by the imparted impulse arising from any of the following contributors, as appropriate:

- SRB fragment impact
- Flyer plate impact
- Static overpressure
- Dynamic pressure
- Vehicle motion at instant of accident

The resulting trajectory of the RTG, GPHS modules, or fueled clads is calculated, and the point of impact with the ground or any structures in the vicinity of the launch pad area is determined. The contact point is characterized as to its location, impact surface, velocity of impact, and whether or not it is within the fireball ensuing from the accident.

The accident environments are modeled in LASEP according to the detail given in the Shuttle Data Book, NSTS 08116. Included in the SRB fragment definition are the following:

- size distribution (by circumferential length)
- velocity range by size
- angular range of release (azimuth) by size
- spin rate range by size
- spatial release point by size
- all as function of MET

Different size distributions are given for both the SRB random case rupture and the RSS destruct events.

As an example of the procedure used in the LASEP, the following paragraphs describe an accident involving a SRB random case rupture. First a Monte Carlo sampling technique is used to select the time in the trajectory (MET), either the left or right SRB, and the failure location including the SRB segment in

which the failure occurs. Then, for each Monte Carlo trial, SRB fragment circumferential bands are generated with size, velocity, spin rate, and angular range of travel being selected randomly for each fragment in each band. The probability of each fragment in these bands hitting the RTG is then determined. For those fragments that can hit the RTG, the one having the highest velocity is chosen to calculate the initial damage to the RTG as well as the subsequent GPHS or fueled clad trajectories, either within the RTG or as free bodies. This approach is used since the fastest fragment will arrive first at the RTG; single hits only are counted since generally the fragment size is as large as or larger than the RTG. Damage to the GPHS fueled clads is then determined based on the hydrocode analysis. The initial velocity imparted to the RTG/modules/FCs is determined on the basis of the hydrocode results. Secondary interaction with the payload bay walls is accounted for again on the basis of the hydrocode analyses. If there is motion of the vehicle when the point in the trajectory is chosen by the initial Monte Carlo sampling, this motion is added vectorially to the velocity of the GPHS/components. The trajectory and impact is then calculated, and any additional damage due to the impact is determined based on the results of the module and bare clad tests (SVTs and BCIs). The results of all (Monte Carlo) trials are tallied and the average and the largest (in the given number of trials) source terms are calculated by the LASEP, both for the initial fragment impact and the subsequent impacts on the ground or launch pad area surfaces. In the LASEP version used for this FSAR, the total damage resulting after a secondary impact is determined by a root-sum-squared combination of distortions from both primary and secondary events.

Features of the LASEP for other accidents include the following:

Explosions (MLP, Flame Trench, Aft Compartment)

- Shuttle bay doors and walls are assumed to strike the RTG because of the implosion effect and the size and nearness of the walls to the RTG.

- The payload doors and walls are oriented essentially face-on to the RTGs. There is not enough room for them to turn edge-on before striking the RTGs.
- The implosion of the payload bay walls around the RTGs does not transfer a net propulsive force to the RTGs. In the absence of any other forces, the RTGs are assumed to fall essentially on a vertical path.
- There is an option available to add in a propulsive force due to the dynamic pressure from the explosion.

Left SRB Thrust Failure/Tower Impact

- Distance from the RTG to the propellant pool surface (on the MLP or in the flame trench) when the explosion occurs is sampled randomly. This is done to account for the vehicle falling back to the pad after the tower impact occurs and allowing the explosion to occur randomly during the fall.
- The orientation of the vehicle (i.e., tilt angle) when the explosion occurs is also sampled randomly.

Vapor Cloud Explosions

- Distance from the RTG to the cloud center when the explosion occurs is determined by the product of the vehicle velocity at the instant of failure times a one (1) second period as recommended in the Shuttle Data Book.

Effect of Assumptions and Conditions

In the development of the LASEP2 program, there are a number of assumptions and conditions that have been employed that are considered to make the results conservative. These include the following:

- 1) SRB fragment orientation
- 2) RTG damage levels due to SRB fragment impact

- 3) Fuel release as a function of distortion
- 4) Treatment of edge-on SRB fragment impact

Each of these areas are discussed in more detail in the following paragraphs.

SRB Fragment Orientation

In the Shuttle Data Book, the SRB fragments are characterized with an orientation and motion in which they are spinning about an axis that is parallel to the longitudinal axis of the SRBs (i.e., X-axis). Combined with this spinning attitude is the translational motion outward from the SRBs. In the Galileo configuration, the RTG longitudinal axis is parallel to the SRB X-axis. This means that, for a SRB fragment whose center-of-gravity is travelling in a direction that will intersect the RTG near its longitudinal mid point, the impact will involve all GPHS modules equally (assuming that the fragment size is as large or larger than the RTG long dimension). In reality, the motion of the SRB fragment, with the fragment being irregular in shape, will probably result in the fragment impacting in a totally random orientation. Consequently, only the GPHS modules in the immediate vicinity of the impact point will receive the major damage, as opposed to all the modules. This would reduce any consequent release of the radioactive fuel as contrasted with the present treatment in LASEP.

RTG Damage Levels

Removal of the RTG converter (leaving the bare GPHS modules intact) by essentially face-on or flat-on SRB fragment impacts has been estimated by a rudimentary energy analysis. Recent test results (obtained after the LASEP2 program was developed and the analyses completed for the FSAR) from the large fragment tests (refer to Appendix G, Volume II, Book 2 of the FSAR) indicate that this analysis is very conservative. For a 56 inch (1.42 m) square fragment, the analysis predicts converter removal at 36 ft/sec (11 m/sec). In the first large fragment test (LFT-1), the converter still contained the GPHS modules after being impacted by a face-on SRB fragment of that size at 377 ft/sec (115 m/sec), although the converter was severely damaged.

Fuel Release as a Function of Distortion

Figure D-18 in Appendix D presents the curves of fuel release as a function of distortion used in LASEP. It is a composite graph using bare clad impact (BCI), safety verification test (SVT) (i.e., impact of full GPHS modules), and fragment gas gun test (FGT) data. The FGT data was used to estimate the threshold of failure. Since there were no failures in the FGT tests, the BCI data was used to establish the shape of the failure curve with extrapolation to complete failure or complete release. The expression for the fit function was selected because it had the correct shape to fit the data including its limits at both zero release and complete release. Figure D-18 has been designed to exhibit the fitting function as a straight line, with the actual zero being accommodated by the ordinate so that data points not involving release can be plotted as opposed to a logarithmic plot. The SVT data points are seen to be insufficient to establish a trend, but they do provide a basis on which to establish a failure threshold around 15% distortion. One can see that the BCI test points do not show release below a distortion of 20%. In LASEP, however, the bare clad impact failure threshold was taken to be the same as the bare module threshold of 15%, thus adding conservatism to the results.

Another factor should be noted. Module releases on ground impact have been based on the SVT test data, in which tests the modules were impacted in the worst case orientation - the large face of the module parallel to the impact surface. In this orientation, the cylindrical axis of the fueled clads is parallel to the impact surface which results in the most severe stress in the hoop direction, also the worse stress for the weld line. Other impact orientations such as a hit on the corner of the module or on an edge would not be expected to result in any release, especially since the releases in the SVT tests were relatively small.

Edge-on Fragment Impact

In LASEP, the distortion of the trailing clads in an edge-on SRB fragment impact is given a value that is half (1/2) of the distortion predicted for the leading clads as determined by the hydrocode analysis (see Appendix C). This

approach was chosen arbitrarily before any appropriate test data was available. In the third large fragment test (LFT-3), a SRB fragment in the edge-on orientation and at a velocity of 313 ft/sec (95.4 m/sec) resulted in one of the leading clads in each of two test modules being breached with gram quantities of fuel simulant released. However, the other two leading clads (those not struck by the fragment edge) and the four trailing clads did not experience distortions exceeding 3.3%. This conservatism in the LASEP treatment is thus seen to be considerable.

3.4.2.2 Accident Environments Not Explicitly Treated

Certain accident environments defined in the Shuttle Data Book (NSTS 08116) are not addressed or treated explicitly either in the LASEP analysis or in the several FASTs for the mission phases. These include:

- 1) Clevis Pin projectiles arising from failures in the Space Shuttle SRBs.
- 2) Auxiliary tank fragments due to failure of the tanks in a Launch Pad fire/explosion scenario or in an Orbiter crash landing.

In addition, most of the accident scenarios that can occur on or near the launch pad or during the early ascent portion of the mission can result in the essentially intact RTG impacting on hard surfaces such as the steel launch platform and service structures and the concrete launch pad apron. If these impacts could occur with the RTG being in an end-on stabilized mode (aerodynamically) at the corresponding terminal velocity, considerable damage could be experienced by the two or three modules nearest the impact end (refer to Appendix C). These impacts also are not treated by the LASEP analysis nor are they addressed in the FASTs for each of the accidents. This section discusses the rationale for exclusion of these environments and damage mechanisms from the events that potentially lead to source terms.

3.4.2.2.1 Treatment of Clevis Pins

The Shuttle Data Book gives the following characteristics for the clevis pins as part of the SRB fragment environment:

Length	:	0.75 inch (1.91 cm)
Diameter	:	0.50 inch (1.27 cm)
Material	:	Steel
Mass	:	0.042 pound (.019 kg)
Velocity	:	715 fps max (218 m/s)

Tests were conducted during the pre-1986 safety test program in which aluminum bullets were fired into GPHS modules and titanium bullets were fired into bare fueled clads over a range of velocities (see Appendix G, Section G.2.2). Based on these tests, the thresholds of failure for the fueled clads were as follows:

Module Configuration

555 m/s (1820 fps) for 18 gm, 50 cal., Al bullet

Bare Clad Configuration

423 m/s (1387 fps) for 3.25 gm, 30 cal., Ti bullet

The ratio of the energy required for breach of the clads in the module configuration compared with that of the clevis pins at the upper end of their velocity range is 6:1. This does not take into account the added protection provided to the clads by the intervening converter structure of the RTG. Clevis pins would not have direct access to bare clads as a result of any accident. If they preceded the other SRB fragments (i.e., if they traveled faster), they would reach the RTGs first and would thus encounter the whole RTG structure. If they followed the other SRB fragments, they would be going slower, and by far the greatest damage would be inflicted by the large SRB fragments. For these reasons and based on the test data, breach of the fueled clads by clevis pins is ruled out.

3.4.2.2.2 Treatment of Auxiliary Tanks

The majority of the tanks in the APU, ARCS, OMS, and PRSDS systems of the Orbiter, the RCS of the IUS, and the RPM in the Galileo spacecraft are made of titanium (i.e., the Ti-6Al-4V alloy). These tanks typically fail by splitting open and relieving pressure. They do not fragment, if they come apart, they are generally in two hemispheres. Design requirements, especially for payloads to be used in the Orbiter, state that:

- It is highly desirable that all pressure vessels be designed so that failure due to overpressure or to material properties will not produce shrapnel.
- Payload pressure vessel structural retention devices/brackets should be capable of withstanding the 9 g crash load limit established for Orbiter structure.
- Pressurized gas vessels must be firmly secured by their mounting brackets to prevent a vessel from becoming a projectile from the thrust of the contained gas if a line or connector occurs. These guidelines are given in the Space Transportation System Payload Safety Guidelines Handbook, JSC 11123, July 1976.

During the NASA Apollo Program, puncture tests were performed on tanks using the Ti-6Al-4V alloy by both Hughes Aerospace Division (Reference 3-4) and by Wyle Laboratories for the Airite Division of Sargent Industries (Reference 3-5). The Hughes tests were performed on Ti-6Al-4V propellant tanks loaded with N_2O_4 at pressures ranging from 100 - 200 psi. Tests were performed by firing 30-30 caliber bullets into the tanks. In all cases, the bullets penetrated both walls, leaving the tanks intact and producing only leakage of the propellant. No shattering or shrapnel effect was observed. The tests performed for Airite were on Ti-6Al-4V helium tanks pressurized to 3350 psig with refrigerated helium. With stable pressure and skin temperature stabilized at 65°F, the tanks were punctured by 1/4-inch diameter pins. As in

the Hughes tests, the only results were a hole accompanied by rapid depressurization. In the case of burst testing, no shattering is encountered with the Ti-6Al-4V alloy.

In the case of the aluminum and Inconel 718 tankage, both puncture and burst testing indicate that no shrapnel is produced. NASA program NAS 7-98, which investigated methods of sealing holes in tanks punctured by micrometeorite penetration, included puncture testing of aluminum containers. The containers were pressurized over a range of 15 to 100 psi. Aerojet Report 2824, Vol. III, indicates that puncture was the only result of penetration by 38-caliber and 22-caliber pellets. Figure 3-8 shows the results of hydrostatic burst testing on two LM ascent stage gaseous oxygen bottles. This response is typical of the pressure vessels considered, indicating that the vessels rip or tear under burst testing rather than shattering and producing shrapnel. The penetration test results which have been described deal only with impact of small particles. However, from the results of the burst testing, it may be inferred that impact by larger fragments would produce a similar effect, i.e., a rip or tear in the area of overstress.

Figure 3-8. Results of Burst Test on LM GO_x Tank - Material, Inconel

The velocities and areal densities of the auxiliary tanks as defined in the Shuttle Data Book can be compared with those of the payload bay wall fragments, also defined in the Shuttle Data Book, for which hydrocode analyses have been performed to determine GPHS damage. The areal density of the payload bay door fragments is 16.9 Kg/m^2 ($.024 \text{ lb/in}^2$). At a velocity of 365 m/s (1200 fps) into the RTG, the payload bay door fragment resulted in a distortion less than 10% for the leading clads (Refer to Appendix C). This is well below the level of 30% for clad breach. From Table B-7, Appendix B of this FSAR, the maximum velocity of any auxiliary tank fragment is 320 m/s (1050 fps) from the Galileo RPM helium tank (titanium). The next highest velocity is 112 m/s (367 fps) from the Orbiter OMS tanks (also titanium). The areal density of these tanks is typically around 6.8 Kg/m^2 ($.0096 \text{ lb/in}^2$). Since the payload bay door fragments have densities higher by a factor of 2.5 and a velocity (analyzed by hydrocode) that is roughly 14% higher than the highest auxiliary tank fragment velocity, the fragments from the auxiliary tanks (if they could exist and with the characteristics defined) would not be expected to result in breach of any fueled clads. Thus, the auxiliary tank fragments are ruled out as far as damaging the fueled clads and are not treated.

3.4.2.2.3 Treatment of Intact RTG Impact

The estimated values for the terminal velocity of the RTG in the various altitudes are as follows:

Side-on Stable: with fins	33 m/s (109 fps)
without fins	55 m/s (180 fps)
Tumbling End-Over-End (without fins)	56 m/s (183 fps)
End-on Stable: (without fins)	116 m/s (380 fps)

These values are for the RTG without appendages such as boom sections or cables.

Based on a typical trajectory such as that obtained from Reference 3-6, the Instantaneous Impact Point (IIP) track for the vehicle trajectory is characterized as follows:

IIP off MLP @ $t + 5.5$ sec

IIP off concrete pad area @ $t + 8.5$ sec

At these times, the vehicle altitude is

64 m (210 ft) @ $t + 5.5$ sec

176 m (578 ft) @ $t + 8.5$ sec

The vacuum free-fall velocities from these heights are:

35 m/s (116 fps) @ 210 ft

59 m/s (193 fps) @ 578 ft

If the vehicle component of velocity in the vertical direction is taken into account in lofting the RTGs to a higher attitude, the potential vacuum free-fall velocity would be:

45 m/s (149 fps) @ $t + 5.5$ sec

75 m/s (245 fps) @ $t + 8.5$ sec

Thus, if the RTG could orient end-on and remain stabilized in that attitude, it could not impact on concrete or steel at the terminal velocity.

During the period from greater than $t + 13$ seconds to around $t + 17$ seconds when the IIP crosses the shoreline (not at 30 seconds as stated in the Shuttle Data Book), the RTG could possibly hit sand at the end-on terminal velocity if it could stabilize initially and remain that way until impact. However, this impact attitude is highly improbable. First of all, a cylinder with a large aspect ratio (i.e., ratio of length to diameter) such as that of the RTG will stabilize side-on. Most probably, the RTG will start out tumbling when it is released from the spacecraft in an accident situation.

When the IIP crosses the shoreline at a MET ~ 17 sec, the vehicle altitude at this time is around 811 m (2660 ft). Based on previous drop tests and analyses of the falling GPHS heat source, a stable attitude did not occur within 2660 feet of fall. Therefore, an end-on stable impact of the RTG is ruled out. An end-on impact of the RTG from a tumbling attitude would occur at a much lower velocity of 56 m/s (183 fps) which is around the value previously tested in the module impact tests (Refer to Appendix G in this FSAR). Impacts on sand at this velocity would not be expected to result in breach of any of the clads (see Appendix C and G of this FSAR). In addition, the RTG converter case and foil basket would be expected to provide effective containment for the heat source modules in a sand impact.

3.4.3 PHASE 0: PRELAUNCH/LAUNCH

This phase of the mission covers the period from the time at which tanking of the liquid propellants begins at approximately T-8 hours to liftoff of the Space Shuttle/IUS vehicle at T-0. The top-level event tree for this phase is shown on Figure 3-2. The total accident probability is seen to be 1.79×10^{-4} , made up of inadvertent RSS destruct at 6.32×10^{-9} and fire/explosion at 1.79×10^{-4} .

3.4.3.1 RSS Destruct

Since the Shuttle SRBs will not have been ignited prior to T-0, there will be no internal chamber pressure with which to generate SRB case and/or propellant fragments. Therefore, this scenario will essentially be characterized by the fire and explosion scenario, and its probability of occurrence will simply add to that for the fire/explosion scenario in Section 3.4.3.2.

3.4.3.2 Fire/Explosion - Branch 0'

This branch of the Prelaunch/Launch Phase (Phase 0) is shown on Figure 3-9. There is no breach of the clads resulting from impact of the payload bay fragments, but initial distortions occur at values less than 10%. Subsequent ground impact by the clads results in a fuel release in 28 of 10,000 trials for an average of 44.3 Ci at a probability of 5.01×10^{-7} . The maximum

Figure 3-9. FAST 0' For Fire/Explosion - Prelaunch/Launch Phase

release is shown as the same as the average release since the probability for the maximum was less than 1×10^{-7} . The release on the ground is always in the fireball on the steel MLP.

In the Fire/Explosion accident, the treatment of the fireball effect on the fuel release particle size distribution is as follows. The vaporized fraction is determined by the contribution from each particle size using the analysis and figures given in Appendix H of Volume II (Book 2) of this FSAR document and summed to produce the total vapor fraction as 0.02 micron sized material. The experimental data fireball model for the liquid propellant fire was used in the analysis. The size of the smaller particles remaining after exposure was determined from the equation:

$$D = D_0 (1 - f_v)^{1/3}$$

where:

D = final particle diameter
 D_o = initial particle diameter
 f_v = fraction vaporized by the fireball

This relationship (as used previously, also) is based on the volume reduction (amount vaporized) and assumes that the particles are spherical. Only particles of 10 micron size and smaller are significantly affected. Tables 3-7, 3-8, and 3-9 at the end of Section 3.0 present a complete listing of the source terms and the particle size distributions for the total mission. LASEP calculates the particle size distribution for each trial that results in a fuel release, and the average or maximum release particle size distribution is printed out as part of the output. Where necessary, the particle size distributions from LASEP are then modified to arrive at the particle size distributions resulting from action of the fireball. This procedure is used throughout the FASTs wherever the fireball effect is applicable.

3.4.4 PHASE 1: ASCENT

Figure 3-3 presents the top level event tree for accidents occurring in the Ascent Phase (Phase 1). The total accident probability is seen to be 4.36×10^{-3} , and the contribution from each accident category is shown.

Accidents resulting from Crash Landing and Ocean Ditch are not carried any farther because of the mild environments. Section 6.2 of the Shuttle Data Book indicates that the impact environment imposed on the RTGs is in the range of 50-125 ft/sec (15-38 m/sec). The impact capability of the GPHS modules has a failure threshold around 54 m/s (177 ft./sec) on hard steel and approximately 65 m/s (213 ft/sec) on concrete as determined from the previous SVT test program. (See Appendix G, Sections G.2.4, G.2.5, and G.3.1). Also, the impact of the RTG's inside the crushing-up Orbiter is much less severe than impacting on hard steel or massive concrete.

FAST branch 1S for SRB failures is shown on Figure 3-10. This figure shows the contribution from each of the failure modes of the SRBs.

Figure 3-10. FAST Branch 1S For SRB Failures

3.4.4.1 SRB Case Rupture - FAST Branch 1S1

Figure 3-11 presents the FAST branch for this accident. There is a difference by which the Monte Carlo LASEP cases are treated for this scenario. The NASA supplied failure probabilities (see Appendix A, Table A-4) indicate that there are six time periods during Phase 1 in which the conditional probabilities of SRB failure have different values. These periods and probability weighting are as follows:

Figure 3-11. FAST 1S1 For SRB Case Rupture - Ascent Phase

<u>MET Period - sec</u>	<u>Case Rupture Conditional Probability</u>
0- 10	0.500
10- 20	0.125
20- 70	0.2361
70-105	.0972
105-120	.0417
120-128	<u>0.0</u>
	1.0000

Since LASEP was not developed to address subsets of a phase with a subsequent combination and weighting, this was done separately outside of LASEP. LASEP was thus exercised five (5) times, once for each of the periods given (the 120-128 sec period had zero probability, and thus no LASEP run was needed).

The procedure used in combining the results from these five (5) runs and determining the source terms resulting from the SRB case rupture accident for the entire phase is described in the following paragraphs.

First of all, one should review the results of the hydrocode analysis (Appendix C). These results indicate that the modules in the end locations in the RTG heat source stack tend to experience higher distortions than do the inner modules when impacted along the length of the RTG by a heavy fragment (such as the SRB case fragments) in a face-on orientation. The end locations refer to the two modules at each end of the heat source stack. Since these results were obtained late in the schedule for the FSAR, the decision was made to treat each grouping of modules separately (i.e., with regard to distortion) rather than modify LASEP to accommodate both in a single run. Therefore, separate runs were made for each case: one run with the mid-module distortion related to velocity of impact, the other with the end-module distortion. The combined effect was then to be calculated outside LASEP.

The results from the LASEP runs were examined in more detail to determine the effect on the source terms. Four different approaches of combining or treating the results were investigated as follows:

- 1) Mid-module deformation was used for all modules in the stack.
- 2) End-module deformation was used for all modules in the stack.
- 3) Deformations were weighted according to the number of modules applicable (i.e., 4/18 for end modules, 14/18 for mid modules), and the resulting fuel releases were combined.
- 4) Fuel releases from both runs (i.e., one run with mid-module deformation, one run with end-module deformation) were combined without weighting to obtain better statistics (i.e., combined results for $2 \times 10,000$ triads).

Approach No. 2 should give the largest average release or source term. The results of this study, however, indicated that approach No. 4 gave the largest average source terms. The largest maximum source term did occur for approach No. 2. The major conclusion of this study is that the dominant influence is the edge-on fragment impacts as contrasted with the face-on impacts, the latter being effective only at the very upper end of the fragment velocity range. The edge-on fragments can be seen to be effective from the damage viewpoint at velocities less than 100 m/s. Also, there is no distinction made in the degree of damage between end modules and mid modules for edge-on fragment impact. For these reasons and for the simplicity of combining runs coupled with the potential for better statistics, the decision was made to make a simple combination of runs for the mid-module and end-module distortion relations.

As previously mentioned, the probability of a SRB case rupture occurring in Phase 1 (Ascent) is not uniform over the entire phase but varies according to the weighting previously given for five (5) subperiods of the phase. A separate run (or runs, with end-module and mid-module deformation relations

given separately) is made using LASEP for each of the five (5) periods and with each having 10,000 triads. Since each subperiod has a different conditional probability of occurrence, each LASEP run must be weighted accordingly by the probability of occurrence for each subperiod. This is equivalent to adjusting the number of trials in each subperiod to account for their influence in the overall phase occurrence.

Table 3-3 presents the results of the LASEP output for each of runs (10,000 trials) made for the five (5) subperiods of Phase 1 along with the weighting factors or conditional probabilities and the total probability of SRB case rupture. As stated previously, the mid and end runs are weighted by their number of occurrences (Ns in Table 3-3) and combined as follows:

Example: 0 - 10 sec subperiod

$$\frac{(13.3 \times 7) + (0.127 \times 1)}{(7 + 1)} = 11.7 \text{ gm/release average based on } 8 \text{ out of } 20,000 \text{ trials}$$

These averages are then weighted by the probability of failure (conditional) by time period as follows:

Time (Sec)	Av. Release - gm (per 20,000 Trials)	N _{av}	Weight Factor
0 - 10	11.7	8	0.5000
10 - 20	0.300	5	0.1250
20 - 70	0.774	3	0.2361
70 - 105	9.79	4	0.0972
105 - 120	256	40	0.0417

If the number of trials per run is sufficient for good statistics, then the average should be representative irrespective of the length of the subperiod and thus does not get weighted. But the number of release occurrences will vary by the length or weight of the period over which it occurs. Weighting

Table 3-3. LASEP Output for SRB Case Rupture Scenario (Phase 1)

TIME (SEC)	MODULE POSITION	AIR RELEASE			
		AV. RELEASE-gm	N _{av}	MAX RELEASE-gm	N _{max}
0 - 10	MID	13.3	7	47.2	1
	END	0.127	1	0.127	1
10 - 20	MID	0.491	3	1.15	1
	END	0.0123	2	0.0234	1
20 - 70	MID	1.06	2	1.50	1
	END	0.192	1	0.192	1
70 - 105	MID	5.96	2	9.55	1
	END	12.6	2	27.2	1
105 - 120	MID	405	19	3163	1
	END	121	21	1371	

SRB CASE RUPTURE PROBABILITY = 1.02×10^{-3}

0 - 10	0.5000
10 - 20	0.1250
20 - 70	0.2361
70 - 105	0.0972
105 - 120	0.0417
	<u>1.0000</u>

the number of occurrences (releases) by the conditional probabilities for each subperiod gives the following weighted number of occurrences over the total phase as related to the $2 \times 10,000$ trials:

$$\begin{array}{rcl}
 0.5000 \times 8 & = & 4.00 \\
 0.1250 \times 5 & = & 0.625 \\
 0.2361 \times 3 & = & 0.708 \\
 0.0972 \times 4 & = & 0.389 \\
 0.0417 \times 40 & = & 1.67 \\
 \hline
 & = & 7.392 \text{ out of } 20,000 \text{ trials}
 \end{array}$$

The average fuel release or source term for the total phase is obtained by weighting each subperiod average by its weighted number of occurrences (see above):

$$\begin{array}{rcl}
 4.00 \times 11.7 & = & 46.8 \\
 0.625 \times 0.300 & = & 0.188 \\
 0.708 \times 0.744 & = & 0.548 \\
 0.389 \times 9.79 & = & 3.81 \\
 1.67 \times 256 & = & 427 \\
 \hline
 & = & 478.346
 \end{array}$$

$$\text{Av. release} = 478.346 / 7.39 = 64.7 \text{ gm or } 815 \text{ Ci.}$$

The average release probability for the phase is:

$$P = 1.02 \times 10^{-3} \times 7.39 / 20,000 = 3.77 \times 10^{-7}$$

The maximum release for the phase resulting from the SRB fragment impacts is not given since its probability is much lower than 1×10^{-7} .

The average release on the ground is calculated in the same manner as well as the probability of the release occurring. As currently structured, however, LASEP does not provide individual releases by surface type (i.e., steel, concrete, sand, ocean) and by location (i.e., within the area affected by the fireball or outside this area). Therefore, the release in each location is

distributed according to the distribution of impacts in each location, which is provided in the LASEP output. For Subbranch 1S1 (SRB Case Rupture - Phase 1)

Av. ground release = 63.6 Ci

Fraction in fireball = 0.298

Fraction outside fireball = 0.702

Av. release in fireball = 63.6 Ci X 0.298 = 19.0 Ci

Av. release outside fireball = 63.6 Ci X 0.702 = 44.6 Ci

$$\begin{aligned} \theta P(\text{overall}) &= 1.02 \times 10^{-3} \times 218.5/20,000 \\ &= 1.12 \times 10^{-5} \end{aligned}$$

The maximum source term for this accident has a probability much lower than 1×10^{-7} and is therefore not given.

The altitude for the average source term is 42,100 feet (12800 m), and it is determined by weighting the average altitude for each of the five subphase time periods by the weighted fraction of trials giving a release in each period. Reference 3-6 is used for the altitude as a function of time for the Ascent Phase.

Another way of treating the SRB Case Rupture accident and the relation of the five (5) periods of failure to the overall weighted average is to treat the accident as if it occurs in five subperiods or subbranches of the main accident. Figure 3-12 depicts the accident in this fashion. The five ovals immediately following the diamond indicating the 1S1 branch Case Rupture accident signify the five subperiods with their corresponding conditional probabilities of occurrence. Only the branch for the 0-10 second period is carried to completion (i.e., until the ground impact release occurs, if applicable). The other four (4) subbranches are continued only to the point at which an air release occurs from SRB fragment impacts with the RTGs. Each of the initial accident ovals corresponds to a separate run made with the

Figure 3-12. SRB Case Rupture Accident - Branch ISI Detailed

LASEP. The diamond showing the initial air release shows the probability for that release and the number of LASEP trials that factor into that probability. For example, in the 0-10 second period a total of eight (8) trials out of 20,000 gave an average release of 11.7 gm or 147 Ci at a probability of:

$$p = 5.1 \times 10^{-4} (8/20,000) = 2.04 \times 10^{-7}$$

The second or ground release occurred in 340 trials with an average of 2.62 gm or 330.0 Ci and a probability of:

$$p = 5.1 \times 10^{-4} (340/20,000) = 8.67 \times 10^{-6}$$

The other values shown on the 0-10 second subbranch refer to the statistics of impact of the RTG or its components on the various surfaces in the launch pad area and whether the object is affected by the fireball (FB) or not (No FB) as determined by LASEP. To determine the weighted average over the entire Phase 1 or 0-128 second period (the 120-128 second period is used as having a zero probability of occurrence for the SRB Case Rupture accident) for the air release, the individual subperiod releases are weighted by the probability of occurrence, as follows:

<u>Release</u>	<u>Probability</u>	<u>Rel.XProb.</u>
11.7 gm	X (2.04x10 ⁻⁷)	= 2.39x10 ⁻⁶
0.300	X (3.20x10 ⁻⁸)	= 9.60x10 ⁻⁹
0.774	X (3.62x10 ⁻⁸)	= 2.80x10 ⁻⁸
9.79	X (1.98x10 ⁻⁸)	= 1.94x10 ⁻⁷
256	X (8.50x10 ⁻⁸)	= 2.18x10 ⁻⁵
Σ =		3.77x10 ⁻⁷ 2.44x10 ⁻⁵

The average release is then:

$$\text{Av. source term} = \frac{2.44 \times 10^{-5}}{3.77 \times 10^{-7}} = 64.7 \text{ gm or } 815 \text{ Ci}$$

at the probability of:

$$p = 3.77 \times 10^{-7}$$

which is seen to be the same as that calculated previously. The average weighted ground release for the entire Phase 1 period is calculated in the same manner.

One benefit of describing the weighted average releases for the phase by the latter method (actually, both methods are identical) is that the effect of the contribution to the risks from each subperiod can be determined if desired. Table 3-3A presents the values of the source terms for each of the subperiods related to the SRB Case Rupture accident. Also, for the air releases, the average altitude of release is given for each subperiod. Table 3-3B presents the corresponding particle size distributions for each of the subperiod source terms.

3.4.4.2 Tower Impact - FAST Branch 1S2

Figure 3-13 presents the FAST branch for this accident. The accident results from the left SRB either failing to ignite at T-0 or experiencing an engine/nozzle failure that causes loss of thrust within the first two (2) seconds after liftoff. The Shuttle subsequently is driven into the Fixed Service Structure (FSS), and the ET is ruptured spilling the propellants onto the MLP and flame trench with an ensuing explosion. After the initial collision with the FSS, the Shuttle is assumed to fall or slide down the structure onto the MLP. The explosion will most likely occur sometime between the initial collision and the time the Shuttle hits the MLP/launch pad, which is accounted for in the LASEP by randomly sampling the Shuttle position at the instant of the explosion. There is no initial breach of the fueled clads by the payload bay fragments. The fuel release occurs on the ground due to the additive distortions from the payload bay wall flyer plate impact and ground impact on the MLP. The source terms are as follows:

Av. 58 Ci @ $P = 5.15 \times 10^{-7}$
 25 trials out of 10,000

Table 3-3A. SRB Case Rupture Subperiod Source Terms

AIR RELEASES

<u>PERIOD</u>	<u>AV. RELEASE Ci</u>	<u>N_{av}</u>	<u>P_{av}</u>	<u>ALT. FT</u>	<u>SIZE CODE</u>
0 - 10 SEC	147	8	2.04×10^{-7}	354	A
10 - 20 SEC	3.78	5	3.20×10^{-8}	2,220	B
20 - 70 SEC	9.75	3	3.62×10^{-8}	20,300	C
70 - 105 SEC	123	4	1.98×10^{-8}	125,000	D
105 - 120 SEC	3230	40	8.50×10^{-8}	148,000	E

GROUND RELEASES

<u>PERIOD</u>	<u>AV. RELEASE Ci</u>	<u>IN FB</u>	<u>SIZE CODE</u>	<u>N_{av}</u>	<u>P_{av}</u>
0 - 10 SEC	29.4	Y	F	340	8.67×10^{-6}
	3.56	N	G		
10 - 20 SEC	21.0	Y	H	384	2.46×10^{-6}
	150	N	I		
20 - 70 SEC	80.2	N	I	2	2.41×10^{-8}

Table 3-3B. Size Codes for Range Safety Destruct Source Terms

SIZE μM	A	B	C	D	E	F	G	H	I	J	K	L	M	N	P	Q	R
0.02	—	—	—	—	—	0.67	—	0.41	—	—	—	—	—	—	0.46	—	—
0-1	0.11	0.21	0.17	0.15	0.07	—	0.09	—	0.04	0.11	0.20	0.15	0.15	0.04	—	0.03	0.04
1-2	0.18	0.33	0.26	0.23	0.11	—	0.23	—	0.14	0.17	0.31	0.23	0.23	0.09	—	0.10	0.14
2-3	0.16	0.29	0.23	0.20	0.09	0.09	0.23	0.06	0.15	0.15	0.27	0.20	0.20	0.08	0.06	0.10	0.15
3-4	0.11	0.19	0.15	0.14	0.06	—	0.13	—	0.08	0.10	0.19	0.14	0.14	0.05	—	0.05	0.08
4-5	0.07	0.13	0.10	0.09	0.04	0.05	0.09	0.006	0.06	0.07	0.12	0.09	0.09	0.03	0.06	0.04	0.06
5-6	0.10	0.18	0.14	0.12	0.06	0.13	0.05	0.06	0.006	0.09	0.17	0.12	0.12	0.05	0.10	0.004	0.006
6-7	0.08	0.15	0.12	0.11	0.05	—	0.07	—	0.03	0.08	0.14	0.11	0.11	0.04	—	0.02	0.03
7-8	0.05	0.10	0.08	0.07	0.03	0.12	0.06	0.04	0.03	0.05	0.10	0.07	0.07	0.03	0.10	0.02	0.03
8-9	0.15	0.28	0.23	0.20	0.09	0.17	0.12	0.05	0.04	0.15	0.27	0.20	0.20	0.08	0.17	0.03	0.04
9-10	0.26	0.48	0.38	0.34	0.16	—	0.17	—	0.05	0.25	0.46	0.34	0.34	0.13	—	0.03	0.04
10-20	0.97	1.80	1.43	1.26	0.58	1.09	1.09	0.61	0.61	0.93	1.71	1.26	1.25	0.49	0.76	0.42	0.61
20-30	0.88	1.63	1.30	1.14	0.53	1.05	1.05	0.61	0.61	0.84	1.55	1.14	1.13	0.44	0.71	0.42	0.61
30-40	0.83	1.53	1.22	1.07	0.50	1.02	1.02	0.61	0.61	0.79	1.45	1.07	1.06	0.42	0.67	0.42	0.61
40-50	0.79	1.46	1.16	1.02	0.47	1.00	1.00	0.61	0.61	0.75	1.39	1.02	1.01	0.40	0.65	0.42	0.61
50-60	0.76	1.41	1.12	0.99	0.46	0.99	0.99	0.61	0.61	0.73	1.34	0.99	0.98	0.38	0.63	0.42	0.61
60-70	0.74	1.36	1.08	0.95	0.44	0.98	0.98	0.61	0.61	0.70	1.29	0.95	0.94	0.37	0.62	0.42	0.61
70-80	0.70	1.29	1.02	0.90	0.42	0.96	0.96	0.61	0.61	0.67	1.22	0.90	0.89	0.35	0.60	0.42	0.61
80-90	0.72	1.33	1.06	0.93	0.43	0.97	0.97	0.61	0.61	0.69	1.27	0.93	0.93	0.36	0.61	0.42	0.61
90-100	0.69	1.27	1.01	0.89	0.41	0.95	0.95	0.61	0.61	0.66	1.20	0.89	0.88	0.34	0.59	0.42	0.61
100-200	6.28	11.6	9.21	8.12	3.76	9.26	9.26	6.05	6.05	5.99	11.0	8.12	8.05	3.15	5.53	4.22	6.06
200-300	5.62	10.4	8.25	7.27	3.36	8.92	8.92	6.02	6.02	5.36	9.85	7.26	7.20	2.82	5.13	4.19	6.03
300-400	5.20	9.60	7.63	6.73	3.11	8.71	8.71	5.99	5.99	4.96	9.12	6.73	6.67	2.61	4.87	4.18	6.00
400-500	4.89	9.03	7.18	6.33	2.93	8.54	8.54	5.97	5.97	4.67	8.58	6.33	6.27	2.46	4.68	4.16	5.98
500-600	4.62	8.56	6.80	6.00	2.77	8.38	8.38	5.93	5.93	4.42	8.13	6.00	5.95	2.33	4.52	4.13	5.94
600-700	4.46	8.26	6.57	5.79	2.68	8.28	8.28	5.92	5.92	4.27	7.85	5.79	5.74	2.25	4.42	4.12	5.93
700-800	4.25	7.88	6.26	5.52	2.55	8.06	8.06	5.88	5.88	4.07	7.48	5.52	5.47	2.14	4.28	4.10	5.89
800-900	4.07	6.76	6.06	5.34	2.47	7.04	7.04	5.84	5.84	3.94	7.24	5.34	5.30	2.07	4.19	4.07	5.58
900-1000	3.87	5.45	5.86	5.16	2.39	5.74	5.74	5.73	5.73	3.81	7.00	5.16	5.12	2.00	4.10	4.06	5.84
1000-2000	32.15	7.09	23.9	32.9	20.5	13.87	13.87	39.3	39.3	32.9	9.11	33.0	33.5	17.3	35.6	39.0	40.4
2000-3000	16.23				16.3	2.98	2.98	1.27	1.27	17.6				14.0	15.9	19.6	
3000-4000					12.8									11.2			
4000-5000					8.25									8.18			
5000-6000					4.45									7.14			
> 6000					6.63									16.1

Figure 3-13. FAST 1S2 For Tower Impact - Ascent Phase

3.4.4.3 Loss of Thrust - FAST Branch 1S3

Refer to Figure 3-14 for this FAST branch. Loss of thrust on one of the SRB's will result in vehicle breakup due to turning moments and aerodynamic forces. For this accident, the vehicle is not assumed to break up before a MET of 10 seconds based on low moments and forces prior to that time, and breakup after that time will result in either a vapor cloud explosion if prior to 30 seconds or to a breakup without explosion if after 30 seconds. The vapor cloud explosion does not result in any initial breach of the fueled clads due to impact by payload bay wall fragments. A source term does occur for some of the ground impacts as shown due to additive distortion, as discussed previously. The resulting source terms are:

Av. source term = 796 Ci in fireball
125 Ci outside fireball

Figure 3-14. FAST 1S3 for SRB Loss of Thrust - Ascent Phase

@P = 3.30×10^{-4}
1325 trials out of 10,000

Max. source term = 1860 Ci outside fireball
@P = 1.39×10^{-4}
557 trials out of 10,000

The maximum release occurs outside the fireball area.

The assumption has been made that vehicle breakup would not occur until after a MET of 10 seconds following a loss-of-thrust accident. This assumption can be examined. Assume that breakup is deferred until after a MET of 10 seconds for 70% of the failures, with breakup occurring during the 0-10 second period for 30% of the failures. The deferral of only 70% of the failures would change only the probabilities for the source terms on branch 1S3; the new values would be:

In Fireball	796 Ci av	@ P = 2.31×10^{-4}
Outside Fireball	125 Ci av	@ P = 2.31×10^{-4}
	1860 Ci max	@ P = 9.73×10^{-5}

However, the 30% of failures (i.e., loss-of-thrust) occurring in the 0-10 second period would add another source term that would be equivalent to that for the launch pad explosion resulting from vehicle breakup shown in Figure 3-17 for the IV branch. This source term would thus be:

26.4 Ci av @ P = 5.78×10^{-6}
210 Ci max @ P = 1.10×10^{-7}

This release would occur within the area affected by the fireball.

3.4.4.4 No SRB Ignition - FAST Branch 1S4

Figure 3-14 also shows this branch. Since the results and damage statistics are from the vapor cloud explosion event, the same FAST branch applies to both. Only the initial failure probabilities are different as are the final

source term probabilities. One should realize that No SRB Ignition applies only to a single SRB and not both simultaneously. The latter failure is considered by NASA to be non-credible. The source terms for this branch are identical to those for Branch 1S3 but with the following probabilities:

Av. @ P = 1.01×10^{-5}
Max. @ P = 4.23×10^{-6}

3.4.4.5 RSS Destruct-FAST Branch 1R

Figure 3-15 is the branch FAST for this accident. Similarly as for the SRB Case Rupture (Branch 1S1), the NASA supplied failure probabilities indicate that there are two time periods during Phase 1 in which the conditional probabilities of RSS Destruct have different values. These periods and probability weighting are as follows:

<u>MET Period - sec</u>	<u>RSS Destruct Conditional Probability</u>
0-10	0.0776
10-128	<u>0.9224</u>
	1.0000

Because the fragment environment model is different for the period after a MET of 105 seconds from that before 105 seconds, different LASEP runs are needed for these two periods. Combined with the difference in the probability weighting for the two periods given (0-10 and 10-128 seconds), a total of three (3) different runs were needed with LASEP: 0-10, 10-105, and 105-120 seconds. The source terms were determined in the same manner as those for the SRB Case Rupture accident presented in Section 3.4.4.1 except that three (3) different periods were used rather than the five (5) for the SRB Case Rupture. The resulting source terms are:

Figure 3-15. FAST IR For RSS Destruct - Ascent Phase

Fuel Release 1 - SRB Fragment Impact

Av. 372 Ci @ $P = 2.71 \times 10^{-10}$
 3.59 trials out of 20,000

The altitude for the average release is 61,200 ft (18,700m) and the maximum release is at 66,300 ft. (20,200m).

Fuel Release 2 - Ground Impact

Av. source term = 10.9 Ci in fireball
 184 Ci outside fireball

@ $P = 1.18 \times 10^{-8}$
156 trials out of 20,000

Similarly as for the SRB Case Rupture accident, the Range Safety Destruct scenario can be analyzed for each of the three (3) applicable subperiods. In this manner, similarly, the effect of the contribution to the risks from each subperiod can be determined if desired. While the detailed sequence tree for this scenario is not presented, Table 3-3C does present the resulting source terms for the air and ground releases. The corresponding particle size codes are listed in Table 3-3D.

3.4.4.6 Aft Compartment Explosion - FAST Branch 1E

The FAST Branch 1E for the Aft Compartment Explosion accident is shown on Figure 3-16. If this accident occurs in the 0-10 sec MET period, the resulting environment is also termed the aft compartment explosion and is characterized, according to the Shuttle Data Book, as a MLP pool explosion with a shallower pool than the MLP explosion from an ET failure. The overpressures are given in Table B-4 of Appendix B of the AMD. If the accident occurs in the 10-30 sec MET period, the environment results from a vehicle breakup with a vapor cloud explosion, and for this accident in the 30-128 sec MET, the result is vehicle breakup with essentially no explosion.

Table 3-3C. Range Safety Destruct Scenario Source Terms

AIR RELEASES

<u>PERIOD</u> <u>Ci</u>	<u>AV.</u> <u>RELEASE</u> <u>Ci</u>	<u>N_{av}</u>	<u>P_{av}</u>	<u>ALT.</u> <u>FT</u>	<u>SIZE</u> <u>CODE</u>
0 - 10 SEC	0.438	2	1.17×10^{-11}	165	A
10 - 105 SEC	433	4	2.24×10^{-10}	54,300	B
105 - 120 SEC	112	4	3.54×10^{-11}	124,000	C

GROUND RELEASES

<u>PERIOD</u>	<u>AV.</u> <u>RELEASE</u> <u>Ci</u>	<u>IN</u> <u>FB</u>	<u>SIZE</u> <u>CODE</u>	<u>N_{av}</u>	<u>P_{av}</u>
0 - 10 SEC	53.9	Y	D	916	5.37×10^{-9}
	0.943	N	E		
	13.3	Y	F		
10 - 105 SEC	298	N	G	115	6.45×10^{-9}

Table 3-3D. Size Codes for Range Safety Destruct Source Terms

SIZE μm	A	B	C	D	E	F	G	H	I	J	K	L
0.02	—	—	—	0.64	—	0.40	—	—	—	—	0.74	0.34
0 - 1	0.40	0.10	0.14	—	0.07	—	0.04	0.39	0.10	0.14	—	—
1 - 2	0.63	0.16	0.22	—	0.21	—	0.14	0.61	0.16	0.21	—	—
2 - 3	0.55	0.14	0.19	0.08	0.21	0.05	0.14	0.53	0.14	0.18	0.09	0.05
3 - 4	0.37	0.09	0.13	—	0.15	—	0.08	0.36	0.09	0.12	—	—
4 - 5	0.24	0.06	0.08	0.02	0.08	0.005	0.05	0.23	0.06	0.08	0.13	0.005
5 - 6	0.34	0.08	0.12	0.10	0.02	0.06	0.005	0.32	0.08	0.11	0.18	0.05
6 - 7	0.29	0.07	0.10	—	0.05	—	0.03	0.28	0.07	0.10	—	—
7 - 8	0.19	0.05	0.07	0.08	0.05	0.04	0.03	0.19	0.05	0.06	0.20	0.04
8 - 9	0.55	0.14	0.19	0.10	0.08	0.04	0.04	0.52	0.14	0.18	0.35	0.04
9 - 10	0.93	0.23	0.32	—	0.10	—	0.04	0.89	0.23	0.31	—	—
10 - 20	3.45	0.86	1.18	0.93	0.93	0.60	0.60	3.31	0.86	1.15	1.29	0.52
20 - 30	3.13	0.78	1.07	0.91	0.91	0.60	0.60	3.01	0.78	1.05	1.18	0.52
30 - 40	2.94	0.73	1.01	0.90	0.90	0.60	0.60	2.82	0.73	0.98	1.10	0.52
40 - 50	2.81	0.70	0.96	0.90	0.90	0.60	0.60	2.69	0.70	0.94	1.05	0.52
50 - 60	2.71	0.67	0.93	0.89	0.89	0.60	0.60	2.60	0.67	0.90	1.02	0.52
60 - 70	2.61	0.65	0.89	0.89	0.89	0.60	0.60	2.50	0.65	0.87	0.98	0.52
70 - 80	2.47	0.62	0.85	0.88	0.88	0.60	0.60	2.37	0.62	0.82	0.93	0.52
80 - 90	2.56	0.64	0.88	0.88	0.88	0.60	0.60	2.46	0.64	0.85	0.96	0.52
90 - 100	2.44	0.61	0.84	0.88	0.88	0.60	0.60	2.34	0.61	0.81	0.91	0.52
100 - 200	22.3	5.55	7.63	8.65	8.65	5.99	5.99	21.4	5.55	7.43	8.36	5.14
200 - 300	19.9	4.97	6.83	8.50	8.50	5.96	5.96	19.1	4.97	6.65	7.48	5.11
300 - 400	16.2	4.60	6.32	8.40	8.40	5.93	5.93	17.7	4.60	6.15	6.92	5.09
400 - 500	12.0	4.32	5.95	8.31	8.31	5.91	5.91	13.4	4.32	5.79	6.51	5.07
500 - 600		4.10	5.64	8.22	8.22	5.87	5.87		4.10	5.48	6.17	5.04
600 - 700		3.96	5.44	8.18	8.18	5.86	5.86		3.96	5.29	5.96	5.03
700 - 800		3.76	5.19	8.03	8.03	5.82	5.82		3.76	5.05	5.68	4.99
800 - 900		3.64	5.02	7.33	7.33	5.78	5.78		3.64	4.88	5.50	4.96
900 - 1000		3.52	4.85	6.67	6.67	5.71	5.71		3.52	4.72	5.31	4.95
1000 - 2000		30.4	37.0	18.7	18.7	41.1	41.1		30.4	38.7	31.0	48.2
2000 - 3000		23.8				0.08	0.08		23.8			1.27
3000 - 4000												
4000 - 5000												
5000 - 6000												
> 6000												

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Figure 3-16. FAST 1E For Aft Compartment Explosion - Ascent Phase

Separate LASEP runs were made for the 0-10 sec and 10-30 sec MET periods. Neither for the vapor cloud explosion nor for the MLP pool explosion was there any breach of the fueled clads by the payload bay wall fragments. Breaching of the clads occurred only for some of the secondary impacts following the vapor cloud explosion based on the addition of clad deformations. The source terms are:

Av. source term = 796 Ci in fireball
125 Ci outside fireball

@ $P = 1.02 \times 10^{-5}$
1325 trials out of 10,000

Max. source term = 1860 Ci outside fireball
@ $P = 4.29 \times 10^{-6}$
557 trials out of 10,000

The maximum release on the ground occurred outside the area of the fireball.

3.4.4.7 Vehicle Breakup - FAST Branch IV

The FAST for this branch is shown on Figure 3-17. Vehicle breakup as given here is due mainly to structural failures in the ET, Orbiter, and Payload. Similarly as for the previous AFT Compartment Explosion accident, and accident in the 0-10 sec. MET period will result in a launch pad explosion, but this explosion can be either a MLP larger (than for an Aft Compartment Explosion) pool explosion or a flame trench explosion. These possibilities are partitioned 50-50 according to the Shuttle Data Book. An occurrence in the 10-30 sec MET results in a vapor cloud explosion, and in the 30-128 sec MET, there is vehicle breakup with no explosion. The only breaches of the fuel clads occur as a result of secondary impacts on the ground, again based on additive clad deformations; there are no releases due to payload bay wall fragments.

Figure 3-17. FAST IV For Vehicle Breakup - Ascent Phase

Fuel Release 1 - Vapor Cloud Explosion w/ Ground Impact

Av. source term = 796 Ci in fireball
125 Ci outside fireball

@ $P = 1.84 \times 10^{-6}$
1325 trials out of 10,000

Max. source term = 1860 Ci outside fireball
@ $P = 7.75 \times 10^{-7}$
557 trials out of 10,000

The maximum release on the ground occurred outside the area affected by the fireball.

Fuel Release 2 - Launch Pad Explosion w/Ground Impact

Av 26.4 Ci @ $P = 7.64 \times 10^{-8}$
105 trials out of 10,000

The total source term for fuel release 2 occurred within the area affected by the fireball.

3.4.5 PHASE 2: SECOND STAGE

Figure 3-4 presents the top-level event tree for accidents occurring in the Second Stage Phase (Phase 2). The total accident probability for this phase is 1.69×10^{-3} , and the contribution from each accident mode is shown. Accidents resulting from Crash Landing and Ocean Ditch are not carried further as was done similarly for Phase 1 and for the same reasons. All of the other failures in the Shuttle components including RSS Destruct result in vehicle breakup since the time period is ≥ 128 seconds, and the breakup remains will reenter. Figure 3-18 presents the details of FAST 2V for the ensuing reentry and impact. Section 6.1 of the Shuttle Data Book addresses the reentry from this accident scenario as related to the breakup of the Orbiter, IUS, and spacecraft and release of the RTGs. Included in that analysis are estimates

Figure 3-18. FAST 2V For Vehicle Breakup/Reentry-Second Stage Phase

of the physical configuration of the RTG or GPHS modules at impact. Section B.3 in Appendix B of this AMD presents a summary of those results. Those results indicate that the RTGs will always reach the surface intact for accidents up to 155 seconds. Between 155 and 210 seconds MET, the RTGs might remain intact. After 210 seconds, the GPHS modules will always be released prior to impact. However, wherever the RTGs can reach the surface intact, the impact area will be in the ocean.

For purposes of this FAST, the 210 second time is used as the time to differentiate between RTG impact and GPHS module impact for a 80% - 20% probability partition, respectively.

The land and ocean fractions as well as the land surface fractions are based on the ground track of the Instantaneous Impact Point (IIP) for the 70 degree launch azimuth as given in Reference 3-7. Figure 3-19 shows a plot of the IIP ground track across Africa. The makeup of the land areas for this track are based on the data presented in Reference 3-8. Land areas around the ground track are referenced to file numbers in the given reference, and the corresponding surface media distributions are used. The file numbers used from Appendix B of Reference 3-8 include 181, 216, 217, 218, 254, 255, 291, and 328. For each of these equal land areas or files, the type of rock outcropping and its associated fraction is summed to arrive at the corresponding overall ground track distribution. The overall fraction of outcropping for the whole phase is determined using the following values for the land portion of the phase. These values represent an average of the ranges given in the reference.

Rock Debris:	90%	
Lithosols:	70%	Outcropping
Stony Phase:	10%	

The resulting distribution for the land area around the African ground track is:

Figure 3-19. Ground Track of the IIP for STS-34

Soil = 0.9303
Rock = 0.0697

The African overfly of the Instantaneous Impact Point (IIP) track covers a period of approximately 5.5 seconds out of the total of $532 - 128 = 404$ seconds for this phase for a ground impact probability of 0.0136. When these values are weighted for the total phase duration, the resulting surface impact fractions are:

Ocean = 0.9864
Land = 0.0136
 Rock = 0.049 land impact given
 Soil/Water = 0.951

The resulting mission probability of an African land impact after the occurrence of an accident is consequently 2.3×10^{-5} .

The potential breach of the intact GPHS modules at impact on the Earth surfaces is treated as follows. In this phase of the mission, the RTG will still be operating under forced cooling through the auxiliary cooling system and will thus be essentially at the launch temperature (i.e., with the iridium clad temperature at 1090°C). A similar condition would result from a minimum gamma ($\gamma_{\min}$), superorbital velocity type of reentry in which a failure of the IUS after deployment from the Shuttle Orbiter would cause the spacecraft with RTGs to reenter with the $\gamma_{\min}$ conditions before the RTG had risen appreciably in temperature after the xenon cover gas had been vented. This type of reentry results in impact temperatures that are appreciably lower than those for the orbital decay type of reentry. Impact testing in the safety test series for the GPHS has included both types of impact conditions. The results of these tests are presented in Appendix G, Section G.2.5. Because of its thermal similarity with that of the $\gamma_{\min}$ impact conditions, the impact response for an African impact is estimated on the basis of the two $\gamma_{\min}$ impact tests in the SVT test series. These tests are the SVT-1 and SVT-2. The specific fuel release from these two tests was .0043 and .0034 gm/mm^2 with crack areas of 25.4 and 8.4 mm^2 , respectively. These result in an average release of .0689 gm or 0.868 Ci per FC.

The size distribution for released material is based on the crack sizes resulting from the impact. In the SVT-1 and SVT-2 tests, the average crack size of all the breaches was around 480 um. The 420 um particle size as usually reported has thus been used as the maximum particle size that can be released; the size distribution for the released material is normalized at this value based on the size distribution for the retained material resulting from SVT-1, since this results in the largest mass fraction in the 10 micron and smaller range. The resulting size distribution is given in Table 3-4.

The fraction of failures occurring is also based on SVT-1 and SVT-2. 3 of 8 FCs failed in the 0° or flat-on tests. This results in a failure fraction of $p = 0.375$. Since there were no other angles tested with the $\gamma_{\min}$ conditions, the results from the orbital decay testing are used. From Table G-15, 0 of 12 FCs failed in the 30° impacts and 1 of 8 failed in the 90° impacts. Thus, the failure statistics according to angle for the $\gamma_{\min}$ and African impacts are:

<u>Angle</u>	<u>Breached</u>
0°	$p = 0.375$
30°	$p = 0.0$
90°	$p = 0.125$

The distribution of impact angles for a random tumbling fall mode is based on the drop tests conducted at the DOE Tonopah Test Range and reported in Reference 3-9. The results from that test are as follows:

<u>Angle</u>	<u>Probability</u>
0-15°	0.0098
16-84°	0.8627
85-90°	0.1275

Table 3-4. Particle Size Distribution For Impact From
Suborbital and γ_{min} Reentries

<u>Particle Size</u> <u>(microns)</u>	<u>Mass Fraction</u>
0- 1	.0096
1- 2	.0024
2- 3	.0035
3- 4	.0027
4- 5	.0023
5- 6	.0060
6- 7	.0016
7- 8	.0047
8- 9	.0068
9- 10	.0093
10- 20	.0424
20- 30	.0375
30- 44	.0472
44- 74	.0509
74-125	.1036
125-177	.0902
177-420	.5796

This distribution coupled with the failure distribution as a function of angle presented previously are combined to produce the overall fraction of GPHS modules which fail on impact,

$$\begin{aligned} p(\text{failure}) &= 0.0098 (0.375) + .8627 (0) + 0.1275 (0.125) \\ &= 0.0196 \text{ per FC} \end{aligned}$$

When a rock impact occurs, the probability of breach and the resulting source term has been presented in the previous paragraphs. To determine the probability of one or more GPHS modules hitting rock, the binomial probability distribution is used. The resulting source terms are obtained:

For 36 modules (2 RTGs):

$$\begin{aligned} p(\text{rock}) &= .0136 \times .049 = .0006664 \\ np &= 36 \times .0006664 = .024 \text{ Modules} \end{aligned}$$

∴ an average of .024 modules will hit rock

The average source term is thus:

$$\begin{aligned} .024 \text{ modules} \times 4 \text{ FC/module} \times .0196 \text{ failures/FC} \times \\ 0.868 \text{ Ci/failure} = 0.00163 \text{ Ci} \end{aligned}$$

The conditional probability for getting the expected value of rock impacts, or .024 modules, cannot be determined precisely by the binomial distribution, but it can be estimated. It will be between the probability for getting zero (0) hits and one (1) hit:

$$\begin{aligned} p(0) &= (1 - .0006664)^{36} \\ &= 0.976 \end{aligned}$$

$$p(1) = 0.0234$$

$$p(2) = 0.000274$$

Since the cutoff for the maximum source term has been selected at a probability of $\leq 1 \times 10^{-7}$, the maximum source term is related to two (2) modules hitting rock:

$$2 \times 4 \times .0196 \times 0.868 = 0.136Ci$$

The probability for both modules hitting rock is

$$\begin{aligned} p &= 1.21 \times 10^{-3} \times .000274 \\ &= 3.32 \times 10^{-7} \end{aligned}$$

3.4.6 PHASE 3: ON ORBIT

The complete FAST for Phase 3 is shown on Figure 3-20, with a total accident probability of 1.58×10^{-4} . The ensuing event for all accidents is an uncontrolled reentry of the Orbiter and IUS with spacecraft. Breakup of the configuration leads to release of the RTGs which then release the GPHS modules due to thermal failure of the RTG converter case. The GPHS modules survive the ensuing reentry intact and then impact on land. The reentry during this period will occur in a random fashion such that any region on Earth between approximately 33° North latitude and 33° South latitude can be impacted because of the 70 degree launch azimuth. However, since Reference 3-8 gave values conveniently only for the 28° North to 28° South latitude band as used in the previous FSAR, these values for the land surface distribution are used herein and are as follows:

Ocean	= 0.7308	
Land	= 0.2692	
Rock	= 0.058	land impact given
Soil/Water	= .942	

The probability of a fueled clad being breached as a result of a GPHS impact on rock following an orbital decay reentry is similarly based on the SVT test results as well as on related design iteration tests (DIT) conducted during the development phase of the GPHS and on the results of the GPHS drop test conducted at the Tonopah Test Range, all reported in Appendix G

Figure 3-20. Phase 3: On Orbit FAST

Section G.2.5. Based on the SVT and DIT tests conducted with the orbital decay conditions, the following statistics resulted:

at 0°	5 of 16 failed or	p = 0.3125
at 30°	0 of 12 failed	p = 0.0
at 90°	1 of 8 failed	p = 0.125

The impact angle statistics from the drop test are as previously given.

<u>Angle</u>	<u>Probability</u>
0-15°	0.0098
16-84°	0.8627
85-90°	0.1275

The resulting failure probability is:

$$\begin{aligned}
 p(\text{failure}) &= 0.0098 (0.3123) + 0.8627 (0) + 0.1275 (0.125) \\
 &= 0.019 \text{ per FC}
 \end{aligned}$$

Based on the release densities in the SVT series, an average for the orbital decay conditions is 0.0133 gm/mm^2 with an average crack area of 23.6 mm^2 . This is based on test SVT-3 through SVT-13, omitting SVT-12 which was at a higher velocity. The resulting average release is 0.31 gm or 3.9 Ci per FC.

For the SVT-3 through SVT-13 tests, the average crack width observed was around 680 um. Here also the 420 um particle size (i.e., one size group reported in the test data) has been used as the maximum particle size that can be released, and the size distribution for the released material is normalized at this value based on the average size distribution for the SVT tests for the retained material. The resulting size distribution is given in Table 3-5.

The source terms are determined similarly as for the Phase 2 failures when rock impact occurs.

Table 3-5. Particle Size Distribution For Impact From
Orbital Decay Reentry

<u>Particle Size</u> <u>(microns)</u>	<u>Mass Fraction</u>
0- 1	.0033
1- 2	.0019
2- 3	.0029
3- 4	.0028
4- 5	.0029
5- 6	.0031
6- 7	.0020
7- 8	.0038
8- 9	.0052
9- 10	.0138
10- 20	.0501
20- 30	.0540
30- 44	.0521
44- 74	.0733
74-125	.1003
125-177	.0887
177-420	.5468

For 36 modules (2 RTGs)

$$p(\text{rock}) = 0.2692 \times 0.058 = .0156$$

$$np = 36 \times 0.0156 = 0.56$$

∴ an average of 0.56 modules will hit rock.

The average source term is thus:

$$\begin{aligned} 0.56 \text{ modules} \times 4 \text{ FC/module} \times .019 \text{ failures/FC} \times 3.9 \text{ Ci/failure} \\ = 0.17 \text{ Ci} \end{aligned}$$

The maximum source term (i.e., with probability cutoff $\leq 1 \times 10^{-7}$) would occur if 4 modules hit rock:

$$4 \times 4 \times .019 \times 3.9 = 1.19 \text{ Ci}$$

The conditional probability for 4 modules hitting rock is.

$$p(4) = .00211$$

The overall probability is:

$$p = 1.58 \times 10^{-4} \times (.00211) = 3.33 \times 10^{-7}$$

3.4.7 PHASE 4: PAYLOAD DEPLOY

Figure 3-21 presents the FAST for Phase 4 - Payload Deploy. The total accident probability is 9.96×10^{-3} . The failures in this phase are grouped into two types for purposes of this FSAR. These are the IUS SRM Case Burst failure and failures related to the other malfunctions in the IUS such as no ignition, separation failures, low thrust and impulse, erratic burns, and guidance failures.

Figure 3-21. Phase 4: Payload Deploy FAST

Section 10.3.3 of the Shuttle Data Book indicates that the IUS SRM-2 shields the RTGs from SRM-1 fragments. Section 10.4.2 states that fragments constituting a potential hazard to the RTGs will consist of chunks of propellant. The Kevlar case material is expected to disintegrate from action of the case disruption by internal pressure as well as by interaction with intervening structure. Based on an analysis of impact on the RTGs by the propellant fragments with the mechanical properties given in Section B.4.2.1 in Appendix B of this FSAR, the GPHS modules will not be damaged. Fragment sizes and velocities from Appendix B were used in the analysis. The modules then released from the RTG converter housing will be subjected to the ensuing reentry in which they will survive intact as previously analyzed and included in Appendix I of this FSAR.

The other failures all result in the various types of reentries:

Delayed	1.27×10^{-3}	12.7%
Orbit Decay	5.89×10^{-3}	59.2%
Powered	1.08×10^{-3}	10.8%
Prompt	3.04×10^{-4}	3.1%
Escape	1.41×10^{-3}	<u>14.2%</u>
		100.0%

Although escape from the Earth's gravitational pull is not a reentry, it is shown since it results from 14.2% of the malfunctions that can potentially lead to reentry.

The average source term is the same as for Phase 3 except that the mission probability of occurrence is different.

$$Av \quad 0.17 \text{ Ci @ } P = 8.54 \times 10^{-3}$$

The maximum source term would occur if 6 modules hit rock:

$$6 \times 4 \times .019 \times 3.9 = 1.78 \text{ Ci}$$

The conditional probability for 6 modules hitting rock is:

$$p(6) = 1.75 \times 10^{-5}$$

The overall probability is:

$$\begin{aligned} P &= 8.54 \times 10^{-3} \times 1.75 \times 10^{-5} \\ &= 1.49 \times 10^{-7} \end{aligned}$$

3.4.8 PHASE 5: VEEGA MANEUVER

The FAST for Phase 5: VEEGA Maneuver is shown on Figure 3-22. The only accident that is of concern for this FSAR is a spacecraft or mission failure that results in a very high speed reentry. Appendix F of this document describes the analyses performed to determine the response of the GPHS modules during the reentry. The results of the analyses show that the aeroshell will fail throughout the range of possible reentry angles (i.e., -5.5 to -90 degrees) because of the very high temperatures in the vicinity of 7000°F (3870°C) and essentially zero strength of the FWPF material at these temperatures plus the effects of aerodynamic loading. The subsequent reentry of the GISs does not result in failure of the GISs even though some reentries do result in high temperatures. The aerodynamic loads are balanced by the internal inertial loads so that there is essentially no net stress across the GIS, and the maximum recession is only on the order of 50 mils out of the total thickness of the GIS wall of 166.5 mils.

For all GIS reentries, the temperature of the iridium clads equals or exceeds the 4200°F (2316°C) carbon (FWPF) - iridium eutectic temperature recently measured by Los Alamos. In that event, the clad will be breached, and the subsequent impact on a hard surface such as rock is assumed to result in essentially complete release of the fuel. If the impact of the GIS occurs on soil or water, the GIS will probably remain intact (although with the clads having failed on the interior of the GIS). While there is no experimental evidence to support this opinion, the judgment is made on the basis of the GIS

Figure 3-22. Phase 5: VEEGA Maneuver FAST

condition in the majority of the module impacts on hard steel in which the GISs are cracked but remain as an entity. An impact on soil would be expected to leave the GIS intact. The resulting source terms are as follows:

For 72 GISs (2 RTGs)

$$p(\text{rock}) = 0.29 \times 0.16 = .0464$$

$$np = 72 \times .0464 = 3.34$$

∴ an average of 3.34 modules will hit rock in a large number of trials.

The average source term is:

$$\begin{aligned} 3.34 \text{ GIS} \times 2 \text{ FC} / \text{GIS} \times 153 \text{ gm fuel} / \text{FC} \times 12 \text{ Ci/gm} \\ = 12900 \text{ Ci} \end{aligned}$$

$$\theta P = 5.0 \times 10^{-7}$$

The extreme maximum source term would occur if all 72 GIS were to hit rock, and the release would be

$$72 \times 2 \times 153 \times 12.6 = 278,000 \text{ Ci}$$

but the probability would be zero for all practical purposes. The conditional probability would be:

$$\begin{aligned} p(72, \text{rock}) &= (.0464)^{72} \\ &= 9.76 \times 10^{-97} \end{aligned}$$

The conditional probability distribution for any number of GISs hitting rock from zero (0) to 72 is presented in Table 3-6. As deduced from that table the total probability of getting greater than thirteen (13) hits is

$$p(\geq 13, \text{rock}) = .00003$$

Table 3-6. Conditional Probability For Hitting Rock
(following VEEGA Reentry)

Number of Hits n	p(n)	n	p(n)	n	p(n)
0	0.03269	26	6.6240×10^{-17}	51	2.7992×10^{-51}
1	0.11451	27	5.4912×10^{-18}	52	5.5015×10^{-53}
2	0.19780	28	4.2941×10^{-19}	53	1.0102×10^{-54}
3	0.22457	29	3.1702×10^{-20}	54	1.7294×10^{-56}
4	0.18850	30	2.2110×10^{-21}	55	2.7540×10^{-58}
5	0.12474	31	1.4575×10^{-22}	56	4.0679×10^{-60}
6	0.067775	32	9.0867×10^{-24}	57	5.5561×10^{-62}
7	0.031093	33	5.3592×10^{-25}	58	6.9918×10^{-64}
8	0.012293	34	2.9912×10^{-26}	59	8.0726×10^{-66}
9	0.0042533	35	1.5802×10^{-27}	60	8.5106×10^{-68}
10	0.0013038	36	7.9024×10^{-29}	61	8.1463×10^{-70}
11	3.5758×10^{-4}	37	3.7412×10^{-30}	62	7.0326×10^{-72}
12	8.8445×10^{-5}	38	1.6767×10^{-31}	63	5.4316×10^{-74}
13	1.9863×10^{-5}	39	7.1123×10^{-33}	64	3.7165×10^{-76}
14	4.0730×10^{-6}	40	2.8551×10^{-34}	65	2.2257×10^{-78}
15	7.6630×10^{-7}	41	1.0843×10^{-35}	66	1.1486×10^{-80}
16	1.3283×10^{-7}	42	3.8940×10^{-37}	67	5.0050×10^{-83}
17	2.1291×10^{-8}	43	9.1100×10^{-39}	68	1.7907×10^{-85}
18	3.1655×10^{-9}	44	4.2394×10^{-40}	69	5.0510×10^{-88}
19	4.3775×10^{-10}	45	1.2835×10^{-41}	70	5.2665×10^{-91}
20	5.6445×10^{-11}	46	3.6657×10^{-43}	71	1.4437×10^{-93}
21	6.8008×10^{-12}	47	9.8670×10^{-45}	72	9.7565×10^{-97}
22	7.6712×10^{-13}	48	2.5005×10^{-46}		
23	8.1144×10^{-14}	49	5.9594×10^{-47}		
24	8.0611×10^{-15}	50	1.3339×10^{-49}		
25	7.5309×10^{-16}				

p (rock) = 0.0464

np (rock) = 72 (.0464) = 3.34 expected number

Since the overall probability for the average source term is 5×10^{-7} , the same magnitude and probability is used for the maximum source term as shown in Table 3-7.

3.4.9 SOURCE TERM SUMMARY - GALILEO MISSION

A compilation of the total group of source terms for the overall Galileo mission is presented in Table 3-7. For this report, the source terms are derived given that a release has occurred. In other words, a zero release is not considered a source term, and it is not weighted with the actual releases to arrive at an average for all trials in a Monte Carlo run. Also, the overall mission probability of getting the source term is based on the initial failure probability times the product of the conditional probabilities, including the Monte Carlo statistics, of arriving at the release. As an example, on Branch 0' FAST, the average fuel release is based on 28 out of 10,000 trials, and the maximum release, on 1 out of 10,000 trials. The 44.3 Ci shown for the average source term is based on the releases occurring in the 28 trials. The mission or overall probability is:

$$\begin{aligned} P &= 1.79 \times 10^{-4} \times 28/10000 \\ &= 5.01 \times 10^{-7} \end{aligned}$$

The maximum release in this case results from only one (1) trial in 10,000 at 141 Ci and with a mission probability of:

$$\begin{aligned} P &= 1.79 \times 10^{-4} \times 1/10000 \\ &= 1.79 \times 10^{-8} \end{aligned}$$

For source terms 1 through 17, the size distribution is determined by the LASEP program directly, except for fireball terms that have been subsequently adjusted according to the procedure described in Section 3.4.3.2. The size codes are shown in Table 3-8 for the average source terms and the maximum source terms. The particle size distributions for impacts from reentry are determined as described in Sections 3.4.5 and 3.4.6 for the Phase 2: Second Stage and Phase 3: On Orbit phases of the mission.

Table 3-7. Galileo Mission FSAR - Source Terms

No	Branch	ID	Av Release Ci	N _{av}	P _{av}	Loc	Alt Ft	In Fire	Size Code	Max Release Ci	N _{max}	P _{max}	Loc	Alt Ft	In Fire	Size Code
1	0'	-	44.3	28	5.01x10 ⁻⁷	G	3	Y	1	44.3	1	5.01x10 ⁻⁷	G	3	Y	15
2	1S1	1	815	7.39	3.77x10 ⁻⁷	A	42100	N	2	-	-	-	-	-	-	-
3	1S1	2	19.0	218.5	1.12x10 ⁻⁵	G	3	Y	3	-	-	-	-	-	-	-
4	1S1	2	44.6	-	-	G	3	N	4	-	-	-	-	-	-	-
5	1S2	-	58.0	25	5.15x10 ⁻⁷	G	3	Y	5	-	-	-	-	-	-	-
6	1S3	-	796	1325	3.30x10 ⁻⁴	G	3	Y	6	-	-	-	-	-	-	-
7	1S3	-	125	-	-	G	3	N	7	1860	557	1.39x10 ⁻⁴	G	3	N	16
8	1S4	-	796	1325	1.01x10 ⁻⁵	G	3	Y	6	-	-	-	-	-	-	-
9	1S4	-	125	-	-	G	3	N	7	1860	557	4.23x10 ⁻⁶	G	3	N	16
10	1R	1	372	3.59	2.71x10 ⁻¹⁰	A	61200	N	8	-	-	-	-	-	-	-
11	1R	2	10.9	156	1.18x10 ⁻⁸	G	3	Y	9	-	-	-	-	-	-	-
12	1R	2	184	-	-	G	3	N	10	-	-	-	-	-	-	-
13	1E	-	796	1325	1.02x10 ⁻⁵	G	3	Y	6	-	-	-	-	-	-	-
14	1E	-	125	-	-	G	3	N	7	1860	557	4.29x10 ⁻⁶	G	3	N	16
15	1V	1	796	1325	1.84x10 ⁻⁶	G	3	Y	6	-	-	-	-	-	-	-
16	1V	1	125	-	-	G	3	N	7	1860	557	7.75x10 ⁻⁷	G	3	N	16
17	1V	2	26.4	105	7.64x10 ⁻⁸	G	3	Y	11	-	-	-	-	-	-	-
18	2V	-	.00163	-	1.21x10 ⁻³	G	3	N	12	0.136	-	3.32x10 ⁻⁷	G	3	N	12
19	3	-	0.17	-	1.58x10 ⁻⁴	G	3	N	13	1.19	-	3.33x10 ⁻⁷	G	3	N	13
20	4	-	0.17	-	8.54x10 ⁻³	G	3	N	13	1.78	-	1.49x10 ⁻⁷	G	3	N	13
21	5	-	12900	-	5.0x10 ⁻⁷	G	3	N	14	12900	-	5.0x10 ⁻⁷	G	3	N	14

ID Identifies a source term on a given FAST branch when more than one occurs.

In Fire(ball)

Y Yes
N No

N_{av}, N_{max} Indicates the number of trials in a Monte Carlo run that produce the given source term.

Size Codes See Table 3-8

Location

A air release at a given altitude (Alt. - ft)
G ground level release given as Alt. = 3 ft.

Table 3-8. Size Codes For Source Terms (Mass Fractions)*

Size μm	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
.02	1.05	-	0.57	-	1.00	0.38	-	-	0.43	-	0.84	-	-	-	0.94	-
1	-	0.14	-	.073	-	-	.038	0.13	-	.042	-	0.96	0.33	0.16	-	.035
2	-	0.22	-	0.19	-	-	0.13	0.20	-	0.15	-	0.24	0.19	.04	-	0.12
3	0.13	0.19	.075	0.20	0.12	0.052	0.14	0.39	.056	0.15	0.11	0.35	0.29	.06	0.12	0.13
4	-	0.13	-	0.11	-	-	.074	0.12	-	.084	-	0.27	0.28	.04	-	.068
5	0.18	.084	.031	.075	0.17	.0051	.052	.077	.0069	.056	.070	0.23	0.29	.04	0.16	.048
6	0.26	0.12	.095	.031	0.25	.053	.0051	0.11	.059	.0069	0.16	0.60	0.31	0.10	0.23	.0048
7	-	0.10	-	.049	-	-	.025	.086	-	.028	-	0.16	0.20	.03	-	.023
8	0.29	.067	.088	.046	0.28	.041	.029	.061	.046	.031	0.15	0.47	0.38	.08	0.26	.027
9	0.50	0.19	0.12	.088	0.47	.042	.041	0.18	.049	.046	0.23	0.68	0.52	0.11	0.45	.038
10	-	0.32	-	0.12	-	-	.042	0.30	-	.049	-	0.93	1.38	0.15	-	.039
20	1.84	1.19	0.89	0.89	1.76	0.57	0.57	1.10	0.63	0.63	1.35	4.24	5.01	0.70	1.66	0.53
30	1.67	1.08	0.87	0.87	1.60	0.57	0.57	1.00	0.63	0.63	1.29	3.76	5.40	0.62	1.50	0.53
40	1.57	1.02	0.85	0.85	1.50	0.57	0.57	0.94	0.63	0.63	1.25	4.72	5.21	0.78	1.41	0.53
50	1.50	0.97	0.84	0.84	1.43	0.57	0.57	0.90	0.63	0.63	1.23	82.43	80.91	97.10	1.35	0.53
60	1.45	0.94	0.83	0.83	1.38	0.57	0.57	0.86	0.62	0.62	1.21	82.43	80.91	97.10	1.30	0.53
70	1.39	0.91	0.82	0.82	1.33	0.57	0.57	0.83	0.62	0.62	1.19	82.43	80.91	97.10	1.25	0.53
80	1.32	0.86	0.81	0.81	1.26	0.57	0.57	0.79	0.62	0.62	1.17	82.43	80.91	97.10	1.19	0.53
90	1.37	0.42	0.82	0.82	1.30	0.57	0.57	0.82	0.62	0.62	1.18	82.43	80.91	97.10	1.23	0.53
100	1.30	0.85	0.81	0.81	1.24	0.57	0.57	0.78	0.62	0.62	1.16	82.43	80.91	97.10	1.17	0.53
200	11.9	7.71	7.92	7.92	11.3	5.67	5.67	7.11	6.21	6.21	11.2	82.43	80.91	97.10	10.7	5.25
300	10.6	6.90	7.71	7.71	10.2	5.64	5.64	6.36	6.17	6.17	10.7	82.43	80.91	97.10	9.57	5.23
400	9.86	6.38	7.57	7.57	9.40	5.62	5.62	5.72	6.14	6.14	10.4	82.43	80.91	97.10	8.86	5.20
500	9.27	6.01	7.47	7.47	8.84	5.60	5.60	5.12	6.11	6.11	10.1	82.43	80.91	97.10	8.33	5.18
600	8.77	5.68	7.36	7.36	8.37	5.56	5.56	3.97	6.07	6.07	9.93	82.43	80.91	97.10	7.89	5.15
700	8.27	5.49	7.29	7.29	7.92	5.55	5.55	3.84	6.05	6.05	9.76	82.43	80.91	97.10	7.62	5.14
800	7.47	5.23	7.15	7.15	7.23	5.51	5.51	3.65	6.00	6.00	9.40	82.43	80.91	97.10	7.27	5.10
900	6.77	4.93	6.54	6.54	6.30	5.48	5.48	3.53	5.91	5.91	7.58	82.43	80.91	97.10	7.03	5.07
1000	5.68	4.60	5.77	5.77	5.78	5.47	5.47	3.41	5.79	5.79	5.46	82.43	80.91	97.10	6.79	5.06
2000	5.52	26.6	24.8	24.8	9.55	44.2	44.2	28.9	39.2	39.2	2.88	82.43	80.91	97.10	11.7	48.3
3000		8.78	1.92	1.92				19.0	.069	.069		82.43	80.91	97.10		
4000		0.53										82.43	80.91	97.10		
5000		0.34										82.43	80.91	97.10		
6000		0.19										82.43	80.91	97.10		
>6000		0.28										82.43	80.91	97.10		

* SIZE CODES 1 - 14 ARE FOR AVERAGE RELEASES
15 & 16 ARE FOR MAXIMUM RELEASES

3.5 REFERENCES

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- 3-3 Letter from J. Cork (JPL) to Dr. D. McConnell (NASA/EL), Re: Teleconference Minutes on Use of NSTS Probabilities, dated May 11, 1988,. Ref. 200-MJC-88-045.
- 3-4 Private communication between F. Anderson, Hughes Aerospace Division Testing, and Dr. E. Gantz, General Electric Missile and Space Division.
- 3-5 Wyle Laboratories, "Puncture Test on Tank," Test Report No. 46959, October, 1965.
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- 3-8 "Worldwide Hard Rock Distribution Study" NUS Corporation and ERDAS, Incorporated, November 1983.
- 3-9 GESP-7190 "Final Test Report, GPHS Drop Test for Impact Orientation." General Electric Co./Space Systems Division, January 14, 1985.