APPENDIX B

PROBABILITIES AND SOURCE TERM METHODOLOGY FOR INADVERTENT REENTRY DURING AN EARTH SWINGBY AND INTERPLANETARY CRUISE FOR THE VVEJGA AND VEEGA TRAJECTORIES

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B.1 EARTH GRAVITY-ASSIST CONSIDERATIONS IN DETERMINING PROBABILITIES

The Proposed Action, the 1999 mission alternative, and the 2001 mission alternative would utilize planetary gravity-assist trajectories to gain enough energy to reach Saturn. A planetary gravity-assist uses the planet's gravity for the extra energy needed by the spacecraft to maintain or increase its velocity so that it can reach its mission destination (in this case, Saturn). The Proposed Action's primary launch opportunity would use a Venus-Venus-Earth-Jupiter-Gravity-Assist (VVEJGA) trajectory to reach Saturn. The spacecraft on this trajectory would make four planetary gravity-assist swingbys-the first two around Venus, the third around the Earth, and the fourth around Jupiter before reaching Saturn. The 1997 secondary and 1999 backup contingency launch opportunities under the Proposed Action as well as the 1999 dual Shuttle alternative would each use a Venus-Earth-Earth-Gravity-Assist (VEEGA) trajectory to reach Saturn. The primary launch opportunity for the 2001 mission alternative would use a non-Earth-gravity-assist trajectory, a 10.3-year Venus-Venus-Venus-Gravity-Assist (VVVGA).

If a failure occurs during a planetary gravity-assist swingby, the spacecraft could be placed in a planet-impacting trajectory. For these launch opportunities, multiple opportunities would exist for planetary impacts to occur during swingby activities: four for the primary launch VVEJGA opportunity (Venus, Venus, Earth, Jupiter swingbys), and three each for the VEEGA (Venus, Earth, Earth swingbys) and VVVGA (Venus, Venus, Venus swingbys) opportunities. The Earth swingby(s) would be the primary concern.

If an accident or failure occurs during the swingby process resulting in loss of control of the spacecraft and the spacecraft is placed on an Earth-impacting trajectory, the three radioisotope thermoelectric generators (RTGs) and 117 radioisotope heater units (RHUs) onboard the Orbiter and 40 RHUs on the Huygens Probe could impact the Earth. (Earth impact is defined as the inadvertent reentry of the spacecraft into the Earth's atmosphere.) The RTGs could reenter the Earth's atmosphere leading to a range of fuel-end states that include intact modules (damaged and undamaged), intact GISS, particulate, and vaporized fuel. Of the 157 RHUs, the 117 in the Orbiter would be predicted to vaporize but the 40 RHUs in the Probe would be expected to survive reentry.

The potential would also exist for a failure to occur that could result in a loss of spacecraft control during the non-swingby or interplanetary cruise portion of the gravity-assist trajectories. If such an event occurred and the spacecraft drifted in its orbit around the Sun, an Earth impact could occur a decade to centuries later, after many revolutions around the Sun. Once the spacecraft has successfully completed its planetary gravity-assist trajectory and the Saturn Orbit Insertion (SOI) has occurred, the spacecraft would come under the gravitational influence of Saturn and would no longer pose a threat of earth impact. Even if SOI is not achieved or a spacecraft failure occurs after the gravity-assists, the resulting trajectories would probably not cross the Earth's torus and would likely eject the spacecraft from the solar system.

Precautions are taken in the mission design to ensure that an inadvertent reentry into Earth's atmosphere resulting in an impact with the Earth's surface does not occur during the Earth-gravity-assist swingbys. This ongoing design is also intended to assure spacecraft control during interplanetary cruise to preclude a potential Earth impact years later.

To this end, a formal design requirement was imposed to ensure the expected probability of Earth impact would not exceed 10^6 (i.e., 1 in a million) (Jet Propulsion Laboratory [JPL] 1993f).

> *Following injection, the probability of Earth impact by the spacecraft shall not exceed 10^{-6} taking into account potential failures.*

To verify that this requirement can be satisfied during this mission, JPL assessed the probability of Earth impact (JPL 1993f). This requirement was interpreted to mean that the expected value of the Earth impact probability, from injection of the spacecraft into its planetary gravity-assist trajectory to Saturn (i.e., from the end of launch Phase 6) to 100 years beyond the nominal Saturn encounter date, should not exceed 10^6.

The JPL study was performed to determine the necessary actions in the design of the spacecraft, ground system, and navigation planning to ensure that the probability of Earth impact satisfied the design requirement (JPL 1993f). The study incorporated a quantitative assessment of the probability of Earth impact, including an evaluation of the uncertainties in the assessment process. Additionally, an independent review panel found the approach taken by JPL to assess the probability of an inadvertent reentry to be sound and reported that JPL's results are reasonable (Cassini Swingby Independent Review Panel 1995).

The following sections present the methodology used for determining the Earth impact probability and the failure mode analysis that leads directly to short-term, long-term, and total probability of an Earth impact from an inadvertent reentry. Two trajectories were evaluated: the VVEJGA trajectory of the primary launch opportunity and the VEEGA trajectories associated with both the 1997 secondary and 1999 backup launch opportunities and the 1999 dual Shuttle launch alternative. Because the VEEGA trajectories for the secondary and backup launch opportunities have essentially the same characteristics, and because the VEEGA trajectories are identical for the 1999 backup launch opportunity and the dual Shuttle launch alternative, only the 1999 launch opportunity is referenced throughout the discussion. The probabilities associated with the secondary launch opportunity are expected to be similar to or less than those for the 1999 launch opportunity.

B.1.1 Methodology

The Earth impact probability developed by JPL consists of short- and long-term components. The short-term component is the contribution resulting from the navigation of the Earth swingby(s) for a given trajectory (VVEJGA or VEEGA). The long-term component is the contribution from a failure during the interplanetary cruise that leads to a disabled spacecraft drifting in an orbit around the Sun, so that the spacecraft could reencounter the Earth sometime beyond the nominal Saturn encounter date. For this analysis, the probability of impact during the first 100 years beyond SOI was considered.

For either component, the Earth impact probability (P_I) can be expressed as:

$$\mathbf{P_I = \sum_i P_F(i)\, P_{I/F}(i)\, P_{NR}(i)} \qquad \text{(C-1)}$$

Where:

P_I = Probability of Earth impact

$P_F(i)$ = Probability of failure of i-th failure mode

$P_{I/F}(i)$ = Probability of a resultant Earth impact trajectory given an occurrence of the i-th failure mode

$P_{NR}(i)$ = Probability of no recovery given the failure mode and the time to impact, this probability is conditional on the occurrence of the failure and on this spacecraft being on an impact trajectory because of the failure.

This relationship represents several important concepts. A number of failure modes contribute to impact probability. One objective of the JPL study was to identify these failure modes. It is important to note that not all failures would place the spacecraft on an impacting trajectory and that all failures would not adversely affect the capability of mission controllers to achieve successful Earth swingby(s), illustrated by the $P_{I/F}$ and P_{NR} terms. For example, the Galileo high-gain antenna anomaly resulted in only a partial deployment of the antenna, which did not prevent the precise delivery of file Galileo Spacecraft at the second Earth swingby.

To keep the short-term impact probability low, a trajectory-biasing strategy is used in the trajectory design and implementation plan to reduce the probability of an Earth Impacting trajectory if a failure were to occur (i.e., to reduce $P_{I/F}$). During most of Cassini's inner solar system journey, the spacecraft would be on a trajectory that, without further maneuvers, would miss the Earth by tens of thousands of kilometers. As part of the Earth impact avoidance strategy, the spacecraft would either be placed on a trajectory passing through the required Earth swingby point just 10 days prior to the Earth swingby for the VVEJGA, or 7 days prior to each of the two Earth swingbys for the VEEGA.

The JPL study determined that, although a trajectory-biasing strategy to control the potential for Earth impact during a planned swingby would affect the probability over the long term, such a strategy could not be relied upon exclusively to control the long-term probability. Failures on legs targeted toward Earth or Venus would tend to result in spacecraft trajectories that remain in the vicinity of Earth's orbit. Failures during legs targeted toward Jupiter or Saturn tend to result in trajectories that would never return to the vicinity of Earth's orbit. Gravity-assists by the massive outer planets, for example, would virtually ensure that failures during the last 73 percent of the primary and the last 44 percent of the backup interplanetary cruise do not result in an Earth impact. Over a long-time period, the Earth impact probability is dominated by third-body perturbations to the spacecraft trajectory and by accidental planetary gravity-assist swingbys while the errant spacecraft is drifting in a Sun orbit. Therefore, the long-term Earth impact

probability would have to be controlled by designing the spacecraft and mission operations so that the failure probabilities would be low.

Not all failures would place the spacecraft on an Earth-impacting trajectory. The PNR term includes the ability to recover control of the spacecraft and successfully apply a corrective maneuver after a failure. If the spacecraft was not completely incapacitated by the failure, then the normal course of action would be to accurately determine the spacecraft trajectory and, if required, command a recovery sequence to modify the trajectory and avoid Earth impact.

B.1.2 Failure Mode Analysis

Two general categories of uncertainty can lead to an Earth-impacting trajectory. First, Earth-impacting trajectories could result from uncertainties in the normal operation of the spacecraft and its navigation system (navigation uncertainties). During a maneuver (i.e., a normal trajectory correction), for example, the actual change in position and/or change in velocity of the spacecraft may differ slightly from the desired change or that estimated by the navigation system. Changes in actual position and/or velocity, if large enough and uncorrected, could lead to Earth impact. Such uncertainties are not considered failures; they are expected variations in the operation of the systems. The second general category would be failures. In general, failures can be classified into three categories: environmentally-induced failures, internal spacecraft failures, and ground-induced failures. These types of failures can result in an anomalous spacecraft velocity change that could place the spacecraft on an Earth-impacting trajectory. A subset of these failures could prevent the spacecraft from being recovered after being placed on an Earth-impacting trajectory.

Of all the environmentally-induced failure modes identified by the JPL study, only micrometeoroid-induced tank rupture was a significant contributor to the short-term Earth impact probability (JPL 1993f). The Cassini spacecraft design would include components to provide protection from micrometeoroids; however, some particles in space have sufficiently high energies to penetrate or overcome those protective measures and damage the spacecraft. Current analyses indicate that the spacecraft on the VEEGA trajectory would require the equivalent of three times the particle shielding protection as used on the VVEJGA trajectory. A rupture of a propellant or a pressurant tank could cause an anomalous spacecraft velocity change and loss of spacecraft control or commandability.

The contribution to Earth impact probability from all other failure modes (environmentally-induced, internal spacecraft failures, and ground-induced) was more than an order of magnitude less than that from micrometeoroid-induced failures. Thus, micrometeoroid-induced failures are the primary factor in evaluation of the probability of an Earth impact during a planned swingby. Other failure modes evaluated included stuck-open thruster valves, main engine valve failures, accelerometer failures, main engine gimbal actuator failures, and anomalous Sun searches due to stellar reference unit or inertial reference unit failures. Coding errors in the Attitude and Articulation Control Subsystem (AACS) and Command and Data Subsystem (CDS) flight software were determined to be the spacecraft software contributors to Earth impact probability (JPL 1993f).

The dominant failure mode for the long-term Earth impact probability was determined to be loss of control due to internal spacecraft system failures. Internal failures include design and implementation errors, common-mode failures, electronic parts failures, hardware failures, and software errors. Ground-induced errors made by spacecraft controllers are sent to the spacecraft and executed. Two categories of ground-induced errors are erroneous ground commands and navigation design errors. These potential ground-induced errors were determined to be insignificant contributors to Earth impact probability.

In addition to these potential failures that could place the spacecraft on an Earth-impacting trajectory, failures that could prevent the spacecraft from being recovered once it is on an Earth-impacting trajectory were also considered. In some cases, the same failure that would place the spacecraft on an impacting trajectory would also prevent recovery.

For the failures that would put the spacecraft on an Earth-impacting trajectory but do not preclude the execution of recovery maneuvers, the key factor in determining whether or not recovery could actually be accomplished and Earth impact avoided is the amount of time remaining before the Earth swingby, not the cause of the initial failure. (Until the spacecraft is close to the Earth swingby, only new failures that would completely disable the spacecraft need to be considered. Other failures can be diagnosed and corrected with sufficient time to make another recovery attempt.) The spacecraft primary disabling failures were determined to be micrometeoroid hits and spacecraft system internal failures. For initial failures that occur very close to swingby (i.e., within 2 days of Earth encounters), it was assumed that there would not be enough time to detect the failure and take corrective action. For failures occurring 39 or more days before Earth encounter, sufficient time would exist for problem diagnosis, development of a recovery plan, and execution of at least one and probably more recovery attempt(s). If a failure occurred between 39 and 2 days before the Earth encounter, there would be time to make only one recovery attempt; any subsequent failure was conservatively assumed to abort recovery attempts. JPL's evaluations indicated that the major contributors during this period would be ground failures preventing successful execution of a recovery maneuver and a spacecraft failure requiring ground intervention (JPL 1993f).

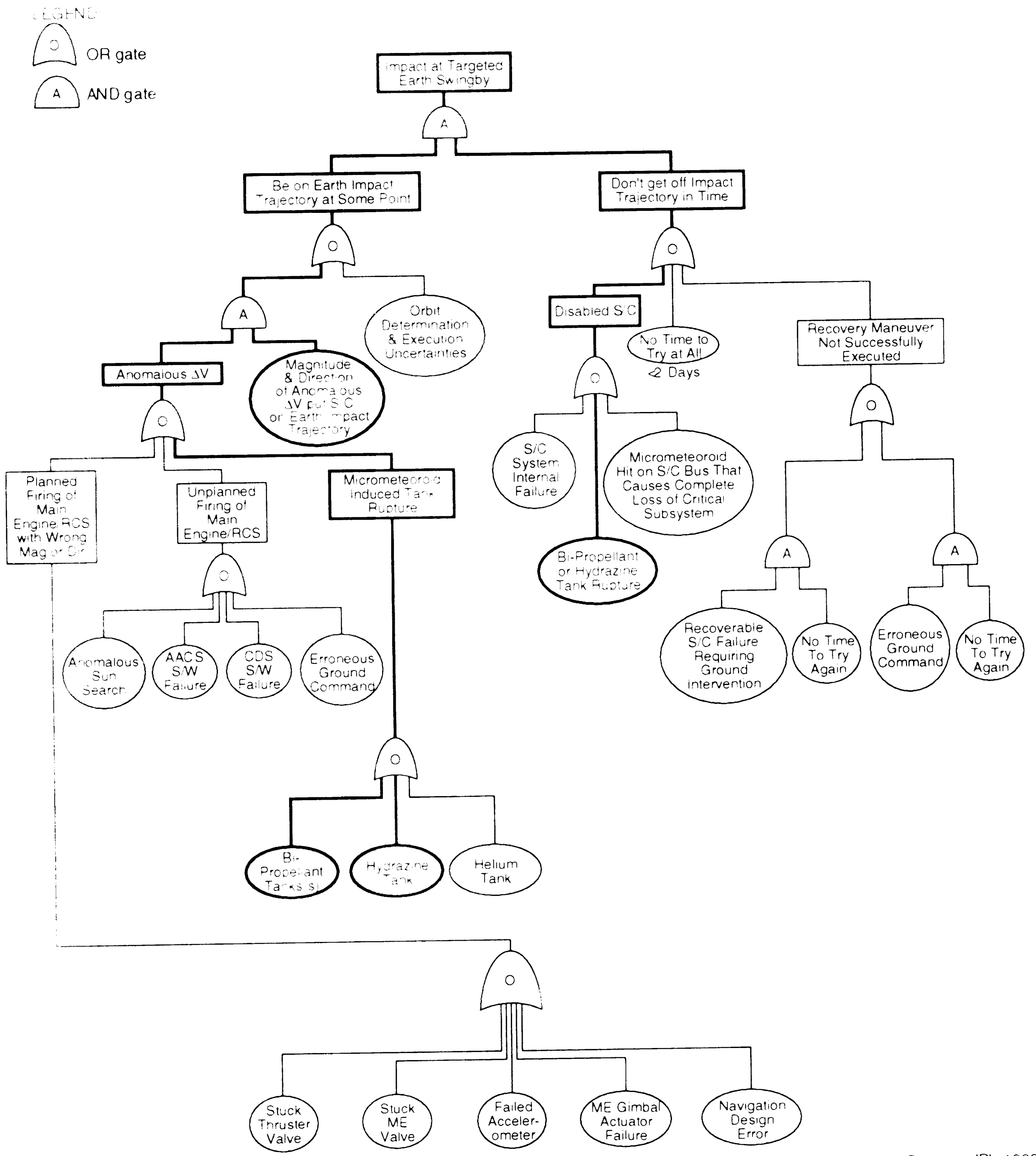
B.1.3 Short-Term Impact Probability

The objective of the trajectory-biasing navigation strategy from the point of Earth escape to the Earth swingby(s) is to satisfy the Earth impact probability while delivering the spacecraft to the necessary Earth swingby aimpoint. The navigation strategy is driven by the requirement to control the trajectory so that the spacecraft can satisfy the mission objectives and maintain a low probability of inadvertent reentry. The navigation strategy discussed here is not concerned with the overall trajectory design, which is controlled by the launch vehicle capabilities and mission objectives, but with the small variations in this trajectory. The trajectory-biasing navigation strategy that would be used for the Cassini mission would break the overall trajectory leading to Earth swingby into segments or steps, where the overall Earth impact probability of each segment would be controlled by biasing the aimpoint to avoid Earth impact. Prior to launch, an analysis would be performed to determine the duration and swingby conditions for each segment of the trajectory. Two rules would guide the analysis: 1) at no point during the mission, from injection into the planetary gravity-assist trajectory to Saturn to the final Earth swingby, would the expected probability of being on an Earth impact trajectory, following completion of a maneuver, be greater than 10^{6}, and 2) if a maneuver terminated early, the probability of an Earth-impacting trajectory would be no greater than that for a completed maneuver. After launch, the Cassini spacecraft would be controlled to these conditions.

Calculation of the short-term probability of Earth impact requires evaluation of three factors: the failure probabilities and associated anomalous velocity changes, the uncertainties in the navigation process, and the characteristics of the spacecraft trajectory. For the purpose of defining an Earth swingby navigation strategy, steps would be taken to minimize the effect of both failures and navigation uncertainties. The navigation strategy would focus on specifying and controlling the spacecraft trajectory conditions given the failure Probabilities and navigation uncertainties.

In general, the Earth impact probability decreases as the swingby altitude increases; therefore, impact avoidance requirements could be satisfied by simply raising the swingby altitude. However, specific swingby conditions would be needed to shape the trajectory, and the spacecraft cannot carry sufficient propellant to replace this effect (except possibly for a very small bias). There would, however, be enough propellant to bring the trajectory in toward the Earth in several steps before the swingby.

The probability of Earth impact is presented as a probability density function (PDF) over the model uncertainties. To calculate a PDF for the short-term Earth impact probability, it was necessary to perform a Monte Carlo simulation for both the primary and backup Fission trajectories. (It is reasonable to assume that the Earth impact probability for the 1997 secondary launch opportunity's VEEGA trajectory would be similar to or less than that estimated for the 1999 launch opportunity.) A best estimate of the short-term Earth impact probability was estimated by calculating the probability of impact for each significant failure mode. To provide an understanding of the contributing failure modes to the short-term Earth impact probability, a logic diagram (see Figure B-1) was generated. In the figure, the significant contributors are in bold (JPL 1993f).



Source: JPL 1993f

FIGURE B-1. SHORT-TERM EARTH IMPACT PROBABILITY LOGIC DIAGRAM

Using values of navigation uncertainty at three confidence levels (i.e., 10 percent, 50 percent or best estimate, and 90 percent) and three values of the anomalous spacecraft velocity change associated with a given failure, the probability of Earth impact was computed along the trajectory at maneuvers or at discrete time steps, depending on the failure mode being considered. The Monte Carlo simulation was performed with random selections of failure mode confidence levels, effects of the failure mode on imparting an Earth-impacting trajectory change, and the probability of recovering spacecraft control given the failure and time of occurrence in the simulated mission. A total of 1000 Monte Carlo runs or simulated missions were performed for each launch opportunity (primary and backup), with each run breaking the mission trajectory into a number of time steps. All failure modes were sampled. By sampling the failure probability and the probability to recover at the 10, 50 (best estimate), and 90 percent confidence levels and the probability of an impact trajectory resulting from the failure at a random time step, a distribution of the overall Earth impact probabilities was developed. The factors, after each had been sampled, were multiplied together to determine the probability of Earth impact at a given time step. The individual probabilities were then summed over the time step and across all failure modes to obtain the overall probability of Earth impact for the given trajectory (Table B-1). Micrometeoroid-induced failures, as noted previously, dominate the failure modes. The analyses performed for the Perseids meteor shower (an event that occurs in August every year) predicted that the Cassini spacecraft while on the VVEJGA trajectory would pass through both enhanced and storm environments but only the enhanced environment would apply while on the VEEGA (backup) trajectory. Calculated (i.e., best estimates) flux levels (of micrometeoroids) in the enhanced environment are about 3 times greater than background, and about 30 times greater than background in the storm environment. The mean values for the short-term probability of Earth impact occurring under the Proposed Action were estimated at 7.6×10^{-7} for the VVEJGA trajectory of the primary launch opportunity and at 4.7×10^{-7} for the backup opportunity's VEEGA trajectory (JPL 1993f).

As additional analyses for the short-term Earth impact case, JPL calculated the distribution of spacecraft reentry angles into Earth's atmosphere. These calculated distributions are representative of the reentry angle estimated for an Earth swingby accident. The Department of Energy used part of the JPL analysis to evaluate the potential consequences to the RTGs and RHUs of an Earth swingby accident. JPL's analysis indicated that reentry angles less than 7 degrees would probably cause the spacecraft (plus RTGs and RHUs) to skip back out of the atmosphere and not impact the Earth. The frequency distributions of reentry angles for the primary launch opportunity's VVEJGA trajectory and for the second Earth swingby in the 1999 launch opportunity's VEEGA trajectory tended to be greatest in the lower entry angles (about 7 to 30 degrees), indicating that this reentry would be more likely to occur in the lower entry angles. Specifically, the reentry would be relatively "shallow." The first Earth swingby of the VEEGA had a nearly uniform distribution of reentry angles between 10 and 80 degrees ranging from shallow to steep. With a shallow reentry, the spacecraft would spend more time passing through Earth's atmosphere before impacting than during a steep reentry. Figures B-2, B-3, and B-4 illustrate the conditional probabilities for various entry angles for the primary and backup launches (JPL 1993f).

TABLE B-1. SHORT-TERM MEAN EARTH IMPACT PROBABILITIES

Failure Mode	Primary (VVEJGA)	1999 (VEEGA)	
		Earth 1	Earth 2
I Environmental Failures			
1) Micrometeroid (the only significant environment failure mode)			
A) Bipropellant Tank	6.11×10^{-7}	1.52×10^{-7}	2.33×10^{-7}
B) Hydrazine Tank	1.13×10^{-7}	2.91×10^{-8}	3.06×10^{-8}
C) Helium Tank	3.02×10^{-8}	7.04×10^{-9}	6.36×10^{-9}
D) Engineering Bus	2.21×10^{-10}	Nil	1.03×10^{-12}
II Major Spacecraft Failures			
1) Stuck-Open Thruster Valve			
A) Z Thruster			
1) Mechanical Failure	1.37×10^{-12}	Nil	Nil
2) Electrical Failure	3.23×10^{-12}	Nil	Nil
B) X Thruster			
1) Mechanical Failure	2.33×10^{-10}	Nil	Nil
2) Electrical Failure	4.86×10^{-11}	Nil	Nil
2) Stuck-Open Main Engine Valve			
A) Mechanical Failure			
1) Oxidizer Valve	Nil	Nil	Nil
2) Fuel Valve	Nil	Nil	Nil
B) Electrical Failure	Nil	Nil	Nil
3) Accelerometer Failure	2.45×10^{-10}	Nil	7.17×10^{-9}
4) Main Engine Gimbal Actuator Failure	2.07×10^{-12}	Nil	2.66×10^{-12}
5) AACS Flight Software Error	3.00×10^{-12}	Nil	Nil
6) CDS Flight Software Error	Nil	Nil	1.60×10^{-9}
7) Anomalous Sun Search	1.35×10^{-11}	Nil	Nil
8) Spacecraft System Internal Failure	1.93×10^{-9}	Nil	2.90×10^{-11}
III Ground-Induced Errors			
1) Erroneous Ground[a] Command	1.76×10^{-10}	1.92×10^{-10}	3.04×10^{-10}
2) Navigation Design[b] Error	6.94×10^{-10}	4.11×10^{-10}	2.40×10^{-10}
TOTAL	7.6×10^{-7}	1.9×10^{-7}	2.8×10^{-7}

Source: JPL 1993f

a. Computed as a bound by setting $P_{I/F} = 1.0$.
b. Computed as a bound by setting ΔV toward the Earth.

Note: Nil indicates that the mean fractional Earth Impact probability is less than 10^{12}; three-digit precision is retained to facilitate addition.

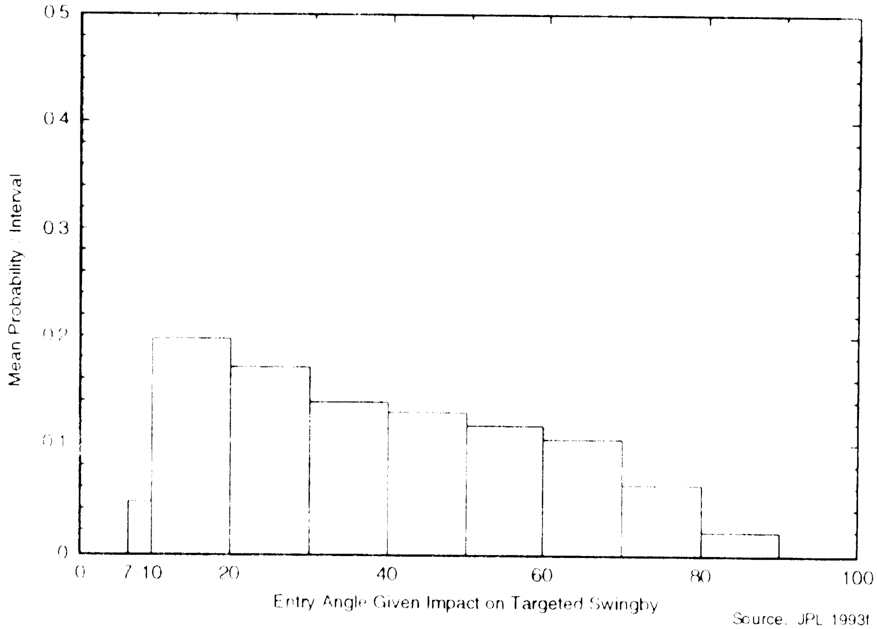


FIGURE B-2. PRIMARY: CONDITIONAL PROBABILITY VERSUS ENTRY ANGLE

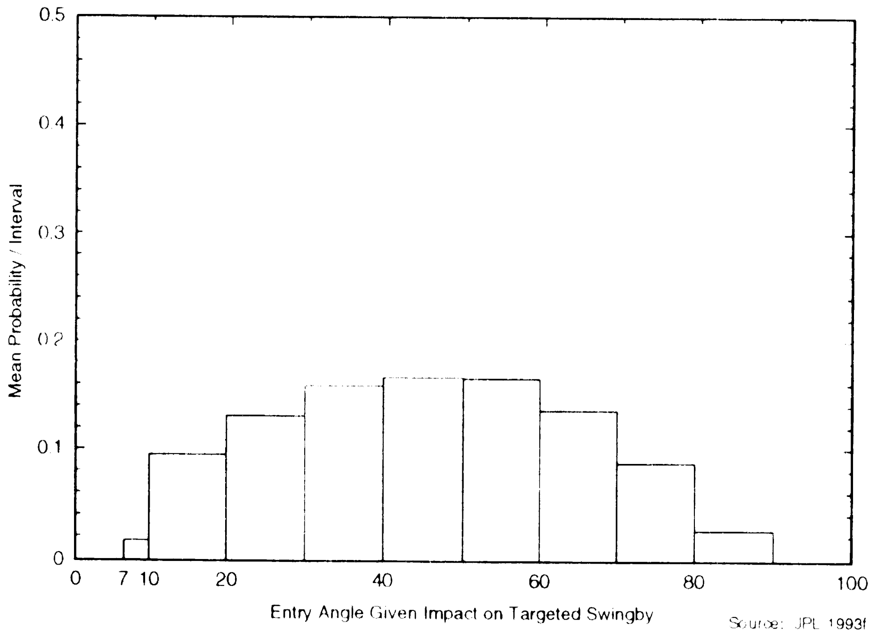


FIGURE B-3. BACKUP - E1: CONDITIONAL PROBABILITY VERSUS ENTRY ANGLE

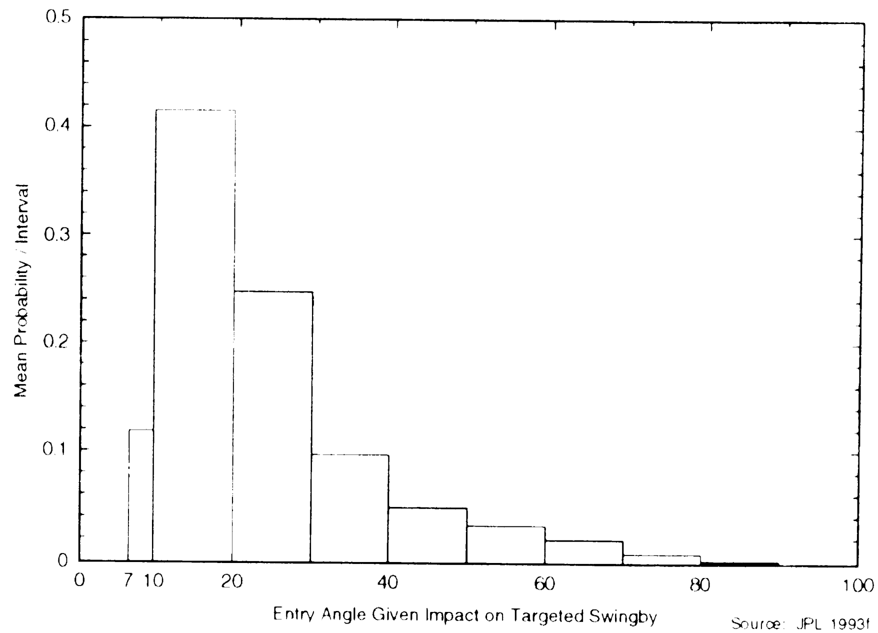


FIGURE B-4. BACKUP - E2: CONDITIONAL PROBABILITY VERSUS ENTRY ANGLE

In addition, JPL calculated the latitudes at which Earth impact would probably occur. The VVEJGA trajectory would most likely result in reentry between the equator and about 30 degrees south latitude (see Figure B-5); the first Earth swingby (see Figure B-6) of the VEEGA trajectory would probably have the greatest spread in reentry/'altitude with most reentries ranging from 36 degrees north latitude to about 17 degrees south latitude. The second Earth swingby of the VEEGA would probably reenter between roughly 23 degrees north latitude and 5 degrees south latitude (see Figure B-7).

B.1.4 Long-Term Impact Probability

The short-term impact analysis indicates that the probability of Earth impact during a targeted Earth swingby is extremely small. However, if control of the spacecraft is lost before SOI and the spacecraft does not impact the Earth during a targeted swingby, there would still be a remote possibility that long-term perturbations to the orbit could cause the spacecraft to eventually reencounter the Earth. JPL's long-term analysis computed the probability of Earth impact through a non-targeted (i.e., unplanned) Earth swingby from the time of spacecraft failure to 100 years beyond the planned SOI date.

To compute the long-term probability of Earth impact, a knowledge of the spacecraft failure probabilities and associated anomalous spacecraft velocity changes, the uncertainties in the navigation process, and the long-term motion of the spacecraft is required. The long-term analysis only evaluated failures causing a loss of spacecraft control with no chance of recovery. Figure B-8 illustrates the logic diagram for this analysis with the dominant scenarios contributing to the long-term Earth impact are in bold.

Because a large number of spacecraft trajectories could result given a failure during interplanetary cruise, a Monte Carlo analysis was performed using thousands of trajectories and a wide range of failure times and associated anomalous velocity changes. Each case included an initial spacecraft orbital state that was then perturbed by navigation uncertainty and any associated velocity changes. Each state was then propagated for 100 years for use in the analysis.

To determine the probability of Earth impact given a failure, a large body of work refined over the past 40 years was used to estimate the probability of impact by Earth-crossing asteroids. Existing theory applicable to lifetime analysis of asteroids and comets was modified to apply to this spacecraft impact analysis. In this method, the number of passages of the spacecraft through the Earth torus (the region of space swept out by the Earth as it orbits the Sun) are used to compute the probability of Earth impact. For an impact to occur, the spacecraft would have to cross through the Earth torus and, at the time of the crossing, the Earth would have to be at a position within the torus to cause impact (JPL 1993f).

The number of torus crossings for all Monte Carlo cases were computed by propagating the initial conditions for each case using a high-precision numerical integration program and then counting each passage through the Earth torus. For a given torus crossing, the Earth-crossing asteroid theory was used to analytically compute the

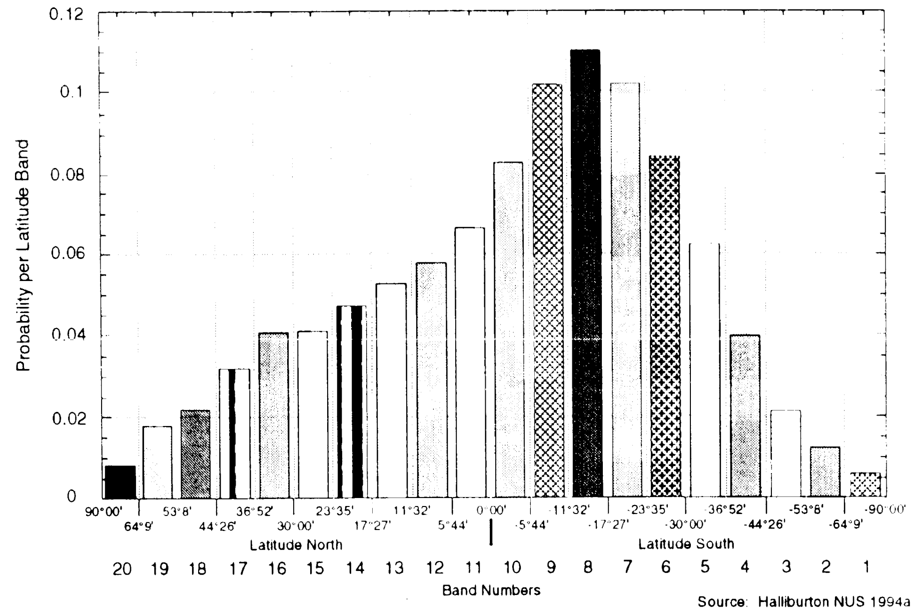


FIGURE B-5. PRIMARY: ENTRY LATITUDE CONDITIONAL PROBABILITY DISTRIBUTION

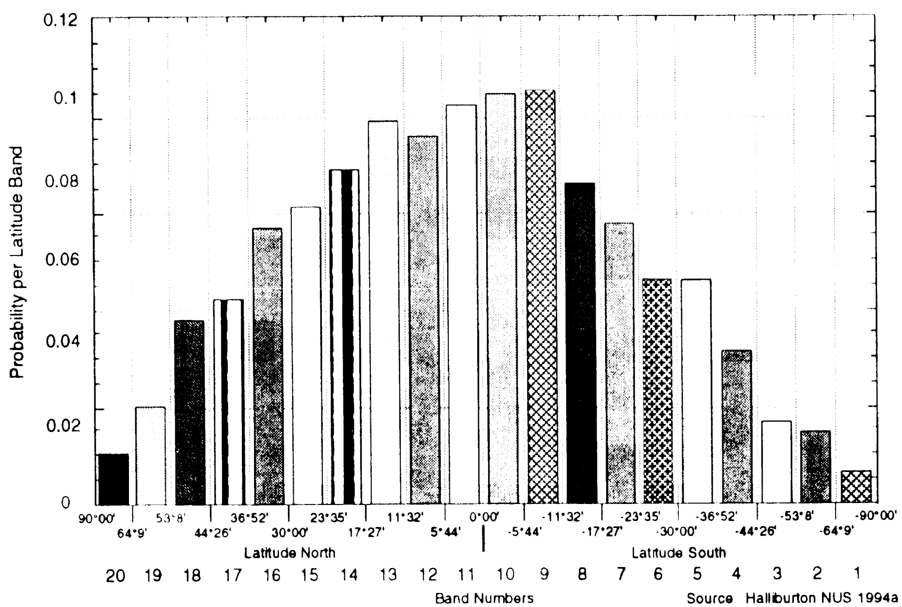


FIGURE B-6. BACKUP - E1: ENTRY LATITUDE CONDITIONAL PROBABILITY DISTRIBUTION

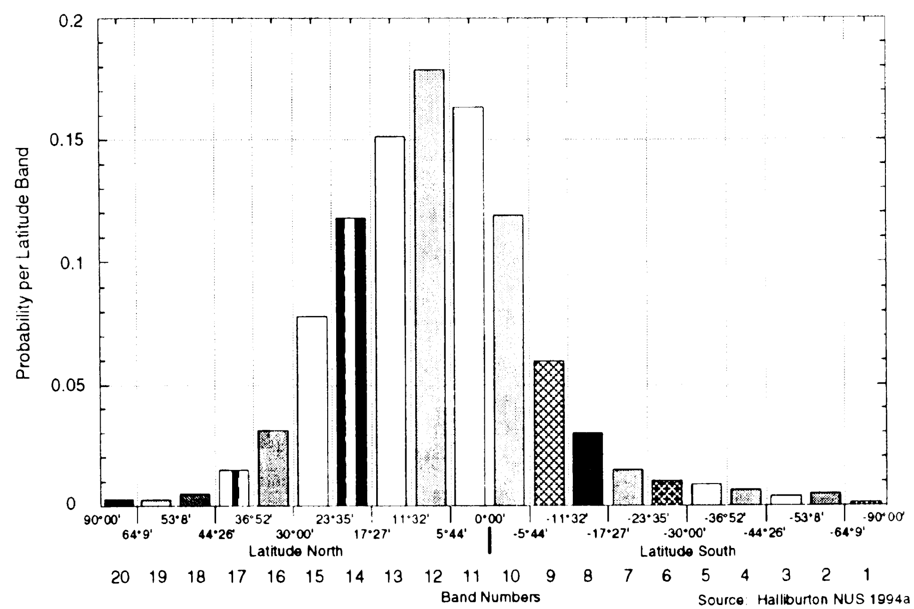
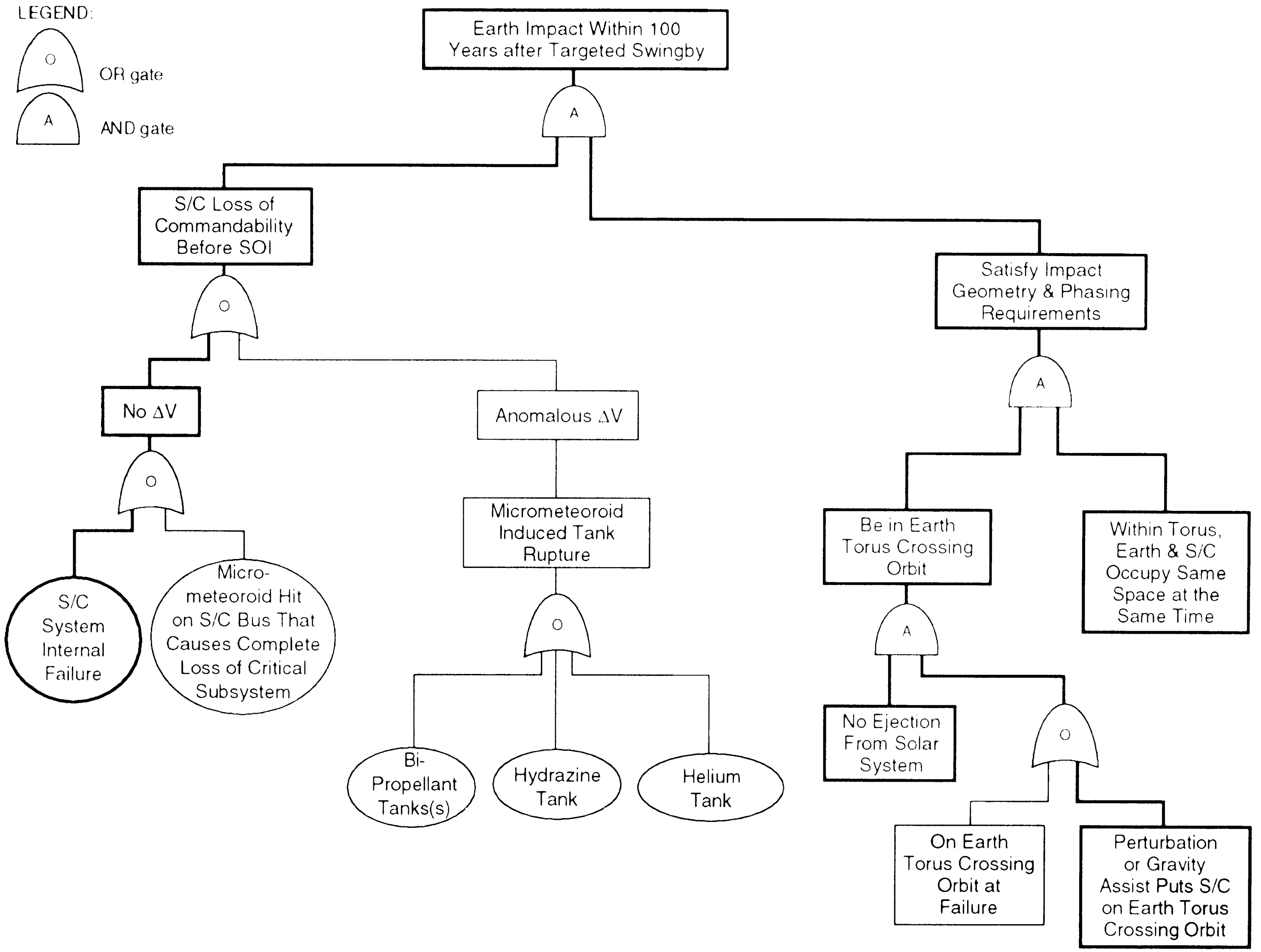


FIGURE B-7. BACKUP - E2: ENTRY LATITUDE CONDITIONAL PROBABILITY DISTRIBUTION



Source: JPL 1993f

FIGURE B-8. LONG-TERM EARTH IMPACT PROBABILITY LOGIC DIAGRAM

probability of the Earth being in the position required for Earth impact. An uncertainty analysis was performed to yield probability distributions for both the number of torus crossings per case and the probability of Earth impact given a torus crossing. These distributions were combined with the spacecraft failure distribution to yield a PDF for the long-term Earth impact probability.

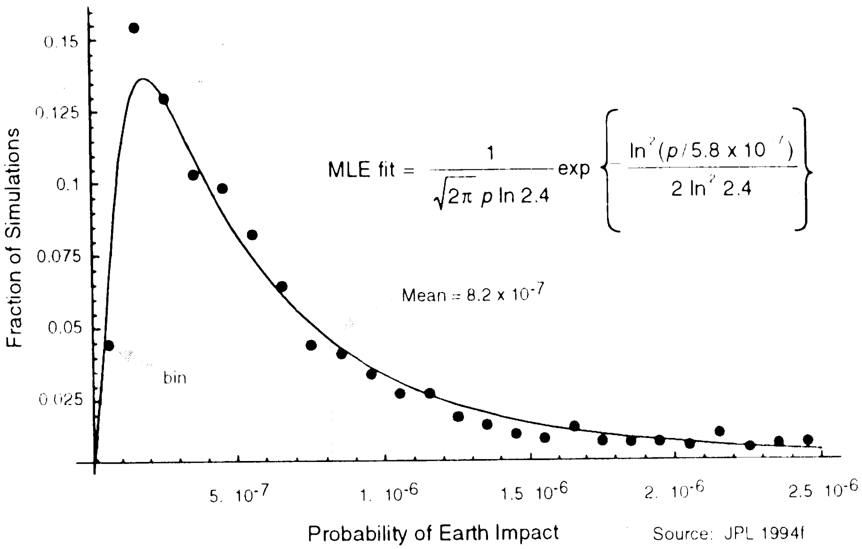
The mean long-term Earth impact probability for 100 years was estimated at 6.0 x 10^{-8} for the primary launch opportunity and 4.0 x 10^{-7} for the backup launch opportunity. The impact probability is larger for the backup opportunity because of the longer cruise duration and the different interplanetary trajectory characteristics. It is reasonable to assume that the probability associated with the secondary launch opportunity would be similar to or less than that for the backup opportunity. An important result of the analysis is that for failures occurring during the latter half of the interplanetary cruise for all launch opportunities, in nearly all cases, the spacecraft would be quickly ejected from the solar system by a strong Saturn gravity assist, thereby precluding any possibility of Earth impact.

As a point of interest, a subset (approximately 20 percent) of all the Monte Carlo cases was also propagated for 1,000 years to study the very long-term probability of Earth impact. The same methodology used for the 100-year case was used for these 1,000 year cases. The mean probability of Earth impact over 1,000 years was about 2.5 times higher for the primary opportunity and about 1.5 times higher for the backup opportunity than that for a 100-year period (JPL 1993f).

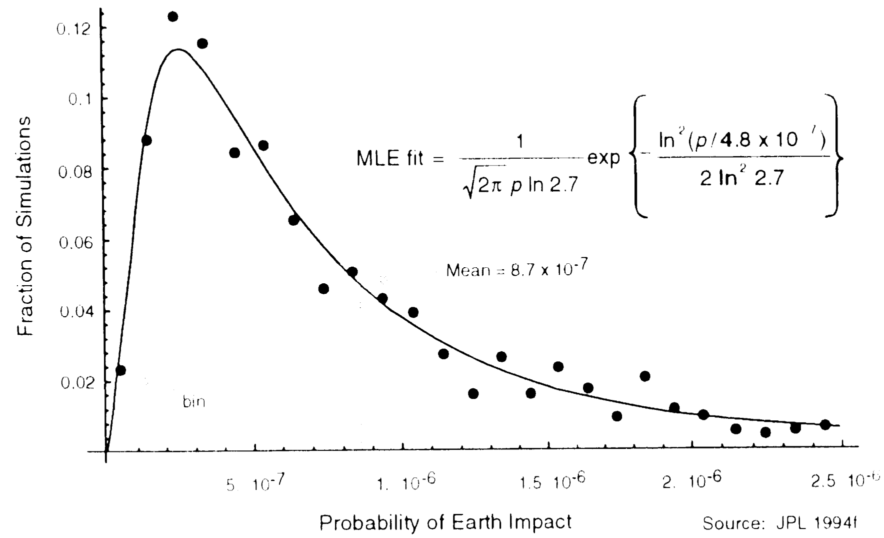
B.1.5 Total Impact Probability

As mentioned previously, the expected probability of Earth impact for the Cassini mission must be less than or equal to one in a million (10^{-6}). A number of parameters can be used to describe the characteristics and interpretation of a PDF (or of a complementary cumulative probability curve). The expected value of a random variable is expressed by the mean of the probability distribution. Thus, this Project requirement is fulfilled when the mean of the assessed probability distribution is less than or equal to 10^{-6}.

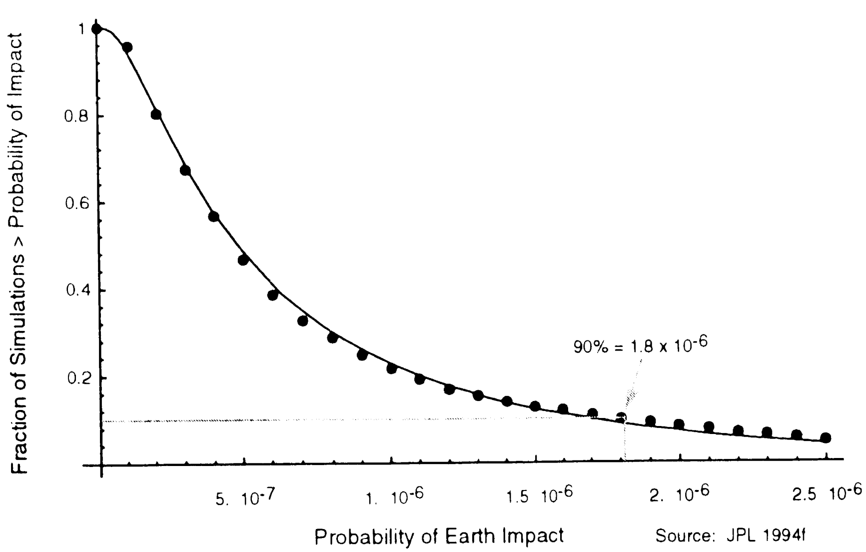
The total Earth impact probability distribution is the probabilistic sum of the short and long-term Earth impact probability distributions. A 1,000-trial Monte Carlo simulation was used to perform this probabilistic summation. Figure B-9 presents the PDF and complementary cumulative probabilities for the primary and backup trajectories. The mean values of these distributions are 8.2 x 10^{-7} for the primary trajectory and 8.7 x 10^{-7} for the backup trajectory. It is reasonable to assume that the value for the secondary launch opportunity would be similar to or less than that for the backup opportunity. Because the mean of both distributions is less than 10^{-6}, the Project Earth swingby requirement is satisfied for all launch opportunities. (Figure B-9 also indicates values below which 90 percent of the possible Earth impact probabilities lie.) During the ongoing process of monitoring the inputs and assumptions used in estimating the probability of accidental Earth impact, small variations are anticipated in the exact PDF parameters. However, the Cassini project would always take those actions necessary to ensure that the expected impact probability mean is held below the 1.0 x 10^{-6} overriding constraint.



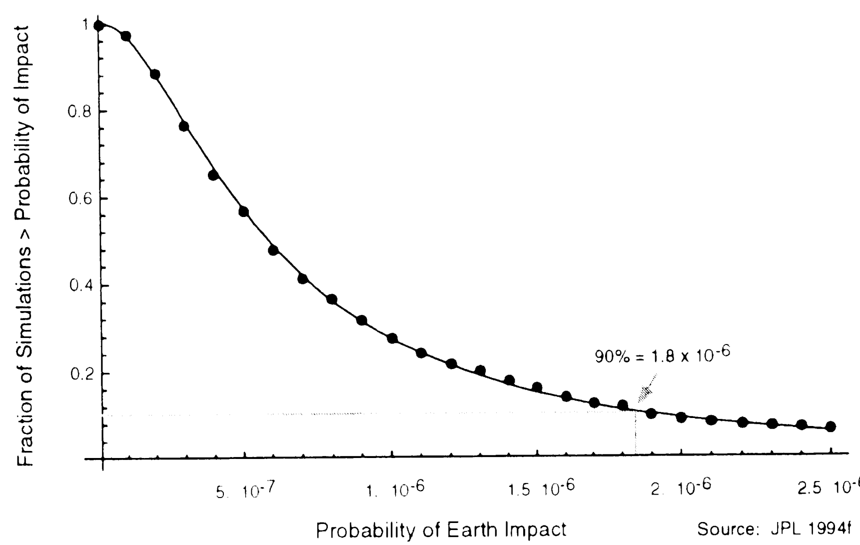
Probability Density Function for the Primary Launch Opportunity



Probability Density Function for the Backup Launch Opportunity



Complementary Cumulative Probability for the Primary Launch Opportunity



Complementary Cumulative Probability for the Backup Launch Opportunity

FIGURE B-9. TOTAL EARTH IMPACT PROABILITY

B.2 EARTH GRAVITY-ASSIST CONSIDERATIONS IN DETERMINING SOURCE TERMS

This section of the appendix presents the methodology used in estimating the source terms for a conditional short-term inadvertent reentry during the VVEJGA and VEEGA trajectories prior to an Earth swingby(s).

For VEEGA short-term inadvertent reentries, reentry velocities would be approximately 16.5 km/s (54,000 ft/s) for the E1 and 17.3 km/s (56,800 ft/s) for the E2 compared to the VVEJGA reentry velocity of 19.1 km/s (62,700 ft/s). For purposes of this EIS, the module reentry response for the VEEGA inadvertent reentries has been conservatively assumed to be the same as for the more severe VVEJGA inadvertent reentry. Source terms for the VEEGA inadvertent reentries have been developed using tied same approach or methodology use for the VVEJGA source terms (Halliburton NUS 1994a).

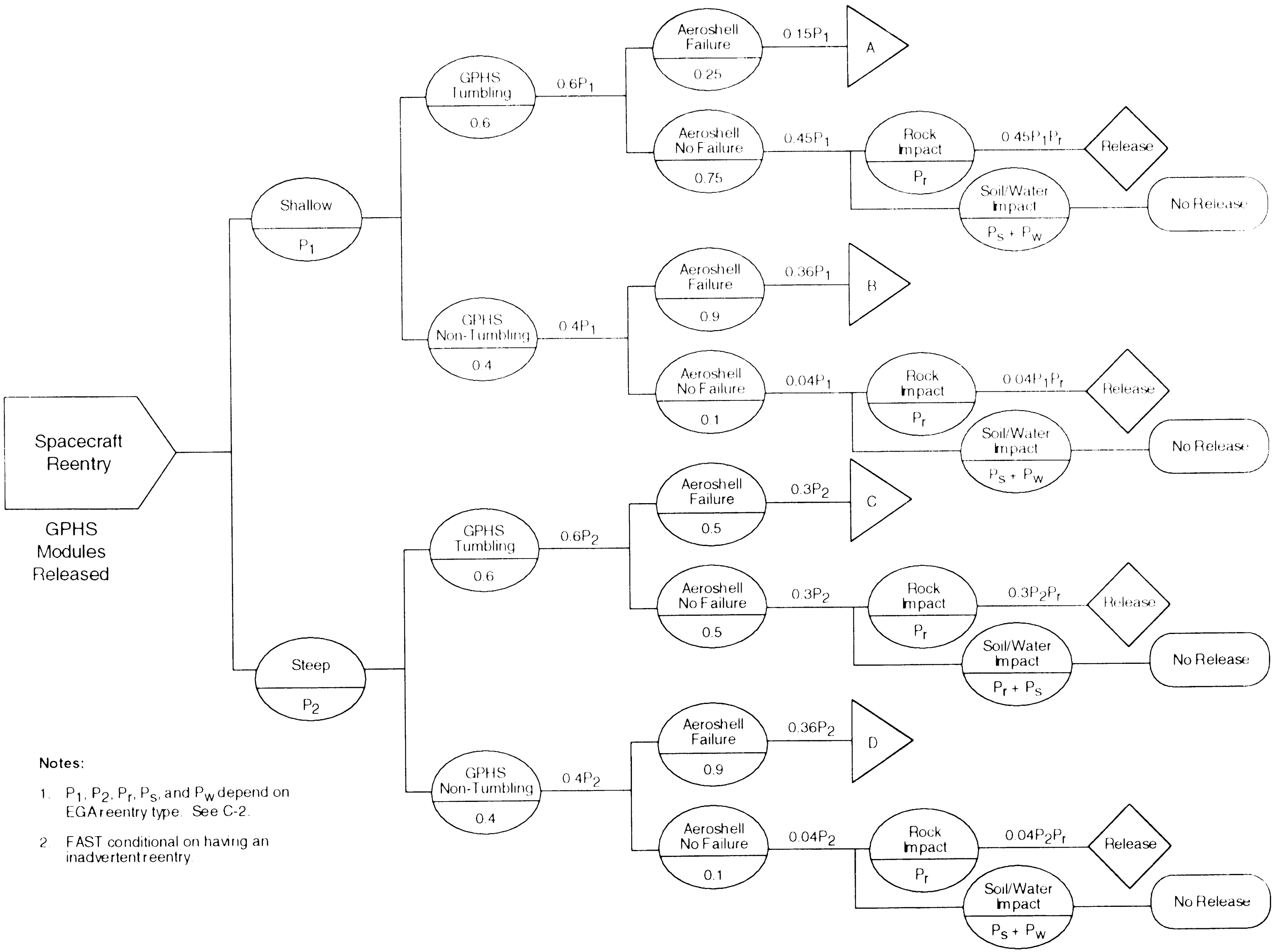
Radiological consequences (i.e., source term) for the long-term inadvertent reentry, cannot be estimated because of several uncertainties. These uncertainties involve the timing of the reentry which affects the inventory of radioactive materials onboard, the reentry-angle, -velocity, and -latitude, and the world population/,density at the time of reentry. In addition, there is uncertainty as to the RTG response to reentry conditions and therefore the resulting fuel end states. Therefore, in the following discussions, an inadvertent reentry applies only to the short-term reentry possibility.

Section B.2.1 presents the methodology for determining the General Purpose Heat Source (GPHS) module reentry response. Section B.2.2 summarizes the source term calculation methods, while Section B.2.3 provides the results of the radiological consequences based on the fuel end states.

B.2.1 Methodology for GPHS Module Reentry Response

As presented in Section 4.1.5.4, a range of fuel end states were postulated to occur as a result of the reentry of the GPHS modules: intact undamaged modules, intact GPHS modules with damaged but intact graphite impact shells (GISs), intact GISS, and particulate and vaporized fuel. U.S. Department of Energy (DOE) staff and contractors with expertise in RTG-reentry and -safety developed probability estimates of the range of these potential fuel end states using Failure Abort Sequence Trees (FASTS) based on available analyses (Martin Marietta Astro Space 1994a). The resulting FASTs are presented in Figure B-10, and are conditional upon having an inadvertent reentry for the VVEJGA or VEEGA. For sequences resulting in a release of plutonium dioxide fuel (i.e., a source term), the final event of release is shown in the form of a diamond. Conditional probabilities for each oval are noted. Important features of the FASTs and their technical bases are as follows:

- Tumbling (as opposed to non-tumbling) of the GPHS module involves full rotation or large oscillations about an axis. Non-tumbling involves the flight orientation in which a side or face of the GPHS module remains more constant even though there may be a slight wobble or flat spin. The branching probabilities for tumbling (0.6) and non-tumbling (0.4) GPHS module are based

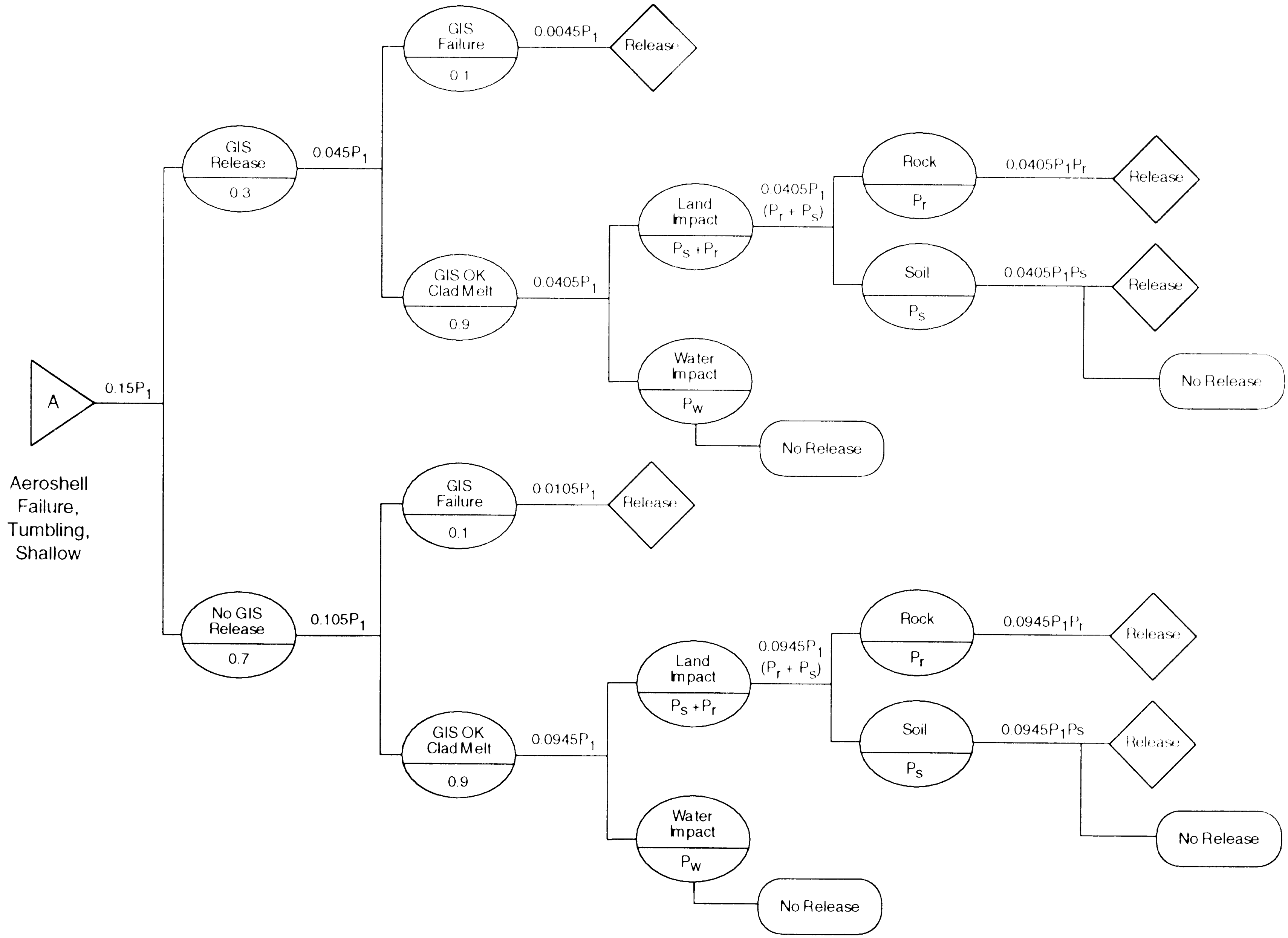


Notes:

1. P_1, P_2, P_r, P_s, and P_w depend on EGA reentry type. See C-2.
2. FAST conditional on having an inadvertent reentry.

Source: Martin Marietta Astro Space 1994a

FIGURE B-10. FAILURE/ABORT SEQUENCE TREES FOR VVEJGA INADVERTENT REENTRY (Page 1 of 5)



Source: Martin Marietta Astro Space 1994a

FIGURE B-10. FAILURE/ABORT SEQUENCE TREES FOR VVEJGA INADVERTENT REENTRY (Page 2 of 5)

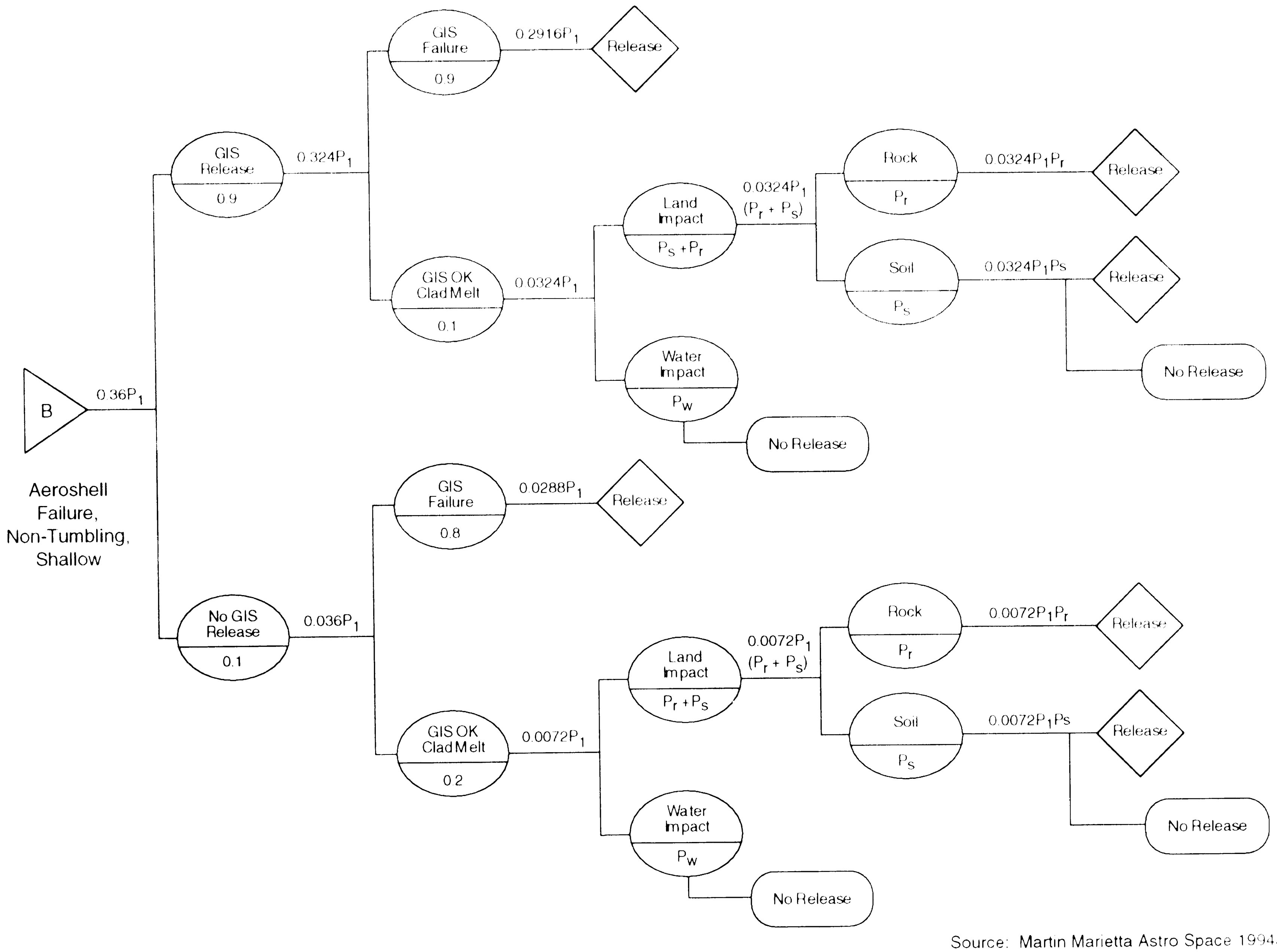
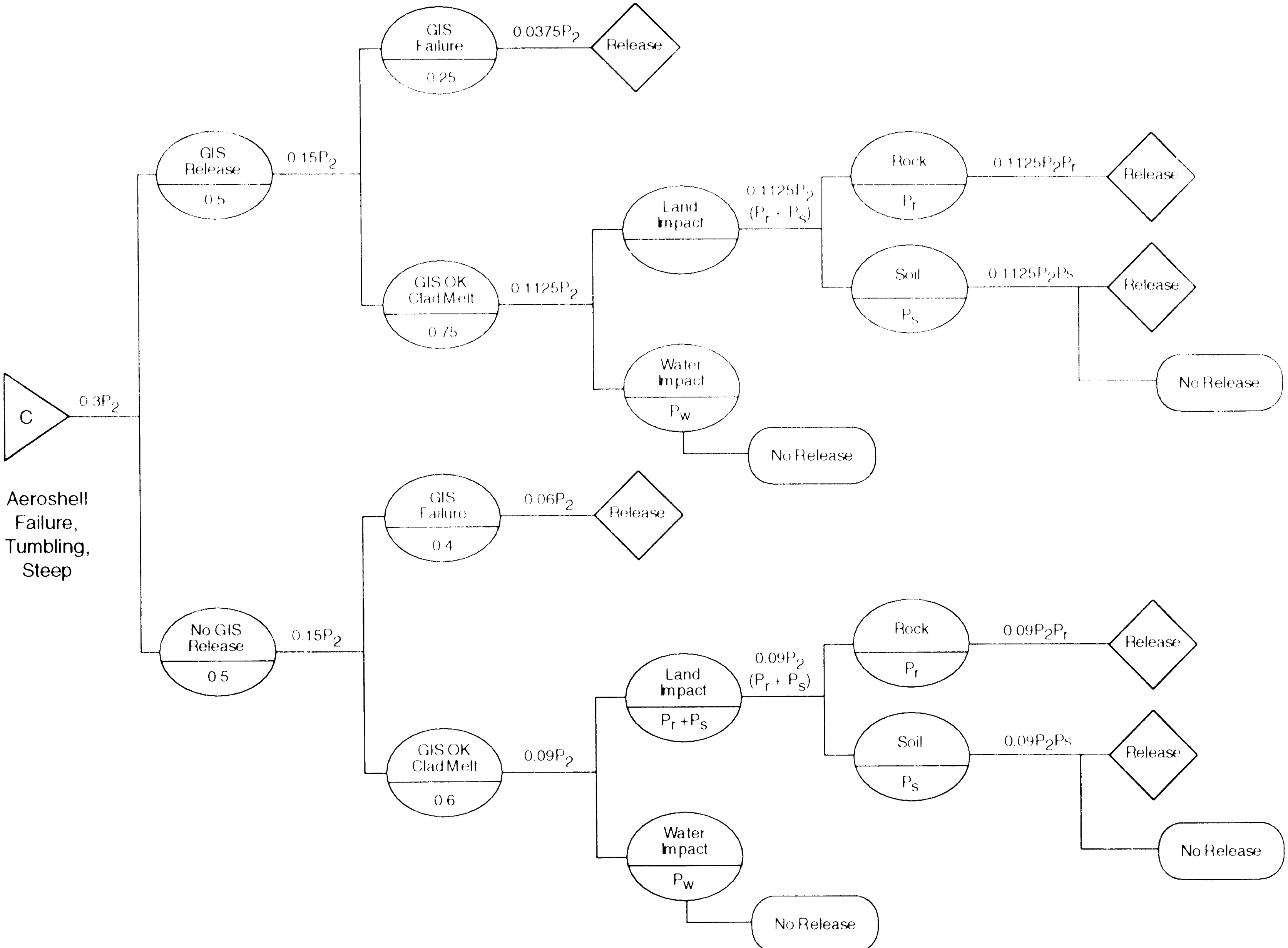
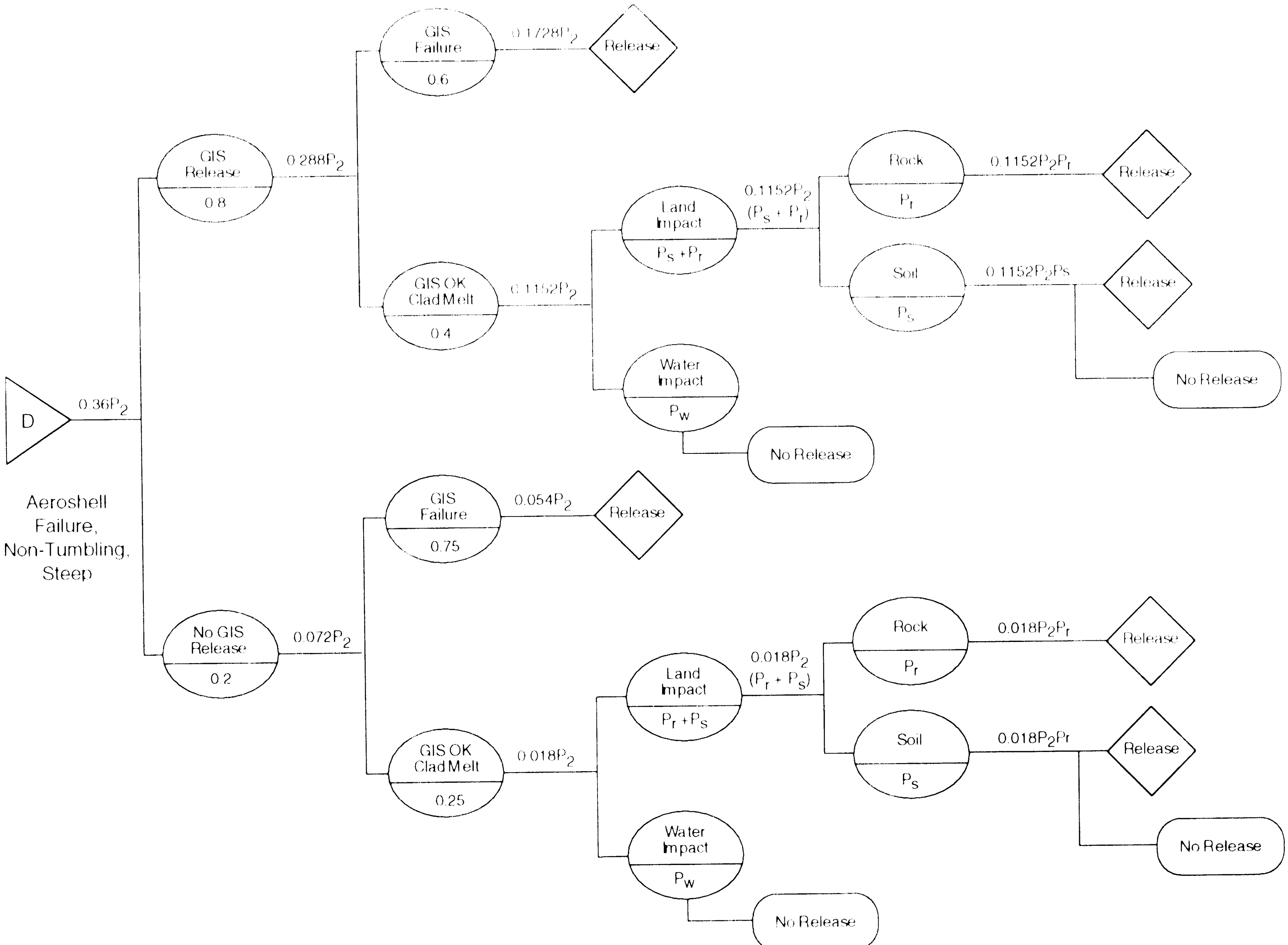


FIGURE B-10. FAILURE/ABORT SEQUENCE TREES FOR VVEJGA INADVERTENT REENTRY (Page 3 of 5)



Source: Martin Marietta Astro Space 1994a

FIGURE B-10. FAILURE/ABORT SEQUENCE TREES FOR VVEJGA INADVERTENT REENTRY (Page 4 of 5)



Source: Martin Marietta Astro Space 1994a

FIGURE B-10. FAILURE/ABORT SEQUENCE TREES FOR VVEJGA INADVERTENT REENTRY (Page 5 of 5)

on 6 degree-of-freedom (6 DOF) motion studies done for the Galileo VEEGA inadvertent reentry conditions (Halliburton NUS 1 994a). A preliminary 6 DOF analyses for the VVEJGA reentry has confirmed the validity of the Galileo results. For the reentry response, the non-tumbling cases have been analyzed as module broadface stable motion. This is considered a conservative approach in that any motion other than the broadface stable would result in lower reentry heating fluxes.

- The potential for ablation of the graphitic components (modules and GISS) due to the reentry heating environment has been the focus of the VVEJGA inadvertent reentry analyses performed to date. The response of intact GISs to VVEJGA reentry conditions has been evaluated in a JPL-sponsored study undertaken by NASA-Ames Research Center and Foils Engineering (Foils Engineering 1993). The results indicated that for ablation due to reentry heating only, GIS burn-through is predicted at reentry angles less than 15 degrees for stable (non-tumbling and non-spinning) GIS configuration. No burn-through was predicted for the spinning GIS configuration, considered in the JPL-sponsored study to have a much higher probability than the stable GIS configuration. However, the probabilities assigned to branching fractions associated with module and GIS failure are higher than that predicted due to reentry heating only, in order to account for structural failures induced by thermal and mechanical stresses under the severe force- and thermal-gradients that would be experienced during the deceleration process to terminal velocity. These types of failures would tend to be more probable under steep-reentry angle conditions. The associated probability trends have been reflected in the FASTs. Based on the best available information (i.e., ablation due to reentry heating only), the increased probability associated with structural failure can be considered to be conservative with respect to consideration of thermal heating only. Structural analyses will be performed as part of the Final Safety Analysis Report (FSAR)-related work.

- The conditional probabilities for a VVEJGA shallow-angle reentry (P_1), and steep-angle reentry (P_2), depend on the Earth-Gravity-Assist entry-angle probability distribution given in Table B-2.

- The conditional probabilities of impacting rock (P_r), soil (P_s), and water (P_w) also presented in Table B-2 depend on the reentry latitude probability distribution show in Figure B-4.

Table B-3 summarizes the inadvertent reentry fuel end state conditional probabilities. The four fuel end states are correlated to the appropriate branching FAST in Figure B-10.

B.2.2 Source Term Calculation

The source term calculations treat the modules independently except with respect to steep and shallow reentry (i.e., all reenter at steep angles or all reenter at shallow

TABLE B-2. SURFACE IMPACT PROBABILITIES FOR SHORT-TERM INADVERTENT REENTRIES

Mission	Reentry Type	Conditional Probabilities					Population Density,[b] persons/km^2 (persons/mi^2)
		Reentry	Water (P_w)	Land	Rock (P_r)	Soil (P_s)	
Primary	Shallow, P_1	0.25	0.749	0.251	0.040	0.211	36.5 (95)
	Steep, P_2	0.75	0.749	0.251	0.040	0.211	36.5 (95)
Backup E1[c]	Shallow, P_1	0.11	0.727	0.273	0.0476	0.225	44.7 (115.8)
	Steep, P_2	0.89	0.727	0.273	0.0476	0.225	44.7 (115.8)
Backup E2[d]	Shallow, P_1	0.54	0.735	0.265	0.0244	0.241	55.6 (144.0)
	Steep, P_2	0.46	0.735	0.265	0.0244	0.241	55.6 (144.0)

Source: Halliburton NUS 1994a

a. Conditional VVEJGA short-term inadvertent reentry probability: 7.6×10^{7}.
b. Population density given land impact based on 1990 population data (Halliburton NUS 1992).
c. Backup E1 conditional short-term inadvertent reentry probability: 1.9×10^{7}.
d. Backup E2 conditional short-term inadvertent reentry probability: 2.8×10^{7}.

TABLE B-3. SUMMARY OF EGA INADVERTENT REENTRY FUEL END STATE CONDITIONAL PROBABILITIES

Fuel End State	FAST Branches Contributing	Shallow		Steep	
		FAST	Probability	FAST	Probability
Intact Modules (Undamaged)	GPHS Tumbling/No Aeroshell Failure	S/C Entry	0.45	S/C Entry	0.30
	Non-Tumbling/No Aeroshell Failure	S/C Entry	0.04	S/C Entry	0.04
		Subtotal	0.49	Subtotal	0.34
Intact Modules (Damaged/GISs Intact)	GPHS Tumbling/Aeroshell Failure	A			
	No GIS Release/GIS OK, Clad Melt		0.0945	C	0.090
	GPHS Non-Tumbling/Aeroshell Failure	B			
	No GIS Release/GIS OK, Clad Melt		0.0072	D	0.018
		Subtotal	0.1017	Subtotal	0.108
Intact GISs	GPHS Tumbling/Aeroshell Failure	A		C	0.1125
	GIS Release/GIS OK, Clad Melt		0.0405		
	GPHS Non-Tumbling/Aeroshell Failure	B		D	0.1125
	GIS Release/GIS OK, Clad Melt		0.0324		
		Subtotal	0.0729	Subtotal	0.2277
Bare Fuel	GPHS Tumbling/Aeroshell Failure	A			
	GIS Release/GIS Failure	A	0.0045	C	0.0375
	No GIS Release/GIS Failure		0.0105	C	0.0600
	GPHS Non-Tumbling/Aeroshell Failure	B			
	GIS Release/GIS Failure	B	0.2916	D	0.1728
	No GIS Release/GIS Failure		0.0288	D	0.0540
		Subtotal	0.3354	Subtotal	0.3243
		Total	1.0000	Total	1.0000

Source: Halliburton NUS 1994a

a. Shallow angle reentry conditional probability: P_1.
b. Steep angle reentry conditional probability: P_2.

angles). The expectation source term for each fuel end state is then determined as a probability-weighted average over all 54 modules.

Table B-4 presents an outline for source term calculation based on four fuel end states and the Earth surface impact conditional probabilities for both VVEJGA and VEEGA inadvertent reentries.

B.2.3. Results of the Radiological Consequences Based on the Fuel End States

Given the inadvertent reentry type (i.e., shallow or steep), the reentry latitude, and surface impact probabilities, radiological consequences were estimated for the fuel end states. Tables B-5, B-6, and B-7 summarize the results of the specific source term contributor (i.e., fuel end state) and the resulting radiological consequences for the VVEJGA and VEEGA inadvertent reentries.

TABLE B-4. EGA INADVERTENT REENTRY SOURCE TERM CALCULATION OUTLINE

Fuel -End State	Shallow: Number of Components	Shallow: Source Term, Ci[a]	Steep: Number of Components	Steep: Source Term, Ci[a]
Intact Module	$N_m = (0.49)\ (54) = 26.5$		$N_m = (0.34)\ (54) = 18.4$	
Rock Impact	N_mP_r	$0.25Q_mN_mP_r$	N_mP_r	$0.25Q_mN_mP_r$
Soil Impact	N_mP_s	-	N_mP_s	-
Water Impact	N_mP_w	-	N_mP_w	-
Intact Module (Damaged/ GIS Intact)	$N_{dm} = (0.1017)\ (54) = 5.5$		Ndm = (0.108) (54) = 5.8	
Rock Impact	$N_{dm}P_r$	$Q_mN_{dm}P_r$	$N_{dm}P_r$	$Q_mN_{dm}P_r$
Soil Impact	$N_{dm}P_s$	$0.25Q_mN_{dm}P_s$	$N_{dm}P_s$	$0.25Q_mN_{dm}P_s$
Water Impact	$N_{dm}P_w$	-	$N_{dm}P_w$	-
Intact GISs	$N_g = (0.0729)\ (108) = 7.9$		Ng = (0.2277) (108) = 24.6	
Rock Impact	N_gP_r	$Q_gN_gP_r$	N_gP_r	$Q_gN_gP_r$
Soil Impact	N_gP_s	$0.25Q_gN_gP_s$	N_gP_s	$0.25Q_gN_gP_s$
Water Impact	N_gP_w	-	N_gP_w	-
Fuel[b]	$F_f = 0.335$	Q_fF_f	$F_f = 0.324$	Q_fF_f

Source: Halliburton NUS 1994

a. Q_m = (132,920 Ci/RTG) / (18 modules/RTG) = 7,384 Ci/module.
   Q_g = (132,920 Ci/RTG) / (36 GISs/RTG) = 3,692 Ci/GIS.

b. F_f = Fraction of total fuel inventory.

TABLE B-5. RADIOLOGICAL CONSEQUENCES FOR VVEJGA INADVERTENT REENTRY
(Shallow and Steep Case)

Reentry Type	Source Term Contributor	Collective Dose, person-Sv (person-rem)[a]		Health Effects[b]		Maximum Individual Dose, Sv (rem)	Land Area, km^2 (mi^2) Above 7.4 x 10^3 Bq/m^2 (0.2 $\mu Ci/m^2$)
		w/o De Minimis	w De Minimis	w/o de Minimis	w de Minimis		
Shallow Reentry	Intact Components[c]	1.17 x 10^{1} (1.17 x 10^{3})	6.74 x 10^{0} (6.74 x 10^{2})	4.10 x 10^{-1}	2.36 x 10^{-1}	2.14 x 10^{-1} (2.14 x 10^{1})	1.02 x 10^{1} (3.94 x 10^{0})
	Mostly Vapor[d]	9.89 x 10^{4} (9.89 x 10^{6})	- -	3.46 x 10^{3}	-	3.51 x 10^{-5} (3.51 x 10^{-3})	- -
	Mostly Particulate[e]	3.49 x 10^{2} (3.49 x 10^{4})	2.01 x 10^{2} (2.01 x 10^{4})	1.22 x 10^{1}	7.04 x 10^{0}	2.78 x 10^{-3} (2.78 x 10^{-1})	5.33 x 10^{3} (2.06 x 10^{3})
	Total	9.93 x 10^{4} (9.96 x 10^{6})	2.08 x 10^{2} (2.08 x 10^{4})	3.48 x 10^{3}	7.28 x 10^{0}	2.14 x 10^{-1} (2.14 x 10^{1})	5.34 x 10^{3} (2.06 x 10^{3})
Steep Reentry	Intact Components	1.87 x 10^{1} (1.87 x 10^{3})	1.08 x 10^{1} (1.08 x 10^{3})	6.54 x 10^{-1}	3.78 x 10^{-1}	3.37 x 10^{-1} (3.37 x 10^{1})	1.63 x 10^{1} (6.29 x 10^{0})
	Mostly Vapor	5.41 x 10^{4} (5.41 x 10^{6})	- -	1.89 x 10^{3}	-	1.92 x 10^{-5} (1.92 x 10^{-3})	-
	Mostly Particulate	5.09 x 10^{2} (5.09 x 10^{4})	2.93 x 10^{2} (2.93 x 10^{4})	1.78 x 10^{1}	1.03 x 10^{1}	2.31 x 10^{-3} (2.31 x 10^{-1})	1.58 x 10^{3} (6.10 x 10^{2})
	Total	5.46 x 10^{4} (5.46 x 10^{6})	3.04 x 10^{2} (3.04 x 10^{4})	1.91 x 10^{3}	1.06 x 10^{1}	3.37 x 10^{-1} (3.37 x 10^{1})	1.60 x 10^{3} (6.18 x 10^{2})

Source: Halliburton NUS 1994a

a. The de minimis dose level for the purpose of this report is 1.0 x 10^{5} Sv (1.0 x 10^{-3} rem) per year.
b. Excess latent cancer fatalities.
c. Includes intact modules (damaged and undamaged) and GISs impacting rock and soil.
d. Fuel released at high altitude in particle sizes less than or equal to 10 microns in physical diameter.
e. Fuel released at high altitude in particle sizes greater than 10 microns in physical manner.

TABLE B-6. RADIOLOGICAL CONSEQUENCES FOR BACKUP E1 INADVERTENT REENTRY
(Shallow and Steep Case)

Reentry Type	Source Term Contributor	Collective Dose, person-Sv (person-rem)[a]		Health Effects[b]		Maximum Individual Dose, Sv (rem)	Land Area, km^2 (mi^2) Above 7.4×10^{3} Bq/m^2 (0.2 $\mu Ci/m^2$)
		w/o De Minimis	w De Minimis	w/o de Minimis	w de Minimis		
Shallow Reentry	Intact Components[c]	1.70×10^{1} (1.70×10^{3})	9.79×10^{0} (9.79×10^{2})	5.95×10^{-1}	3.43×10^{-1}	2.61×10^{-1} (2.61×10^{1})	1.16×10^{1} (4.48×10^{0})
	Mostly Vapor[d]	1.24×10^{5} (1.24×10^{7})	- -	4.34×10^{3}	-	3.41×10^{-5} (3.41×10^{-3})	- -
	Mostly Particulate[e]	4.90×10^{2} (4.90×10^{4})	2.82×10^{2} (2.82×10^{4})	1.72×10^{1}	9.87×10^{0}	3.01×10^{-3} (3.01×10^{-1})	5.70×10^{3} (2.20×10^{3})
	Total	1.25×10^{5} (1.25×10^{7})	2.92×10^{2} (2.92×10^{4})	4.38×10^{3}	1.02×10^{1}	2.61×10^{-1} (2.61×10^{1})	5.71×10^{3} (2.20×10^{3})
Steep Reentry	Intact Components	2.71×10^{1} (2.71×10^{3})	1.56×10^{1} (1.56×10^{3})	9.49×10^{-1}	5.46×10^{-1}	5.03×10^{-1} (5.03×10^{1})	1.85×10^{1} (7.14×10^{0})
	Mostly Vapor	6.32×10^{4} (6.32×10^{6})	- -	2.21×10^{3}	-	1.74×10^{-5} (1.74×10^{-3})	- -
	Mostly Particulate	7.27×10^{2} (7.27×10^{4})	4.18×10^{2} (4.18×10^{4})	2.54×10^{1}	1.46×10^{1}	2.89×10^{-3} (2.89×10^{-1})	1.52×10^{3} (5.87×10^{2})
	Total	6.40×10^{4} (6.40×10^{6})	4.34×10^{2} (4.34×10^{4})	2.24×10^{3}	1.52×10^{1}	5.03×10^{-1} (5.03×10^{1})	1.54×10^{3} (5.95×10^{2})

Source: Halliburton NUS 1994a

a. The de minimis dose level for the purpose of this report is 1.0×10^{5} Sv (1.0×10^{-3} rem) per year.
b. Incremental latent cancer fatalities.
c. Includes intact modules (damaged and undamaged) and GISs impacting rock and soil.
d. Fuel released at high altitude in particle sizes less than or equal to 10 microns in physical diameter.
e. Fuel released at high altitude in particle sizes greater than 10 microns in physical manner.

TABLE B-7. RADIOLOGICAL CONSEQUENCES FOR BACKUP E2 INADVERTENT REENTRY
(Shallow and Steep Case)

Reentry Type	Source Term Contributor	Collective Dose, person-Sv (person-rem)[a]		Health Effects[b]		Maximum Individual Dose, Sv (rem)	Land Area, km^2 (mi^2) Above 7.4×10^3 Bq/m^2 (0.2 $\mu Ci/m^2$)
		w/o De Minimis	w De Minimis	w/o de Minimis	w de Minimis		
Shallow Reentry	Intact Components[c]	1.61×10^{1} (1.61×10^{3})	9.27×10^{0} (9.27×10^{2})	5.64×10^{-1}	3.24×10^{-1}	3.25×10^{-1} (3.25×10^{1})	8.34×10^{0} (3.22×10^{0})
	Mostly Vapor[d]	1.52×10^{5} (1.52×10^{7})	- -	5.32×10^{3}	-	4.16×10^{-5} (4.16×10^{-3})	- -
	Mostly Particulate[e]	6.16×10^{2} (6.16×10^{4})	3.55×10^{2} (3.55×10^{4})	2.16×10^{1}	1.24×10^{1}	2.97×10^{-3} (2.97×10^{-1})	5.72×10^{3} (2.20×10^{3})
	Total	1.53×10^{5} (1.53×10^{7})	3.64×10^{2} (3.64 x104)	5.36×10^{3}	1.27×10^{1}	3.25×10^{-1} (3.25×10^{1})	5.73×10^{3} (2.21×10^{3})
Steep Reentry	Intact Components	2.78×10^{1} (2.78×10^{3})	1.60×10^{1} (1.60×10^{3})	9.73×10^{-1}	5.60×10^{-1}	3.90×10^{-1} (3.90×10^{1})	1.44×10^{1} (5.56×10^{0})
	Mostly Vapor	1.02×10^{7} (1.02×10^{7})	- -	3.57×10^{3}	-	2.81×10^{-5} (2.81×10^{-3})	- -
	Mostly Particulate	8.11×10^{2} (8.11×10^{4})	4.67×10^{2} (4.67×10^{4})	2.84×10^{1}	1.63×10^{1}	1.52×10^{-2} (1.52×10^{0})	2.25×10^{3} (8.69×10^{2})
	Total	1.03×10^{5} (1.03×10^{7})	4.83×10^{2} (4.83×10^{4})	3.60×10^{3}	1.69×10^{1}	3.90×10^{-1} (3.90×10^{1})	2.26×10^{3} (8.73×10^{2})

Source: Halliburton NUS 1994a

a. The de minimis dose level for the purpose of this report is 1.0×10^{5} Sv (1.0×10^{-3} rem) per year.
b. Incremental latent cancer fatalities.
c. Includes intact modules (damaged and undamaged) and GISs impacting rock and soil.
d. Fuel released at high altitude in particle sizes less than or equal to 10 microns in physical diameter.
e. Fuel released at high altitude in particle sizes greater than 10 microns in physical manner.

Executive Summary

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