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Probabilistic Analysis of the Inadvertent Reentry of the Cassini Spacecraft's Radioisotope Thermoelectric Generators

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As part of the launch approval process, the Interagency Nuclear Safety Review Panel provides an independent safety assessment of space missions—such as the Cassini mission—that carry a significant amount of nuclear materials. This survey article describes potential accident scenarios that might lead to release of fuel from an accidental reentry during an Earth swingby maneuver, the probabilities of such scenarios, and their consequences. To illustrate the nature of calculations used in this area, examples are presented of probabilistic models to obtain both the probability of scenario events and the resultant source terms of such scenarios. Because of large extrapolations from the current knowledge base, the analysis emphasizes treatment of uncertainties.

KEY WORDS: Probabilistic risk analysis; spacecraft reentry; uncertainty analysis; source terms

1. INTRODUCTION

Evaluation of the safety of space missions using radioactive materials may require extrapolation of the knowledge base to include new and severe reentry conditions, as was the case for the recent Cassini mission. Such extrapolations demand a thorough treatment of uncertainties in estimating the overall mission safety. The Cassini mission review and analyses[(1)] relied on both detailed and simplified models to assess the effects of uncertainties in heating and trajectory parameters on overall probabilities of release of radioactive fuel materials should there be a reentry during the Venus-Venus-Earth-Jupiter-gravity-assist (VVEJGA) swingby of Earth.

This article provides examples from that study to illustrate the methodology. The method embodied representation of significant scenarios during an inadvertent reentry, the probabilities of those scenarios, and their consequences. Consequences, discussed herein, are in terms of amount of fuel released from a radioisotope thermoelectric generator (RTG)[2] and the statistically estimated cancer fatalities in the world's population. The discussion emphasizes the importance of considering reasonable alternative scenarios, uncertainties in the probabilities, and uncertainties in the consequences. To illustrate the nature of calculations used in this area, examples are presented of probabilistic models to obtain both the probability of scenario events and the resultant source terms of such scenarios. This analysis was performed in support of the Interagency Nuclear Safety Review Panel, which is empaneled, as the need arises, to support the Executive Office of the President in deliberations regarding the nuclear safety of a mission involving radioactive materials.

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[2] One or more RTGs is used for outer planet and deep space exploration because at this time they are the only reliable, long-lived sources of electricity to power control systems, scientific instruments, and communications.

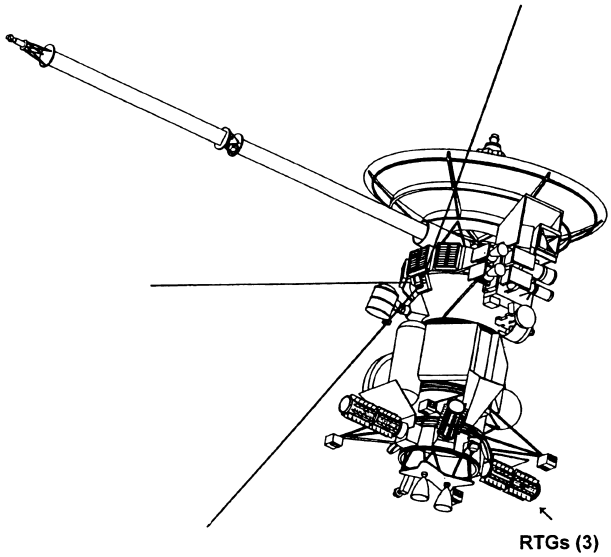

Fig. 1. Cassini spacecraft showing three RTGs.

2. APPROACH OVERVIEW

An event tree framework was used for this risk assessment to discover and analyze the spectrum of end states and consequences associated with variations in VVEJGA scenarios. Two or more scenarios have the same end state if they have a similar effect on the reentering RTG and its components. Consequences of interest are source terms (amount of fuel released, location of release, etc.) and collective population health effects over a 50-year period. Each scenario is depicted in an event tree as a set of discrete events, whose probabilities exhibit uncertainty. Consequences arising from the scenarios are also uncertain, and their calculation included uncertainty having to do with their natural stochastic processes and uncertainty having to do with our state-of-knowledge about the processes.

Review of Cassini reentry safety was greatly facilitated by the detailed analysis and computations described in the Cassini Final Safety Analysis Report.[2] Simplified models,[3] calibrated by comparison with the detailed models of the reference, were used to help understand and quantify uncertainties associated with the thermal and structural response of the RTG to reentry.

3. APPLICATION TO CASSINI VVEJGA ACCIDENT SCENARIOS

3.1. Introduction to the Spacecraft Configuration

Understanding the discussion of scenarios requires an overall familiarization of the configuration of the Cassini space vehicle (CSV) which carries three RTGs (Fig. 1). An RTG uses nuclear materials for the production of heat. As shown in Fig. 2, an RTG has an aluminum housing that contains (1) heat source modules of radioactive plutonium dioxide (PuO_2) surrounded by graphite, and (2) components needed for thermoelectric conversion of energy generated by decay of the radioactive PuO_2. An RTG is generally cylindrical with diameter of about 0.43 meters and length about 1.2 meters.

The radioactive material is contained within 18 graphite "bricks" called general purpose heat source (GPHS) modules. Each module contains about 600 grams of fuel and has roughly the dimensions of a stack of five plastic CD-ROM cases. As depicted in

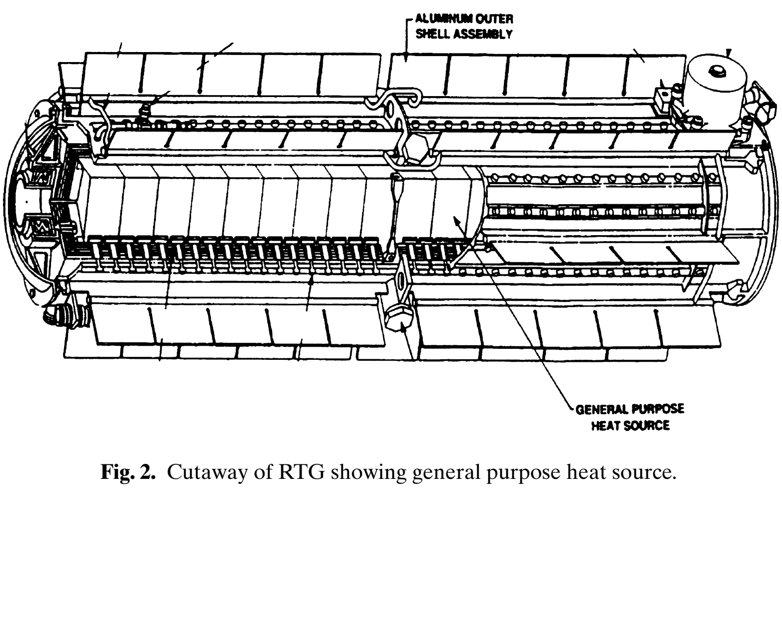

Fig. 2. Cutaway of RTG showing general purpose heat source.

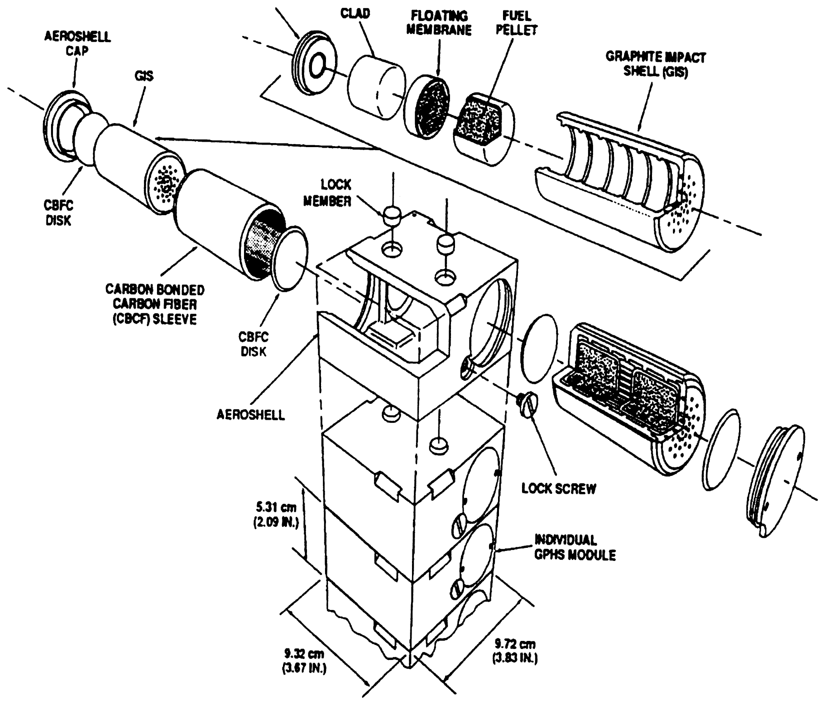

Fig. 3. Detail of GPHS module showing graphite impact shell and clad.

Fig. 3, the outer portion of the module is a graphite weave aeroshell. Within the aeroshell are two graphite impact shells (GISs). Within each GIS are two small (0.2 inch × 0.2 inch) iridium-clad fuel cylinders. Each cylinder contains about 151 grams of fuel about 71% (by weight) of which is Pu-238. The remainder is composed of other isotopes of plutonium including 239 through 242, other actinides, and oxygen (which is chemically bound to the heavy metal to form the plutonium dioxide).

3.2. Summary of Accident Progression

The path that the spacecraft takes to Saturn involves gravity-assist maneuvers via Venus, Earth, and Jupiter as shown in Fig. 4. The spacecraft design and trajectory protocol developed by Jet Propulsion Laboratory[4,5] has accounted for internal malfunctions and micrometeoroid impacts during the flight through the solar system and has designed recovery procedures to further reduce the likelihood that a mishap could accidentally cause the CSV to reenter the atmosphere during its flyby of Earth.

Should reentry occur, however, the spacecraft would essentially disintegrate from the extreme aerodynamic heating and stresses engendered by the very high spacecraft velocity (approximately 19 km/sec). The aluminum structures of the three RTGs are predicted to melt very early in the reentry and allow their 54 GPHS modules to be exposed directly to the sharply rising aerodynamic heating and aerostructural stresses. The graphite modules are designed to

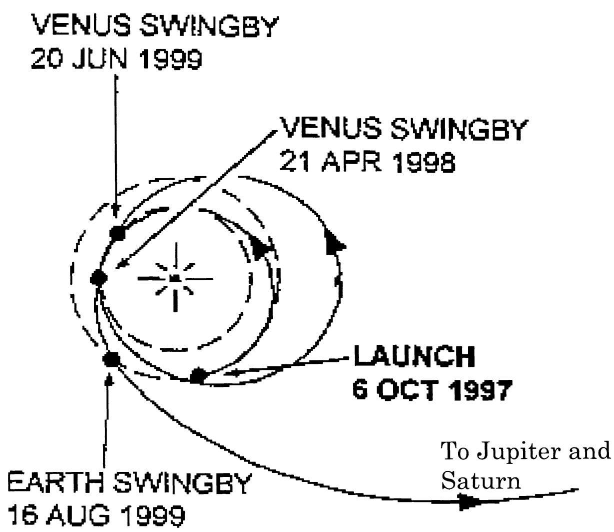

Fig. 4. Venus-Venus-Earth-Jupiter gravity-assist maneuvers.

protect the PuO_2 from standard orbital reentry environments. The key question is whether the design margin is sufficient to allow it to survive this nonstandard high speed reentry from a mishap during the VVEJGA maneuvers. Failure of the protective GPHS aeroshell would release the GISs, each of which contains two iridium-clad pellets of radioactive PuO_2.

Analysis of the response of these components was complicated by (1) the severe reentry conditions; (2) the predicted high temperatures possible for the reentry; (3) aerodynamic loads which were a factor of 10 higher than for a standard ballistic reentry from, for example, Earth orbit; (4) by uncertainties in the structural and thermal properties; and (5) modeling uncertainties in thermal response and ablation chemistry of the GPHS aeroshells and GISs. The survival was also found to be a function of the attitude and dynamics of the components during the heating phase. For example, a spinning GIS was less likely to fail than a stable, nonspinning GIS, because the material loss due to heating would be confined to one area in a nonspinning GIS.

Analyses[1,2] predicted that the GPHS modules would fail structurally for entry flight path angles steeper (more negative) than −16°. Such a failure would release the GISs into an environment where they would be exposed to severe loads and heating, possibly leading to failure. Failure of a GIS would allow direct aerodynamic heating on the iridium-clad fuel pellets. Reentry heating would cause clads to melt and much of the fuel would become small particles or vapor. Larger debris pieces, including whole GIS modules, clad fuel pellets, and pieces of the fuel from failed GISs would impact Earth, some on land and some in water.

3.3. Event Tree

An event tree (Fig. 5) was constructed to delineate reasonable variations of scenarios. Across the top of the event tree are the factors (or "events") that most influence the probability of and amount of fuel release. A synopsis of these events follows.

- *Spacecraft Reentry.* The initiating event is accidental reentry of the spacecraft. The dominant causal mechanism of this event is micrometeor impact on a part of the spacecraft, such as a tank, that can produce a change in velocity and direction. A change in vector that causes an intersection with the Earth is very

Yes → / No ↓	SpaceCraft Reentry	Steep Path Angle? (>16°)	FOS GPHS Orientation?	Aeroshell Failure at Altitude?	GIS Release?	SOS/ns or Near End On GIS Orientation?	GIS Failure at Altitude?	Clad Melt?	Terra Firma Impact?	End State	Nominal Sequence Frequency
		St	F	Af	Gr	So	Gf	M	T		
	9.5E-07	0.89	0.85	1.00	0.90	0.67	0.97			A	4.9E-07
							0.03	Assume clad melts	0.23	B	3.7E-09
						0.33	0.00			A	0.0E+00
			1				1.00	Assume clad melts	0.23	B	5.7E-08
					0.10	conservative assumption owing to lack of data				A	8.4E-08
				0.00					0.23	D	0.0E+00
			Non-FOS								
			0.15							Xfer to 1	
		Shallow									
Legend		0.11	0.85	0.62	0.90	0.67	0.00			A	0.0E+00
OI =	Ocean Impact						1.00	0.50	0.23	B	3.9E-09
A = At altitude release								0.50	0.23	C	3.9E-09
B = GIS impact on Terra Firma/						0.33	GIS intact until impact	0.50	0.23	B	1.9E-09
clad melt								0.50	0.23	C	1.9E-09
C = GIS impact on Terra Firma/					0.10		0.00			A	5.6E-09
clad OK				0.38					0.23	D	7.9E-09
D = GPHS impact on Terra Firma			0.15	If not FOS, then GPHS survives to impact					0.23	D	3.7E-09
_ _ _ _ = event not relevant											
			Total Air Release=		5.8E-07						
△ = point of transfer			*Total Land Release=*		8.4E-08						
			Total Ocean Impact =		2.9E-07						

Fig. 5. VVEJGA maneuver accident event tree. Across the top all the factors that most influence the probability of and amount of fuel release. See text for further descriptions.

unlikely. The mission designers at the Jet Propulsion Laboratory used probabilistic modeling of the spacecraft's path from Venus to Earth, in conjunction with a design policy of biasing the path so that most failures would cause the CSV to miss Earth. The mean estimated probability for the CSV to reenter the Earth's atmosphere during the flyby maneuver is less than 10^{-6}.[4,5]

- *Steep Path Angle?* The distinction between steep and shallow reentry path angles is defined as the demarcation between different aeroshell failure mechanisms. Reentry path angles designated as steep are characterized by aerostructural failure such that GISs tend to be released during the high heating portion of the trajectory. Reentry at shallow angles tend to be characterized by aerothermal ablation failure.
- *Face-on Stable (FOS) GPHS Orientation?* Reentering spacecraft can exhibit a variety of motions. However, rotational or tumbling motion would tend to be highly damped early in the trajectory, achieving a few revolutions per minute before the aeroshells would be released. Wind tunnel data indicates a weakly statically stable trim point at face-on stable.[1]
- *Aeroshell Failure At-altitude?* Calculations suggest that aerostructural failures occur early in the heat pulse, before peak thermal loading and temperature, for reentry path angles of approximately $-16°$ and steeper.[3] Therefore, there is essentially no uncertainty that structural failure would occur for both FOS and non-FOS orientations during steep reentry. However, for shallow reentry angles aeroshell failure is highly dependent on modeling assumptions. The effect of these alternative models was mathematically included in the uncertainty analysis that led to the probability estimates shown in Fig. 5.
- *GIS Release?* Data from ballistic reentry vehicles indicate that aeroshell thermostructural failure would likely lead to virtual disintegration of the aeroshell with little chance for GIS retention. Therefore, aeroshell breakup will lead to free-falling GISs as independent ballistic bodies.
- *Side-on Stable (SOS)/Not Spinning (ns) or Near End-on GIS Orientation?* Wind tunnel data and COSMOS data[6,7] indicate that GISs will exhibit two stable trim points with a preference for side-on stable.
- *At-Altitude GIS Failure?* Thermal ablation appears to be the only reasonable failure mode for the GISs. Similar to aeroshells, failure may or may not be calculated, depending on the modeling assumptions. The modeling uncertainties were included in developing the probability estimates. This is discussed further in the next section.
- *Clad Melt?* Fuel cladding was calculated to melt if GISs are exposed to the air stream following aeroshell failure.
- *Terra Firma Impact?* GIS and aeroshells may not be effective at preventing additional fuel release upon hitting the ground. Potential releases of fuel into large bodies of water were considered to be effectively isolated from people.[8]

Each scenario in Fig. 5 is associated with a probability of occurrence. The numbers shown in Fig. 5 are mean values of the underlying probability distributions for the event. The probability of each scenario, therefore, is a product of the branch point probabilities and the initiating reentry probability. Probabilities leading to the same end state are summed to obtain the total end state probability. For example, the total estimated probability of at-altitude releases is the sum of the probabilities of scenarios that end in end state A. The analysis indicates that the likelihood of an aeroshell surviving the reentry without releasing fuel is relatively small. Event tree framework allows visualization of alternative reentry scenarios, as well as calculation of uncertainty in the probability of occurrence of events.

4. EXAMPLE DEVELOPMENT OF MODEL UNCERTAINTIES USING A PARAMETRIC MODEL

It is not practical to include all models and equations of the study in this article. However, a typical situation in space nuclear power applications is that models are created by attempts to best interpret and characterize sparse data. An example is the calculation of the probability of GIS failure at altitude. In this situation, alternative hypotheses about heat transfer and ablation chemistry, during ablation of a GPHS module as it fell through the atmosphere, created a continuum of alternative models.

Apostolakis[9] proposed a formalism for the solution of an unconditional model of the world for a probabilistic model with parameter uncertainties and uncertainties in the model itself. From Equation (6) in Apostolakis[9] (p. 1361) we have

$$\bar{h}(A \mid H) = \sum_{i=1}^{n}\left[\int h_i(A \mid \theta_i, M_i, H)\pi_i (\theta_i \mid M_i, H)d\theta_i\right]p(M_i \mid H). \quad (1)$$

In Equation (1), $h_i(A \mid \theta_i, M_i, H)$ is the conditional probability distribution over event A, given parameter vector θ under assumptions M using all previous relevant knowledge, H. The distribution h_i is the solution of the ith conditional model of the world. The distribution $\pi_i(\theta_i \mid M_i, H)$ is the probability density function (PDF) over the parameter vector θ_i of the ith conditional model reflecting uncertainty in those parameters. The factor $p(M_i \mid H)$ is the analyst's probability about the accuracy of the ith set of assumptions (i.e., ith model). For this example, Equation (1) is modified such that M is treated as a continuous variable,

$$\bar{h}(A \mid H) = \int\left[\int h(A \mid \theta, M, H)\pi (\theta \mid M, H)d\theta\right]p(M \mid H)dM. \quad (2)$$

In many such situations of interest, the uncertainty in the parameters, θ, is much smaller than the uncertainty associated with the alternative model hypotheses. Therefore, $\pi(\theta \mid M, H)$ may be approximated as unity, leading to

$$\bar{h}(A \mid \theta, H) \cong \int h(A \mid \theta, M, H)p(M \mid H)dM. \quad (3)$$

In Equation (2), if it turns out that modeling uncertainty is small in comparison to parameter uncertainty, then the following approximation is valid:

$$\bar{h}(A \mid M, H) \cong \int h(A \mid \theta, M, H)\pi(\theta \mid M, H)d\theta. \quad (4)$$

An example of an ablating module during EGA reentry will be presented to illustrate use of Equation (3). By analogy, it should be obvious that the result shown below could be obtained using Equation (4) as well.

We are interested in the probability of aeroshell or GIS failure, owing to burnthrough, as a function of reentry angle, A_r. This is particularly important when attempting to calculate GIS ablation because sensitivity studies, using deterministic calculations of ablation during reentry, show that GIS failure depends on the hypothesized model used in the calculation. Alternative models stem from many alternative data sets associated with (1) total heat transfer into and out of the GIS or aeroshell, and (2) carbon ablation chemistry. A heat transfer factor, H_F, was defined in order to span the range of effects of alternative heat transfer models. The factor is multiplicative on the deterministic heat transfer calculational results and is normalized such that the "best estimate" is unity. Sensitivity studies allowed development of a PDF of the heat transfer factor, $p(H_F)$ which is presented in Fig. 6.

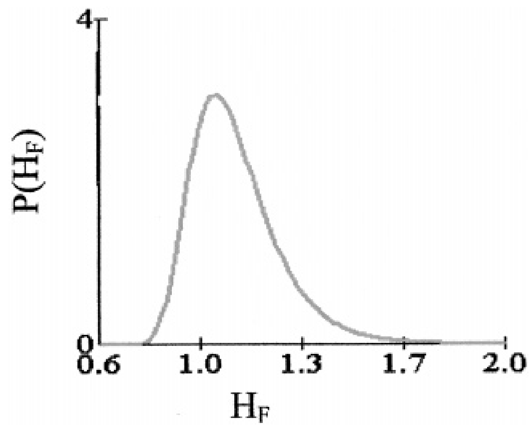

Fig. 6. Representation of heat transfer model uncertainty as the parameter H_F.

Uncertainty in calculated graphite ablation arises from thermochemical properties, particularly the carbon species vapor pressure, and other properties that determine carbon species chemical enthalpies. In addition, carbon mechanical erosion is also a possible ablation enhancement mechanism. A "chemistry factor" (C_F) was defined such that the nominal "best estimate" calculation is represented by $C_F = 1$. Again sensitivity studies, combined with alternative chemistry models from the literature, allow development of a PDF of the chemistry factor, $p(C_F)$. The probability of GIS or aeroshell failure, therefore, can be expressed as $f_G(A_r \mid H_F, C_F)$, which is the conditional probability of GIS failure for reentry angle A_r given the joint occurrence of H_F and C_F.

For each A_r and H_F/C_F combination of interest, a stagnation point ablation calculation on the face of the GIS or aeroshell estimated whether the wall recession (i.e., ablation) was greater than or equal to the original wall thickness. In this way, a response surface for f_G was developed in which the elements were either one, if recession was greater than or equal to the original wall thickness, or zero, if not.

If the probability f_G were to depend only on one of the models (e.g., heat transfer and not chemistry) then the analogy to Equation (3) would be obvious with $h(A \mid \theta, M) = f_G(A_r \mid H_F)$ and $p(M) = p(H_F)$. However, we note that H_F and C_F are independent, as are their PDFs. Therefore, a straightforward extension of the formalism of Equation (3) is possible. For a particular GIS orientation, there obtains

$$f_G(A_r) \cong \iint f_G(A_r \mid H_F, C_F)p(H_F)p(C_F)dC_F dH_F \quad (5)$$

In essence, we have expressed modeling uncertainties in heat transfer and ablation chemistry as parameter uncertainties in the factors H_F and C_F. Recognizing the similarity of form of Equations (3) and (4) it is apparent that Equation (5) would also result from the use of Equation (4) as a starting point.

The solution was done numerically using discretized probability distributions for H_F and C_F with a discretized response surface. An example result is $f_G(-16° < A_r < -90°) = 0.97$ for the side-on stable nonspinning orientation.

5. EXAMPLE SOURCE TERM CALCULATIONS

Each end state is associated with consequences. The consequences described in this article are source terms and collective cancer fatalities over 50 years. Source terms were calculated as a progression of the disassembly of a module. The following quantities were obtained:[1]

- Number of GPHS modules failed in air and as a result of ground impact
- Number of GISs failed in air and as a result of ground impact
- Amount of fuel released in air
- Amount of fuel particles less than 10 microns released in air and as a result of ground impact
- Amount of Plutonium that is released in air, continues on a ballistic trajectory to land, and becomes small particles upon impact.

The results of each quantity are expressed as a family of complementary cumulative distribution functions that reflects the analyzed uncertainties. Because there were 54 modules and 2 GISs per module in the original three RTGs aboard Cassini, and because, once released, modules act independently to a reasonably good approximation, simple binomial models may be used as illustrated in the following sections.

5.1. Number of Module Failures In Air

A typical binomial model is the number of module failures in air, N_S, which is a function of the total number of modules available for failure during a specific reentry. Reentry angle, A_r, module orientation, O, and the probability of failure of an individual module, $P_S(A_r, O)$, characterize each reentry. Module orientation and reentry angle are also treated as random variables with probabilities P_O and P_A, respectively. For a particular orientation and reentry angle,

$$N_S = \mathbf{B}[N_M, P_A \cdot P_O \cdot P_S(A_r, O)], \quad (6)$$

Where **B[ ]** denotes a binomial distribution, N_M is the total number of binomial trials which corresponds to the total number of modules (54) on the CSV. The second term in the bracket is the probability of aeroshell failure per trial for a particular reentry angle and orientation.

5.2. Number of GIS Failures in Air

Because GISs are inside of modules, the number of GIS failures in air, N_G, depends on the previously calculated number of module failures, as depends on the reentry scenario and is binomially distributed as follows:

$$N_G = \mathbf{B}[N_{GM} \cdot N_S, P_{GO} \cdot P_{GR} \cdot f_G] \quad (7)$$

where, $N_{GM} = 2$, the number of GIS in a module, N_S is given by Equation (6), P_{GO} is the probability of a GIS orientation (e.g., side-on stable not spinning), P_{GR} is the probability of GIS release from the module given a module failure, and f_G is the probability of an individual GIS failure for a particular reentry angle and orientation as given by Equation (5). P_{GO} has a mean value shown in Fig. 5 of 0.67 for side-on stable nonspinning orientation. Similarly, Fig. 5 shows that the mean value of P_{GR} is 0.9. The quantities P_{GO}, P_{GR}, and f_G were needed both in the calculation of the scenario probabilities and in the source term estimation.

5.3. In-Air Source Term

The amount of fuel released of respirable size (less than 10 microns) from a single GIS that failed at altitude has been calculated.[2] The method was to determine the amount of fuel that would melt owing to aerodynamic heating. A stable droplet size of molten fuel was calculated assuming a Weber number of 2. There is some uncertainty associated with the estimation of the stable droplet size, which centers on the selection of the Weber number of 2. This Weber number is appropriate for benign, low velocity, conditions such as would be found in a stream from a garden hose. At the conditions of GIS failure

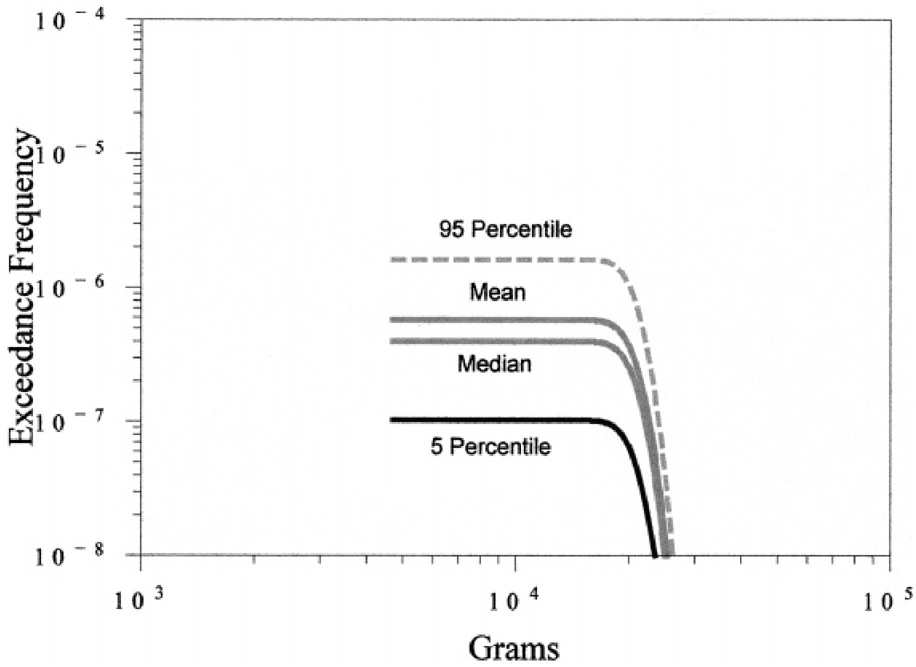

Fig. 7. Estimated VVEJGA maneuver source term in grams of PuO_2 fuel.

(i.e., velocity in the thousands of feet per second) higher Weber numbers would apply and catastrophic instabilities would occur in the molten fuel layer. Extremely small microspheres (i.e., less than 10 microns) would occur directly from the molten fuel layer exposure to the wind stream. Additional heating would not be necessary for this high velocity phenomenon to produce microspheres in the respirable range. Therefore, for a failed module and GIS during a steep angle of reentry, the range of fuel released is approximately 43% to 100% of its inventory, where the lower bound corresponds to the estimate for a Weber number of 2.

5.4. Source Term Results

Figure 7 presents results for the total amount of fuel released into the atmosphere. The separation of the curves along the *y*-axis derives primarily from the uncertainty in scenario frequency. The variation in results along the *x*-axis derives from the source term parameters and models. Figure 8 compares the amount of small particles (i.e., less than 10 microns) released into the atmosphere and initially suspended in air, with those that result from the initial deposit of fuel on the ground owing to the continued ballistic trajectory of the modules and GISs. The differences in the curves relates to the effectiveness of aerodynamic thermal effects in breaking up the modules and dispersing the fuel in the atmosphere.

6. COLLECTIVE CANCER FATALITY ESTIMATES

The amount of small particle PuO_2 released in air was calculated as contributing to worldwide collective dose over a 50-year period. Because of the large dilution of such releases over the globe, there is a distinct likelihood of no health effects from this accident. However, the traditional way of conservatively estimating the statistical possibility of health effects is to hypothesize linearity in the dose to health effects relationship down to essentially zero doses. Making this hypothesis and distributing the source term uniformly over the world, the source term (in curies) may be converted, by use of simple conversion factors, to health effects in terms of statistical occurrences of latent cancers over a 50-year period.[1]

These estimates are subject to uncertainty associated with variations among the population within the database with respect to intake factors, pathway factors, and human susceptibility. The primary uncertainty, however, associated with estimating collective dose (in person-rem) using a worldwide model is the

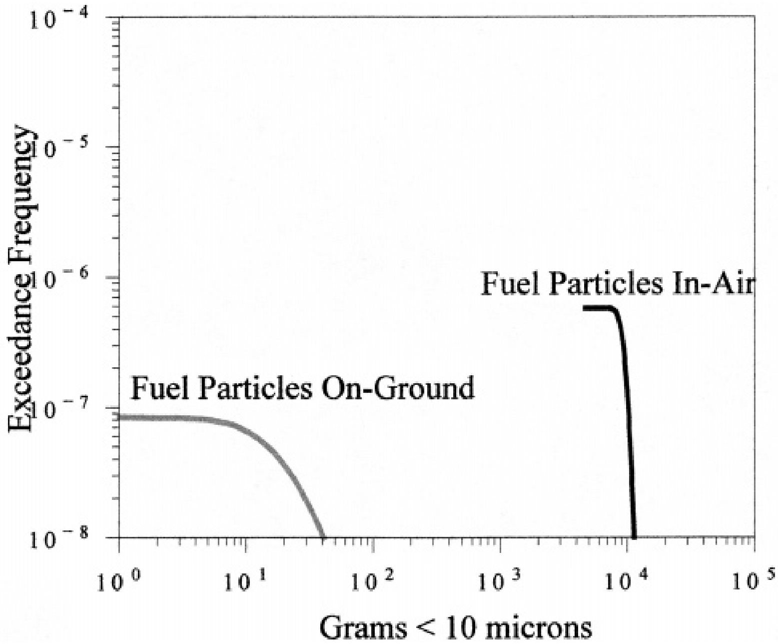

Fig. 8. Comparison of airborne versus ground deposited PuO_2 fuel.

population density itself.[1] Figure 9 shows the results, which are dominated by the material that is suspended in air. The most visible manifestation of uncertainty is associated with the initiating event frequency. This is largely responsible for the different confidence levels among the risk curves.

The amount of small particle plutonium that is initially deposited on the ground is calculated as contributing to a very localized dose to a few individuals who are postulated to be in the vicinity over a 50-year period. Because of the very small contribution of fuel that initially resides on the ground relative to fuel ini-

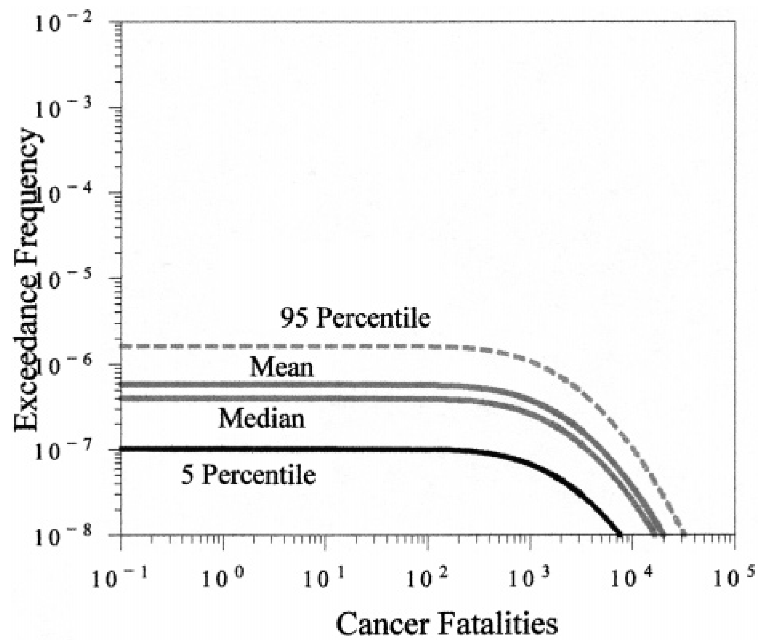

Fig. 9. Estimated VVEJGA health effects.

tially suspended in air, as illustrated in Fig. 8, the contribution of fuel initially deposited on the ground is not noticeable on the scale of this chart.

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