CONDUCT AND RESULTS OF THE INTERAGENCY NUCLEAR SAFETY REVIEW PANEL'S EVALUATION OF THE ULYSSES SPACE MISSION

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Abstract

The recent 6 October 1990 launch and deployment of the nuclear-powered Ulysses spacecraft from the Space Shuttle *Discovery* culminated an extensive safety review and evaluation effort by the Interagency Nuclear Safety Review Panel (INSRP). After more than a year of detailed independent review, study, and analysis, the INSRP prepared a Safety Evaluation Report (SER) on the Ulysses mission, in accordance with Presidential Directive/National Security Council memorandum 25. The SER, which included a review of the Ulysses Final Safety Analysis Report (FSAR) and an independent characterization of the mission risks, was used by the National Aeronautics and Space Administration (NASA) in its decision to request launch approval as well as by the Executive Office of the President in arriving at a launch decision based on risk-benefit considerations. This paper provides an overview of the Ulysses mission and the conduct as well as the results of the INSRP evaluation. While the mission risk determined by the INSRP in the SER was higher than that characterized by the Ulysses project in the FSAR, both reports indicated that the radiological risks were relatively small. In the final analysis, the SER proved to be supportive of a positive launch decision. The INSRP evaluation process has demonstrated its effectiveness numerous times since the 1960s. In every case, it has provided the essential ingredients and perspective to permit an informed launch decision at the highest level of our Government.

INTRODUCTION

An extensive flight safety review is required, per Presidential Directive (The White House, 1977), each time the United States plans to launch a spacecraft using a nuclear power source. The review, which culminates in an independent evaluation of the radiological risk of the mission by an Interagency Nuclear Safety Review Panel (INSRP), is documented in a Safety Evaluation Report (SER). The SER then serves as a key element in the Presidential risk-benefit launch decision. The U.S. flight safety review and launch approval process for nuclear-powered space missions, described by Sholtis et al. (1990), was applied to the Ulysses mission during the period September 1989 to September 1990.

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THE ULYSSES MISSION AND NUCLEAR POWER SYSTEM

The Ulysses mission is a joint endeavor of the European Space Agency and the National Aeronautics and Space Administration (NASA) to study the sun and its polar regions. The mission began with a daytime launch of the spacecraft aboard the Space Shuttle *Discovery* from the Kennedy Space Center, Florida, on 6 October 1990. Shortly after being deployed from the Space Shuttle Orbiter, a two-stage Inertial Upper Stage (IUS) booster and a Payload Assist Module-Special Class booster propelled the spacecraft from an Earth parking orbit into an escape trajectory toward Jupiter. The transit time for the spacecraft to arrive at Jupiter is approximately 1 year and 4 months. Near Jupiter, the spacecraft will receive a gravity assist that will propel the spacecraft into a solar orbit that descends out of the ecliptic plane of the solar system. The trajectory will carry the spacecraft past the South Pole of the Sun during May-September 1994 and over the North Pole of the Sun 1 year later. Although the mission officially ends in September 1995, the spacecraft will remain in an elliptical orbit about the Sun with a perihelion of approximately 1.3 astronomical units (AU) and an aphelion of about 5.0 AU.

Because the Ulysses mission involves a Jupiter flyby, solar power was not practicable and a nuclear power system was selected. Specifically, a single General Purpose Heat Source Radioisotope Thermoelectric Generator (GPHS-RTG), containing approximately 11kg of plutonium-238 oxide, provides the prime source of electric power for the Ulysses mission. The quantity of radioactive material contained in this GPHS-RTG necessitated an independent evaluation of the radiological risk of the Ulysses mission by the INSRP.

THE INSRP REVIEW

The scope of the INSRP review included consideration of accidents that could potentially result in the release of plutonium fuel into the environment during prelaunch operations, launch, ascent, on-orbit deployment, orbit insertion, and the Earth escape trajectory. To fulfill its responsibility, the INSRP and its five subpanels first reviewed the body of pertinent safety analysis reports and test data. The Ulysses Final Safety Analysis Report, or FSAR, (GE, 1990) served as the prime input for the INSRP review. Based on this review, specific areas were identified for further study. The INSRP then conducted independent analyses. Those efforts resulted in the resolution of many issues, but some remained and were deemed to require alternative treatment. Those remaining issues were treated by the INSRP through the development and use of alternative assumptions, models, or interpretation of data. These alternative positions were then incorporated into the various computer codes and calculational routines as modifications. Finally, baseline and sensitivity calculations were conducted to determine the collective effect of the modifications made.

In all, the INSRP analyzed 19 accidents associated with the Ulysses mission, each of which had the potential for fuel release to the environment. Of those 19 accidents, 11 were retained by the INSRP as "key" accidents for subsequent meteorological dispersion, health effects, and risk analysis. The eight accidents dropped from further consideration either had extremely small ($\lesssim$2mg) to no projected fuel releases to the environment or their overall probability of fuel release was extremely small ($\lesssim 10^{-9}$).

For the 11 key accidents carried through the complete analysis, two separate source terms were used--one representing an average fuel release amount and the other representing a fuel release amount characteristic of the tail of the fuel release distribution. This latter source term, labeled the "average of the top 5-percent source term," was obtained by averaging all of the fuel releases above the 95th percentile from each of the accident fuel release distributions. A summary of the fuel release data obtained for the average source terms and the average of the top 5-percent source terms, by accident type (e.g., random solid rocket booster, SRB, failure) and by mission elapsed time (MET), is provided in Tables 1 and 2, respectively (INSRP, 1990).

TABLE 1. **SUMMARY OF FUEL RELEASES FOR KEY ACCIDENT SCENARIOS (AVERAGE SOURCE TERMS).**

Phase	MET	Accident Type	Probability of Initiating Event	Conditional Probability of Fuel Release	Aggregate Fuel Release Probability	Source Terms		Release Phenomena
						Grams	Curies	
0	T-6 hr to T=0	On-Pad External Tank Explosion	2.9×10^{-3}	3.0×10^{-3}	8.6×10^{-6}	0.08 Ground	1.0	Coagulation and Plume Transport Aloft
1	0–2 sec	Tipover/Tower Impact	1.9×10^{-4}	4.4×10^{-3}	8.3×10^{-7}	0.06 Ground	0.8	Coagulation and Plume Transport Aloft
1	0–10 sec	Near-Pad External Tank Explosion	1.2×10^{-3}	2.4×10^{-3}	2.9×10^{-6}	0.1 Ground	1.2	Coagulation and Plume Transport Aloft
1	0–10 sec	Near-Pad SRB Random Failure (Air/Ground Release)	1.5×10^{-3}	3.6×10^{-3}	5.2×10^{-6}	2.0 Air 4.3 Ground	24 50	Air: Vaporization, Coagulation, & Plume Transport Aloft. Ground: Coagulation; 4-Meter Puff 2 Meters Off the Ground
1	0–10 sec	Near-Pad SRB Random Failure (Ground Release Only)	1.5×10^{-3}	3.0×10^{-2}	4.5×10^{-5}	1.9 Ground	23	Coagulation; 4-Meter Puff 2 Meters Off the Ground
1	10–20 sec	Early Ascent SRB Random Failure (Air/Ground Release)	3.7×10^{-4}	3.8×10^{-3}	1.4×10^{-6}	1.4 Air 2.5 Ground	16 30	Air: Vaporization, Coagulation, & Plume Transport Aloft. Ground: 4-Meter Puff 2 Meters Off the Ground
1	10–20 sec	Early Ascent SRB Random Failure (Ground Release Only)	3.7×10^{-4}	4.6×10^{-3}	1.7×10^{-6}	8.5 Ground	100	Coagulation; 4-Meter Puff 2 Meters Off the Ground
1	20–57 sec	Early, Mid-Ascent SRB Random Failure	5.7×10^{-4}	2.8×10^{-3}	1.6×10^{-6}	1.2 Air 0.05 Ground	14 0.6	Air: Plume Transport Aloft. Ground: 4-Meter Puff 2 Meters Off the Ground
1	57–105 sec	Late, Mid-Ascent SRB Random Failure	3.6×10^{-4}	4.2×10^{-3}	1.5×10^{-6}	6.0 Air	72	Worldwide Transport Aloft
1	105–120 sec	Late Ascent SRB Random Failure	1.7×10^{-4}	2.1×10^{-2}	3.6×10^{-6}	23.7 Air	280	Worldwide Transport Aloft
2, 3, or 4	120 sec til IUS Burns Complete	Inadvertent Reentry and Land Impact	1.7×10^{-3} †	3.6×10^{-1}	6.2×10^{-4}	0.032 Ground (Rock)	0.4	4-Meter Puff 2 Meters Off the Ground

† Includes the probability of an inadvertent reentry and, given reentry, that the GPHS modules hit land.

TABLE 2. **SUMMARY OF FUEL RELEASES FOR KEY ACCIDENT SCENARIOS (AVERAGE OF THE TOP 5 % SOURCE TERMS).**

Phase	MET	Accident Type	Probability of Initiating Event	Conditional Probability of Fuel Release	Aggregate Fuel Release Probability	Source Terms		Release Phenomena
						Grams	Curies	
0	T-6 hr to T=0	On-Pad External Tank Explosion	2.9×10^{-3}	1.5×10^{-4}	4.4×10^{-7}	0.23 Ground	2.7	Coagulation and Plume Transport Aloft
1	0–2 sec	Tipover/Tower Impact	1.9×10^{-4}	2.2×10^{-4}	4.2×10^{-8}	0.24 Ground	2.8	Coagulation and Plume Transport Aloft
1	0–10 sec	Near-Pad External Tank Explosion	1.2×10^{-3}	1.3×10^{-4}	1.5×10^{-7}	0.32 Ground	3.8	Coagulation and Plume Transport Aloft
1	0–10 sec	Near-Pad SRB Random Failure (Air/Ground Release)	1.5×10^{-3}	1.7×10^{-4}	2.6×10^{-7}	32.1 Air 28.1 Ground	380 330	Air: Vaporization, Coagulation, & Plume Transport Aloft. Ground: 4-Meter Puff 2 Meters Off the Ground
1	0–10 sec	Near-Pad SRB Random Failure (Ground Release Only)	1.5×10^{-3}	1.5×10^{-3}	2.3×10^{-6}	21.3 Ground	250	4-Meter Puff 2 Meters Off the Ground
1	10–20 sec	Early Ascent SRB Random Failure (Air/Ground Release)	3.7×10^{-4}	1.9×10^{-4}	6.9×10^{-8}	20.3 Air 11.8 Ground	240 140	Air: Vaporization, Coagulation, & Plume Transport Aloft. Ground: 4-Meter Puff 2 Meters Off the Ground
1	10–20 sec	Early Ascent SRB Random Failure (Ground Release Only)	3.7×10^{-4}	2.3×10^{-4}	8.4×10^{-8}	32.8 Ground	390	4-Meter Puff 2 Meters Off the Ground
1	20–57 sec	Early, Mid-Ascent SRB Random Failure	5.7×10^{-4}	1.4×10^{-4}	7.9×10^{-8}	20.9 Air 0.7 Ground	250 8.7	Air: Plume Transport Aloft. Ground: 4-Meter Puff 2 Meters Off the Ground
1	57–105 sec	Late, Mid-Ascent SRB Random Failure	3.6×10^{-4}	2.1×10^{-4}	7.5×10^{-8}	106 Air	1260	Worldwide Transport Aloft
1	105–120 sec	Late Ascent SRB Random Failure	1.7×10^{-4}	1.1×10^{-3}	1.8×10^{-7}	269 Air	3200	Worldwide Transport Aloft
2, 3, or 4	120 sec til IUS Burns Complete	Inadvertent Reentry and Land Impact	1.7×10^{-3} †	1.4×10^{-1}	2.3×10^{-4}	0.063 Ground (Rock)	0.8*	Two 4-Meter Puffs 2 Meters Off the Ground

† Includes the probability of an inadvertent reentry and, given reentry, that the GPHS modules hit land.

* This involves two separate releases at two different locations; each of 0.032g or 0.375 Ci.

RESULTS

Summaries of the radiological health impacts obtained from the INSRP Ulysses evaluation are provided in Table 3 (for the average source terms) and Table 4 (for the average of the top 5-percent source terms).

To determine and convey our state of knowledge about the radiological risks associated with the Ulysses mission more completely, the INSRP also performed an integrated risk assessment, incorporating treatment of both variance and uncertainty. The results of that assessment are illustrated in Figures 1, 2, and 3.

These results and the discussions which follow were taken from the Ulysses SER (INSRP, 1990).

DISCUSSION OF RESULTS

The overall mean calculated probability of an accident occurring through deployment and boost toward Jupiter, regardless of any considerations regarding fuel release, was of the order of 1 in a 100. Given an initiating accident during the Ulysses mission, there was an additional (conditional) probability of failing one or more plutonia fueled clads and releasing radioactive material into the environment. This would require either (1) a SRB failure that results in high velocity fragments impacting the GPHS-RTG with sufficient energy to severely damage the fueled clads and release plutonia or (2) an explosion that results in hard surface ground impacts of GPHS-RTG hardware at or near terminal velocity. If an accident had resulted in reentry of the spacecraft during late ascent or from Earth orbit, the aeroshell modules were designed, and have been assessed, to withstand atmospheric reentry intact. For a fuel release to occur as a result of a reentry event, the aeroshell modules must subsequently strike hard surfaces. Such a release would be small and localized; thus, it must occur in the immediate vicinity of people for exposures to occur.

No credible mechanism was identified that could result in a release of radioactive material prior to installation of the GPHS-RTG on the Ulysses spacecraft and the loading of propellants into the External Tank of the Space Shuttle. In addition, once the spacecraft leaves the influence of the Earth's gravity toward Jupiter, no credible mechanism was identified that can return the spacecraft and its radioactive materials to the vicinity of Earth.

It should be pointed out that the most likely, and thus, the expected result for all accident scenarios was no fuel release and that the expected outcome for the Ulysses mission was a successful launch and deployment.

An interesting finding of the INSRP evaluation was that a *Challenger*-type accident was projected to yield no fuel release to the environment.

For each key accident scenario, two single point source term estimates were calculated: (1) an average source term and (2) an average of the top 5-percent source term. For the average source terms, the calculated number of cancer fatalities ranged from 0.002, with a probability of about 1 in 29,000, to 3, at approximately 1 in a million. For the average of the top 5-percent source terms, the calculated number of cancer fatalities ranged from 0.008, with a probability of about 1 in a million, to 36, with a probability of less than 1 in 100 million. In all cases, calculated fatalities were those that might be expected within the 50-year period following an accident where it is assumed that no intervention or mitigation is taken. (Note: For health effects greater than one, the calculated fatalities were, for all practical purposes, entirely due to high altitude fuel releases that would result in extremely small doses to the world population. For such doses, the collective and individual risk increments are calculable, but not demonstrable. In fact, the possibility of zero risk cannot be ruled out of a strict statistical analysis of data, especially when predicted risks are $<10^{-5}$. Consequently, an

TABLE 3. RADIOLOGICAL HEALTH IMPACT (AVERAGE CASE).

Phase	Accident Type	Source Term Air/Ground in Curies	Release Probability	Maximum Individual Dose in rem over 50 Years	Population Potentially Exposed	Collective Dose in Person-rem		Collective Organ Dose in Person-rem				Total Health Effects	Frequency of Health Effects in Events/Mission
						1st yr	50 yr	Lung	Liver	Bone	RBM†		
0	On-Pad External Tank Explosion	~/1.0	8.6×10^{-6}	7.8×10^{-4}	6.3×10^{5}	18	28	0.013	59	330	27	0.007	3.5×10^{-8}
1	0–2s Tipover/ Tower Impact	~/0.8	8.3×10^{-7}	5.7×10^{-4}	6.3×10^{5}	17	26	0.01	58	340	27	0.007	3.2×10^{-7}
1	0–10s Near-Pad External Tank Explosion	~/1.2	2.9×10^{-6}	9.4×10^{-4}	6.3×10^{5}	20	32	0.015	65	370	29	0.008	1.2×10^{-8}
1	0–10s Near-Pad SRB Random Failure (Air/Ground Release)	24/50	5.2×10^{-6}	2.0×10^{-2}	7.4×10^{5}	460	610	320	1400	8100	650	0.2	2.7×10^{-6}
1	0–10s Near-Pad SRB Random Failure (Ground Release Only)	~/23	4.5×10^{-5}	7.0×10^{-3}	6.1×10^{5}	160	188	160	530	3100	250	0.07	6.3×10^{-6}
1	10–20s Early Ascent SRB Random Failure (Air/Ground Release)	16/30	1.4×10^{-6}	9.7×10^{-3}	1.3×10^{6}	240	320	350	610	3400	270	0.09	7.0×10^{-7}
1	10–20s Early Ascent SRB Random Failure (Ground Release Only)	~/100	1.7×10^{-6}	2.2×10^{-2}	6.2×10^{5}	500	590	490	1600	9600	770	0.2	7.0×10^{-7}
1	20–57s Early, Mid-Ascent * SRB Random Failure	14/0.6	1.6×10^{-6}	2.3×10^{-4}	6.2×10^{5}	5.7	130	18	17	93	75	0.05	8.8×10^{-7}
1	57–105s Late, Mid-Ascent * SRB Random Failure	72/–	1.5×10^{-6}	–	Worldwide	–	2900	–	–	–	–	0.08	1.1×10^{-6}
1	105–120s Late Ascent * SRB Random Failure	280/–	3.6×10^{-6}	–	Worldwide	–	1.1×10^{4}	–	–	–	–	3	9.1×10^{-7}
2, 3, or 4	Inadvertent Reentry and Land Impact	~/0.4	6.2×10^{-4}	8.6×10^{-1}	1.96×10^{3}	5.9	7.2	–	–	–	–	0.002	3.5×10^{-5}

* Assumes 40 person–rem/Ci, based on ICRP (1986), and 2.9 E–4 health effects per person–rem for air releases.

† RBM is red bone marrow.

TABLE 4. RADIOLOGICAL HEALTH IMPACT (AVERAGE OF TOP 5% SOURCE TERMS).

Phase	Accident Type	Source Term Air/Ground in Curies	Release Probability	Maximum Individual Dose in rem over 50 Years	Population Potentially Exposed	Collective Dose in Person-rem		Collective Organ Dose in Person-rem				Total Health Effects	Frequency of Health Effects in Events/Mission
						1st yr	50 yr	Lung	Liver	Bone	RBM†		
0	On-Pad External Tank Explosion	~/2.7	4.4×10^{-7}	2.0×10^{-3}	6.3×10^{5}	42	66	0.033	130	760	60	0.02	$\sim 1 \times 10^{-7}$
1	0–2s Tipover/ Tower Impact	~/2.8	4.2×10^{-8}	2.2×10^{-3}	6.3×10^{5}	49	76	0.036	160	900	71	0.02	$<1 \times 10^{-8}$
1	0–10s Near-Pad External Tank Explosion	/3.8	1.5×10^{-7}	3.0×10^{-3}	6.3×10^{5}	63	98	0.048	200	1100	89	0.02	$\sim 3 \times 10^{-8}$
1	0–10s Near-Pad SRB Random Failure (Air/Ground Release)	380/330	2.6×10^{-7}	2.1×10^{-1}	7.0×10^{5}	3000	4100	2900	7500	4.0×10^{4}	3200	0.9	$<1 \times 10^{-8}$
1	0–10s Near-Pad SRB Random Failure (Ground Release Only)	~/250	2.3×10^{-5}	8.9×10^{-3}	6.1×10^{5}	1500	1700	2200	4500	2.6×10^{4}	2100	0.6	$<1 \times 10^{-8}$
1	10–20s Early Ascent SRB Random Failure (Air/Ground Release)	240/140	6.9×10^{-8}	4.4×10^{-2}	1.2×10^{6}	1200	1600	1300	3000	1.6×10^{4}	1300	0.4	$<1 \times 10^{-8}$
1	10–20s Early Ascent SRB Random Failure (Ground Release Only)	~/390	8.4×10^{-8}	1.1×10^{-1}	6.1×10^{5}	2300	2600	3200	7000	4.1×10^{4}	3300	0.9	$<1 \times 10^{-8}$
1	20–57s Early, Mid-Ascent * SRB Random Failure	250/8.7	7.9×10^{-8}	2.1×10^{-3}	6.4×10^{5}	64	1800	160	160	880	71.0	0.6	$<1 \times 10^{-8}$
1	57–105s Late, Mid-Ascent * SRB Random Failure	1260/–	7.5×10^{-8}	–	Worldwide	–	5.0×10^{4}	–	–	–	–	14	$<1 \times 10^{-8}$
1	105–120s Late Ascent * SRB Random Failure	3200/–	1.8×10^{-7}	–	Worldwide	–	1.3×10^{5}	–	–	–	–	36	$<1 \times 10^{-8}$
2, 3, or 4	Inadvertent Reentry and Land Impact	~/0.8	2.3×10^{-4}	3.3	1.0×10^{4}	23	28	–	–	–	–	0.008	$\sim 1 \times 10^{-6}$

* Assumes 40 person–rem/Ci, based on ICRP (1986), and 2.9 E–4 health effects per person–rem for air releases.

† RBM is red bone marrow.

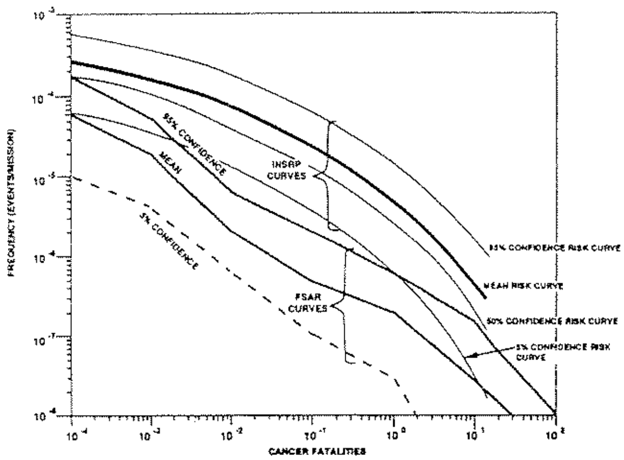

Figure 1. Approximation Of Total Mission Radiological Risk By Sum Of All Scenarios.

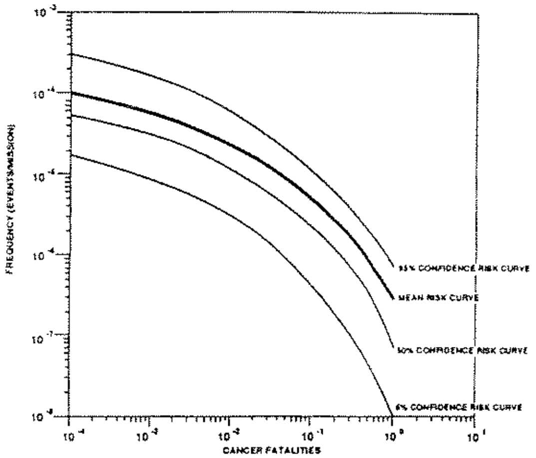

Figure 2. Approximation Of Local Florida Radiological Risk By Sum Of All Scenarios Prior to 57 sec MET.

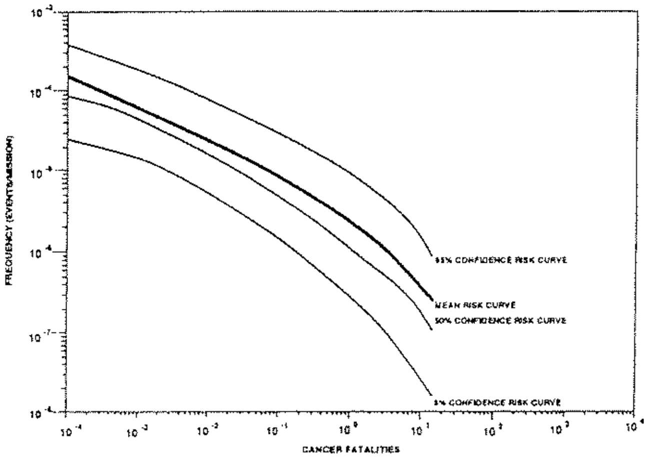

Figure 3. Approximation Of Worldwide Radiological Risk By Sum Of All Scenarios After 57 sec MET.

important point regarding these radiological risk increments or additions is frequently omitted; that is, that these risks are expressions of a probability distribution and are not a certainty.)

Overall, based on the INSRP integrated risk assessment for the entire Ulysses mission, one can conclude with 95-percent confidence that the probability of one or more cancer fatalities was less than 1 in 100,000, and the probability of 12 or more cancer fatalities was less than 1 in a million. Similarly, one can conclude with 95-percent confidence that the likelihood of one or more cancer fatalities in local Florida was less than 1 in a million, and that the likelihood of one or more cancer fatalities worldwide was less than 1 in 100,000. (Note: The breakpoint for effects in local Florida and worldwide effects occurs for projected fuel releases at a MET of approximately 57 seconds, when the launch vehicle reaches the stratosphere.)

To place the health-related risks calculated in the INSRP analysis in some perspective, a comparison with a similar type of exposure and risk is useful. Two such comparisons were provided. First, a comparison was made between the highest 50-year dose calculated to be received by any individual and the radon background dose received by that same individual for the same time period. Second, a comparison was made between the natural occurrence of fatal cancer in the population and the highest added incremental cancer risk to any single individual.

It is generally accepted that of the 350 mrem average annual background radiation dose experienced by the population, approximately 0.2 rem (with a probability of 1) is due to naturally occurring radon daughter product exposure. Thus, the lifetime (50-year) accumulated radon dose to an individual in the population would be 10 rem. If one compares this with the calculated 50-year maximum dose of 0.21 rem (with a probability of less than 1 in 4 million) to the maximally-exposed individual in the local Florida population, that individual would receive approximately 2 percent of the radon background. In the case of the maximum 50-year individual dose of 3.3 rem (with a probability of much less than 1 in 4,000) calculated for the maximally-exposed individual in the world population, that individual would receive approximately 33 percent of the radon background. Calculated exposures to the remaining population would be a small fraction of these percentages.

Compared with the nominal 20-percent lifetime cancer fatality risk that everyone faces, the highest calculated added individual risk associated with the Ulysses mission increased lifetime cancer risk to no more than 20.00015 percent. If one considers that the likelihood of an accidental release that results in fatal cancer was less than 1 in 100,000, the actual added risk of fatal cancer associated with the Ulysses mission was much smaller than 0.00015 percent.

Thus, the INSRP analysis suggested that the radiological risks associated with the Ulysses mission were relatively small.

While the mission risk determined by the INSRP in the SER was higher than that characterized by the Ulysses project in the FSAR, as illustrated in Figure 1, both reports indicated that the radiological risks were relatively small. In the final analysis, the SER proved to be supportive of a positive launch decision.

The INSRP evaluation process has demonstrated its effectiveness 24 times since the 1960s. In every case, it has provided the essential ingredients and perspective to permit an informed launch decision at the highest level of our Government.

Acknowledgments

The authors thank the INSRP subpanel members, current and past, as well as previous INSRP coordinators. These individuals spent countless hours to permit completion of the INSRP subpanel reports and the Ulysses SER. Without the diligence and assistance of these dedicated individuals, the INSRP review of the Ulysses space mission could not have been completed and the Ulysses SER, as well as this paper, would not have been possible.

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