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Radiological Risk Analysis of
Potential SP-100 Space Mission Scenarios

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1.0 INTRODUCTION AND SUMMARY

This report presents a radiological risk analysis of three representative space mission scenarios utilizing a fission reactor that produces 100 kilowatts of electricity based on SP-100 technology. The mission profiles considered are:

- (1) A high-altitude (>300-year orbital lifetime) mission, launched by a TITAN IV launch vehicle, boosted by chemical upper stages into its operational orbit
- (2) An interplanetary nuclear electric propulsion (NEP) mission, started directly from a Shuttle parking orbit
- (3) A low-altitude (50-year orbital lifetime) mission, launched by the Shuttle and boosted by a chemical stage to its operational orbit, with subsequent disposal boost after operation

The radiological risk analysis provides reasonable estimates of the potential environmental risks that could be posed by accidents involving the nuclear reactor systems used in future SP-100 missions. The three missions were selected to represent the many potential SP-100 applications⁽¹⁾, with reactor operation at altitudes ranging from low (300-km Shuttle orbit) to high (800-km orbit with >300-year orbital lifetime). When SP-100 is chosen to power a specific spacecraft and mission, the civilian or military user will have the responsibility to comply with NEPA requirements and to obtain launch approval. The NEPA review will address all significant environmental impacts of which accidents are one category. The launch approval will be based on acceptable environmental impacts and will include a detailed assessment of safety. The safety assessment will include safety analyses and safety verification tests that are applicable to the actual reactor power system design and mission scenarios selected by

the user. Part of the user's design process will involve making tradeoff decisions to achieve mission objectives and, among these, safety will be very important. The actual risk assessments made by the user will be more detailed but should be similar in approach to those presented in this analysis, and although specific quantitative results might differ, the results of this analysis are representative of the range of potential radiological risks from SP-100 use in space.

The results of the risk analysis of potential SP-100 missions are presented in Table 1-1. The total statistically expected population dose for the three missions varies from about 0.5 to 3.0 person-rem. This dose is the total dose, integrated over all exposed individuals. The average individual's exposure would be many orders of magnitude lower, and substantially less than that due to background radiation. In Table 1-1 it can be seen that for the three missions the risk contribution from all phases prior to reactor operation is negligibly low. This results directly from the fact that prior to operation the SP-100 reactor only contains on the order of 15 curies of radionuclides. The more significant risk contributors from the other phases vary from mission to mission, but in all cases are quite low. Also, for the mission profiles considered, the population doses from intact reactor components following land impact were found to be much less than those from atmospherically dispersed fission products. This is because of the potential lifetime exposure of the general population to the residual radioactivity in the case of atmospheric dispersal.

Using the conservative BEIR III⁽¹⁹⁾ linear dose response model, the radiological health effects, expressed as statistically expected latent fatalities per mission, are calculated to be:

o	TITAN-Launched High-Orbit Mission	0.00007
o	Shuttle-Launched NEP Mission	0.00006
o	Shuttle-Launched Low-Orbit Mission	0.00036

Table 1-1
SP-100 Mission Health Effects Summary

Mission/Phase	Statistical Expected Total Population Dose Per Mission (Person-rem)	Statistical Latent Fatalities Per Mission
TITAN High-Orbit Mission		
Prelaunch/Launch	3.1E-03	
Ascent	1.0E-03	
High Orbit	<u>5.8E-01</u>	
Mission Total	5.9E-01	7.1E-05
Shuttle NEP Mission		
Prelaunch/Launch	6.7E-04	
Ascent/First Stage	2.2E-03	
Second Stage	3.0E-04	
On-Orbit	1.2E-04	
NEP	<u>5.1E-01</u>	
Mission Total	5.1E-01	6.1E-05
Shuttle Low-Orbit Mission		
Prelaunch/Launch	6.7E-04	
Ascent/First Stage	2.2E-03	
Second Stage	3.0E-04	
On-Orbit	3.6E-02	
Low-Orbit Operation	2.8	
Post-Operation Disposal	<u>1.1E-01</u>	
Mission Total	3.0	3.6E-04

These results include the health effects of possible operational and accident scenarios that result in dispersed fuel and fission products and, in some instances, direct dose from a previously operated intact reactor. These very low health effects clearly indicate that future SP-100 missions can be designed and conducted to present a low risk to the public and the environment, even if future risk analyses based on mission-specific parameters yield results that vary by several orders of magnitude from those in this report.

The analytical approach used to perform the risk assessments is based on the accepted approach used for safety analyses of past and current space missions employing nuclear power sources, e.g., SNAPSHOT (SNAP2/10A Reactor in 1965), Voyager (MHW-RTG in 1977), Galileo (GPHS-RTG to be launched in near future). This approach is also consistent with a recent U.S. Department of Transportation report entitled, Hazard Analysis of Commercial Space Transportation (20). Based on the assumed hypothetical mission scenarios and the latest SP-100 generic design information⁽²⁾, accident scenarios and associated probabilities were generated, and presented as Failure Event Tree Summaries. These event trees were used to evaluate the effects of failure modes and accidents that could result in potential impacts on public health risk.

To quantify the likelihood of occurrence of the different accident paths of the event trees, two classes of accident and failure probabilities were used: those associated with the launch vehicle and those associated with the performance of the SP-100 Space Reactor Power System (SRPS). The launch vehicle accident probabilities were consistent with the latest safety analyses and risk assessments for missions using nuclear power sources. The best-estimate probabilities used to describe the functional performance of the SP-100 SRPS were derived from a mixture of design goals, preliminary engineering estimates based on

performance of past similar components, and preliminary design calculations.

For each accident sequence, radionuclide source terms were identified, based on the type of accident and the prior reactor operating history. Because of the similarity of many of the accident environments and possible responses of the SP-100 reactor, generic source term types and fuel and fission product release fractions were defined for previously unfissioned fuel and for previously fissioned fuel. The evaluation of the radiological impact of the postulated scenarios involving fuel and fission product releases into the environment included: analyses of the dispersion and time behavior of the released radioactivity to determine the concentrations in air, soil, and water as a function of time; analyses of ingestion, inhalation, and external radiological doses through each environmental pathway; and evaluations of the radiological impact in terms of the population doses received and the resulting health effects.

The details of the risk analysis are presented in the following chapters. Chapter 2.0 presents the generic SP-100 Space Reactor Power System design information upon which the analyses were based. Chapter 3.0 describes the radiological risk analysis, including the mission descriptions, accident scenarios, source terms, and associated probabilities. Chapter 4.0 summarizes the methodology used in the analysis.

2.0 NUCLEAR POWER SYSTEM SUMMARY DESCRIPTION

2.1 General Description

The SP-100 Space Reactor Power System (SRPS) utilized for the three hypothetical space missions is taken to be the SP-100 Reference Flight System (RFS) design as presented at the July 1988 Project Information Meeting⁽²⁾. It is recognized that although the specific designs may vary depending on mission requirements, the fundamental technology and design approach remains the same. The RFS is rated at 2400 kilowatts of thermal power and its thermoelectric power conversion subsystem will produce 100 kilowatts of electricity. As shown in Figures 2-1 and 2-2, it is a lithium-cooled fast spectrum reactor with uranium nitride fuel enriched to an average of approximately 96% U²³⁵. The principal reactor structural and fuel-cladding material is a refractory niobium-based alloy and, in addition, the fuel cladding has a bonded rhenium liner. Reactor reactivity is controlled by 12 movable reflector elements, with additional safety shutdown margin provided by 7 internal safety rods. The secondary lithium loop transfers the waste heat to a titanium-beryllium deployable radiator, and although the SP-100 power system can be reconfigured to meet specific mission requirements, it is assumed in this analysis that the reference configuration shown in Figure 2-1 is employed for the three hypothetical missions.

2.2 Design Safety Features

The SP-100 Space Reactor Power System is being designed to meet stringent safety requirements⁽³⁾, and the results of the preliminary design activities have shown that these safety requirements can be met. It is planned that the safety of the SP-100 design will be verified through test and analysis during the Ground Engineering System program and any subsequent flight

Figure 2-1 SP-100 Space Reactor Power System

Figure 2-2 SP-100 Reactor Power Assembly

program. Although the information developed to date is not final or complete, it provides an adequate basis for the scoping assessments performed in this study.

Five major safety features have been incorporated in the SP-100 design to minimize radiological risk.

Safety of Unirradiated U²³⁵ Fuel

The SP-100 fuel was chosen to be uranium nitride highly enriched in the isotope U²³⁵. Since the reactor will not be operated prior to launch, except for some very low power qualification tests, no radioactive fission products will have been generated. Therefore, the fuel will not present a radiological hazard during launch, even if some fuel is dispersed in a major launch accident. Moreover, the lithium coolant in the core (melting point 186° C) will be frozen during the launch and until the reactor is started up in its operational orbit. Initial calculations show that the SP-100 core containing solid lithium retains its basic structural integrity and configuration when subject to blast or impact loads including those from flyer plates or shrapnel. Therefore, significant fuel releases are unlikely.

Assured Shutdown in Accident Scenarios

The SP-100 reactor is designed to remain subcritical when subjected to a wide range of accident scenarios, including water immersion and flooding, burial, or launch explosions. The rhenium fuel cladding liners and neutron barrier around the core provide increased spectral-shift neutron absorption to control reactivity in the case of flooding. Internal neutron absorber rods with mechanical latches to preclude their removal during blast or impact scenarios are provided. A honeycomb reactor internal structure will restrain the fuel rods from moving in the case of blast or impact.

Diverse and Redundant Shutdown Mechanisms

The SP-100 Reactor Instrumentation and Control Subsystem is designed to reliably shut the reactor down in the event of any of a number of postulated potentially serious off-normal conditions, including: over-temperature, loss of coolant, loss of altitude or attitude control, and extended loss of communications. Redundant, autonomous on-board controllers provide protection should communication with the ground be lost. Diverse and redundant instrumentation and sensors are provided to ensure a highly reliable control system.

Since both in-core safety rods and movable reflector control elements are provided, there is ample reactivity control for shutdown from operating conditions. Very high shutdown reliability goals (unreliability of less than 10^{-6}) for shutdown can be met, since operation of only a few control elements or safety rods in one of many possible combinations are necessary, and power reduction to very low levels is almost certain. Furthermore, as reactor operation continues, fewer operating control elements or safety rods are required for shutdown. Even in the case of a loss-of-coolant accident (LOCA), the loss of the lithium from the core introduces sufficient negative reactivity to promptly decrease power to very low levels.

Intact Reentry and Impact

To ensure intact reentry and impact, a carbon-carbon composite reentry nose cone has been incorporated in the design. The reentry cone maintains the reactor vessel temperature sufficiently low so that the desired structural configuration is maintained. Also, the lithium coolant in the core remains below its melting temperature, adding to the resiliency of the core upon impact.

Loss-of-Coolant Accident (LOCA) Protection

For some orbital missions, the existing and anticipated space debris fields increase the likelihood of an on-orbit impact that could initiate a loss of reactor coolant. To provide mitigation for those low probability accidents, an independent auxiliary coolant loop is incorporated in the design to maintain fuel rod temperatures below those at which any significant cladding damage and fuel or fission product release could occur. In conjunction with the honeycomb core support structure, this approach would maintain the basic structural integrity and configuration of the reactor, and the capability for post-mission disposal would not be compromised.

2.3 Generic Accident and Failure Probabilities

Accident and failure probabilities used in this report can be grouped into two classes: those associated with the launch vehicle and those associated with the performance of the SP-100 Space Reactor Power System. For the two missions using the Space Shuttle, the launch accident probability estimates are the same as those used in the Safety Analysis for the forthcoming Galileo mission^(4, 5, 6). Catastrophic Shuttle failure probabilities are shown in Table 2-1. For the TITAN-launched mission, the launch accident probabilities were taken from the TITAN IV RTG Safety Databook⁽⁷⁾. Thus, the launch vehicle accident probabilities used in this radiological risk assessment are consistent with the latest safety analysis and risk assessments for missions using nuclear power sources.

The probabilities used to describe the functional performance of the SP-100 SRPS are summarized in Table 2-2. They are based on a combination of technical specifications and design goals⁽³⁾ for SP-100, coupled with the results of preliminary design work as

Table 2-1

Catastrophic Shuttle Failure Modes and Probabilities

	Mission Phase	Vehicle Failure Mode	Mean Failure Probability During Phase
0	Prelaunch/ Launch	Launch Pad Fire/ Explosion* Inadvertent Range Safety System (RSS) Destruct*	1.79 x 10 ⁻⁴ <u>6.32 x 10⁻⁹</u>
			Phase Subtotal 1.79 x 10 ⁻⁴
1	Ascent/ First Stage	SRB Failure Case Rupture* Tower Impact* Loss of Thrust* No Ignition*	1.02 x 10 ⁻³ 2.06 x 10 ⁻⁴ 2.49 x 10 ⁻³ <u>7.59 x 10⁻⁵</u>
			Subtotal 3.80 x 10 ⁻³
		RSS Destruct* Aft Compartment Explosion* Vehicle Breakup* Crash Landing Ocean Ditch	1.51 x 10 ⁻⁶ 3.95 x 10 ⁻⁴ 8.98 x 10 ⁻⁵ 3.79 x 10 ⁻⁶ <u>7.21 x 10⁻⁵</u>
			Phase Subtotal 4.36 x 10 ⁻³
2	Second Stage	Vehicle Breakup Orbital Failure ET Failure SSME Failure Payload Failure RSS Restart	2.37 x 10 ⁻⁴ 1.90 x 10 ⁻⁵ 1.23 x 10 ⁻³ 2.40 x 10 ⁻⁵ 2.40 x 10 ⁻⁶ <u>1.58 x 10⁻⁶</u>
			Subtotal 1.51 x 10 ⁻³
		Crash Landing Ocean Ditch	8.85 x 10 ⁻⁶ <u>1.68 x 10⁻⁴</u>
			Phase Subtotal 1.69 x 10 ⁻³
3	On-Orbit	Orbiter Reentry/ Breakup	1.58 x 10 ⁻⁴

* Severe explosion hazard.

Table 2-2

SP-100 Failure Probabilities Assumed for Risk Analysis

Event	Conditional Probability	Basis
Minor damage to reactor as result of blast or impact	0.01	Rugged design, results of preliminary calculations.
Nuclear excursion and disassembly of damaged reactor	0.0001	Large shutdown margin, design calculations, experiments, mechanical latches.
Failure to start reactor	0.001	Reliable design, checked before launch and deployment.
Failure to shut reactor down	10^{-6}	Diverse and redundant control, only a few control elements needed negative reactivity from LOCA. Reactor slowly shuts down by reactivity depletion after full-power operation.
On-orbit breakup		
NEP	10^{-6}	Short time in debris field.
During orbital operation or reentry	0.0001	Time-weighted probability of damage from debris hit.

reported in the July 1988 Project Information Meeting⁽²⁾. The probabilities represent the best current engineering estimates of the SP-100 Program staff, and are consistent with reliability predictions used within the nuclear industry. For accident scenarios, a 10^{-6} probability (beyond credible) is used for postulated events that are beyond the design basis. A 10^{-4} probability is used for "unlikely" events, those for which the design is expected to be able to be validated by test or analysis. A 10^{-2} probability is used for "likely" events, those that are well within the operational envelope and design basis. Because of the early stage of the SP-100 design, the SP-100 probabilities are preliminary "best estimate" values and are intended to be representative of expected ranges of probabilities. However, they are reasonable and appropriate for this radiological risk assessment, and are adequate for indicating the relative importance of the various contributors to public health risk.

2.4 Generic Source Terms

For each of the three missions, fission product buildup resulting from specified periods of operation and fission product decay after shutdown have been evaluated using the ORIGEN⁽⁸⁾ code. In addition, generic release fractions common to all missions have been identified for the accident consequences that have the potential for releasing radioactive material to the environment:

- o Nuclear excursion and disassembly subsequent to land or ocean impact
- o Reentry release from a damaged reactor
- o Land or ocean impact of a damaged reactor
- o Land or ocean impact of an operating reactor

The assumptions made in deriving each source term for the accident scenarios are described below.

Nuclear Excursion and Disassembly Subsequent to Land or Ocean Impact

Should an accident result in immersion of the reactor in a moderator such as water, or burial in dry or wet sand, the SP-100 reactor is designed to remain subcritical, with margin. However, to account for the highly unlikely chance of a combination of events causing criticality of a shutdown reactor, or the scenarios of reentry of a reactor that has shut itself down over time and is just subcritical, or the reentry of a just critical operating reactor, it was assumed that in such circumstances the SP-100 reactor would undergo a self-limiting excursion and disassembly similar to that experienced by the SNAP 10A Reactor in the SNAPTRAN-3 Test⁽⁵⁾. The SNAP reactor criticality was terminated in less than 15 milliseconds by internal hydrogen gas pressure in the fuel resulting from a deposition of approximately 40 megawatt-seconds of fission energy. It is estimated based on conservative modified Bethe-Tait methods⁽⁶⁾ that a similar SP-100 excursion and disassembly would release on the order of 100 megawatt-seconds of energy.

In one possible scenario the UN fuel would rapidly be heated to its melting point of about 3100 K at which point the cladding would instantly melt, and the internal nitrogen pressure would blow the pins apart. The lithium vapor pressure at these temperatures is sufficient to rupture the reactor vessel, disperse the fuel rods, and terminate the reactor criticality. Since the reactor peak-to-average power ratio is about 1.4, the center of the core will reach the high temperatures required for disassembly before the rest of the core, thus limiting the amount of fission products generated, and fuel and fission products released. Later in the reactor operating life, with the buildup of gaseous and

volatile fission products, an excursion would cause the internal rod pressure to increase faster and limit the excursion to a lower energy release.

The release of radionuclides resulting from the nuclear excursion and disassembly would be highly variable, depending on the operating history of the reactor, and the rate of reactivity addition during the accident. For this study, release fractions of 100% noble gases, 25% volatiles, and 10% particulates have been assumed for all of these events. These fractions are believed to be conservative based on comparison with values recommended by the U.S. Nuclear Regulatory Commission to analyze core disruptive accidents for liquid metal reactors. For a land excursion, the radionuclides would likely be confined to a low-altitude release. In the case of water impact, the radionuclides are expected to be released primarily to the water body.

Reentry Release from a Damaged Reactor

The SP-100 reactor is designed to remain intact during reentry and subsequent impact. Therefore, in this study, the reactor is assumed to survive intact with a high probability should an inadvertent reentry occur. However, as a possible result of damage to the reactor or reentry nose cone from debris hits while in orbit or while passing through the debris field, some reentry burnup damage and dispersal is assumed with low probability. An examination of the fallout footprint debris associated with Cosmos-954 concluded that approximately 80% of the reactor fuel had vaporized on reentry with the remaining 20% depositing as non-inhalable particulates in the footprint area⁽¹¹⁾. Since SP-100 uses high-temperature refractory materials and is designed for intact reentry while Cosmos was designed to burn up, 10% of the SP-100 core is assumed in this study to be vaporized and 90% is assumed to impact the land or ocean in pieces of varying sizes.

It has also been assumed that the 10% fuel release at high altitude includes noble gases, halogens, and particulates.

For reentry release from a damaged reactor it is assumed that vapor and particulates reenter according to the atmospheric dispersion models described in Sections 4.2.1 and 4.2.2. Larger core debris is conservatively assumed to have the same orbital lifetime as the fully deployed SP-100 SRPS. Fuel pins, fuel pellets, and the reactor core itself would all have ballistic coefficients about 10 times that of the fully deployed SRPS and would therefore have a much longer orbital lifetime.

Land or Ocean Impact of a Damaged Reactor

In the case of land or ocean impact of a damaged reactor, it is conservatively assumed that mechanical forces cause at most 1% of the fuel to be released as fine particulates. This is based on the amounts of particulates observed after impact tests of other metal clad ceramic fuel and is thus consistent with severe mechanical damage to the reactor without a nuclear excursion. Moreover, the presence of the solid lithium coolant will also inhibit the release of the particulates.

For a previously operated reactor, any volatile fission products and noble gases that may have been generated in the fuel and diffused to the gas plenum are assumed to be released. Based on in-pile tests of UN fuel, this plenum inventory is taken to be 3% of that generated.

Land or Ocean Impact of Operating Reactor

For the cases of land or ocean impact of an operating reactor, it is assumed that since the reactor is just critical before impact it will undergo a nuclear excursion and disassembly, with the same energy release and source terms previously identified. In

addition, because of its prior operating history, any fission product inventory is subject to release in the same percentages. Similarly, a reactor that has gradually shut itself down by reactivity depletion over time will be just subcritical at impact and thus will also undergo a nuclear excursion and disassembly.

The different types of generic reactor source terms defining the fractions of UN fuel and fission products released to the environment as a result of an accident are summarized in Table 2-3. Source term types A through C are for previously unfissioned fuel while source term types D through G are for previously fissioned fuel.

Table 2-3

Reactor Source Term Types and Release Fractions

Accident	Unfissioned Fuel	Fissioned Fuel
<u>Land or Ocean Impact</u>		
Damaged reactor in subcritical configuration	Type A 1% fuel particulates	Type D Same as A, plus 3% noble gases, 3% volatiles
Damaged reactor resulting in nuclear excursion and disassembly	Type B 100 Mw-sec excursion, 100% noble gases, 25% volatiles, 10% particulates	Type E Same as B, plus same fractions of accumulated fission product inventory
Impact of operating reactor	Not applicable	Type F Same as E, with fission product inventory per operating history
<u>Reentry Release from Damaged Reactor</u>		
High-altitude release and footprint on land or ocean	Type C 90% debris, 10% fuel vapor 10% particulates	Type G Same as C, plus 10% noble gases, 10% halogens, 10% volatiles

3.0 MISSION RISK ANALYSIS

3.1 TITAN-Launched High-Orbit Mission

3.1.1 Mission Description

The hypothetical High-Orbit Mission utilizes a spacecraft powered by the previously described SP-100 Space Power Reactor System, launched by a TITAN IV from Kennedy Space Center. The launch vehicle is similar to that used for the Voyager Mission except that Stages III and IV are assumed to be replaced by a SP-100 configuration similar to that shown in Figure 3-1. The final stage to be placed into the high (>300 year) polar orbit consists of the SP-100 Space Reactor Power System and payload. The definitions of the mission phases are as follows:

Phase 1: Prelaunch/Launch - Mating of spacecraft to launch vehicle at T-1 days to ignition for launch at T-0 seconds. Ignition at T-0 until the instantaneous impact point (IIP) clears the Cape Canaveral land mass at T+23 seconds.

Phase 2: Ascent Phase - From T+23 seconds until high-orbit injection at T+537 seconds.

Phase 3: High-Orbit Phase - From T+537 seconds until the reactor eventually reenters after 300 years.

3.1.2 Accident Scenarios and Probabilities

The High-Orbit Mission event trees are summarized in Figure 3-2, with path identifiers and cumulative path probabilities tabulated in the right margin. In performing the risk analysis for the TITAN-launched mission, the accident scenarios and associated

Figure 3-1 Titan Launch Configuration for High-Orbit Mission

Figure 3-2
TITAN-Launched High Orbit Mission Failure Event Tree Summary
(Sheet 1 of 2)

Figure 3-2
TITAN-Launched High Orbit Mission Failure Event Tree Summary
(Sheet 2 of 2)

probabilities are taken to be those developed in support of the TITAN IV Data Book⁽⁷⁾. Failure modes and their respective probabilities are grouped together according to the ultimate impact on public health risk. For the launch malfunction (8.42×10^{-4}) it is assumed that because of the design shutdown margin under severe accident scenarios, an intact critical configuration will result only through an unlikely undefined series of events with a probability of 10^{-4} . The intact subcritical configuration (approximately 0.99 probability) is the most likely outcome based on preliminary design analyses showing the strength of the reactor when exposed to blast waves, shrapnel and flyer plates, and reentry impact. However, a nominal (0.01 probability) minor damage accident with limited release of fuel with no fission products is also assumed. Ascent failures, having a probability of 5.16×10^{-3} , result in a 0.85 probability of ocean impact, because the launch track is primarily over the South Atlantic and Indian Oceans. Since the reactor will be designed for intact reentry with adequate shutdown margin, it is assumed that the reactor will only impact in a critical configuration with a probability of 10^{-4} , which will result in an immediate self-limiting nuclear excursion and disassembly.

Subsequent to achieving the desired high orbit, the reactor is started up with an assumed probability of 0.999. The probabilities for the branches representing eventual reentry are the same as for the previous phases with the exception that the probability of reentry of a damaged reactor is increased from 0.01 to 0.05 after 300 years due to greater likelihood of possible on-orbit damage, and that the land and ocean impact probabilities (0.71 and 0.29) reflect the random reentry sequence probabilities rather than the launch track land-ocean fractions. If the active shutdown mechanisms fail due to an incredible (10^{-6} probability) combination of events, the reactor eventually shuts itself down because of reactivity depletion over time. For these cases the reactor would be just subcritical upon impact and is assumed to

undergo a self-limiting excursion and disassembly whether impacting on land or water. A 10^{-4} probability is assumed for damage due to debris hits resulting in on-orbit reactor breakup during operation or damage to the reentry nose cone such that some reentry dispersal of reactor debris occurs, with footprints on either land or ocean plus some high-altitude release.

3.1.3 Risk Analysis

Radionuclide inventories specific to the TITAN-launched high-orbit mission were computed for the following scenarios:

Normal Operation

7.3 years at full power, followed by 292.7 years shutdown in the 300-year orbit.

On-Orbit Breakup

Breakup after 7.3 years at full power, at time of maximum fission product inventory. Vapor and particulates reenter according to the atmospheric dispersion model, larger debris reenters after 292.7 years of decay in the 300-year orbit.

Failure To Shut Down

7.3 years at full power, gradual shutdown of 3.85 years at 75% power and 3.85 years at 25% power, followed by 285 years shutdown in the 300-year orbit.

These inventories together with the unfissioned fuel inventories and the fission product inventory generated during a 100 megawatt-second excursion are identified for each path in Table 3-1 by "Operating History/Source Term Descriptors." Table 3-1 also identifies the "Release Type" used in the analysis for each path, as well as the respective path identifier and cumulative path probability taken from Figure 3-2. The health effect consequences calculated by the methodology discussed in Chapter 4 are tabulated

Mission Phase	Release Area		Path ID	Release Type	Operating History/Source Term Descriptor	Release Probability	Release Consequences, Person-rem	Risk, Person-rem Expectation
	Launch Area	Worldwide						
Prelaunch/Launch	Land	-	2	A	1	8.42E-06	6.37E-01	5.36E-06
	"	-	3	B	2	8.42E-08	3.72E+04	3.13E-03
Ascent	"	Ocean	5	A	1	4.38E-05	7.57E-07	3.32E-11
	-	"	6	B	2	4.38E-07	3.93E-05	1.72E-11
	-	Land	8	A	1	7.73E-06	2.23E-01	1.72E-06
	-	"	9	B	2	7.73E-08	1.30E+04	1.00E-03
High Orbit	-	Ocean	11	A	1	8.45E-06	7.57E-07	6.40E-12
	-	"	17	D	3	3.52E-02	1.98E-04	6.97E-06
	-	"	12	B	2	8.45E-05	3.93E-05	3.32E-12
	-	"	18	E	4	7.02E-05	1.11E-03	7.79E-08
	-	Land	14	A	1	1.49E-06	2.80E-01	4.17E-07
	-	"	19	Intact	3	2.74E-01	9.33E-09	2.56E-09
	-	"	20	D	3	1.44E-02	1.96	2.82E-02
	-	"	15	B	2	1.49E-08	1.63E+04	2.43E-04
	-	"	21	E	4	2.88E-05	1.63E+04	4.69E-01
	-	High Altitude/Land	22	G	5/6	2.88E-05	8.25E+02	2.38E-02
	-	High Altitude/Ocean	23	G	5/6	7.05E-05	8.08E+02	5.70E-02
	-	Land	24	E	7	2.88E-07	2.09E+04	6.02E-03
	-	Ocean	25	E	7	7.05E-07	1.42E-03	1.00E-09
Mission Risk = 5.88E-01								

Operating History/Source Term Descriptor

- 1 - Unfissioned fuel, t = 0
- 2 - Excursion/Unfissioned fuel, t = 0
- 3 - 7.3 years operation, 292.7 years shutdown, subcritical
- 4 - 7.3 years operation, 292.7 years shutdown, excursion
- 5 - 7.3 years operation
- 6 - 7.3 years operation, 292.7 years shutdown
- 7 - 7.3 years operation, (100% power), 3.85 years (75%), 3.85 years (25%), 285.4 years shutdown, excursion

Table 3-1
Summary of Radiological Risk
for Titan-Launched High-Orbit
Mission

both as population dose (person-rem) and as risk expectation value (person-rem multiplied by probability of occurrence).

3.2 Shuttle-Launched Nuclear Electric Propulsion (NEP) Mission

3.2.1 Mission Description

The NEP Mission is based on a Jet Propulsion Laboratory (JPL) study to explore Neptune following a more than 10-year interplanetary trajectory utilizing a Neptune Orbiter/Probe spacecraft combination⁽¹²⁾. The spacecraft, shown in Figure 3-3 from a recent JPL study⁽¹³⁾, consists of the 100-kilowatt SP-100 Space Reactor Power System coupled to an ammonia arcjet propulsion module. For an actual mission, tradeoffs to best achieve mission objectives will be made among Shuttle or Expendable Heavy Lift Vehicle payload mass limitations, NEP propellant mass, mass of possible chemical boost stage, orbits and times for mission phases, and the mission risk. However for this analysis, it has been assumed as a limiting case that the reactor and NEP unit are started up in a Shuttle orbit. Higher orbits achieved through lighter payloads or through chemical boost prior to NEP start would have lower associated risk and would be considered by the mission user.

The spacecraft would be launched by the Space Shuttle from Kennedy Space Center. The Space Shuttle, shown in Figure 3-4 consists of the Orbiter, two Solid Rocket Boosters (SRBs), and an External Tank (ET). The launch configuration of the payload in the Shuttle Bay is shown in Figure 3-5. The mission profile for the Space Shuttle, shown in Figure 3-6, includes placing the spacecraft into a 300-km parking orbit. After deployment from the Space Shuttle, the reactor would be started up and the arcjet propulsion would be initiated. The spacecraft would gradually spiral outward from the Earth, reaching Earth-escape velocity after approximately 430 days, at which time the proper trajectory towards Neptune would be established. During the outward spiral, the orbital

Figure 3-3 Proposed Spacecraft Configuration for Conceptual SP-100 NEP Mission

Figure 3-4 Space Shuttle Layout (Top)

Figure 3-5 Launch Configuration for a Shuttle-Launched Orbital Mission

Figure 3-6 Space Shuttle Mission Profile

inclination will be gradually changed from 28.5° Shuttle Orbit to 0° Mission Orbit.

The mission is divided into five phases as follows:

- Phase 0: Prelaunch/Launch - Begins with the liquid propellant fueling of the launch vehicle at T-8 hours and ends at T-0 seconds following ignition of the Space Shuttle Main Engines (SSMEs) and Solid Rocket Boosters (SRBs).
- Phase 1: Ascent/First Stage - From T-0 seconds to T+128 seconds, at which time SRB separation occurs.
- Phase 2: Second Stage - From T+128 seconds to T+532 seconds, at which time the External Tank (ET) separation occurs and the Orbiter reaches parking orbit.
- Phase 3: On-Orbit - From T+532 seconds or when parking orbit is reached until the spacecraft is deployed from the Orbiter and the reactor is started.
- Phase 4: NEP - From the time of reactor startup until Earth escape. This phase is divided into subphases 4a, Low-Orbit, and 4b, High-Orbit, to better illustrate the effects of increased orbital lifetime on reducing radiological risk.

3.2.2 Accident Scenarios and Probabilities

In performing the risk analysis, the accident scenarios and associated probabilities were consistent with similar analyses performed for the Galileo Mission⁽⁴⁾ based on References 5 and 6. The NEP Mission failure event trees are summarized in Figure 3-7, with path identifiers and cumulative path probabilities listed at the right margin. Rather than identify all of the different

Figure 3-7
NEP Mission Failure Event Tree Summary
(Sheet 1 of 3)

Figure 3-7
NEP Mission Failure Event Tree Summary
(Sheet 2 of 3)

Figure 3-7
NEP Mission Failure Event Tree Summary
(Sheet 3 of 3)

failure modes and their respective probabilities, they are grouped together according to the ultimate impact on public health risk. For example, accident events during the Ascent/First Stage Phase include tipover, tumbling, explosion or fire resulting from failures in the SRBs or in the SSMEs. However, all of these failures will have similar possible results of reactor criticality, fuel dispersal from a reactor damaged by fire or impact or no fuel release from an intact reactor.

In Phase 0, Prelaunch/Launch, possible accidents include a launch pad fire and explosion, SRB case rupture (T-6 to T-0 seconds), and vehicle breakup. It is assumed that all malfunctions are catastrophic, leading to explosions. Given the SP-100 reactor design approach and the results of preliminary design analyses showing that the reactor and its neutron absorber safety rods can withstand Shuttle explosion blast effects, as well as shrapnel and flyer plates, and maintain its subcritical configuration when immersed in water or buried in dry or wet sand, a critical configuration is an unlikely event (10^{-4} probability). However, a nominal damage probability of 0.01 is assumed in which some fuel release occurs, leaving approximately a 0.99 probability of having an intact reactor in a subcritical configuration. These three possible accident configurations are used consistently throughout this analysis, unless otherwise noted.

In Phase 1, Ascent/First Stage, the launch tower is cleared by the vehicle at T+2 seconds. Possible accidents include launch pad fire and explosion, launch tower impact, SRB case rupture, range destruct, and vehicle breakup. The Instantaneous Impact Point (IIP) is over land from T-0 to T+17 seconds, and over water from T+17 to T+128 seconds. During the later portions of this phase, contingency abort modes and return to landing site are possible. Again, as in Phase 0, all malfunctions are assumed to be catastrophic. The possible abort modes are neglected in this phase,

but their contribution to potential risks can be seen from the abort scenarios shown in Phase 2.

For Phase 2, Second Stage, there is the potential for a catastrophic vehicle breakup due to explosion. In addition, there is a probability of non-catastrophic malfunction that would permit the Orbiter to land safely, crash on landing, or ditch in the ocean. Crashes on landing may also result in tangential impacts of the reactor, with lower likelihood of failure. Because part of the track for the Phase passes over Africa, there is a proportional 0.15 probability of land impact.

For the Phase 3, On-Orbit, because of the possibility of human intervention to correct some malfunctions, there is an assumed low probability of 0.005 for failure to deploy the spacecraft from the Orbiter into a Shuttle orbit. If the SP-100 SRPS were not placed in orbit, it would result in an attempted landing of the Orbiter with the spacecraft onboard. It is also assumed that major system malfunctions are identified prior to deployment and are either corrected or the spacecraft is returned to earth in the Orbiter. The probabilities for these events are included in the branch for "failure to separate the spacecraft from the Shuttle." There is also a 0.001 probability of failing to start the reactor once it is deployed, leading to reentry of the cold reactor. In this case, no fission products would be generated and the cold reactor would survive reentry and impact with 0.01 probability of damage with some fuel release and 10^{-4} probability of reaching a critical configuration.

Phase 4, NEP, has been divided into low-orbit and high-orbit subphases. The high-orbit subphase is defined after 16 days, when the spacecraft will have reached an orbital lifetime in excess of 300 years, sufficient time for the decay of the significant onboard fission product inventory. Should the propulsion system or reactor fail before raising the spacecraft orbit to a high

orbit, there are probabilities of either having a recently operated reactor or an operating reactor reenter the Earth's atmosphere. Because of the high reliability of reactor shutdown coupled with the added assurance of shutdown to low power due to loss of coolant or partial safety rod insertion, failure to fully shut down the reactor is taken to be incredible (10^{-6}). Many different low, partial power conditions could result from the possible combinations of operating history and limited functioning of the control and safety systems. Because of the large available shutdown margin and the fact that only one safety rod or two to three control elements are sufficient to reduce power to very low levels, the range of possible reentry power levels and probabilities was characterized by a 1% power operation which represents an upper bound for the analysis of the operating reactor scenario.

Should a malfunction occur in high orbit, the reactor would have time to shut itself down by reactivity depletion at partial power even if the active control and safety systems completely failed to operate. Consequently, only reentry of a thermally cold reactor is a possible scenario. It is also reasonable to assume that the NEP unit can be designed in a manner to preclude long-term misdirected burns and prompt reentry of an operating reactor, since it only imparts low delta-V impulses resulting in gradual changes to the spacecraft velocity for long times. Real-time corrections will also reduce likelihood of prompt reentry. The probability of success for the NEP Phase is taken to be 0.97. The SP-100 SRPS is being designed to withstand anticipated space environments including micrometeoroids, debris, and electromagnetic radiation. It is anticipated that the NEP unit and mission module will be also designed to operate reliably, particularly in critical areas such as communication and control. Although these operational probabilities are judgmental, they are reasonable in light of the assumption that mission planners would not undertake the mission without a high probability of success.

3.2.3 Risk Analysis

The risk analysis for the propulsion portion of NEP Mission requires that representative values be chosen for the rapidly increasing orbital lifetime and linearly increasing radionuclide inventory. For an actual NEP Mission these would be determined by the reactor power level, spacecraft mass, specific impulse of the propulsion system and initial orbital altitude. For the hypothetical SP-100 powered NEP Mission, starting from a 300-km Shuttle orbit, the orbital lifetime increases from 25 days to 45 days at 325 km and 80 days at 350 km as shown in Figure 3-8. At approximately 800 km the orbital lifetime is 300 years. Although there is substantial uncertainty in these numbers due to actual sunspot activity at the time of the mission, these values are consistent with those shown in Reference 20.

The next parameter of importance is the orbit-raising capability of the propulsion system for the actual mission spacecraft. The 100-kw SP-100 NEP Mission described in Reference 13 shows that it requires 14 days, or an average of 77 km/day, to increase the orbital altitude from 925 km to 2000 km. Similarly, Reference 21 shows that for a 30-kw SP-100 NEP Mission from a Shuttle orbit, 10 days is required to raise the orbit from 300 km to 1400 km, or an average of 110 km/day. While neither of these mission profiles is the same as the profile described in Section 3.2.1, they are similar and support the conservative assumption of an average initial altitude increase of 25 km/day used for this risk assessment. Combining this orbit-raising capability with the altitude versus lifetime curve of Figure 3-8 yields the plot of orbital lifetime versus NEP operating time, shown in Figure 3-9.

Based on this curve, radionuclide inventories were computed for the following histories:

- 1 day operation, 45 days decay
- 2 days operation, 80 days decay
- 3 days operation, 130 days decay
- 4 days operation, 215 days decay
- 8 days operation, 1350 days decay
- 16 days operation, 292.7 years decay

Internal doses were evaluated for each of these inventories, and a maximum was observed at about 2 days of NEP operation. This was then used to characterize the low-orbit NEP portion of the mission. A similar trend was seen in Reference 21, but since the external dose (prompt) is more sensitive to short-lived nuclides, while the internal dose (50-year cumulative) is dominated by the longer-lived nuclides, the peak external dose was observed at about 1 to 2 days of NEP operation. Because the doses monotonically decrease as a function of operating time beyond the peak value, the 16-day operation followed by 292.7 years decay, typical of the 300-year orbit, was used to conservatively characterize the high-orbit NEP portion of the mission.

Radionuclide inventories specific to the Shuttle-launched NEP Mission were computed for the following scenarios:

Normal Operation

Low-orbit NEP - 2 days operation followed by 80 days shutdown in a 80-day orbit.

High-orbit NEP - 16 days operation followed by 292.7 years shutdown in a 300-year orbit.

On-Orbit Breakup

Low-orbit NEP - breakup in a 80-day orbit after 2 days at full power, at time of maximum fission product inventory.

FIGURE 3-8 ORBITAL LIFETIME OF SP-100 REFERENCE FLIGHT SYSTEM DESIGN - 100 kWE

FIGURE 3-9 NEP MISSION OPERATING CHARACTERISTICS

Mission Phase	Release Area		Path ID	Release Type	Operating History/Source Term Descriptor	Release Probability	Release Consequences, Person-rem	Risk, Person-rem Expectation
	Launch Area	Worldwide						
Prelaunch/Launch	Land	-	2	A	1	1.79E-06	6.37E-01	1.14E-06
	"	-	3	B	2	1.79E-08	3.72E+04	6.66E-04
Ascent/First Stage	-	Land	5	A	1	5.81E-06	6.37E-01	3.70E-06
	-	"	6	B	2	5.81E-08	3.72E+04	2.16E-03
	-	Ocean	8	A	1	3.79E-05	9.92E-06	3.76E-10
	-	"	9	B	2	3.79E-07	5.18E-04	1.96E-10
Second Stage	-	Land	11	A	1	2.25E-06	2.23E-01	5.02E-07
	-	"	12	B	2	2.25E-08	1.30E+04	2.93E-04
	-	Ocean	14	A	1	1.28E-05	7.57E-07	9.69E-12
	-	"	15	B	2	1.28E-07	3.93E-05	5.03E-12
	-	Land	16	A	1	8.82E-06	2.23E-01	1.97E-06
	-	"	18	B	2	1.80E-10	1.30E+04	2.34E-06
On-Orbit	-	Land	19	A	1	2.43E-04	6.37E-01	1.55E-04
	-	"	21	B	2	4.97E-09	3.72E+04	1.85E-04
	-	Ocean	23	A	1	7.02E-06	7.57E-07	5.31E-12
	-	"	24	B	1	7.02E-08	3.93E-05	2.76E-12
	-	Land	26	A	1	2.87E-06	5.02E-01	1.44E-06
	-	"	27	B	2	2.87E-08	2.93E+04	8.41E-04
NEP, Low-Orbit	-	Ocean	29	D	3	2.10E-04	1.29E-04	2.71E-08
	-	"	30	E	4	2.10E-06	7.23E-04	1.52E-09
	-	Land	31	Intact	3	8.51E-03	8.71E-06	7.41E-08
	-	"	32	D	3	8.59E-05	5.39E+03	4.63E-01
	-	"	33	E	4	8.59E-07	3.01E+04	2.59E-02
	-	"	34	F	5	8.56E-09	6.19E+04	5.30E-04
	-	Ocean	35	F	5	2.10E-08	1.37E-03	2.88E-11
	-	High Altitude/Land	36	G	6/3	8.59E-09	1.00E+03	8.59E-06
	-	High Altitude/Ocean	37	G	6/3	2.10E-08	6.70E+01	1.41E-06

Table 3-2 (Page 1 of 2)
Summary of Radiological Risks
for Shuttle-launched NEP Mission

Mission Phase	Release Location		Path ID	Release Type	Operating History/Source Term Descriptor	Release Probability	Release Consequences, Person-rem	Risk, Person-rem Expectation
	Launch Area	Worldwide						
NEP, High-Orbit	-	Ocean	39	D	7	1.02E-05	2.04	2.08E-05
	-	"	40	E	8	2.04E-06	1.17E-04	2.39E-10
	-	High Altitude/Ocean	41	G	9/7	2.04E-06	2.64E+02	5.39E-04
	-	Land	42	Intact	7	4.17E-04	1.21E-15	5.05E-09
	-	"	43	D	7	4.17E-04	1.23E-02	5.13E-06
	-	"	44	E	8	8.34E-07	1.92E+04	1.60E-02
	-	High Altitude/Land	45	G	9/7	8.34E-07	2.64E+02	2.20E-04
Mission Risk = 5.11E-01								

Operating History/Source Term Character

- 1 - Unfissioned fuel, t = 0
- 2 - Excursion/Unfissioned fuel, t = 0
- 3 - 2 day operation, 80 day shutdown, subcritical
- 4 - 2 day operation, 80 day shutdown, excursion
- 5 - 2 day operation, (100%), 80 days (1%), excursion
- 6 - 2 day operation
- 7 - 16 day operation, 300 years shutdown, subcritical
- 8 - 16 day operation, 300 years shutdown, excursion
- 9 - 16 day operation

Table 3-2 (Page 2 of 2)
Summary of Radiological Risks
for Shuttle-launched NEP Mission

Vapor and particulates reenter according to the atmospheric dispersion model, larger debris reenters after 80 days of decay in 80-day orbit.

High-orbit NEP - 16 days operation followed by 292.7 years shutdown in a 300-year orbit.

Failure to Shut Down

High-orbit NEP - 7.3 years at full power, gradual shutdown of 3.85 years at 75% power and 3.85 years at 25% power, followed by 285 years shutdown in 300-year orbit.

Reentry of Operating Reactor

2 day operation at full power, followed by 80 days at 1% power in 80-day orbit.

These inventories together with the unfissioned fuel inventories and the fission product inventory generated during a 100 megawatt-second excursion are identified for each path in Table 3-2 by "Operating History/Source Term Descriptors." Table 3-2 also identifies the "Release Type" used in the analysis for each path, as well as the respective path identifier and cumulative path probability taken from Figure 3-7. The health effect consequences calculated by the methodology discussed in Chapter 4 are tabulated for each path, both as population dose (person-rem) and as risk expectation value (person-rem multiplied by probability of occurrence).

3.3 Shuttle-Launched Low-Orbit Mission

3.3.1 Mission Description

The Low-Orbit Mission utilizes a spacecraft powered by the SP-100 SRPS previously described, launched by the Space Shuttle from Kennedy Space Center. The spacecraft with an unspecified

surveillance or communication function is attached to a booster stage and assumed to have a configuration similar to that shown in Figure 3-3 for the conceptual SP-100 NEP Mission. The launch profile for the Space Shuttle portion of this mission is identical to that shown previously in the NEP Mission, including placing the spacecraft and attached booster stage into a 300-km-high parking orbit. After deployment from the Space Shuttle the booster stage will raise the spacecraft to about a 700-km-high polar orbit with an estimated orbital lifetime of 50 years. Following separation from the booster stage, the reactor will be started up if an acceptable orbit has been attained. Following 7 years of operation the reactor will be shut down. It will then be boosted for permanent disposal using a low delta-V chemical or NEP stage.

The mission is divided into six phases as follows:

- Phase 0: Prelaunch/Launch - Begins with the liquid propellant fueling of the launch vehicle at T-8 hours and ends at T-0 seconds following ignition of the Space Shuttle Main Engines (SSMEs) and Solid Rocket Boosters (SRBs).
- Phase 1: Ascent/First Stage - From T-0 seconds to T+128 seconds, at which time SRB separation occurs.
- Phase 2: Second Stage - From T+128 seconds to T+532 seconds, at which time the External Tank (ET) separation occurs and the Orbiter reaches parking orbit.
- Phase 3: On-Orbit - From T+532 seconds or when parking orbit is reached until the spacecraft is deployed from the Orbiter and the reactor is started.
- Phase 4: Low-Orbit Operation - From reactor startup in its operational orbit until 6 months after reactor

shutdown. If reactor fails to actively shut down it is assumed that the reactor is allowed to gradually shut itself down, rather than to attempt to boost an operating reactor.

Phase 5: Post-Operation Disposal - From 6 months after reactor shutdown until reactor is successfully boosted for disposal.

Several alternatives are being considered to minimize risk to the environment after the reactor is shut down. These include leaving it in its operating orbit (if it is already in a long duration orbit); raising it to a higher orbit; or sending it out of Earth orbit entirely. The post-operation boost could be accomplished by a propulsion unit that is an integral part of the spacecraft or by a separate propulsion unit that would be attached to the spacecraft after its mission is completed. The ultimate choice will be based on the relative reliability of the technology options at the time of selection. With the overriding concern to maintain safety and to avoid risk to the environment, it is highly unlikely that a low-orbit mission as described in this section would be proposed unless a reliable disposal option was available. The tradeoff of reducing risk by raising the altitude of the operational orbit would always be available to the potential user.

3.3.2 Accident Scenarios and Probabilities

In performing the risk analysis, the accident scenarios and associated probabilities shown in Figure 3-10 are consistent with those previously discussed for the NEP mission in Section 3.2.2, and are identical for the first three phases; Pre-launch/Launch, Ascent/First Stage, Second Stage, and for the Shuttle portion of Phase 3, On-Orbit. In Figure 3-10 the path identifiers and cumulative path probabilities are tabulated in the right margin.

Figure 3-10
Shuttle-Launched Low Orbit Mission Failure Event Tree Summary
(Sheet 1 of 3)

Figure 3-10
Shuttle-Launched Low Orbit Mission Failure Event Tree Summary
(Sheet 2 of 3)

Figure 3-10
Shuttle-Launched Low Orbit Mission Failure Event Tree Summary
(Sheet 3 of 3)

In the On-Orbit Phase, from T+532 seconds, the spacecraft and propulsion module are deployed from the Orbiter to be boosted to low-Earth orbit with a 50-year lifetime. If the spacecraft and propulsion module are not fully deployed from the Shuttle (probability 0.005), or if a malfunction is detected prior to deployment, they may be returned to Earth with the Orbiter in normal or abnormal reentries with an attempted landing. The failures of concern once the spacecraft is successfully deployed are failure of the propulsion system to boost to operational orbit (probability 0.04), which would result in the early reentry of the unoperated reactor with high probability of intact impact, or an upperstage explosion sufficient to damage the reactor, resulting in reentry dispersal (10^{-4}) of some unirradiated fuel.

In the Low-Orbit Operation Phase, the reactor is in its planned operating orbit. Should the reactor fail to start, no fission products would be generated and the cold reactor is assumed to survive reentry and impact with 0.01 probability of minor damage resulting in some fuel release and 10^{-4} probability of reaching a critical configuration. Since these paths are essentially the same as for the "failure to boost to low orbit" paths, they have been combined for simplicity. Once the reactor is started, two failure scenarios are considered, failure to shut the reactor down, and loss of spacecraft control. Both result in the reentry of the previously operated reactor from the 50-year orbit. Because of the high reliability of reactor shutdown coupled with the added assurance of partial shutdown due to loss of coolant or partial safety rod insertion, failure to shut down the reactor is taken to be incredible (10^{-6}). Also, should a malfunction occur in low-Earth orbit, the reactor would have time to reduce power to very low (essentially zero) power levels by reactivity depletion at partial power during the 50-year orbital decay even if the active control and safety systems failed to operate. Therefore, the range of possible operating and decay scenarios has been characterized by a 7.3-year full power operation, a 3.85-year 75%

power operation, and a 3.85-year 25% power operation (representing a linear decrease from full to zero power over 7.7 years) followed by 35 years of radioactive decay. In this scenario the reactor would be slightly subcritical at impact and would undergo a self-terminating excursion and disassembly.

In the failure event tree for Phase 4, it was assumed that if the reactor could not be shut down, the mission controller would elect not to try to boost the operating reactor for disposal. For this scenario, since the reactor will be just subcritical when it re-enters, impact on land or water is assumed to result in a prompt self-limiting excursion and disassembly. In a specific mission this choice could be made to minimize risk, balancing the reliability of the boost system and boost alternatives against the decaying of the reactor power and its radioactive inventory over time. Other alternatives could be considered, such as delaying the boost for 10 years or more, until after the reactor has shut itself down, if a reliable boost system is available. The evaluation of these options is beyond the scope of this assessment, because it is mission specific.

In the Post-Operation Disposal Phase, the failure to boost has been assigned a probability of 0.001, because of the mission need for a highly reliable system. The possible failure modes have been characterized by a 0.99 probability of a malfunction resulting in delayed reentry and a 0.01 probability resulting in early reentry, based on the expectation that reliable low delta-V boost systems can be designed and built so that the probability of early reentry would be reduced substantially. The delayed reentry branch has been combined with the 50-year orbital decay branch of Phase 4, for simplicity. The early reentry branch of the recently operated reactor is assumed to have the same probabilities for damage and land/water impact as used previously.

3.3.3 Risk Analysis

Radionuclide inventories specific to the Shuttle-launched low-orbit mission were computed for the following scenarios:

Failure To Boost after Operation

Delayed reentry - 7.3 years at full power, followed by 42.7 years shutdown in the 50-year orbit.

Early reentry - 7.3 years at full power, followed by 0.5 years of decay before boost attempt.

On-Orbit Breakup

Breakup after 7.3 years at full power, at time of maximum fission product inventory. Vapor and particulates reenter according to the atmospheric dispersion model, larger debris reenters after 42.7 years of decay in the 50-year orbit.

Failure To Shut Down

7.3 years at full power, gradual shutdown of 3.85 years at 75% power and 3.85 years at 25% power, followed by 35 years shutdown in the 50-year orbit.

These inventories together with the unfissioned fuel inventories and the fission product inventory generated during a 100 megawatt-second excursion are identified for each path in Table 3-3 by "Operating History/Source Term Descriptors." Table 3-3 also identifies the "Release Type" used in the analysis for each path, as well as the respective path identifier and cumulative path probability taken from Figure 3-10. The health effect consequences calculated by the methodology discussed in Chapter 4 are tabulated for each path, both as population dose (person-rem) and as risk expectation value (person-rem multiplied by probability of occurrence).

Mission Phase	Release Area		Path ID	Release Type	Operating History/Source Term Descriptor	Release Probability	Release Consequences, Person-rem	Risk, Person-rem Expectation
	Launch Area	Worldwide						
Prelaunch/Launch	Land	-	2	A	1	1.79E-06	6.37E-01	1.14E-06
	"	-	3	B	2	1.79E-08	3.72E+04	6.66E-04
Ascent/First Stage	-	Land	5	A	1	5.80E-06	6.37E-01	3.69E-06
	-	"	6	B	2	5.80E-08	3.72E+04	2.16E-03
	-	Ocean	8	A	1	3.78E-05	9.92E-06	3.75E-10
	-	"	9	B	2	3.78E-07	5.18E-04	1.96E-10
Second Stage	-	Land	11	A	1	2.25E-06	2.23E-01	5.02E-07
	-	"	12	B	2	2.25E-08	1.30E+04	2.92E-04
	-	Ocean	14	A	1	1.28E-05	7.57E-07	9.69E-12
	-	"	15	B	2	1.28E-07	3.93E-05	5.03E-12
	-	Land	16	A	1	8.82E-06	2.23E-01	1.97E-06
	-	"	18	B	2	1.80E-10	1.30E+04	2.34E-06
On-Orbit	-	Land	19	A	1	2.43E-04	6.37E-01	1.55E-04
	-	"	21	B	2	4.97E-09	3.72E+04	1.85E-04
	-	High Altitude/Land	22	C	1	2.87E-05	6.37E+01	1.83E-03
	-	High Altitude/Ocean	23	C	1	7.02E-05	7.57E-05	5.31E-09
	-	Ocean	25	A	1	2.81E-04	7.57E-07	2.13E-11
	-	"	26	B	2	2.81E-06	3.93E-05	1.10E-10
	-	Land	28	A	1	1.15E-04	5.02E-01	5.77E-05
	-	"	29	B	2	1.15E-06	2.93E+04	3.37E-02
Low-Orbit	-	Ocean	31	A	1	6.74E-06	7.57E-07	5.10E-12
	-	"	32	B	2	6.74E-07	3.56E-05	2.40E-11
	-	Land	34	A	1	2.75E-06	3.88E-01	1.07E-06
	-	"	35	B	2	2.75E-07	2.27E+04	6.24E-03
	-	High Altitude/Land	36	G	3/5	2.75E-05	5.86E+04	1.61
	-	High Altitude/Ocean	37	G	3/5	6.74E-05	8.11E+02	5.47E-02
	-	Land	38	F	4	2.75E-07	2.72E+05	7.48E-02

Table 3-3 (Page 1 of 2)
Summary of Radiological Risks for
Shuttle-Launched Low-Orbit Mission

Mission Phase	Release Location		Path ID	Release Type	Operating History/Source Term Character	Release Probability	Release Consequences, Person-rem	Risk, Person-rem Expectation
	Launch Area	Worldwide						
Low-Orbit (Continued)	-	Ocean	39	F	4	6.74E-07	3.38E-01	2.28E-07
	-	"	41	D	5	6.74E-05	4.70E-02	3.17E-06
	-	"	42	E	6	6.74E-07	2.62E-01	1.77E-07
	-	Land	43	Intact	5	2.72E-03	2.33E-05	6.34E-08
	-	"	44	D	5	2.75E-05	3.80E+04	1.04
	-	"	45	E	6	2.75E-07	2.12E+05	5.83E-02
Post Operation	-	Ocean	47	D	5	6.60E-06	4.70E-02	3.10E-07
	-	"	48	E	6	6.60E-08	2.62E-01	1.73E-08
	-	Land	49	Intact	5	2.67E-04	2.33E-05	6.22E-09
	-	"	50	D	5	2.69E-06	3.80E+04	1.02E-01
	-	"	51	E	6	2.69E-08	2.12E+05	5.70E-03
	-	Ocean	53	D	7	6.66E-08	3.45E-04	2.30E-11
	-	"	54	E	8	6.66E-10	7.06E-01	4.70E-10
	-	High Altitude/Ocean	55	G	7	6.66E-10	1.02E+03	6.79E-07
	-	Land	56	Intact	7/5	2.69E-06	4.15E-04	1.12E-09
	-	"	57	D	7	2.72E-08	1.96E+03	5.33E-05
	-	"	58	E	8	2.72E-08	1.10E+04	2.99E-04
	-	High Altitude/Land	59	G	7/8	2.72E-10	1.68E+04	4.41E-06
Mission Risk = 3.00								

Operating History/Source Term Character

- 1 - Unfissioned fuel, t = 0
- 2 - Excursion/Unfissioned fuel, t = 0
- 3 - 7.3 years operation
- 4 - 7.3 years operation (100% power), 3.85 years (75%), 3.85 years (25%), 35 years shutdown
- 5 - 7.3 years operation, 42.7 years shutdown, subcritical
- 6 - 7.3 years operation, 42.7 years shutdown, excursion
- 7 - 7.3 years operation, 0.5 years shutdown, subcritical
- 8 - 7.3 years operation, 0.5 years shutdown, critical

Table 3-3 (Page 2 of 2)
Summary of Radiological Risks for
Shuttle-Launched Low-Orbit Mission

4.0 MISSION RISK ANALYSIS METHODOLOGY

The accident scenarios considered for each mission utilizing a space reactor power system could result in a radiological risk to the general population. Accident scenarios could release fuel and fission products that would be dispersed into the environment and could interact with the general population through various exposure pathways leading to inhalation, ingestion, and external radiological doses. Additionally, intact or dispersed reactor parts containing fuel or radioactive structure could produce external radiation exposure as could a reactor criticality accident. The methodology used in evaluating the radiological risk associated with the missions considered in this study is summarized in this section and described in detail in Reference 14.

The evaluation of the radiological impact of postulated scenarios involving fuel and fission product releases into the environment includes the following steps:

1. Identification of postulated accident release modes, including the probability of release and the release location
2. Source term definition, including the amount of each radionuclide released and the corresponding chemical form and particle size distribution
3. An analysis of the dispersion and time behavior of the released radioactivity to determine the concentrations in environmental media (air, soil, and water) as a function of time

4. An analysis of ingestion, inhalation and, external radiological doses through each environmental exposure pathway
5. An evaluation of the radiological impact in terms of the population doses received and the resulting health effects

These steps in the analysis are described further below. The results of applying this methodology to the three missions studied are found in Section 3.1.3, 3.2.3, and 3.3.3.

4.1 Accident Scenarios and Source Term Definition

Generic source terms for accident consequences that have the potential for releasing radioactive material to the environment were defined in Section 2.4. The accident scenarios and probabilities for each mission were developed in Section 3.0. The specific activity of each fuel and fission product radionuclide at the time of initial release was evaluated using the ORIGEN code⁽⁸⁾, and included the operating history of the reactor systems. To account for long-term behavior of released radionuclides in the environment, specific activities were also calculated for time steps from 10^2 second to 10^{11} seconds (over 3,000 years) following release.

4.2 Environmental Radionuclide Concentrations

Environmental concentrations for up to 150 radionuclides were calculated as a function of time for the following types of releases:

- o High-altitude vapor releases
- o High-altitude particulate releases
- o Low-altitude (including ground-level) releases
- o Aquatic releases

In order to account for the radiological impact over long time periods, the environmental concentrations due to a given release were calculated in 10 time steps ranging from 10^2 to 10^{11} seconds.

In evaluating population exposure pathways on a launch area and worldwide basis, information on the distribution of land, fresh water, ocean, population, and food supplies in the affected region was required. This information was based on that presented in the Overall Safety Manual, Volumes 2 and 3, for releases occurring in the Kennedy Space Center vicinity and on a worldwide basis⁽¹⁵⁾.

4.2.1 High-Altitude Vapor Releases

High-altitude vapor releases (particles less than or equal to 10 microns) result from partial or complete burnup due to reentry heating. The transport of such vapor is governed primarily by worldwide atmospheric circulation patterns. The atmosphere can be divided into three compartments: the mesosphere (45-km altitude), the stratosphere (10-45 km), and the troposphere (0-10 km).

Transport between these atmospheric compartments has been described in an approximate manner by an exponential box model, analogous to radioactive decay, in which a residence half-life is assigned to each compartment⁽¹⁴⁾. The residence half-lives used, based on fallout data derived from nuclear weapons testing, were 5 years, 1.4 years, and 10 days for the mesosphere, stratosphere, and troposphere, respectively. Latitudinal variation of the ground-level activity derived from the high-altitude release at a given latitude is also based on nuclear weapons fallout data.

For high-altitude vapor releases at a given latitude, the model predicts the normalized ground plane and airborne concentrations as a function of latitude and time after release.

4.2.2 High-Altitude Particulate Releases

High-altitude particulate releases (greater than 10 microns in diameter) can occur under the same conditions that result in high-altitude vapor releases described above. The resulting particulates will follow trajectories to the Earth's surface that are determined by the mass, size, and shape of each particle, the release altitude, as well as the winds and density profile of the atmosphere.

The atmospheric dispersion of such particulates released at high altitudes has been described in Reference 14. In this model, the trajectories of individual mass elements are determined based on the rate of change of latitude, longitude, and altitude due to local windspeed components and the terminal fall velocity of the particles. A particle size distribution typical of fractured fuel was used.

Inputting the release altitude and latitude, the model predicts the ground plane concentration as a function of affected area. Resuspension and weathering of ground plane deposition are taken into account.

4.2.3 Low-Altitude Releases

Low-altitude dispersion of fuel can result from ground-level releases following land impact or resuspension of activity previously deposited derived from both high- and low-altitude releases. Calculation of time-integrated airborne and ground concentrations resulting from low-altitude releases are based on the models presented in Reference 14.

4.2.4 Aquatic Releases

Aquatic transfer processes include the interaction of airborne dispersed activity and intact sources with water bodies. These interactions include fuel dissolution, transfers to sediment, and concurrent covering of intact sources by sedimentation and encrustation.

Average aquatic concentrations were calculated as a function of time for the 10 discrete time steps mentioned previously. The average concentrations were calculated based on reference volumes required to produce annual fish/seafood and drinking water to persons within the affected fallout area, accounting for the land/water fraction within the area.

4.3 Radiological Dose Calculations

Population doses were calculated for both dispersed fuel and intact source as described below.

4.3.1 Radiological Doses (Dispersed Fuel and Fission Products)

Radiological doses due to dispersed fuel were calculated in discrete time steps following the release using as inputs the results of the environmental concentration calculations described in the previous section. In performing the dose calculations, the average population density in the region coupled with the average radionuclide concentrations during each discrete time step following release are used to calculate the time-integrated population dose in terms of person-rem. This yields population dose, but no information on dose distribution such that a maximum individual dose can be identified. A computer code, TDOS, was developed by NUS to evaluate the doses in discrete time steps using the dose methodology presented in NRC Regulatory Guide 1.109(16). For population exposures during each time step, the

resulting 50-year integrated dose commitments were evaluated for the following pathways:

- o Inhalation
- o Cloud immersion
- o Ground plane radiation
- o Vegetation ingestion
- o Meat ingestion
- o Milk ingestion
- o Water ingestion
- o Aquatic foods ingestion

Resulting health effects, as described in Section 4.4 are also calculated by TDOS⁽¹⁷⁾.

4.3.2 Radiological Doses (Intact Sources)

Radiological doses due to external radiation from intact reactor configurations have been evaluated based on the radiation dose levels calculated for the SP-100 for various operating and shutdown periods as reported in Reference 18. An expectation approach to population exposure, similar to that described in Chapter 7 of Reference 20, was taken based on the population density in the affected area. An expectation radius from the source to the first person was based on the average area per person. The radii of subsequent persons were calculated in a similar manner.

For the mission profiles considered, external radiation dose from intact reactor components following land impact was found not to be a large contributor to the reported population dose for several reasons. First, the reactor shutdown period prior to reentry allowed sufficient decay to reduce external radiation to relatively low levels. Second, population exposure to intact reactor sources was limited to 24 hours, considered sufficient

time for authorities to locate, evaluate, and cordon off the impact area. Thus, the doses due to atmospherically dispersed fission products were found to dominate the risks because of the potential lifetime (50-year) exposure of the general population to the residual radioactivity.

4.4 Radiological Health Effects

Health effects could be associated with radiological doses resulting from dispersed fuel and intact sources. A linear dose response model was used in evaluating long-term population effects based on the NAS-NRC Committee on the Biological Effects of Ionizing Radiation (BEIR) as presented in the BEIR III report⁽¹⁹⁾. The linear dose response model assumes the health effects, in terms of excess cancer fatalities, are proportional to the dose, even for vanishingly small doses. Excess cancer fatalities in this case means those that would occur in addition to the normal incidence of cancer fatalities. The health effects estimator used in this analysis, based on BEIR III, was 120 excess cancer fatalities per million person-rem. If one accepts the concept of de minimis, a dose level below which no health effects occur (on the order of 1 mrem/yr), the calculated health effects would be lower than would be the case when a linear dose response model were used as in the present analysis.

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