

manned space flight nuclear system safety

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Volume III

REACTOR SYSTEM PRELIMINARY NUCLEAR SAFETY ANALYSIS

Part 3

NUCLEAR SAFETY ANALYSIS DOCUMENT (NSAD)



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JANUARY 1972

FINAL REPORT
MANNED SPACE FLIGHT NUCLEAR SYSTEM SAFETY

VOLUME III — REACTOR SYSTEM PRELIMINARY
NUCLEAR SAFETY ANALYSIS

PART 3 — NUCLEAR SAFETY ANALYSIS
DOCUMENT (NSAD)

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FOR
NATIONAL AERONAUTICS AND SPACE ADMINISTRATION
GEORGE C. MARSHALL SPACE FLIGHT CENTER
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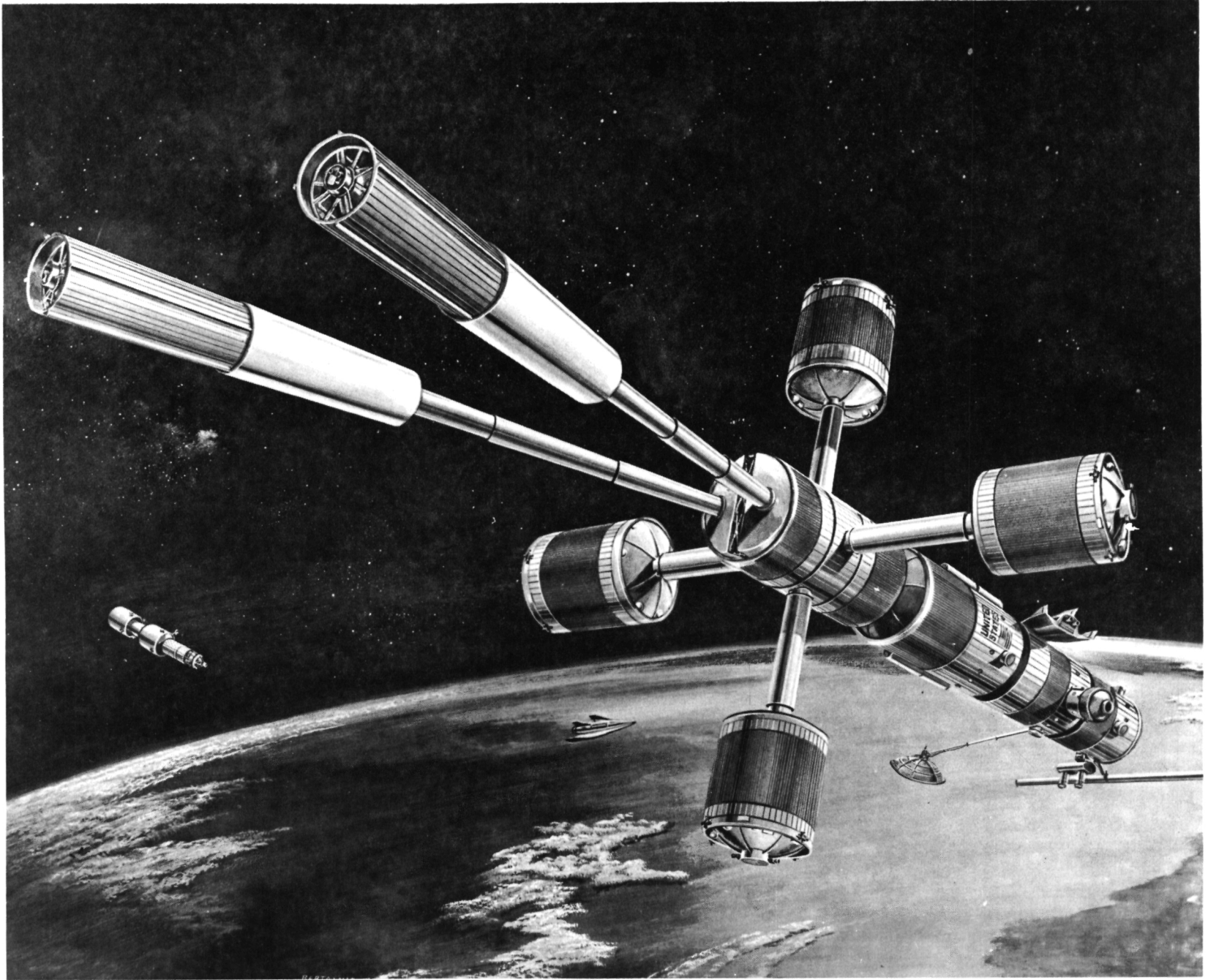
ABSTRACT

The Nuclear Safety Analysis Document (Volume III Part 3) is one of three documents of the Preliminary Safety Analysis Report (PSAR) - Reactor System as applied to a Space Base program.

The NSAD summarizes the mission and the credible accidents/events which may lead to nuclear hazards to the general public. The radiological effects and associated consequences of the hazards are discussed in detail. The probability of occurrence is combined with the potential number of individuals exposed to or above guideline values to provide a measure of accident and total mission risk.

The overall mission risk has been determined to be low with the potential exposure to or above 25 rem limited to less than 4 individuals per every 1000 missions performed. No radiological risk to the general public occurs during the prelaunch phase at KSC. The most significant risks occur from prolonged exposure to reactor debris following land impact generally associated with the disposal phase of the mission where fission product inventories can be high.

Safeguards such as positive tracking and location devices or recovery by the Space Shuttle can further reduce overall risk. The end of mission risk from a destructive excursion or quasi-steady state operation can be substantially reduced by providing for a permanent shutdown of the reactor prior to disposal.



FOREWORD

The establishment and operation of large manned space facilities in earth orbit would constitute a significant step forward in space. Such long duration programs with orbital stay times of up to ten years would benefit the earth's populace and the scientific community by providing:

1. A flexible tool for scientific research.
2. A permanent base for earth oriented applications.
3. A foundation for the future exploration of our universe.

Specifically, the NASA objectives include earth surveys and scientific disciplines of astronomy, bioscience, chemistry, physics and biomedicine, as well as the development of technology for space and earth applications.

Operational and design requirements, of large manned space vehicles, differ from those of the Mercury, Gemini, and Apollo programs. Of particular interest are the radiation survivability and nuclear safety requirements imposed by nuclear power reactors and isotopes and the long term interaction with the natural radiation environment.

The General Electric Company under contract to NASA-MSFC (NAS8-26283) has performed a study entitled "Space Base Nuclear System Safety" for the express purposes of addressing the nuclear considerations involved in manned earth orbital missions. The study addresses both operational and general earth populace and ecological nuclear safety aspects. The primary objective is to identify and evaluate the potential and inherent radiological hazards associated with such missions and recommend approaches for hazard elimination or reduction of risk.

Work performed utilized the Phase A Space Base designs developed for NASA by North American Rockwell and McDonnell Douglas as baseline documentation.

The study was sponsored jointly by NASA's Office of Manned Space Flight, Office of Advanced Research and Technology, and Aerospace Safety Research and Data Institute. It was performed for NASA's George C. Marshall Space Flight Center under the direction of Mr. Walter H. Stafford of the Advanced Systems Analysis Office. He was assisted by a joint NASA and AEC advisory group, chaired by Mr. Herbert Schaefer of NASA's Office of Manned Space Flight.

The results of the study are presented in seven volumes, the titles of which are listed in Table A. A cross-reference matrix of the subjects covered in the various volumes is presented in Table B.

Table A. Manned Space Flight Nuclear System Safety Documentation

<u>Volume</u>		<u>Document No.</u>
I	Executive Summary	
Part 1	Space Base Nuclear Safety	72SD4201-1-1
Part 2	Space Shuttle Nuclear Safety	72SD4201-1-2
II	Space Base Preliminary Nuclear Safety Analysis	
Part 1	Nuclear Safety Analysis (PSAR)	72SD4201-2-1
Part 1A	Appendix-Alternate Reactor Data (CRD)	72SD4201-2-1A
III	Reactor System Preliminary Nuclear Safety Analysis	
Part 1	Reference Design Document (RDD)	72SD4201-3-1
Part 2	Accident Model Document (AMD)	72SD4201-3-2
Part 2A	Accident Model Document - Appendix	72SD4201-3-2A
Part 3	Nuclear Safety Analysis Document (NSAD)	72SD4201-3-3
IV	Space Shuttle Nuclear System Transportation	
Part 1	Space Shuttle Nuclear Safety	72SD4201-4-1
Part 2	Terrestrial Nuclear Safety Analysis	72SD4201-4-2
V	Nuclear System Safety Guidelines	
Part 1	Space Base Nuclear Safety	72SD4201-5-1
Part 2	Space Shuttle/Nuclear Payloads Safety	72SD4201-5-2
VI	Space Base Nuclear System Safety Plan	72SD4201-6
VII	Literature Review	
Part 1	Literature Search and Evaluation	72SD4201-7-1
Part 2	ASRDI Forms	72SD4201-7-2*

*Limited distribution

This study employs the International system of units and where appropriate the equivalent English units are specified in brackets. A list of Conversion Factors and a Glossary of Terms is included in the back of each volume.

Table B. Study Area Cross Reference

	DOCUMENTATION						
	VOL I	VOL II	VOL III	VOL IV	VOL V	VOL VI	VOL VII
	72SD4201-1 Part 1 Space Base - Executive Summary Part 2 Space Shuttle - Executive Summary	72SD4201-2 Part 1 PSAR-Space Base Part 2 Appendix (CRD)	72SD4201-3 Part 1 RDD-Reactor System, Space Base Part 2 AMD-Reactor System Part 2A AMD Appendix Part 3 NSAD-Reactor System	72SD4201-4 Part 1 Space Shuttle Nuclear Safety Part 2 Terrestrial Nuclear Safety Analysis	72SD4201-5 Part 1 Guidelines - Space Base Part 2 Guidelines - Space Shuttle	72SD4201-6 System Safety Plan	72SD4201-7 Part 1 Literature Search and Evaluation Part 2 ASRDI Forms
* <input type="checkbox"/> 4 PRIMARY DISCUSSION							
<input type="radio"/> SUMMARY OR SUPPLEMENTAL DISCUSSION							
*Section number is included where appropriate							
STUDY AREAS							
SPACE BASE PROGRAM							
Reference Vehicle Data	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>
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Radiation Environment/Hazards	<input type="radio"/>	<input type="checkbox"/> 6 <input type="checkbox"/> 6, A	<input type="checkbox"/> 3-5	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/> 5
Radiation Effects	<input type="radio"/>	<input type="checkbox"/> 5	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/> 6
Mission Support Nuclear Safety	<input type="radio"/>	<input type="checkbox"/> 6, 7	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>
Orbital Operations Nuclear Safety	<input type="radio"/>	<input type="checkbox"/> 5, 7	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>
Design & Operational Considerations	<input type="radio"/>	<input type="checkbox"/> 7	<input type="radio"/>	<input type="radio"/>	<input type="checkbox"/>	<input type="radio"/>	<input type="radio"/> 5
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SPACE SHUTTLE PROGRAM							
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Nuclear Payload Integration	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>
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LITERATURE REVIEW DATA							
Approach and Cross Index	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="checkbox"/>
ASRDI Forms	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="checkbox"/>

ABBREVIATIONS

ADM	Add-on Disposal Modules	IRV	Isotope Re-Entry Vehicle	PCS	Power Conversion System
AEC	Atomic Energy Commission	IU	Instrument Unit	PM	Power Module
ALS	Advanced Logistic System (Space Shuttle)	IVA	Intra Vehicular Activity	PSAR	Preliminary Safety Analysis Report
AMD	Accident Model Document	KSC	Kennedy Space Center	RAD	Radiation Absorbed Dose
ASRDI	Aerospace Safety Research Data Institute	LCC	Launch Control Center	RCS	Reaction Control System
BOL	Beginning of Life	LD	Lethal Dose (% Probability)	RDD	Reference Design Document
BPCL	Brayton Power Conversion Loop	LOX	Liquid Oxygen	REM	Roentgen Equivalent Man
BRU	Brayton Rotating Unit	LV	Launch Vehicle	RMU	Remote Maneuvering Unit
DOD	Department of Defense	MCC	Mission Control Center	RNS	Reusable Nuclear Shuttle
DOT	Department of Transportation	MDAC	McDonnell Douglas Corporation	R/S	Reactor/Shield
ECLS	Environmental Control and Life Support	MHW	Multi-Hundred Watt	RSO	Radiation Safety Officer
EM	Electro Magnetic	ML	Mobile Launcher	RTG	Radioisotope Thermoelectric Generator
EOD	Earth Orbital Decay	MPC	Maximum Permissible Concentration	SB	Space Base
EOL	End of Life	MSC	Manned Spacecraft Center	SAR	Safety Analysis Report
EOM	End-of-Mission	MSFC	Marshall Space Flight Center	SEHX	Separable Heat Exchanger
EPS	Electrical Power System	MSS	Mobile Service Structure	S-IC	First Stage of Saturn V
ETR	Eastern Test Range	NA	Non-Applicable	S-II	Second Stage of Saturn V
EVA	Extra Vehicular Activity	NAB	Nuclear Assembly Building	SNAP	Space Nuclear Auxiliary Power
FC	Fuel Capsule	NAR	North American Rockwell	SNAPTRAN	Space Nuclear Auxiliary Power Transient
FPE	Functional Program Element	NASA	National Aeronautics and Space Administration	TAC	Turbine Alternator Compressor
G&C	Guidance and Control	NC	Non-Credible	TEM	Thermoelectric Electro Magnetic Pump
GSE	Ground Support Equipment	NCRP	National Committee on Radiation Protection	TLD	Thermo Luminescent Dosimeter
HX	Heat Exchanger	NSAD	Nuclear Safety Analysis Document	USAF	United States Air Force
ICRP	International Committee on Radiation Protection	OPSD	Orbital Propellant Storage Depot	VAB	Vehicle Assembly Building
IDM	Integral Disposal Module	ORNL	Oak Ridge National Laboratory		
INT-21	Intermediate Saturn Stages				
IR	Infrared				

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SECTION I

INTRODUCTION

The Preliminary Safety Analysis Report (PSAR) - Reactor System presents a preliminary but comprehensive assessment of public and ecological safety of the Zirconium Hydride (ZrH) Brayton cycle reactor electrical power system as applied to a Space Base Program. The reference power system hereafter referred to as the reactor power module was derived from the Phase A Space Base studies recently performed for NASA by McDonnell Douglas Corporation (MDAC) and North American Rockwell (NAR) (References 1-1 and 1-2).

Results of the analysis have led to the conclusion that the use of a reactor power module in space operations can present a low risk to the general public. Although specific risk values are presented, the intent is to provide a reference from which future configuration changes (affecting failure modes, probabilities, source terms, etc.) can be factored into the analysis. Therefore, the results of this study can serve as a point of departure for the nuclear safety analysis of reactor power modules on future manned space missions.

The PSAR is presented in three separate documents as follows:

Volume III, Part 1 - Reference Design Document (RDD)

Volume III, Part 2 - Accident Model Document (AMD)

Volume III, Part 3 - Nuclear Safety Analysis Document (NSAD)

Figure 1-1 illustrates the basic logic and structure of the PSAR. The Nuclear Safety Analysis Document (NSAD) is contained in this volume. The NSAD describes the radiological consequences of credible events/accidents that lead to the release of radioactive materials or to radiation exposure to the general public and ecological system. The radiological consequences are determined by radiation exposure and risk calculations. The reference mission is discussed in some detail to emphasize the built-in safeguard design and operational features and indicate where additional safety considerations can be applied to further reduce the risk.

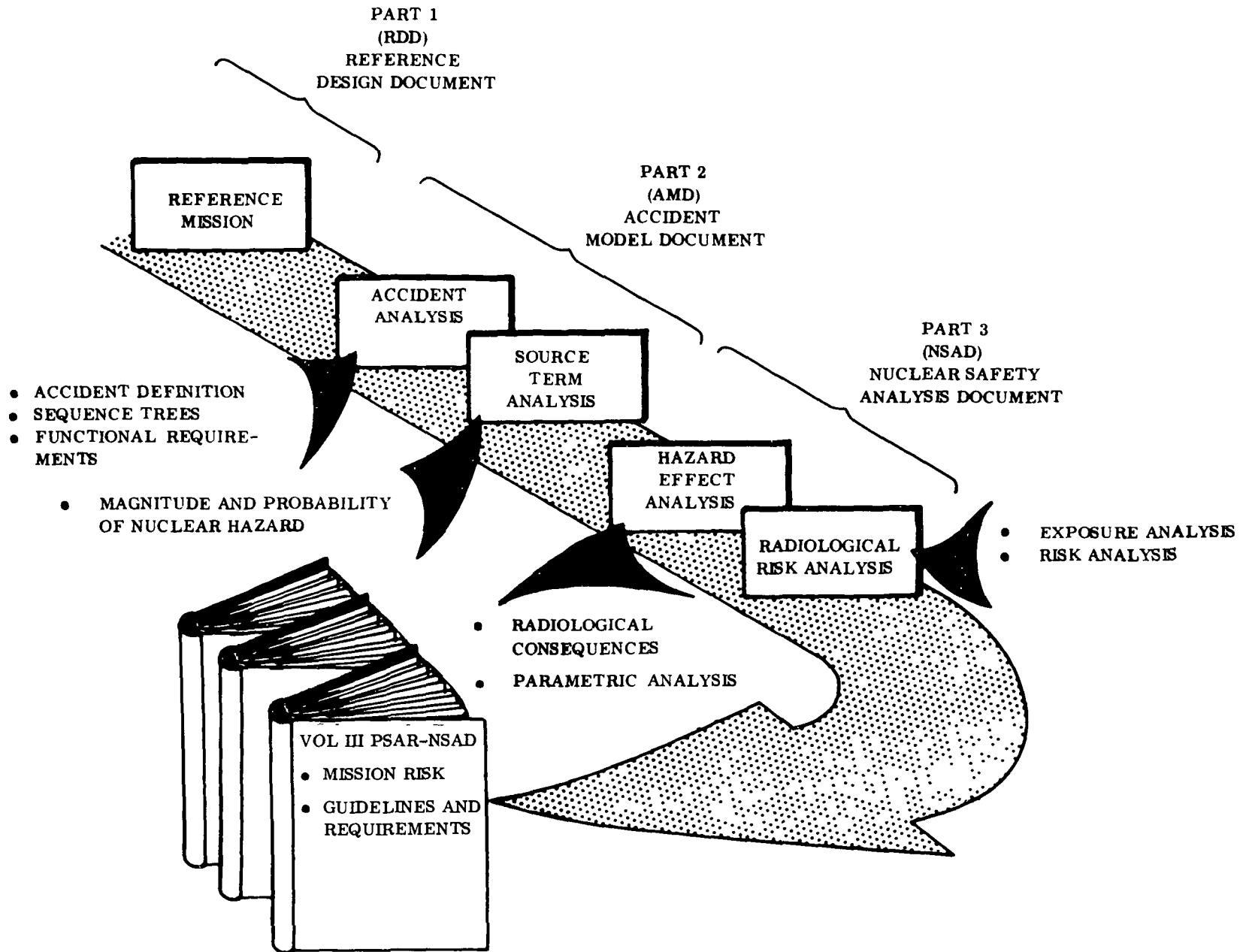


Figure 1-1. Terrestrial Nuclear Safety Analysis Approach

The RDD and AMD supplement the NSAD. The RDD contains a description of: (1) safety related systems, subsystems, and components; (2) the mission; and (3) the supporting facilities and operations necessary to accomplish the mission. The AMD serves to identify the occurrence and probability of events and failures which can lead to public nuclear safety hazards and establish the radiological source terms characterizing the nuclear hazard.

The NSAD is organized as follows. Section 2 provides a brief description of the approach used in the safety analysis leading to the identification of the radiological risk involved in performing the mission. Summary data of the reference mission and power module is contained in Section 3. The radiological consequences of mission accidents (hazard effects) are presented in Section 4. This data is combined with accident probabilities and source terms in Section 5 to provide a determination of the accident and total mission risk to the general public. Some of the primary data of the safety analysis is presented parametrically in Section 6 to permit an evaluation of the sensitivity of the results presented in Sections 4 and 5 to changes in conditions and basic assumptions. Mission accident characteristics, source terms, probabilities and radiological exposure models are contained in the appendices.

As intended, the analysis is only concerned with public rather than crew safety. Crew safety is addressed in the Space Base PSAR - Volume II, Part 1, 72SD4201-2-1.

REFERENCES

- 1-1. "Space Base Concept Data"; MDC GO576 prepared under contract NAS 8-25140; McDonnell Douglas Corporation; June 1970.
- 1-2. "Space Base Definition"; SD70-160 prepared under contract NAS 9-9953; North American Rockwell; July 1970.

SECTION 2

SAFETY ANALYSIS APPROACH

2.1 GENERAL

The fundamental terrestrial nuclear safety objectives in the application of nuclear reactors to a Space Base Program are (1) the prohibition of any radiation exposure to the general public during normal mission operations and (2) insurance that the general public will not be subjected to any significant radiation risk when considering all credible accident conditions.

To conform to these rigid requirements, the following design objectives are necessary:

1. The reactor should be inherently safe when exposed to accident conditions (i. e., no criticality accidents from core compaction, control drum rotation, water moderation or spurious control system malfunction).
2. The reactor operation history prior to launch should be limited to minimize the fission product inventory in the core at the time of launch.
3. At the completion of the operational phase, the reactor should be safely disposed of or recovered. A boost to a high long-lived orbit to permit sufficient time for fission product decay prior to a potential uncontrolled reentry due to orbital decay and subsequent earth impact is considered the primary disposal mode for the analysis.

Accidents can occur which may subject the reactor to environments beyond the limitations of its components and result in potential exposure to the populace. When subjected to certain accident environments, containment of fission products cannot be assured. Identification of all accidents and failure modes which could lead to radiation exposures is required to assess the risk involved in utilizing the reactor for its intended mission. The exposure modes to the general population from potential accidents are:

1. Direct exposure from reactor prompt radiation and radioactive materials.
2. Internal exposure from inhalation of radioactive materials.
3. Internal exposure from ingestion of radioactive materials.

2.2 APPROACH

Figure 1-1 illustrates the overall approach followed for the terrestrial safety evaluation. The "reference mission", presented in the RDD, was subjected to an "Accident Analysis" to identify all possible launch vehicle and reactor power module failures which may endanger the safety of the reactor. Potential failure modes of the reactor power module which may result in the escape of fission products, radioactive debris, or in radiation exposure to the general public were identified. Where appropriate, analytical models were developed to describe the severity of the resulting accident and to determine the response of the reactor to the imposed failure mode.

The environment into which the fission products are released determines the means by which the released fission products are dispersed and the overall extent of contamination. Ground level releases of fission products result in a local distribution of activity, whereas the fission products which are released to the upper atmosphere are distributed over most of the Earth's surface at a very low concentration.

The quantity, type and location of fission products which may be released in each accident are called "Source Terms". These source terms, as well as the source term probabilities, were determined for all identified accidents and reactor power module failure modes. This data, presented in the AMD, together with specified release environments were used to determine (1) the associated "Hazard Effects" (radiological consequences) and (2) the "Radiological Risk" to the general public. This document is primarily concerned with these two areas. The general approach taken in these analyses is shown in Figure 2-1 and discussed in the following two subsections.

2.2.1 HAZARD EFFECT ANALYSIS

The consequences associated with a given accident/event are directly related to the responses of the reactor power module. These potential responses are identified along with their relative probability of occurrence on the Abort Sequence Trees presented in Appendix D of the AMD. Using the source terms developed, calculations are then made of the direct and indirect doses to the whole body versus distance for each given accident. This dose

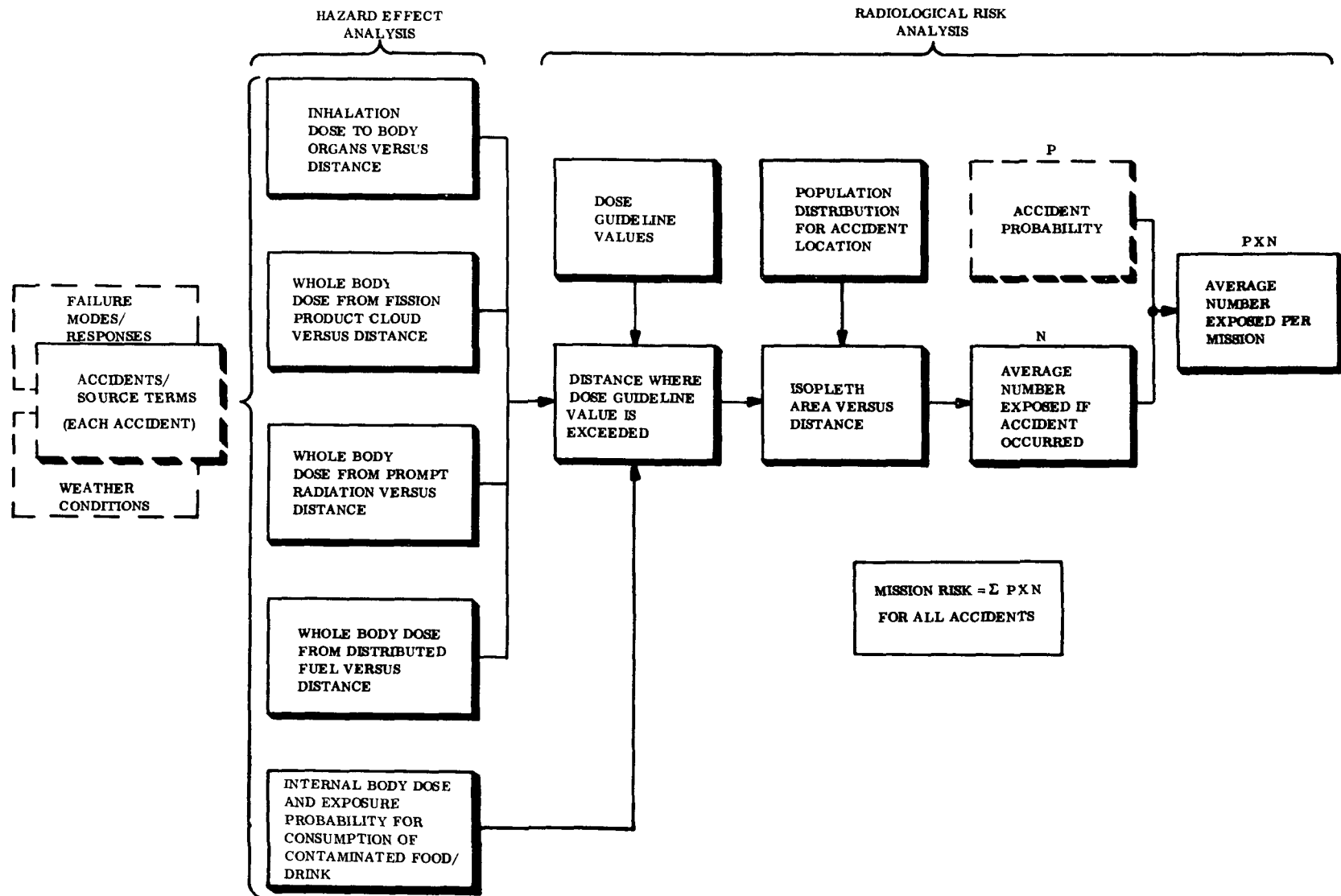


Figure 2-1. Hazard Effect and Radiological Risk Analysis

data, which is very sensitive to weather conditions and release altitude, provides the isopleth areas associated with each accident. In general, worst case Pasqual F conditions were assumed (Figure 2-2). The sensitivity to weather is treated parametrically in Section 6. When combined with potential accident locations (related to population density), the calculation of the average number of people exposed to a given accident, can be made.

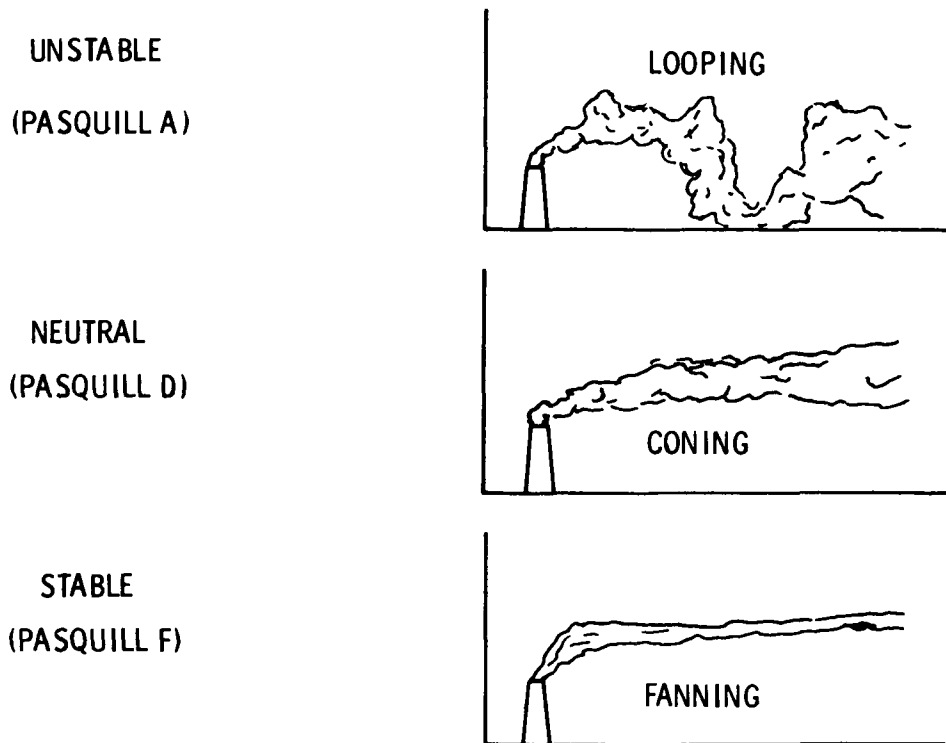


Figure 2-2. Weather Conditions

2.2.2 RADIOLOGICAL RISK ANALYSIS

For a realistic radiological risk assessment, it is necessary to consider the probability (P) and the number of people exposed (N) to the radiation hazards resulting from all potential accidents during the entire mission.

2.2.2.1 Radiation Dose Criteria

The number of people considered exposed is based on the use of dose "guideline" values (an individual exposed to a "guideline" dose or above is considered exposed). However, since the dose guideline is a threshold value, any individual exposed to less than this value is not considered exposed. The guideline values used (Table 2-1) are the same as those employed on previous SNAP-10A and SNAP-8 safety evaluations.

Table 2-1. Dose Guideline Values

Body Organ	Dose Guideline Values - Rem
Whole Body	25
Thyroid	300
Bone (70-year)	150
Lower Large Intestine	75

At these levels there are normally no detectable clinical effects. Although injury may occur at below the dose guideline values, its probability is quite low (Reference 1).

The whole body and thyroid dose guideline values given in Table 2-1 are derived from commercial nuclear reactor power plant siting criteria as specified in the Code of Federal Regulations 10CFR100 (Reference 2). The bone and lower large intestine dose guideline values are from the Department of Materials and Licensing (DML-Docket 50-268) (Reference 3).

2.2.2.2 Application of the Probabilistic Philosophy

Space nuclear power systems safety analyses have been based on a statistical approach. In evaluating the nuclear power system for a Space Base Program, it was necessary to describe as completely as possible the hazards associated with the planned mission and to estimate the probabilities of their occurrences. The risk associated with each accident is taken as the product of the number of people exposed (N) to dose guideline values as a result of a specific accident and the probability of exposure from that accident (P) (Figure 2-2). The mission risk is the summation of these products for all the accidents in the mission ($= \sum P \times N$ for all mission accidents).

2.2.2.3 Determination of Risk

The risk to the general public incurred by a release of radioactive material or by an excessive radiation exposure was assessed through the use of an exposure index calculated for each potential radiation exposure event. The exposure index is defined as the average number of

people who may be exposed to the dose guideline values specified in Table 2-1 for each radiation exposure event in the mission. The objective of this evaluation was to provide the information required for a risk versus benefit decision for flight approval.

In addition, since all potential accidents are considered, the relative risk of each accident was designated. The most hazardous/high risk accidents could then be carefully evaluated to determine additional safeguards to improve system safety.

2.3 REFERENCES

- 2-1 C.A. Willis, "Radiological Aspects of Reentry Burnup of SNAP Reactors", NAA-SR-11761, North American Aviation-Atomics International, March 25, 1966.
- 2-2 "Code of Federal Regulations" 10CFR100, U.S. Atomic Energy Commission.
- 2-3 DML-Docket 50-268, Department of Materials and Licensing, U.S. Atomic Energy Commission.

SECTION 3

NOMINAL MISSION

3.1 SYSTEM DESCRIPTION (SUMMARY)

The Space Base electrical power is supplied by two independent zirconium hydride (ZrH) nuclear reactors. A detailed description is provided in Volume III Part 1. Each reactor is rated at 600 kWt and normally operates at 330 kWt. Three Brayton Power Conversion Systems (PCS) are coupled to each reactor with one in operation and the remaining two on stand-by. During normal operation, 50 kW of net electrical power is obtained from one Brayton system.

Nominal lifetime of the reactor is five years while that of each PCS is assumed to be 2.5 years. The reference zirconium hydride reactor shown in Figure 3-1 is completely surrounded by shielding. The reactor core, 0.29 meters in diameter, contains 295 fuel elements supported in a triangular pitch array. The fuel elements consist of a uranium zirconium alloy with a composition of 10.5 weight percent fully enriched uranium. The alloy is massively hydrided, 6.3×10^{22} atoms/cm³ to provide neutron moderation. The fuel element cladding, which is a 0.38 mm (0.015 in.) thick nickel alloy tube, protects the fuel from the NaK coolant and also contains the fission products and hydrogen moderator.

The reactor is controlled by ten control drums which surround the core. Rotation of the drums varies the amount of neutron reflection into the core and thus provides reactor control. This is accomplished by utilizing control drums that are composed of a neutron-reflective material (BeO) on one side and an absorber material (Ta-10W) on the other. Drum rotation is produced by a stepper motor operating through an integral gear set with a 6:1 ratio. In the fully shutdown position, the gear teeth are disengaged by an electrically operated cam lockout device to prevent drum rotation due to launch acceleration.

A prepoison (Gadolinium-155) is used in the core to reduce the reactivity variation during the planned lifetime to less than the $\$9.00$ control provided by the control drums. As nuclear operation proceeds, reactivity losses occur due to uranium burnup, fission product accumulation, and hydrogen loss from the fuel elements. The prepoison is consumed during operation and provides reactivity compensation.

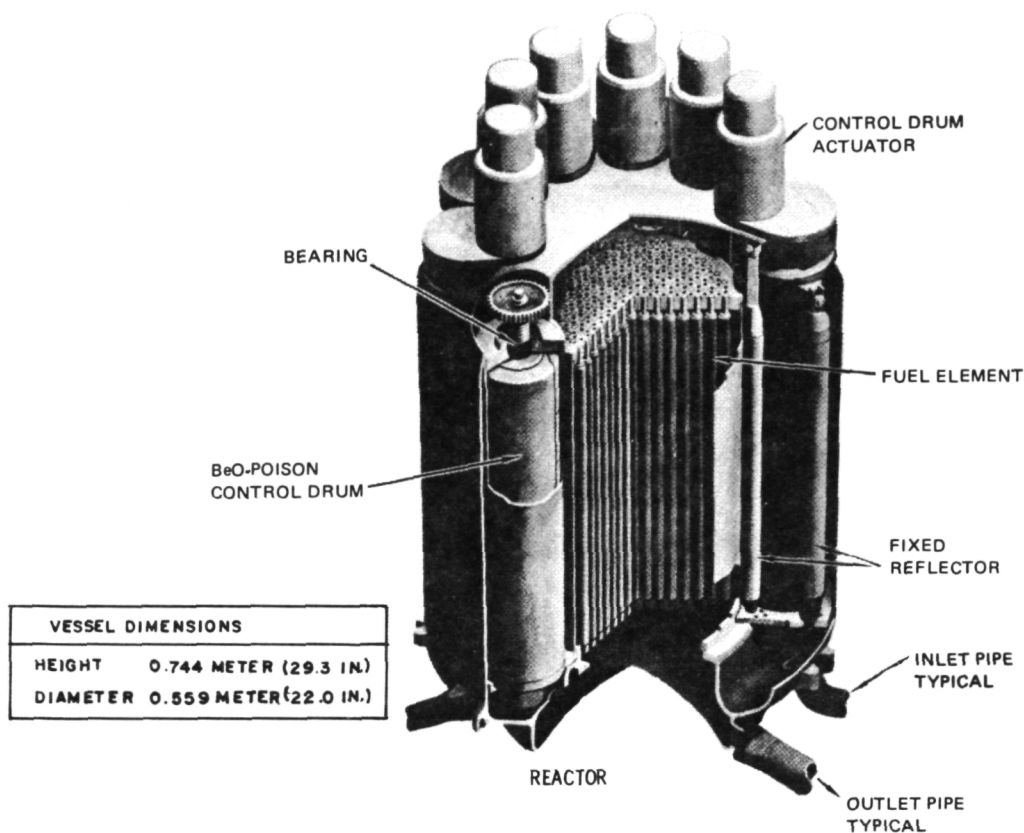


Figure 3-1. Reference Zirconium Hydride Reactor

The reactor power modules are assumed to be launched from Complex 39 at Kennedy Space Center. An Interim-21 launch vehicle will boost the reactor power systems to rendezvous with the Space Base that has been previously launched into a 500 km (273 nm) earth orbit. Space tugs will withdraw the reactor power modules from the payload shroud, and dock them to the Space Base. Each reactor will be brought to power (330 kWt) to provide the required 100 kWe to the Space Base. At the completion of five years operation or at the end of lifetime, each reactor will be shutdown, separated from the Space Base, and inserted into a 990 km (535 nm) circular orbit with the disposal propulsion system. The high orbit disposal permits essentially complete decay of the fission product inventory prior to eventual earth impact. The disposal orbit decay life is over 1100 years.

3.2 MISSION PHASES

A brief description of the four mission phases (Prelaunch, Launch/Ascent, Orbital Operations, and End of Mission Reactor Disposal) is presented below.

3.2.1 PRELAUNCH - PHASE I

The Prelaunch Phase includes the following activities:

1. Transportation
2. Receipt, inspection and storage
3. Prelaunch checkout and assembly
4. Launch vehicle/payload integration and test
5. Launch complex/range integration and test
6. Countdown

3.2.1.1 Transportation

The transportation of the reactor power module to KSC will be accomplished in such a manner that the power module is nearly in a completely assembled configuration. Separable sections of the radiator and shield are permitted if liquid metal lines are not broken. The power module will be shipped in an environmentally controlled shipping container "transporter" which provides the proper monitoring equipment. Prior reactor operation at the manufacturing facility shall be limited to low power critical testing to minimize the buildup of a core fission product inventory.

The power module within its transporter, will be off-loaded from the transport vehicle which may be a plane, railcar or barge, and transported to the Nuclear Assembly Building (NAB) for receipt inspection.

Three reactor power modules will be delivered to KSC, two for the launch and one as a back-up. The delivery schedule for the three reactors is ninety days, sixty days and forty-five days prior to launch.

3.2.1.2 Receipt, Inspection and Storage

The transporter and power module will receive a comprehensive receiving inspection for proper configuration, visual damage, and monitoring of instruments designed to record shock loads and environmental conditions such as humidity, air chemical composition and radiation. A detailed inspection is made for visual damage, fluid leaks, system integrity and electrical harness and umbilical connections. Provisions must be made for the discharging and purging of the liquid metal systems such that if a leak were detected, the system can be properly prepared for safe shipment back to the manufacturing facility. Reactor control safety devices are checked.

Provision for storage of three power modules shall be required for storage times of at least one year. During the operational mission, a minimum of two replacement power modules are stored in a ready condition.

3.2.1.3 Prelaunch Checkout and Assembly

Prelaunch checkout takes place prior to booster integration or placement into storage and consists of a series of subsystem verification tests to assure the integrity and functional operation of the power module. Pressure and leak tests will be made and the power module coolant system will be operated to verify functioning of the PCS, valves, EM pumps, and fluid lines. Electrical connections and harnesses will receive continuity tests. Each reactor control drum shall be checked to verify operation and response characteristics. Mechanical interlocks and detailed procedures are used to eliminate the possibility of start-up. No criticality tests are made at KSC (limited reactor power operation at manufacturer's facility is permitted).

Power module systems tests will be performed where booster and spacecraft interface electrical signals can be sent, received and sequenced for prelaunch and in-flight operation simulation. Electrical and mechanical interfaces with the launch vehicles and spacecraft will be checked to ensure compatibility. Booster interface rings and shrouds are used in checking mechanical interface conformance. A complete radiological protection plan will be used to enforce nuclear safety regulations. Following prelaunch testing, the power

module will be prepared for transportation to the VAB or Mobile Launcher (ML) for integration with the launch vehicle. This operation includes the addition of the reactor/radiator shrouds and the installation of all special instruments and safing of all ordnance devices.

3.2.1.4 Launch Vehicle/Payload Integration

Launch vehicle integration tests may be performed in the VAB or at Launch Complex 39. In either case, the power module should be scheduled as late in the sequence as possible. Launch vehicle integration consists of hardware mating and interface and combined systems tests required to acquire launch readiness. Countdown demonstrations are performed and certain post-launch conditions are simulated such as power module separation, umbilical disconnect and instrumentation for power transfers.

Limited loading checks with the booster and the handling devices will be performed utilizing a dummy payload. Mechanical and electrical interfaces are simulated. A simulated system launch readiness and countdown test is performed in the above configuration to insure compatibility of instrumentation, environmental and support systems. A continuous and comprehensive systems status check and flight readiness test is performed prior to the actual ignition sequences and liftoff.

3.2.1.5 Launch Complex/Range Integration

The launch vehicle complete with reactor power module(s) installed is moved to Launch Complex 39 via the ML crawler/transporter at T-8 days (Considerably less launch pad time is assumed compared to that employed on Apollo launches). At all times the shroud is maintained in position around the power module(s). Power module instrumentation monitored includes umbilical and separation circuit connections, radioactivity, environmental conditions and control circuit continuities. Telemetry and range verification tests are conducted. A simulated countdown, propellant loading and pressure tests are made.

3.2.1.6 Countdown

The countdown is initiated at T-2 days where flight readiness and functional systems tests are performed on major subsystems of the INT-21. Ordnance is installed prior to launch

vehicle cryogenic loading. At this point, launch pad accessibility is greatly restricted. Throughout the final phases of the countdown, continuous monitoring is provided. At T-1 hour, the terminal countdown is initiated after the completion of all flight readiness checks and propellant loading sequences. At T-187 seconds, an automatic sequence is initiated for the start of the engines. Swing arms are around the vehicle until the automatic sequence is initiated. Termination of this phase is at liftoff which occurs at T + 9 seconds.

3.2.2 LAUNCH/ASCENT - PHASE 2

The INT-21 launch vehicle will be used to boost the reactor power module(s) to orbit from Launch Complex 39 at KSC. One or two complete reactor power modules will be launched on one INT-21. The power module requires insertion into a 500 km (273 nm) orbit inclined 55 degrees to the earth's equatorial plane for rendezvous with the Space Base. The flight azimuth through the atmosphere of this orbit is 46 degrees, measured east of north, as a result of current range safety requirements at the Eastern Test Range (ETR). Since the ETR flight azimuth restriction is not compatible with the desired orbit inclination, a plane change is performed during the boost to orbit. The plane change maneuver to establish the desired orbit is performed during the portion of flight where Inertial Guidance Mode (IGM) is providing launch vehicle steering commands.

The launch trajectory traverses over Eurasia prior to orbital insertion. The trajectory passes over France, Switzerland, Italy, Albania, Greece, Israel, Jordan and Saudi Arabia.

3.2.3 ORBITAL OPERATIONS - PHASE 3

The orbital operations phase begins following successful docking of the two reactor power modules to the Space Base. Docking will be followed by an EVA to make the electrical and control circuit connections at the boom interface. After the reactor power modules have been checked out and cleared for startup, the power module booms are extended into the normal operating position.

The expected automatic startup sequence is initiated from the Space Base control room. A controlled speed stepping sequence individually single steps the drums in order as planned

into the startup program; the stepping speed is reduced as criticality approaches. The reactor is brought slowly through criticality and up to operating temperature and power. It is assumed that each reactor operates continuously at 330 kWt for the duration of its five-year mission.

3.2.4 END OF MISSION/REACTOR DISPOSAL - PHASE 4

At the completion of the normal lifetime of the reactor, or after any accident which permanently damages the reactor or power conversion system, the reactor will be boosted to a 990 km (535 nm) disposal orbit altitude where the fission product inventories will be allowed to decay to acceptable levels prior to eventual reentry which is expected to occur after a calculated 1167 years. After reactor shutdown the sequence of events required for checkout, separation, and orbital transfer with the disposal system are:

1. Preparation Sequence for Reactor Disposal

Stabilize temperature (heaters on)

Guidance and control checkout

Gyro checkout

Sensor checkout

Separate (spring release to provide a ΔV of ~ 0.4 m/sec)

2. Post Separation Alignment

Stabilize attitude for alignment

Acquire horizon with sensors

Scan for, and acquire sun

Uncage gyros

3. Orbit Transfer

Stabilize attitude for transfer initiation

Yaw maneuver

Spin about roll axis

Ignite first two rockets

Despin and stabilize

Gyro attitude reference alignment

Attitude maneuver for circularization burn

Spin about roll axis

Ignite second two rockets.

The 1167 year orbital lifetime is determined from the power module ballistic coefficient. This disposal orbit lifetime can be increased to approximately 10,000 years by separation of the reactor and its shield to increase the ballistic coefficient. The study does not consider reactor separation a part of the reference mission. However, the significantly increased orbital lifetimes achievable by a separation of the reactor/shield from the remainder of the power module provides terrestrial nuclear safety advantages.

SECTION 4

RADIOLOGICAL EVALUATION OF MISSION ACCIDENTS (HAZARDS EFFECT ANALYSIS)

The safety analysis approach discussed in Section 2 has been used in determining the radiological consequences and associated risk to the general public of each accident, for each mission phase and for the entire mission. This section addresses the consequences (potential doses to whole body and various organs) of the accidents and identifies those with the highest probability of occurrence.

4.1 SUMMARY OF ACCIDENTS AND SOURCE TERMS

A complete description of the mission accidents, failure modes, probability of occurrence, and radiological source terms are presented in the AMD, Volume III, Part 2. The characteristics of the mission accidents (accident description, causes, probability, consequences and hazard location) developed in the AMD and their corresponding risk values as determined in Section 5, are summarized in Appendix B of this document.

Fission product inventories, amounts released and radiation levels from the reactor/fuel elements for each accident case are presented in Table 4-1. Reference should be made to Section 5 of the AMD for the associated source term probabilities.

4.2 RADIOLOGICAL EXPOSURE MODES

The radiological exposure modes to the general public from potential accidents are direct external exposure from reactor prompt radiation and radioactive materials and internal exposure from inhalation and ingestion of radioactive material. The consequences resulting from a reactor accident are directly related to the type and extent of exposure mode presented. Potential exposure modes for the ZrH reactor power module are summarized in Table 4-2.

Table 4-1. Accident Case Source Terms (After 330 kWt for Five Years)

Case No	Time After Shutdown (t _g)	Isotope	Total Inventory @ t _g (Curies)	Source Terms for Released Fission Products (No Excursion)						Source Terms for Reactor and Fuel Elements					
				Land Impact		Water Impact		Release at Altitude (Curies)		Land Impact			Water Impact		
				Total Release to Air (Curies)	Release to Air From Single Fuel Element (Curies)	Release to Air (Curies)	Release to Water (Curies)	100% Released	90% Released	50% Released	Scattered Debris ¹ (r/hr)	Single Fuel Element ² (r/hr)	Quasi-Steady State Operation ³	Immersed Reactor ³ (r/hr)	Single Fuel Element ² (r/hr)
4 6 4 31 5 6 5 31	1 Day	Kr-83m Kr-85 Kr-85m Kr-87 Kr-88 Xe-131m Xe-133m Xe-133 Xe-135m Xe-135 I-131 I-132 I-133 I-134 I-135 I-136 I-137 I-138 I-139 Sr-90 Cs-137 Ba-137m Ce-144 Pr-144	6 3x10 ⁰ 2 5x10 ² 1 03x10 ² 2 25x10 ⁻² 2 39x10 ¹ 8 4x10 ¹ 3 95x10 ² 1 73x10 ⁴ 4 55x10 ² 6 4x10 ³ 7 95x10 ³ 9 6x10 ³ 9 x10 ³ 3 75x10 ⁻⁴ 1 44x10 ³ --- --- --- --- 2 02x10 ³ 2 x10 ³ 1 78x10 ³ 1 64x10 ⁴ 1 64x10 ⁴	6 3x10 ⁰ 2 5x10 ² 1 03x10 ² 2 25x10 ⁻² 2 39x10 ¹ 8 4x10 ¹ 3 95x10 ² 1 73x10 ⁴ 4 55x10 ² 6 4x10 ³ 7 95x10 ³ 9 6x10 ³ 3 2x10 ¹ 3 1x10 ¹ 1 44x10 ³ --- --- --- --- 1 01x10 ² 1 x10 ² 8 9x10 ¹ 8 2x10 ² 8 2x10 ²	2 1x10 ⁻² 0 85 0 35 7 7x10 ⁻⁵ 8 1x10 ⁻² 2 8x10 ⁻¹ 1 3 5 9x10 ⁻¹ 2 2x10 ¹ 2 7x10 ¹ 3 2x10 ¹ 3 1x10 ¹ --- 4 9 --- --- --- 0 34 0 34 0 3 2 8 2 8	2 5x10 ⁻³ 10 4 1 8 1x10 ⁻⁴ 9 6x10 ⁻¹ 3 3 16 6 9x10 ² 2 9x10 ² 1 1x10 ³ 1 04x10 ³ 1 25x10 ³ 1 17x10 ³ --- 1 8x10 ² --- --- --- 81 80 71 6 5x10 ² 6 5x10 ²	1 06x10 ⁻² 43 17 3 4x10 ⁻³ 4 1 14 68 2 9x10 ³ 77 1 1x10 ³ 7 95x10 ³ 9 6x10 ³ 9 x10 ³ --- 1 44x10 ³ --- --- --- 2 02x10 ³ 2 x10 ³ 1 78x10 ³ 1 64x10 ⁴ 1 64x10 ⁴	6 3x10 ⁰ 5 7x10 ⁰ 2 5x10 ² 1 03x10 ² 2 25x10 ⁻² 2 39x10 ¹ 8 4x10 ¹ 3 95x10 ² 1 73x10 ⁴ 4 55x10 ² 6 4x10 ³ 7 95x10 ³ 9 6x10 ³ 9 x10 ³ 3 75x10 ⁻⁴ 1 44x10 ³ --- --- --- --- 1 8x10 ³ 1 8x10 ³ 1 8x10 ³ 1 6x10 ³ 1 6x10 ³	5 7x10 ⁰ 2 2x10 ² 9 3x10 ¹ 5 1x10 ¹ 2 2x10 ¹ 2 2x10 ¹ 7 6x10 ¹ 3 6x10 ² 1 6x10 ⁴ 4 1x10 ² 5 8x10 ³ 7 2x10 ³ 8 6x10 ³ 8 1x10 ³ 3 4x10 ⁻⁴ 1 3x10 ³ --- --- --- --- 1 8x10 ³ 1 8x10 ³ 1 6x10 ³ 1 5x10 ⁴ 1 5x10 ⁴	3 2 1 3x10 ² 9 3x10 ¹ 5 1x10 ¹ 1 13x10 ⁻² 1 2x10 ¹ 4 2x10 ¹ 2 x10 ² 8 7x10 ³ 2 28x10 ² 3 2x10 ³ 4 x10 ³ 4 8x10 ³ 4 5x10 ³ 1 9x10 ⁻⁴ 7 2x10 ² --- --- --- --- 1 01x10 ³ 1 x10 ³ 9 x10 ² 8 2x10 ³ 8 2x10 ³	67 600 (1 kW _t power operation assumed) Neutrons 7700 rem/hr Gamma 210 r/hr ↓	5000 38 (1 kW _t power operation assumed) Neutrons 3 9x10 ⁻³ rem/hr Gamma 13 4 r/hr ↓			
3 22 3 23 3 28 4 1 4 10 4 11 5 10 5 11	2 5 Years	Kr-85 Sr-90 Cs-137 Ba-137m Ce-144 Pr-144	2 12x10 ² 1 92x10 ³ 9 6x10 ¹ 1 9x10 ³ 1 69x10 ³ 1 8x10 ³ 1 8x10 ³	2 12x10 ² 9 6x10 ¹ 9 5x10 ¹ 8 5x10 ¹ 8 5x10 ¹ 9x10 ¹ 9x10 ¹	0 72 0 33 0 32 0 29 0 31 0 31	8 5 0 0 76 76 68 72 72	36 77 76 72 72	2 12x10 ² 1 92x10 ³ 1 9x10 ³ 1 69x10 ³ 1 8x10 ³ 1 8x10 ³	1 9x10 ² 1 73x10 ³ 1 71x10 ³ 1 52x10 ³ 1 62x10 ³ 1 62x10 ³	1 06x10 ² 9 6x10 ² 9 5x10 ² 8 5x10 ² 9 x10 ² 9 x10 ²	0 57 5 1 (1 kW _t power operation assumed) Neutrons 7700 rem/hr Gamma 210 r/hr ↓	43 0 33 (1 kW _t power operation assumed) Neutrons 3 9x10 ⁻³ rem/hr Gamma 13 4 r/hr ↓			
3 3 3 6 3 15 3 18 3 21 4 3 5 3	3 5 Years	Kr-85 Sr-90 Cs-137 Ba-137m Ce-144 Pr-144	1 98x10 ² 1 86x10 ³ 1 84x10 ³ 1 64x10 ³ 7 7x10 ² 7 7x10 ²	1 98x10 ² 9 3x10 ¹ 9 2x10 ¹ 8 2x10 ¹ 3 9x10 ¹ 3 9x10 ¹	0 67 0 31 0 31 0 28 0 13 0 13	7 9 0 0 74 74 66 31 31	34 74 74 66 31 31	1 98x10 ² 1 86x10 ³ 1 84x10 ³ 1 64x10 ³ 7 7x10 ² 7 7x10 ²	1 78x10 ² 1 68x10 ³ 1 66x10 ³ 1 57x10 ³ 6 9x10 ² 6 9x10 ²	99 9 3x10 ² 9 2x10 ² 8 2x10 ² 3 9x10 ² 3 9x10 ²	0 41 3 7 (1 kW _t power operation assumed) Neutrons 7700 rem/hr Gamma 210 r/hr ↓	31 0 24 (1 kW _t power operation assumed) Neutrons 3 9x10 ⁻³ rem/hr Gamma 13 4 r/hr ↓			
3 2 3 5 3 8 3 9 3 10 3 14 3 17 3 20 4 2 4 4 4 7 4 9 4 12 4 13 4 19 4 39 5 2 5 4 5 7 5 9 5 12 5 13 5 39	5 Years	Kr-85 Sr-90 Cs-137 Ba-137m Ce-144 Pr-144	1 75x10 ² 1 76x10 ³ 1 74x10 ³ 1 55x10 ³ 2 13x10 ² 2 13x10 ²	1 75x10 ² 8 8x10 ¹ 8 6x10 ¹ 7 8x10 ¹ 1 1x10 ¹ 1 1x10 ¹	59 3 29 26 0 37 0 37	7 0 0 0 70 70 62 8 5 8 5	30 70 70 62 8 5 8 5	1 75x10 ² 1 76x10 ³ 1 74x10 ³ 1 55x10 ³ 2 13x10 ² 2 13x10 ²	1 58x10 ² 1 58x10 ³ 1 57x10 ³ 1 40x10 ³ 1 92x10 ² 1 92x10 ²	88 8 8x10 ² 8 7x10 ² 7 8x10 ² 1 07x10 ² 1 07x10 ²	0 35 3 2 (1 kW _t power operation assumed) Neutrons 7700 rem/hr Gamma 210 r/hr ↓	27 0 20 (1 kW _t power operation assumed) Neutrons 3 9x10 ⁻³ rem/hr Gamma 13 4 r/hr ↓			
4 5 4 27 4 35 5 5 5 27 5 35	11 Years	Kr-85 Sr-90 Ca-137 Ba-137m Ce-144 Pr-144	118 1520 1500 1340 1 15 1 15	118 76 75 67 0 6 0 6	0 4 0 26 0 25 0 23 0 02 0 02	4 7 0 0 61 60 54 0 46 0 46	20 61 60 54 0 46 0 46	118 1520 1500 1340 1 15 1 15	106 1370 1350 1200 1 04 1 04	59 760 750 670 0 6 0 6	0 24 2 1 (1 kW _t power operation assumed) Neutrons 7700 rem/hr Gamma 210 r/hr ↓	18 0 14 (1 kW _t power operation assumed) Neutrons 3 9x10 ⁻³ rem/hr Gamma 13 4 r/hr ↓			
4 26 4 29 5 26 5 29	21 Years	Kr-85 Sr-90 Cs-137 Ba-137m	65 1140 1120 1000	65 57 56 50	0 22 0 19 0 19 0 17	2 6 0 0 46 45 40	11 1140 1020 1000 900	65 1140 1020 1000 900	59 570 560 500	33 570 560 500	0 19 1 7 (1 kW _t power operation assumed) Neutrons 7700 rem/hr Gamma 210 r/hr ↓	14 5 0 11 (1 kW _t power operation assumed) Neutrons 3 9x10 ⁻³ rem/hr Gamma 13 4 r/hr ↓			
4 38	30 Years	Kr-85 Sr-90 Cs-137 Ba-137m	33 930 890 800	33 47 45 40	0 11 0 16 0 15 0 14	1 3 0 0 37 36 32	5 6 37 36 32	33 930 890 800	30 940 800 720	17 470 450 400	0 15 1 3 (1 kW _t power operation assumed) Neutrons 7700 rem/hr Gamma 210 r/hr ↓	11 3 0 087 (1 kW _t power operation assumed) Neutrons 3 9x10 ⁻³ rem/hr Gamma 13 4 r/hr ↓			
3 11 3 12 4 22 4 23 4 32 4 36 5 22 5 23 5 32 5 36	44 Years	Kr-85 Sr-90 Cs-137 Ba-137m	11 5 670 620 550	11 5 34 31 28	0 039 0 115 0 105 0 095	0 46 0 0 25 22	2 27 25 22	11 5 670 620 550	10 4 600 560 495	5 8 335 310 275	0 1 0 92 (1 kW _t power operation assumed) Neutrons 7700 rem/hr Gamma 210 r/hr ↓	7 7 0 059 (1 kW _t power operation assumed) Neutrons 3 9x10 ⁻³ rem/hr Gamma 13 4 r/hr ↓			
4 34 5 34	70 Years	Kr-85 Sr-90 Cs-137 Ba-137m	1 42 324 280 250	1 42 16 14 12 5	0 0048 0 054 0 048 0 042	0 057 0 0 0 0 0 0	0 24 13 11 10	1 42 324 280 250	1 28 290 250 225	0 71 162 140 125	0 051 0 46 (1 kW _t power operation assumed) Neutrons 7700 rem/hr Gamma 210 r/hr ↓	3 8 0 029 (1 kW _t power operation assumed) Neutrons 3 9x10 ⁻³ rem/hr Gamma 13 4 r/hr ↓			
4 28 4 40 5 40 5 28	106 Years	Kr-85 Sr-90 Cs-137 Ba-137m	0 17 150 120 107	0 17 7 5 7 5 4	--- 0 25 0 24 0 18	0 0068 0 0 0 0 0 0	0 17 3 28 22	0 17 150 120 107	15 135 108 96	0 09 75 60 54	0 22 0 19 (1 kW _t power operation assumed) Neutrons 7700 rem/hr Gamma 210 r/hr ↓	1 6 0 12 (1 kW _t power operation assumed) Neutrons 3 9x10 ⁻³ rem/hr Gamma 13 4 r/hr ↓			
4 30 5 30	377 Years	Sr-90 Cs-137 Ba-137m	0 18 0 094 0 084	0 09 0 047 0 042	--- --- ---	0 0 --- ---	--- --- ---	0 18 0 094 0 084	16 0 85 0 76	0 09 0 047 0 042	2x10 ⁻⁵ 1 8x10 ⁻⁴ (1 kW _t power operation assumed) Neutrons 7700 rem/hr Gamma 210 r/hr ↓	1 48x10 ⁻³ 1 1x10 ⁻⁵ (1 kW _t power operation assumed) Neutrons 3 9x10 ⁻³ rem/hr Gamma 13 4 r/hr ↓			

NOTES 1 Dose Measured at Center of Debris Distribution, 1 Meter above Ground
 2 Dose Measured at 1 Meter from Fuel Element
 3 Dose Measured at 1 Meter from Core Surface
 4 Fission Product Gases Released in Orbit

FOLDOUT FRAME 1

FOLDOUT FRAME 2

Table 4-2. Potential Exposure Modes

	EXPOSURE MODE	HAZARD SOURCE	POSSIBLE CAUSES (ACCIDENTS)
E X T E R N A L	<u>DIRECT</u>	PROMPT RADIATION FROM INTACT REACTOR	<ul style="list-style-type: none"> ● INADVERTENT REACTOR EXCURSION ● QUASI-STEADY STATE CRITICAL
	INTACT REACTOR	GAMMA RADIATION FROM INTACT REACTOR	<ul style="list-style-type: none"> ● FISSION PRODUCT DECAY ● ACTIVATED MATERIALS
	DISASSEMBLED REACTOR	AIRBORNE ACTIVATED MATERIALS AIRBORNE FISSION PRODUCTS (CLOUD) GROUND DEPOSITED FISSION PRODUCTS ACTIVATED STRUCTURAL DEBRIS SCATTERED FUEL ELEMENTS	<ul style="list-style-type: none"> ● DESTRUCTIVE REACTOR EXCURSION ● IMPACT ● FIREBALL AND EXPLOSION AT LAUNCH ● ORBITAL COLLISION AND EXPLOSION
I N T E R N A L	<u>INGESTION</u>	GROUND DEPOSITED FISSION PRODUCTS FISSION PRODUCTS IN DRINKING WATER ACTIVATED MATERIALS IN DRINKING WATER FISSION PRODUCTS IN MARINE LIFE WATER ACTIVATED MATERIALS IN MARINE LIFE WATER GROUND DEPOSITED ACTIVATED MATERIALS	<ul style="list-style-type: none"> ● DESTRUCTIVE REACTOR EXCURSION ● GROUND OR WATER IMPACT ● REENTRY ABLATION OF INDIVIDUAL FUEL ELEMENTS ● EXCESSIVE REENTRY HEATING AND BURNUP ● WATER IMPACT OF FUEL ELEMENTS ● FIREBALL AND EXPLOSION AT LAUNCH ● ORBITAL COLLISION AND EXPLOSION
	<u>INHALATION</u>	AIRBORNE ACTIVATED MATERIALS AIRBORNE GASEOUS FISSION PRODUCTS AIRBORNE PARTICULATE FISSION PRODUCTS	<ul style="list-style-type: none"> ● DESTRUCTIVE REACTOR EXCURSION ● IMPACT AND REACTOR DISASSEMBLY ● EXCESSIVE REENTRY HEATING AND BURNUP ● REENTRY ABLATION OF INDIVIDUAL FUEL ELEMENTS ● FIREBALL AND EXPLOSION AT LAUNCH ● ORBITAL COLLISION AND EXPLOSION

4.2.1 DIRECT EXTERNAL EXPOSURE

Accidental reactor criticality presents several radiological hazards. The dominant consideration for steady state operation and for near proximity to an excursion is the prompt radiation field. This direct external radiation exposure results in neutron and gamma exposure to the whole body.

Radioactive material direct exposure also results in a whole body exposure. A reactor disassembly on land impact due to high velocity impact loads, or by a destructive excursion can result in the dispersal of reactor debris and fuel elements at the impact location which can present a direct whole body exposure hazard to the general public. Distributed fuel elements are assumed to be spread evenly over a 50 meter radius. Another direct whole body exposure source may come from a fission product cloud release from a reactor disassembly. An individual located downwind of the release will receive a whole body direct external exposure as the fission product cloud passes by.

4.2.2 INTERNAL EXPOSURE

The release of fission products to the atmosphere and the downwind dispersion by the prevailing meteorological conditions may result in an inhalation exposure. Fission products deposited in the lungs are absorbed into the body and accumulate in the critical organs. Fallout of fission products from a cloud results in a ground deposited activity which may contaminate vegetation and potable water and consequently may result in an ingestion exposure to the populace and ecology.

In the event that fission products are released to pasture land, the ground deposited activity may be quickly metabolized into the milk of dairy cows. Consumption of the contaminated milk by an individual will result in a thyroid exposure from the radioiodines and a bone exposure by strontium-90.

Since approximately one-half percent of the land area in the United States is occupied by reservoirs, the possibility exists where a reactor may impact into a reservoir and contaminate the drinking water. The release of activity may result from a high velocity impact disassembly or from a destructive excursion. The potential exposure from the consumption of contaminated drinking water as well as contaminated milk can be minimized by providing a tracking capability so that the reactor impact location can be quickly identified. The area can then be surveyed by a properly equipped recovery team to determine the extent of contamination and to quarantine all water or milk which would result in unacceptable radiation exposures to the general public.

Although present estimates would indicate no radiological problem exists from radioactive material released to the ocean, it is difficult to be certain that some small amount of marine life may not be contaminated. However, the probability of catching the marine life for human consumption is remote, except in shallow coastal waters and the continental shelf.

High altitude dispersal of fission products would cause only a slight increase in the diffuse radioactive burden of the atmosphere as a whole. However, this slight increase is applicable to most of the world's population, with biological effects (both somatic and genetic) that may be indeterminate and difficult to distinguish statistically from natural background levels.

4.3 ACCIDENT CONSEQUENCES

A discussion of the radiological consequences resulting from the key accidents in each mission phase is presented in the following subsections.

4.3.1 PRELAUNCH

The Prelaunch Phase begins with the installation of the ZrH reactor power modules atop the INT-21 in the VAB and terminates at ignition of the S-IC booster engines. The total phase abort probability is 7×10^{-3} . Prelaunch Phase aborts which can result in a fission product release or a radiation hazard are:

1. Reactor dropped while being mated to launch vehicle
2. Tip over of the reactor/launch vehicle during transport to the launch pad
3. Explosion and fire on the launch pad during launch vehicle fueling (reactor falls back on launch pad)
4. Liquid metal fire.

The potentially hazardous consequences arising from these accidents in order of declining probability are:

- | | |
|--|----------------------|
| 1. Radiation shield damaged | 1.5×10^{-3} |
| 2. Fuel cladding breached, primary system ruptured | 5×10^{-5} |
| 3. Quasi-steady state critical operation | 2×10^{-5} |
| 4. Nondestructive reactor excursion | 1×10^{-5} |
| 5. Reactor disassembly | 6.6×10^{-6} |
| 6. Destructive reactor excursion | 3.4×10^{-6} |

The most serious accident consequence which is remotely possible during the Prelaunch Phase is a destructive excursion at Launch Complex 39. A destructive excursion may occur by a rapid insertion of reactivity by control drum motion on land impact or by over moderation following water immersion.

The degree of hazard associated with a destructive excursion is not only dependent upon the magnitude of the excursion but also on the residual fission product inventory in the core which is generated during preflight criticality testing. A study was conducted to determine the consequences of a launch complex destructive excursion with a reactor that has experienced a limited preflight operating history. The power histories considered are shown in Table 4-3.

Table 4-3. Preflight Operational History Study

Power Level Watts	Operating Time Hours	Watts-hours
10.0	2.4	24.0
1.0	24.0	24.0
4.0	24.0	96.0
0.1	24.0	2.4
100.0	288.0	28,800.0

The flight SNAP-10A reactor experienced 16 watt-hours of preflight operating history. The total body dose for all cases is shown in Figure 4-1 for zero shutdown time followed by a destructive excursion. Normally there will be a several week shutdown period prior to shipment from the manufacturer's facility to the launch complex. Since a substantial fraction of the fission product activity generated during the preflight operation is short-lived, a major portion of inventory will have decayed before it could possibly become involved in an accident. The total dose from 100-watt operation for 12 days followed by 60 days shutdown is shown in Figure 4-2 and is compared to a 100 MW-sec destructive excursion of a reactor core with no previous operating history. It can be seen in Figure 4-2 that the residual fission product activity 60 days after 100-watt operation for 288 hours is small compared to the fission products generated by the 100 MW-sec excursion. Therefore, it appears that limited preflight reactor operation followed by a 60-day shutdown will not significantly increase the hazard should a destructive excursion occur.

The total body dose shown in Figures 4-1 and 4-2 is a summation of the external exposure from immersion in a fission product cloud and internal exposure to the whole body from inhalation. In addition to the total body exposure, other types of exposure that occur at the same time are:

1. Inhalation exposure to other body organs
2. Whole body prompt radiation exposure.

The inhalation, cloud, and prompt neutron and gamma doses are shown in Figure 4-3 as a function of distance from the reactor. Pasquill F weather conditions were again considered in this calculation for conservatism.

The locus of downwind isopleth centerline distances for total body dose equivalent to natural background is shown in Figure 4-4 for an accident occurring at Launch Complex 39 at KSC. The total body dose in this case includes prompt neutron and gamma in addition to that from cloud immersion and inhalation exposures to the whole body.

In the event of an accident at KSC, radiation exposure to the ground crew will be minimized since they will be situated at a safe distance (greater than 5 km from the launch pad). As seen in Figure 4-4, the total body dose from the accident is equivalent to the yearly natural background level at about 4 km from Launch Complex 39. Following an accident, access to the radiation zone in the vicinity of the reactor debris will be restricted by the recovery crew.

For an accident involving water impact, a nondestructive excursion may occur which would result in the doses shown in Figure 4-5. It was assumed that a quasi-steady state power level of one kW thermal may possibly occur. The dose rates shown are for an unshielded configuration for conservatism. The dose for one hour is less than the yearly background level of 150 mrem at less than 300 meters from the reactor. Recovery personnel will cordon off the area to minimize radiation exposure until the reactor can be shutdown and removed from the area. Chemical poisons may be added to the water, the reactor removed or the water may be drained from the pool to effect shutdown of the reactor should the reactor fail to shutdown by itself. The limited heat rejection capability is expected to cause fuel element failure and subsequent shutdown.

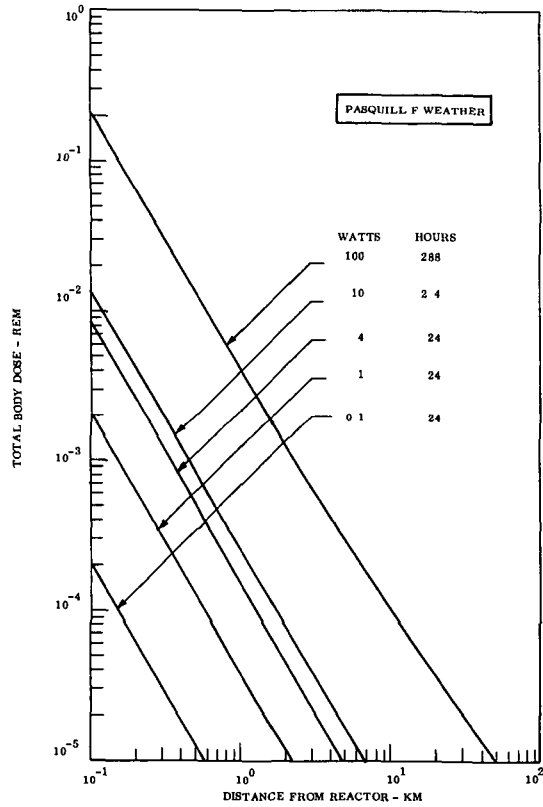


Figure 4-1. Total Body Dose at Shutdown for Different Preflight Operating Histories

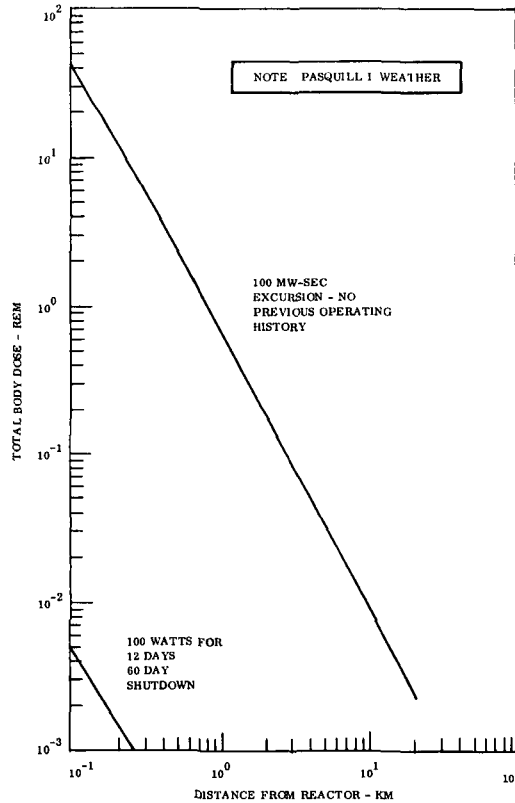


Figure 4-2. Comparison of Total Body Dose for 100 Mw-Sec Excursion with that for Preflight Operations

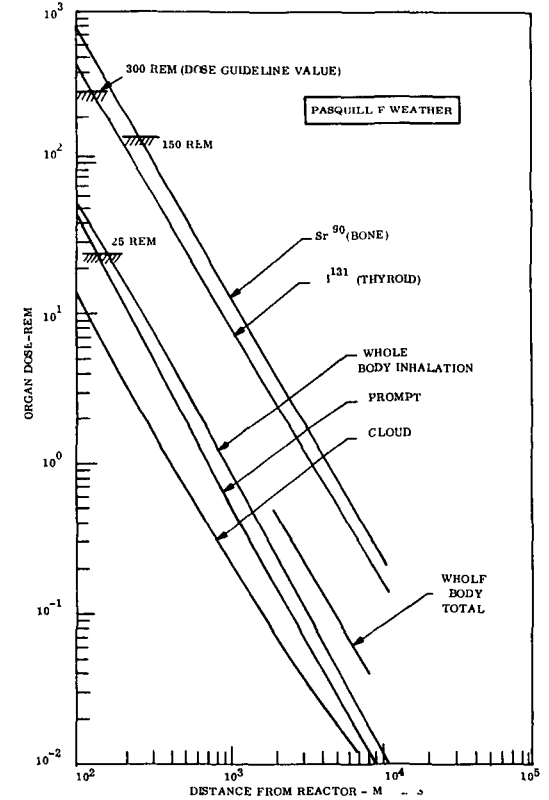
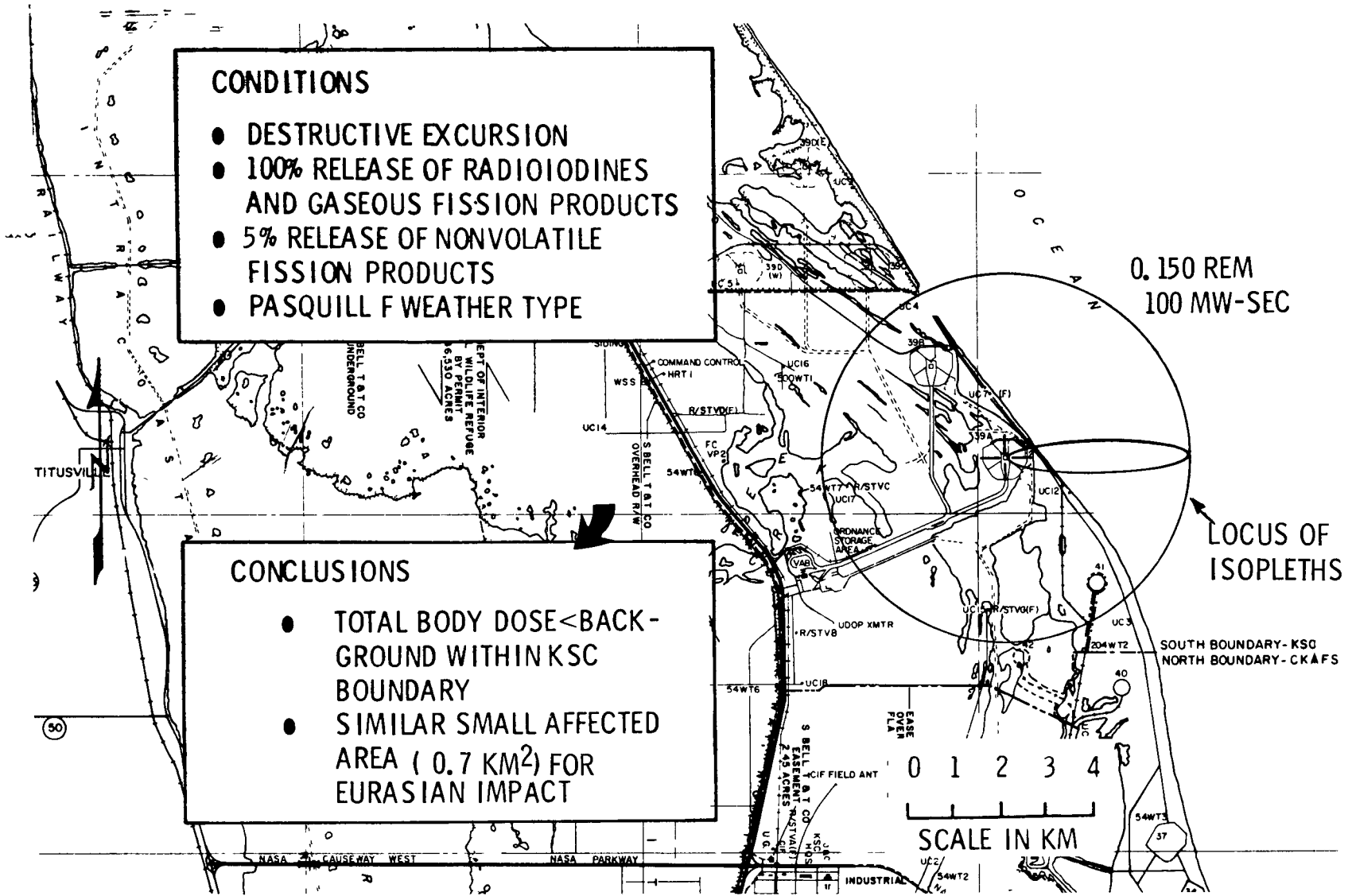


Figure 4-3. Exposures for 100 Mw-Sec Excursion



4.3.2 LAUNCH/ASCENT

One or two complete reactor power module(s) will be launched with an INT-21 launch vehicle from Complex 39 at KSC. The reactor power module requires insertion into a 500 km (273 nm) orbit inclined 55 degrees to the earth's equatorial plane for rendezvous with the Space Base. This phase is initiated at S-IC booster ignition and is terminated at rendezvous and docking with the Space Base. The total phase abort probability is 6.8×10^{-2} . The accidents which may occur during the Launch/Ascent phase which may possibly lead to a fission produce release or a radiation hazard are:

1. Launch pad abort, explosion and fire
2. Abort, explosion and fire at altitude
3. Abort, no explosion and fire at altitude
4. Accidental collision while attempting to dock
5. Failure to dock with Space Base
6. Failure to remove thermal shroud
7. Failure to rendezvous with Space Base.

The possible consequences from these accidents in order of declining probability of occurrence are:

- | | |
|---|----------------------|
| 1. Deep ocean reactor impact | 4×10^{-2} |
| 2. Power module left in low earth orbit | 9.4×10^{-3} |
| 3. Reactor impact at KSC | 6.5×10^{-3} |
| 4. Reactor impact on U.S. Continental Shelf | 4.9×10^{-3} |
| 5. Reactor impact in Eurasia | 3.2×10^{-3} |
| 6. Launch pad abort | 2.2×10^{-4} |
| 7. Reactor disassembly at altitude | 3.7×10^{-5} |

4.3.2.1 Land Impact Followed by Destructive Excursion

During launch, land impact may occur on KSC or in Eurasia along the trajectory which passes over France, Switzerland, Italy, Albania, Greece, Israel, Jordan and Saudi Arabia. An unlikely possibility exists (2.6×10^{-5}) that a destructive excursion may occur upon land impact by a rapid insertion of reactivity caused by a combination of control drum motion and core compaction, or by overmoderation from water immersion. The energy release from the destructive excursion again is assumed to be 100 MW-sec. The inhalation, cloud and prompt neutron and gamma doses are shown in Figure 4-3 for Pasquill F weather conditions as a function of distance from the reactor.

The downwind distance for total body dose equivalent to natural background (150 mrem/yr) is approximately 4 km. This is the immediate exposure to which the dose from the reactor debris must be added for a prolonged exposure.

4.3.2.2 Land Impact Followed by Disassembly

High velocity impact can also result in a disassembly without a destructive excursion (2.3×10^{-3}). However, it is conservatively assumed that the fractional release of fission products is the same for both the destructive excursion and for reactor disassembly resulting from high velocity impact. The relative probability of reactor disassembly without an excursion is about a factor of 100 greater than that resulting from a destructive excursion. The one year integrated dose for a high velocity land impact disassembly of the reactor is shown in Figure 4-6 as a function of distance away from the reactor. The very small reactor core fission product activity is for 100 watts preflight operation for 288 hours followed by a 60-day shutdown period prior to launch.

The model used for the disassembled reactor was based on the SNAPTRAN destructive test data (Reference 4-1). It was assumed that the fuel elements and fuel particles were distributed uniformly on the ground within a 50 meter radius from the impact point. The dose rate at a plane one meter above the ground is shown in Paragraph 4.4.3.4 of the AMD (Volume III, Part 2) as a function of time after shutdown. These dose rates were integrated over a one year period to yield the integrated dose from distributed fuel for the two orbital decay cases shown in Figure 4-6. The one day and five year cases are considered possible events in the launch/ascent phase.

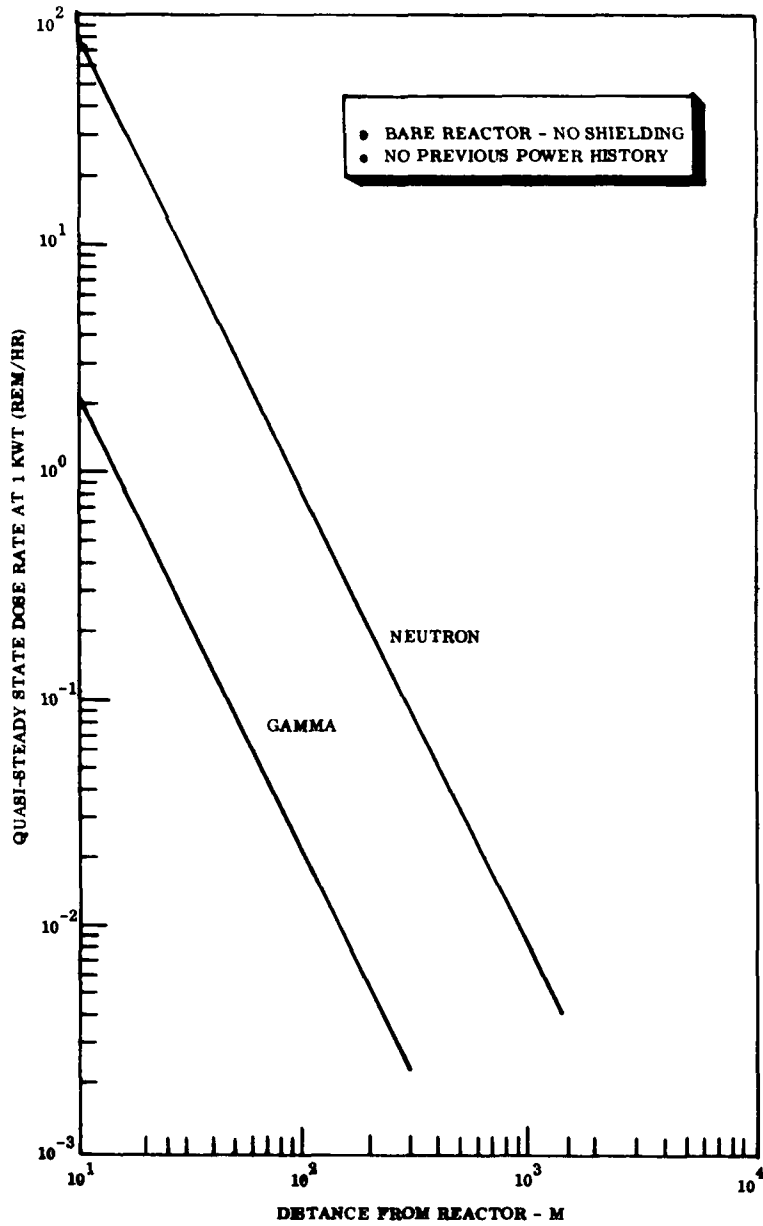


Figure 4-5. Dose Rate from Quasi-Steady State Operation - 1 kWt

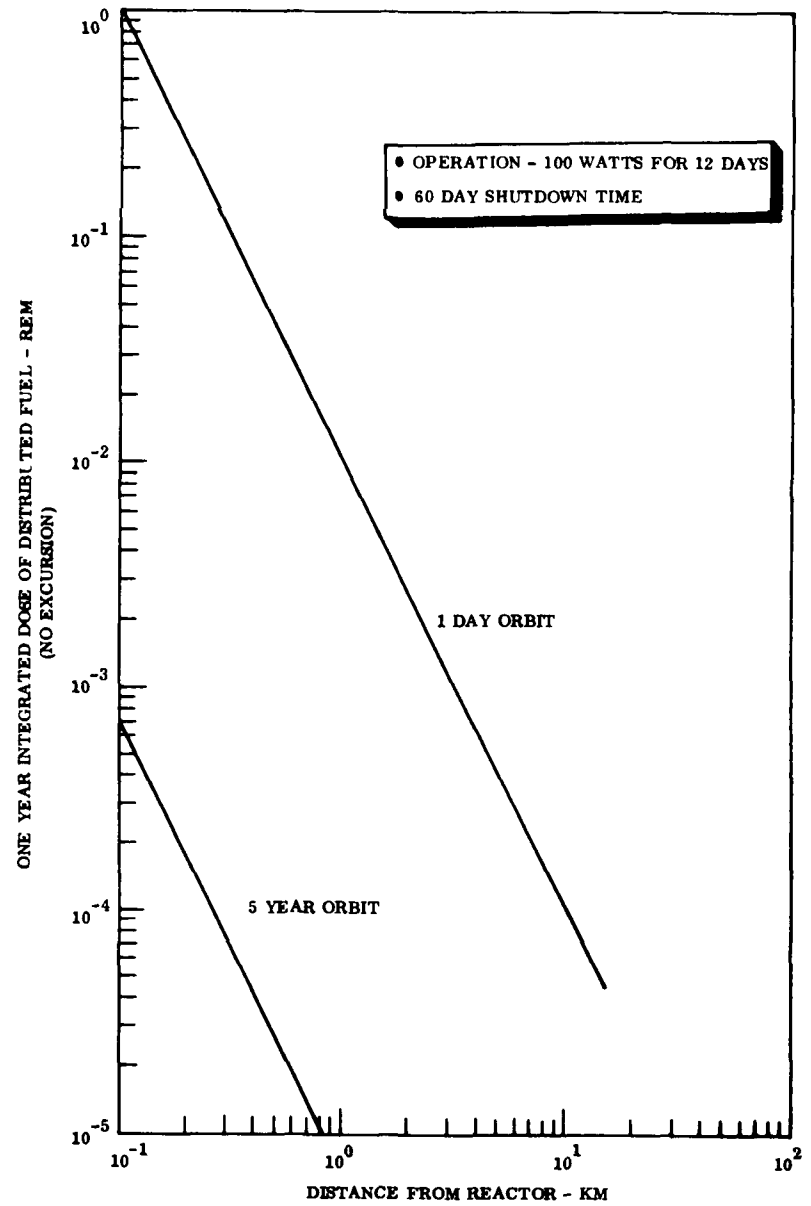


Figure 4-6. One Year Integrated Dose of Distributed Fuel, No Excursion

4.3.2.3 Reentry Burnup Followed by High Altitude Release

The reactor may not survive reentry. As a consequence, fission products and other radioactive debris may be released to the upper atmosphere where it will be widely dispersed. Most of the activity will burnup into fine particles which will fallout predominately in the hemisphere where the accident has occurred. The dose from this exposure mode will be extremely low but a large fraction of the general public will be exposed. For the one day orbital decay case with 100-Watt/288-hour/60-day shutdown preflight operational history, the maximum inhalation dose at sea level from a stratospheric release of Sr⁹⁰ and I¹³¹ would be about 4×10^{-12} and 9×10^{-15} rem, respectively.

4.3.3 ORBITAL OPERATIONS

In the baseline mission each of the two reactors will be operated at a power level of 330 kWt for a period of five years. Although an accident may occur within this five-year operational period, it is conservatively assumed that five years at 300 kWt power level is the initial condition for all aborts which may occur after the reactor is initially taken to power. This assumption will result in the maximum fission product and activated material inventory in the reactor.

The Orbital Operations Phase abort probability is 5×10^{-2} and the accidents which may lead to a fission product release or a radiation hazard are:

1. Equipment failure aboard Space Base necessitating early abandonment
2. Accidental collision or explosion in orbit
3. Reactor control system malfunction or reactor operational procedure error
4. Loss of critical electrical power system component.

The possible consequences from the above accidents in order of declining probability of occurrence are:

1. Reactor impacts in deep ocean area	8.1×10^{-4}
2. Reactor impacts on land	3.1×10^{-4}
3. Destructive reactor excursion in orbit	2.2×10^{-4}
4. Reactor fails during reentry, fuel elements released from core	1.7×10^{-4}
5. Reactor impacts shallow water	3.5×10^{-5}
6. Reactor disassembly in orbit	2.2×10^{-5}
7. Reactor impacts in reservoir	3.1×10^{-7}

4.3.3.1 Land Impact Followed by Disassembly

Land impact may occur randomly between 55 degrees N to 55 degrees S latitudes. Upon land impact, a reactor disassembly may occur due to high impact velocities. The orbital decay times calculated for the accidents which may terminate in a land impact disassembly are 3.5, 5 and 44 years during the orbital operations phase. Consequently, the radiation exposures will differ for the accidents because of the various fission product decay times. The one year integrated dose from distributed fuel for high velocity impact disassembly is shown in Figure 4-7.

4.3.3.2 Land Impact Followed by Destructive Excursion

A destructive excursion can also occur on land impact by a rapid insertion of reactivity by a combination of control drum rotation and core compaction, or by overmoderation by water immersion. A 100 MW-sec energy release is assumed to result from the destructive excursion. The one year integrated dose for distributed fuel from a destructive excursion on land is shown in Figure 4-8 for the orbital decay times that are possible in the phase.

The whole body dose from immersion in a fission product cloud is shown in Figure 4-9 for a reactor high velocity impact disassembly with no excursion as well as for a destructive excursion. In both cases the fission product release fractions were assumed to be equivalent. The Sr^{90} inhalation dose to the bone for these cases is shown in Figure 4-10.

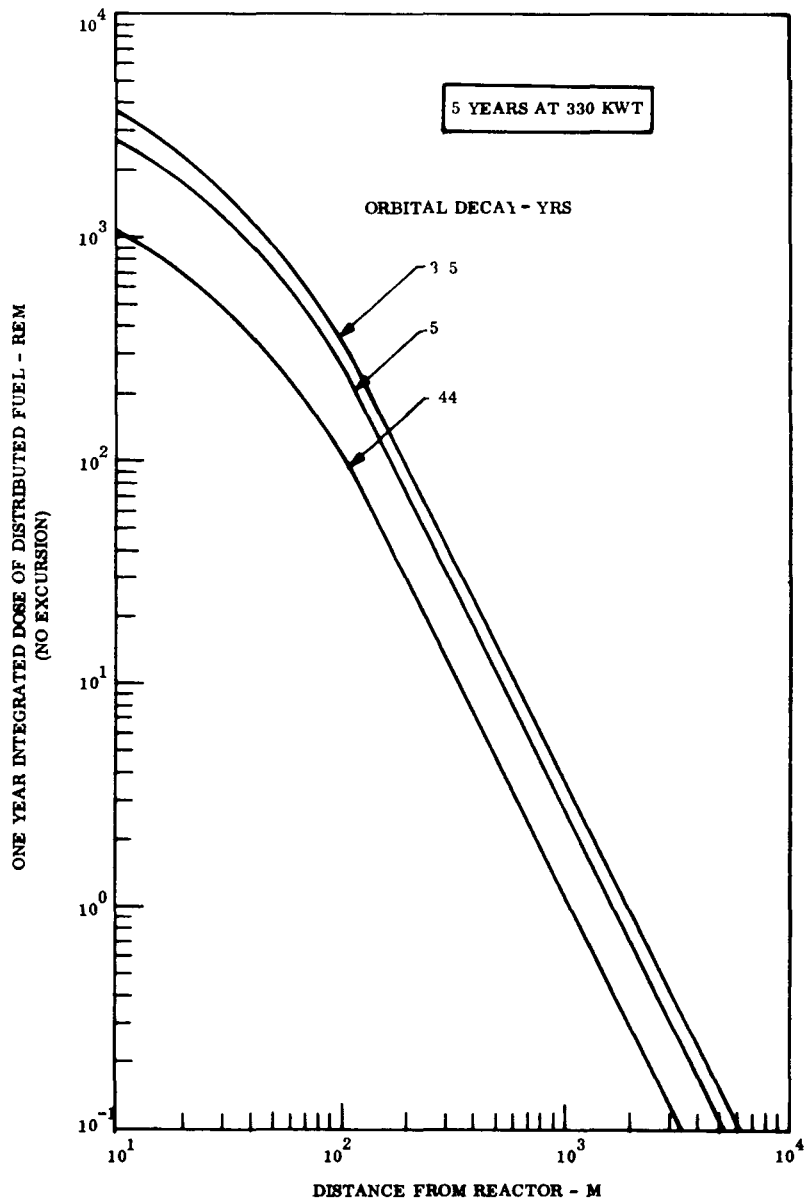


Figure 4-7. One Year Integrated Dose of Distributed Fuel for 3.5, 5 and 44 Years Orbital Decay Times, No Excursion

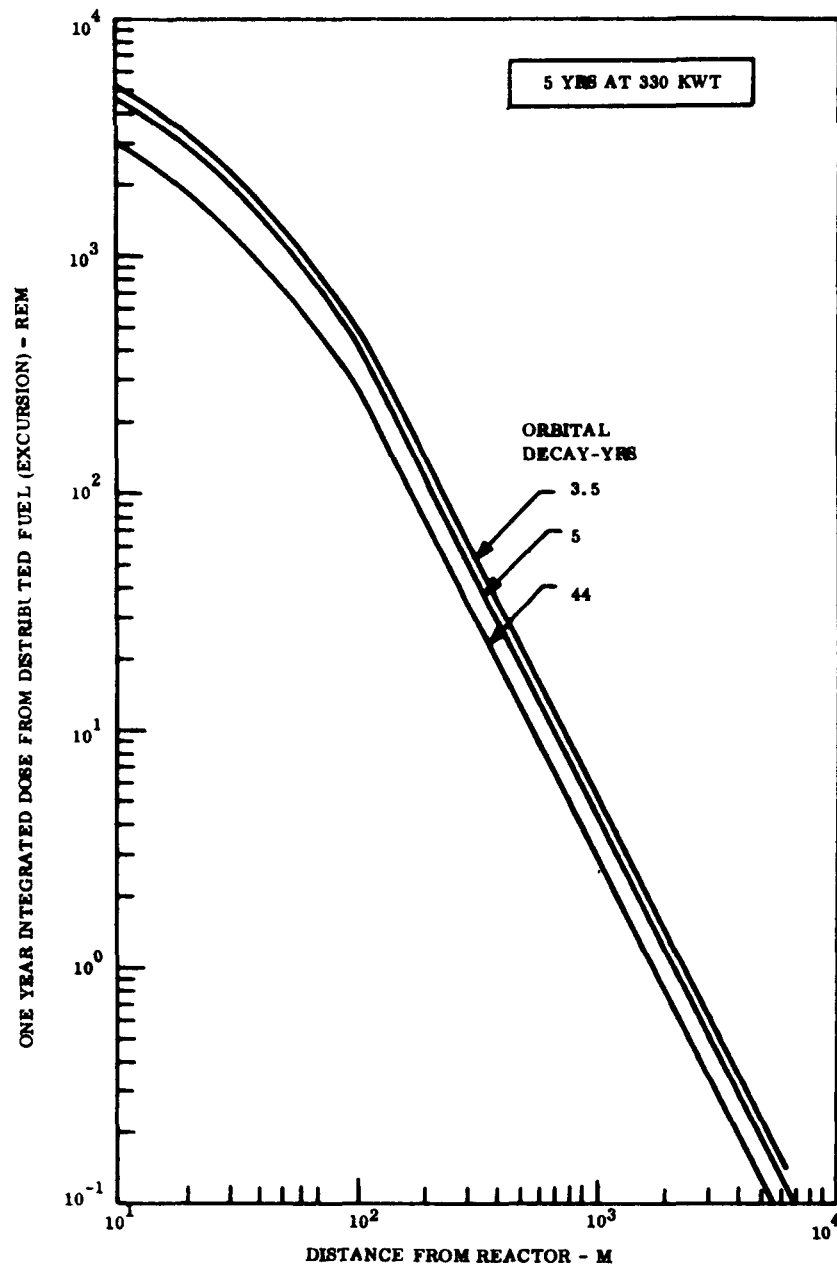


Figure 4-8. One Year Integrated Dose of Distributed Fuel for 3.5, and 44 Years Orbital Decay Times, Excursion

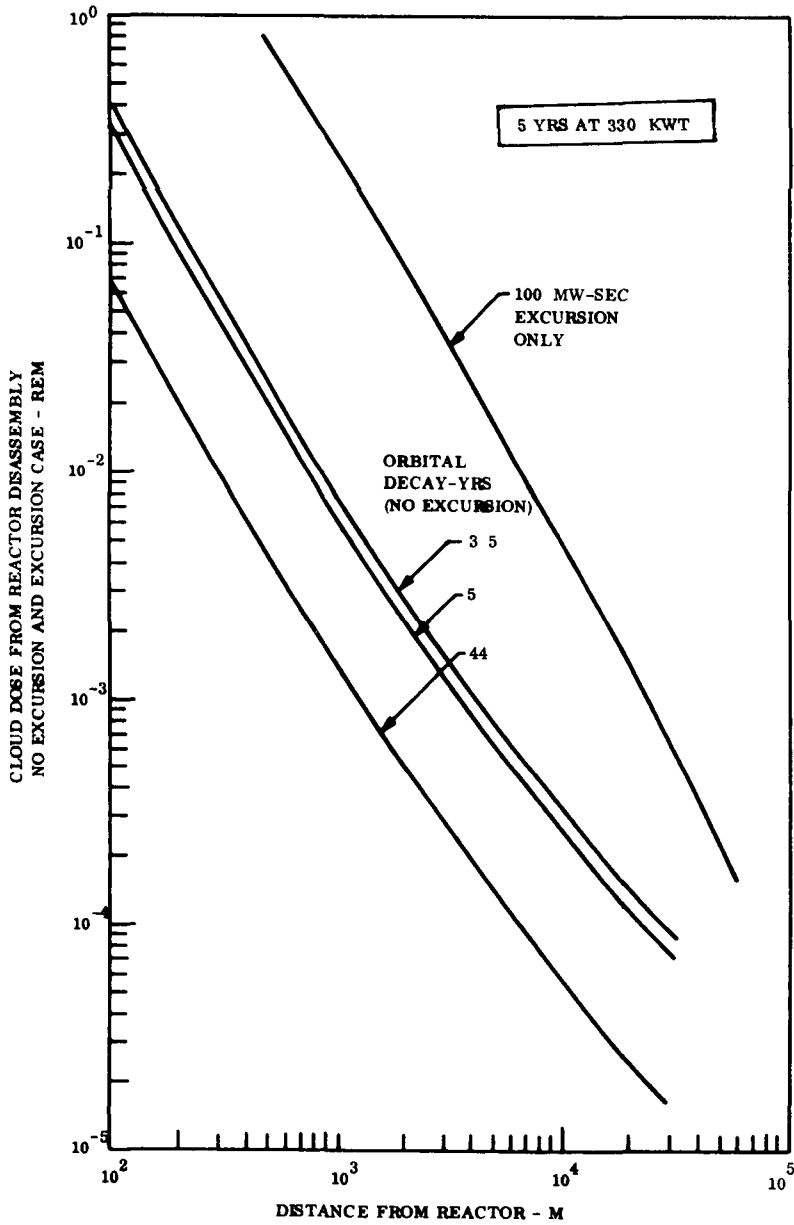


Figure 4-9. Cloud Dose from Reactor Disassembly With and Without Excursion

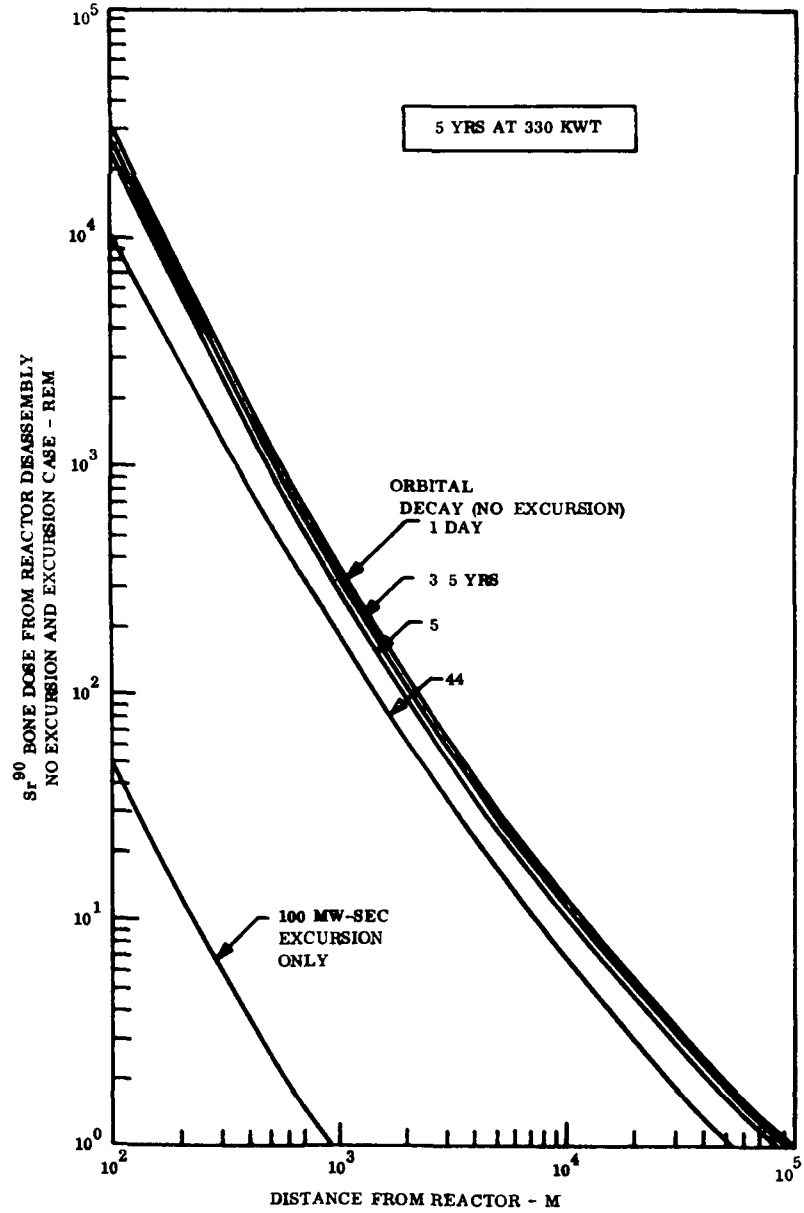


Figure 4-10. Sr⁹⁰ Bone Dose from Reactor Disassembly With and Without Excursion

4.3.3.3 Accidents in Orbit

Some of the orbital operation accidents result in fuel element rupture and the subsequent release of gaseous and volatile fission products into the primary coolant. A loss of hydrogen moderator will also occur which will permanently shutdown the reactor preventing an excursion on land impact. Ruptured fuel elements may be the consequence of an accident involving the tearing away of the power module from the Space Base. The primary heat rejection system will be lost and thus, the reactor temperatures may increase (~ 1100 to 1300°K) to cause fuel cladding rupture due to excessive hydrogen pressures generated. Another accident which can cause fuel cladding rupture involves a collision or explosion which ruptures the primary coolant piping. The loss of coolant in the core region may then cause excessive temperatures which are beyond the containment capability of the fuel elements.

For the case where fission products are released to the primary coolant, this activity will be released to the upper atmosphere when the reentry aerothermal forces cause rupture of the primary coolant system. This activity will, therefore, not be available for release upon land impact of the reactor.

4.3.4 REACTOR DISPOSAL

At the completion of the normal lifetime of the reactor (5 years operation at 330 kWt), or after any accident which permanently damages the reactor or power conversion system, the reactor will be boosted to a 990 km (535 nm) disposal altitude where the fission product inventory will decay to an acceptable safe level prior to eventual reentry. The Reactor Disposal Phase abort probability is 1.35×10^{-2} and the major accidents which may lead to a radiation hazard to the general public include:

1. Guidance and control failure
2. Failure to separate power module from Space Base
3. Failure of the primary propulsion system
4. Accidental collision with Space Base or related system
5. Misaligned thrust vector

Because of the various modes of failure during the disposal orbit insertion sequence, several different orbital lifetimes are possible which may range from one day to 377 years. A successful 990 km (535 nm) disposal orbit has a calculated lifetime of 1167 years.

4.3.4.1 Direct External Exposure from Reactor Disassembly and Excursions on Land

Upon earth impact, disassembly of the reactor is assumed to take place by high velocity impact loads or by a destructive excursion. The resulting radioactive debris on the ground will be the greatest hazard to the general public since it is possible that the exposure could last a long time before discovery of the accident location. The one year integrated doses are shown in Figures 4-11 and 4-12 for the various orbital decay times as a function of distance from the reactor for the case of disassembly without excursion. For the destructive excursion case, the one-year integrated doses are shown in Figures 4-13 and 4-14. The variation of the one-year integrated dose as a function of orbit lifetime (reactor shutdown time) is shown in Figures 4-15 and 4-16 at 100 and 1000 meters from the accident location for the no excursion disassembly case and the destructive excursion disassembly case, respectively.

To obtain an indication of the integrated whole body dose for a shorter exposure period than one year, an estimate was made for a 30-day exposure. For the one-day orbital decay case, the 30-day integrated dose is 2.1×10^2 rem at 100 meters which is about one-third lower than that for the one-year value. For 3.5 year and greater orbital decay times, the 30-day integrated dose is about one-tenth of the one-year value.

4.3.4.2 Internal Exposure from Reactor Disassembly and Excursions on Land

The release of fission products in a high velocity impact disassembly or a destructive excursion due to control drum rotation/core compaction on land impact may result in an inhalation exposure to anyone downwind of the release. Figure 4-17 indicates the I^{131} thyroid dose for Pasquill F weather conditions. The one-day orbital decay I^{131} dose for a high velocity impact disassembly and for a destructive excursion are equivalent since the I^{131} inventory in the core is not significantly increased by the excursion. It is assumed that both types of disassemblies release 100 percent of the radioiodines. For a 3.5-year orbital decay or greater, there is essentially no I^{131} inventory in the core prior to impact. Thus, the I^{131} thyroid dose for 3.5 years or greater orbital decay is entirely due to the release of I^{131} that is generated during the excursion.

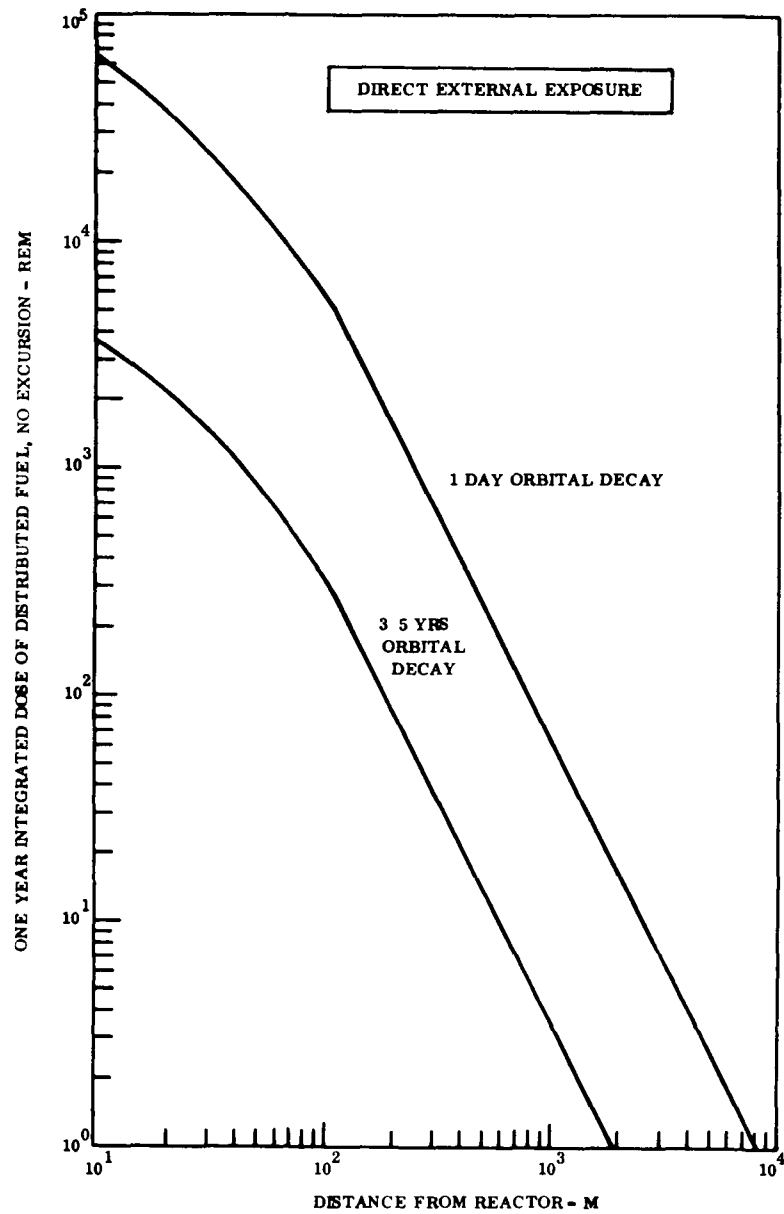


Figure 4-11. One Year Integrated Dose of Distributed Fuel for 1 Day and 3.5 Years Orbital Decay, No Excursion

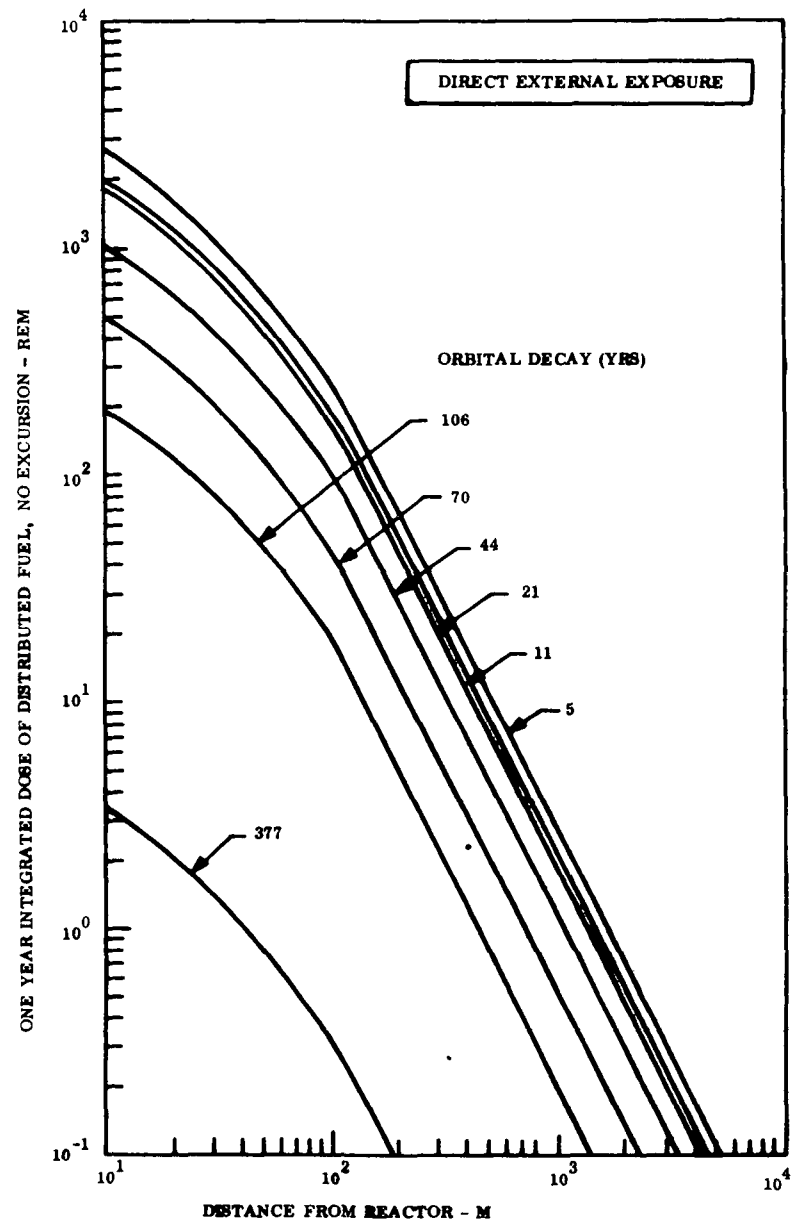


Figure 4-12. One Year Integrated Dose of Distributed Fuel for 5 to 377 Years Orbital Decay, No Excursion

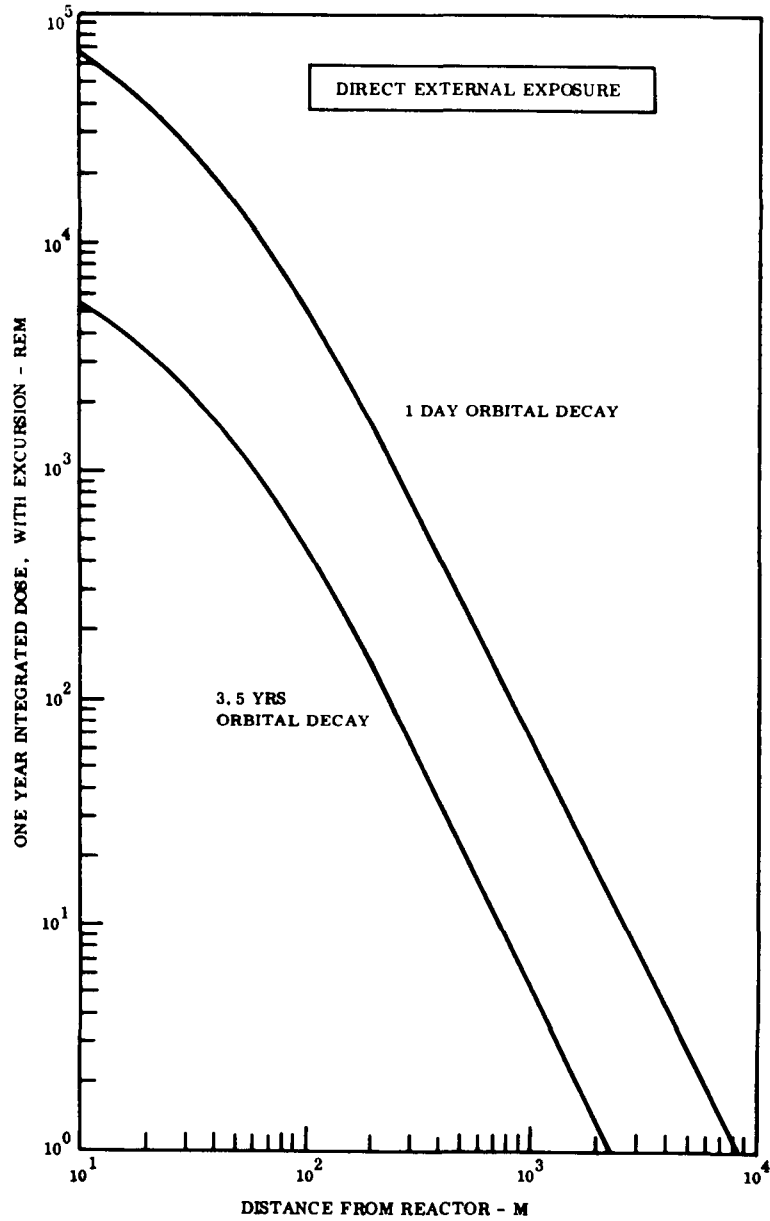


Figure 4-13. One Year Integrated Dose of Distributed Fuel for 1 Day and 3.5 Years Orbital Life, Excursion

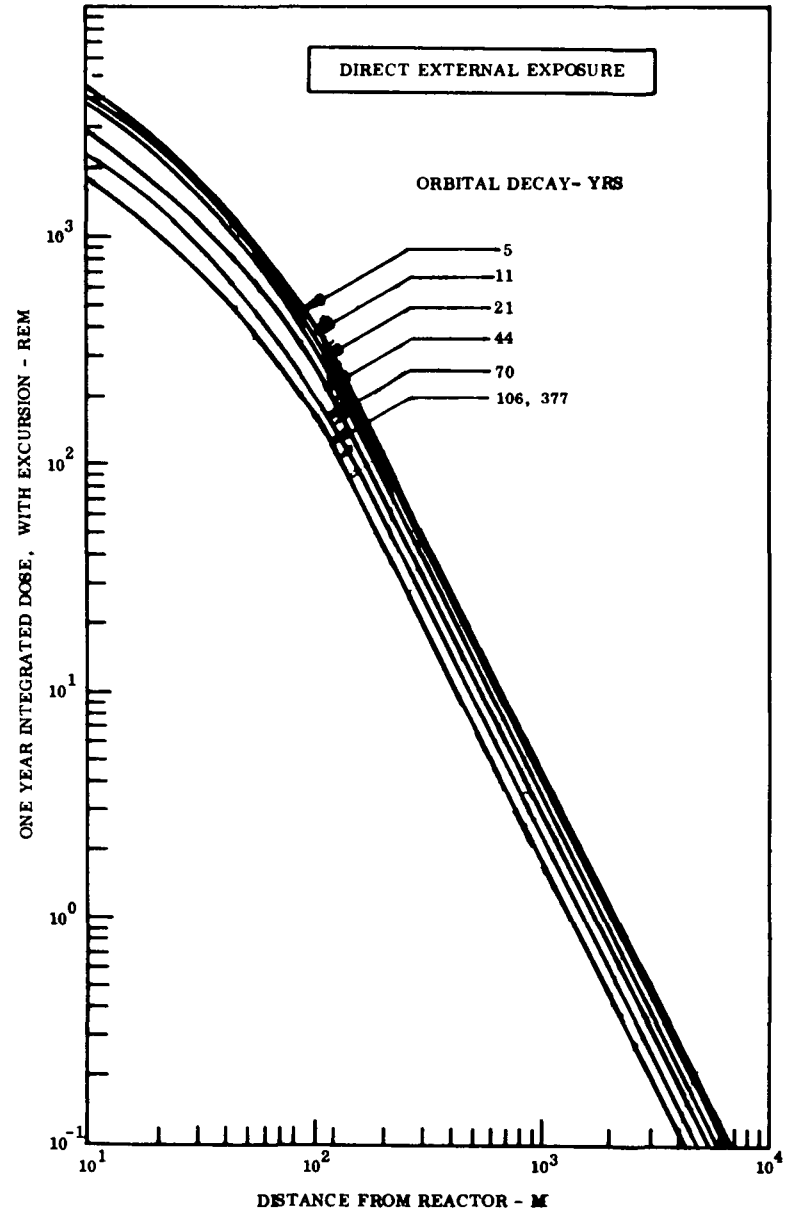


Figure 4-14. One Year Integrated Dose of Distributed Fuel for 5 to 377 Years Orbital Decay, Excursion

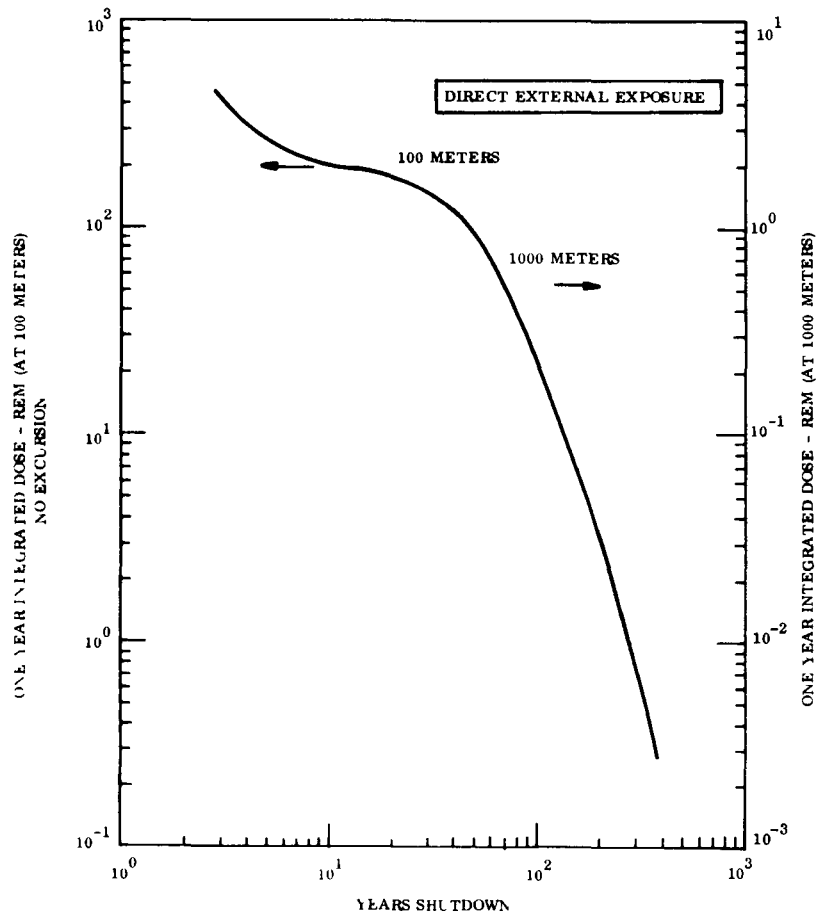


Figure 4-15. One Year Integrated Dose of Distributed Fuel at 100 and 1000 Meters for Various Orbital Decay Times (No Excursion)

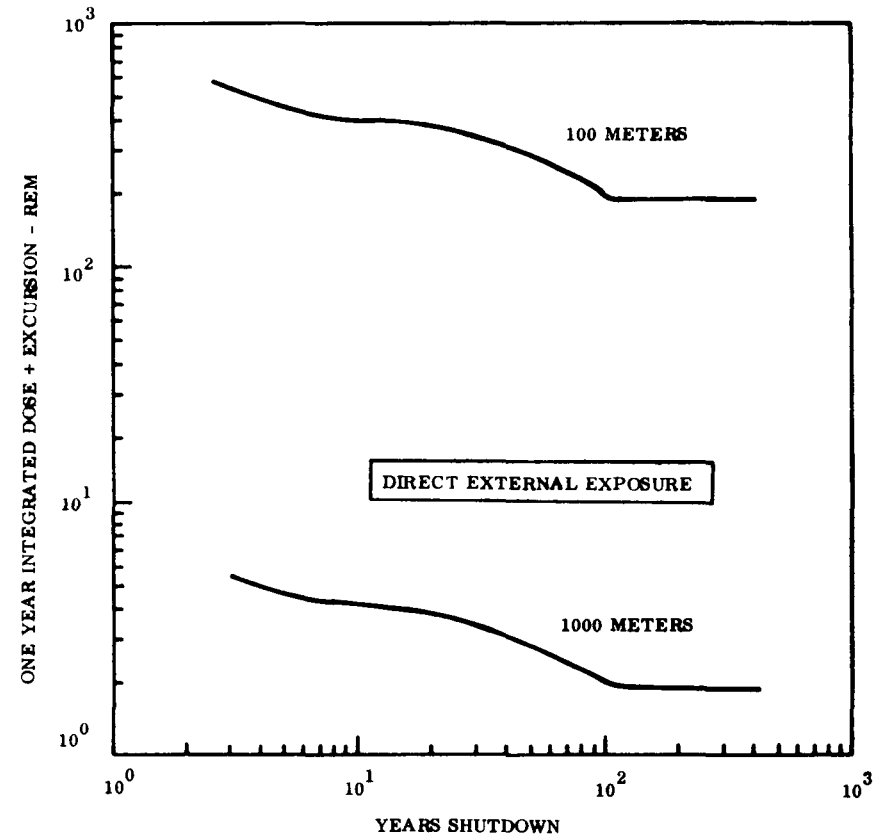


Figure 4-16. One Year Integrated Dose of Distributed Fuel at 100 and 1000 Meters for Various Orbital Decay Times (Excursion)

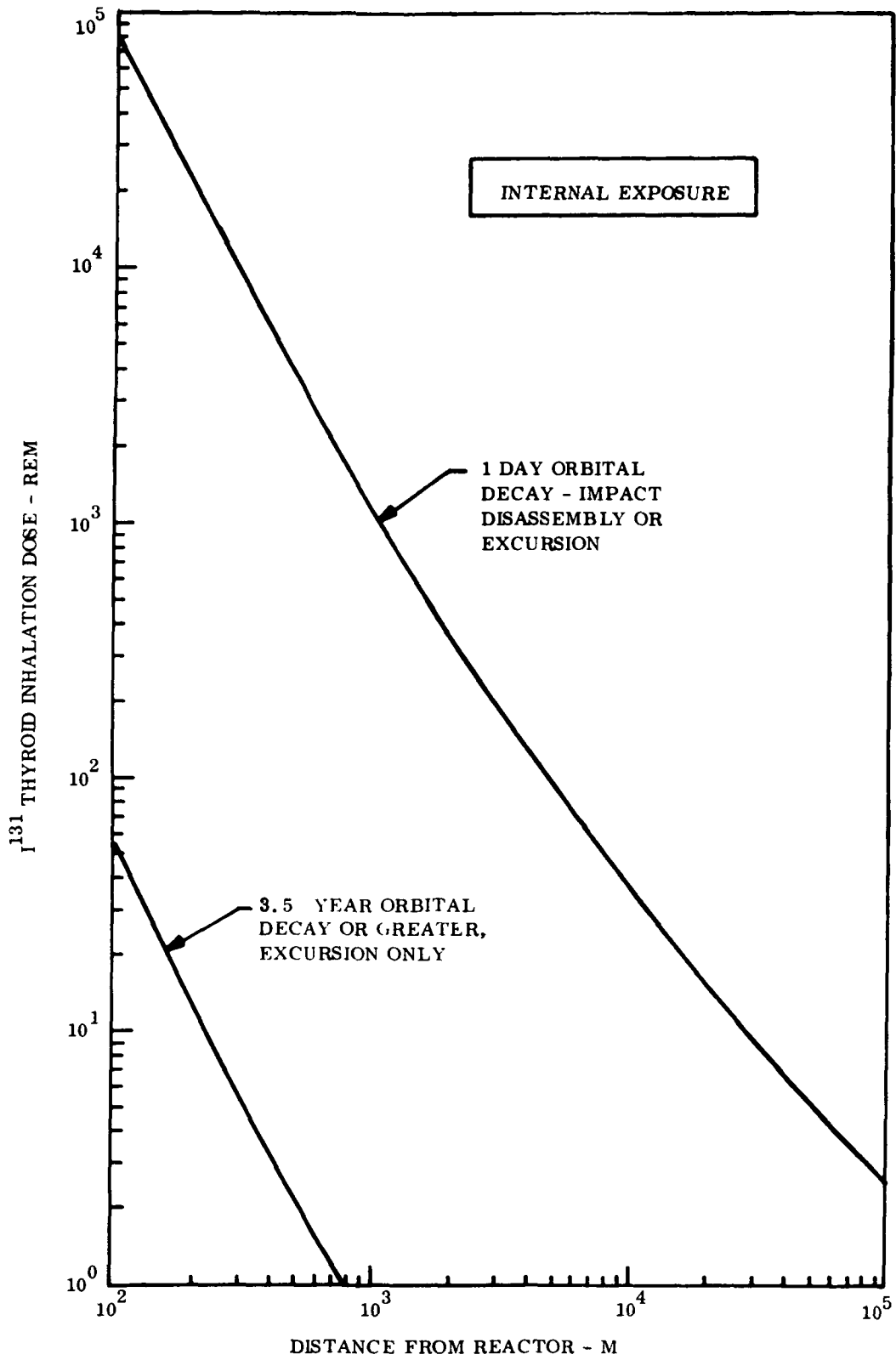


Figure 4-17. ^{131}I Thyroid Inhalation Dose With and Without Excursion/Disassembly

The Sr⁹⁰ bone dose from inhalation during passage of a fission product cloud is presented in Figures 4-18 and 4-19 for a high velocity impact disassembly and for a destructive excursion, respectively. These results are again for Pasquill F weather conditions for the orbital decay cases possible in the reactor disposal phase of the mission. The Sr⁹⁰ inhalation doses for the two cases are slightly higher for the destructive excursion than for the impact disassembly up to the 21-year orbital decay accident, since the Sr⁹⁰ generated by the excursion is less than 10 percent of the reactor core inventory for five years operation at 330 kWt. For orbital decays greater than 21 years, the contribution from the destructive excursion becomes progressively greater. As the pre-impact Sr⁹⁰ inventory decays, the excursion produced Sr⁹⁰ becomes more significant.

4.3.4.3 Total Exposure from Destructive Excursion on Land (Worst Case)

The following types of exposures are shown in Figure 4-20 for a destructive excursion on land following a one-day orbital decay:

1. I¹³¹ thyroid inhalation exposure
2. Sr⁹⁰ bone inhalation exposure
3. One year integrated whole body exposure from distributed fuel
4. Whole body exposure from immersion in fission product cloud
5. Whole body exposure from prompt neutrons and gammas.

The dose guideline values are indicated for the corresponding exposure modes. For this one-day orbital decay case, which results in the highest exposures, no guideline values are exceeded beyond 2500 meters down-wind of the accident. As a comparison, the exposures resulting from a destructive excursion following a 3.5-year orbital decay are presented in Figure 4-21. During the 3.5-year orbital decay, the shorter lived fission products in the reactor core have decayed substantially. Thus, the I¹³¹ thyroid, one-year integrated, and fission product cloud doses are reduced markedly over those calculated for the one-day orbital decay case. Only the long-lived Sr⁹⁰ bone dose and the prompt gamma and neutron levels are essentially unchanged.

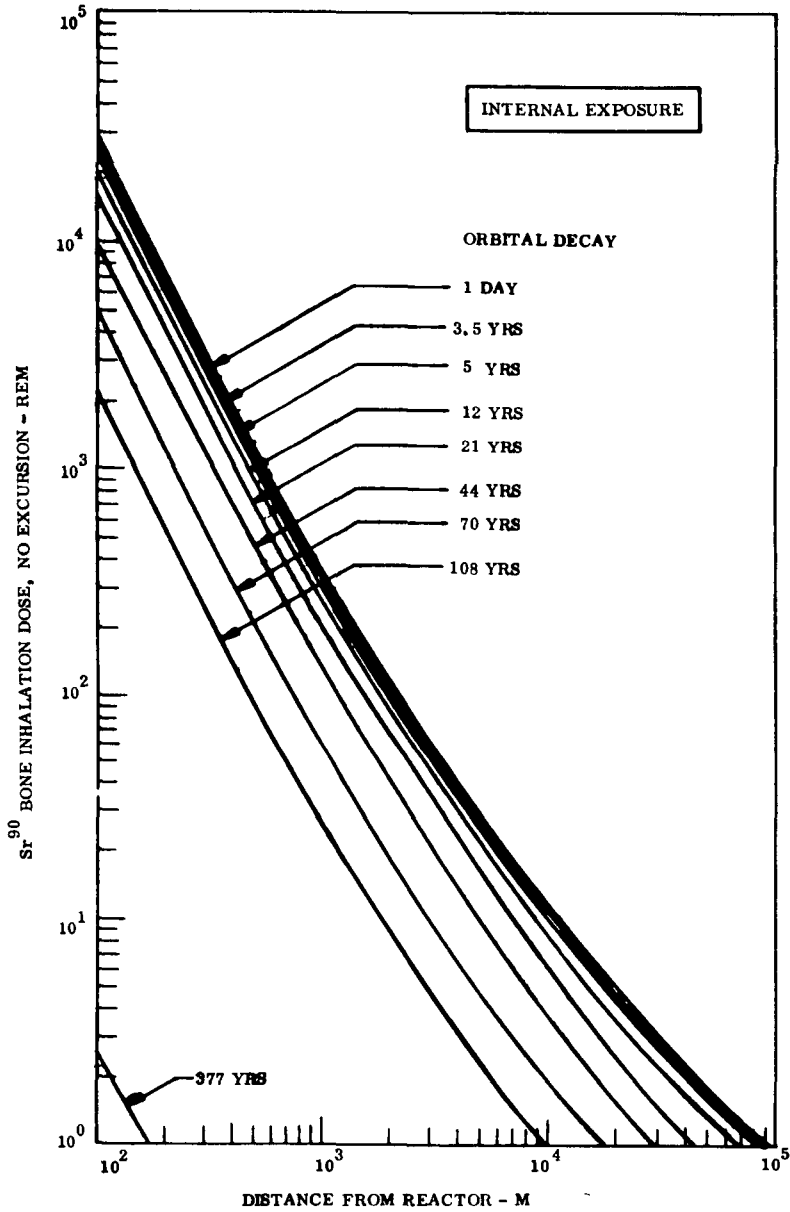


Figure 4-18. Sr^{90} Bone Dose from Inhalation for 1 Day to 377 Year Orbital Decay Time, No Excursion

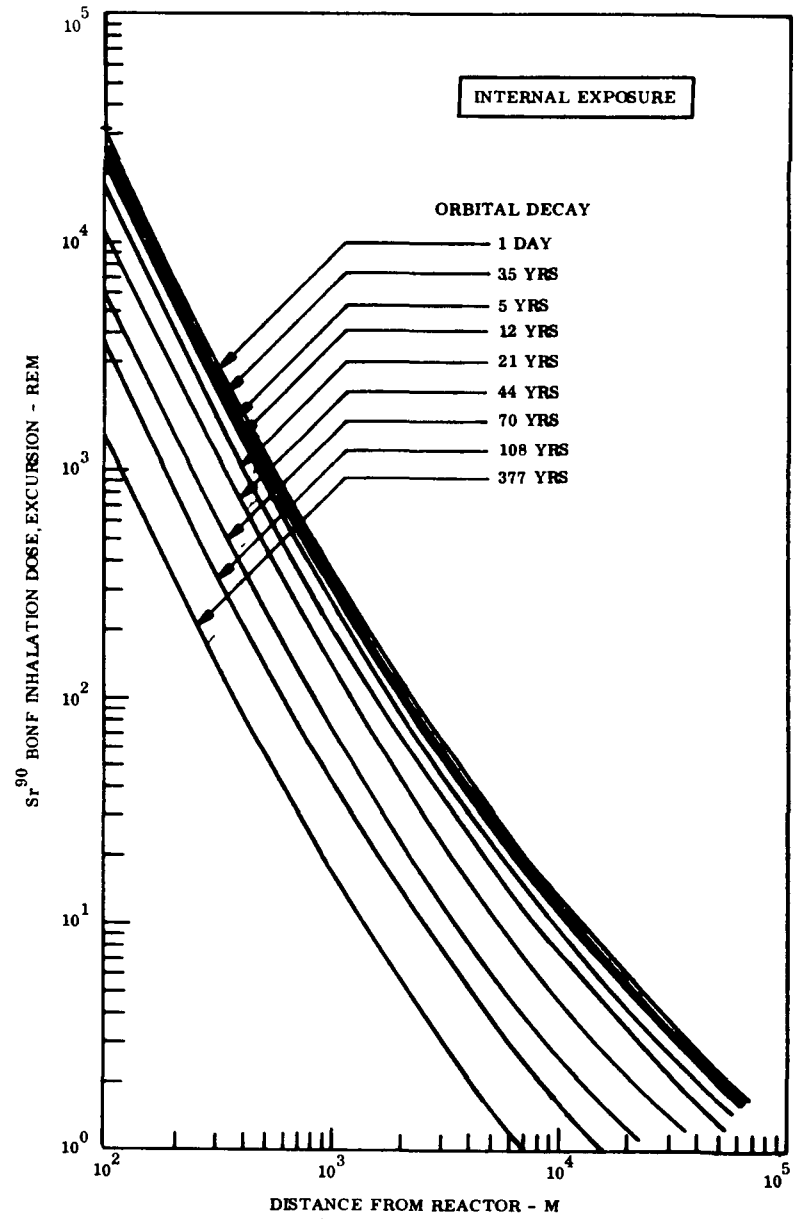


Figure 4-19. Sr^{90} Bone Dose from Inhalation for 1 Day to 377 Year Orbital Decay Time, Excursion

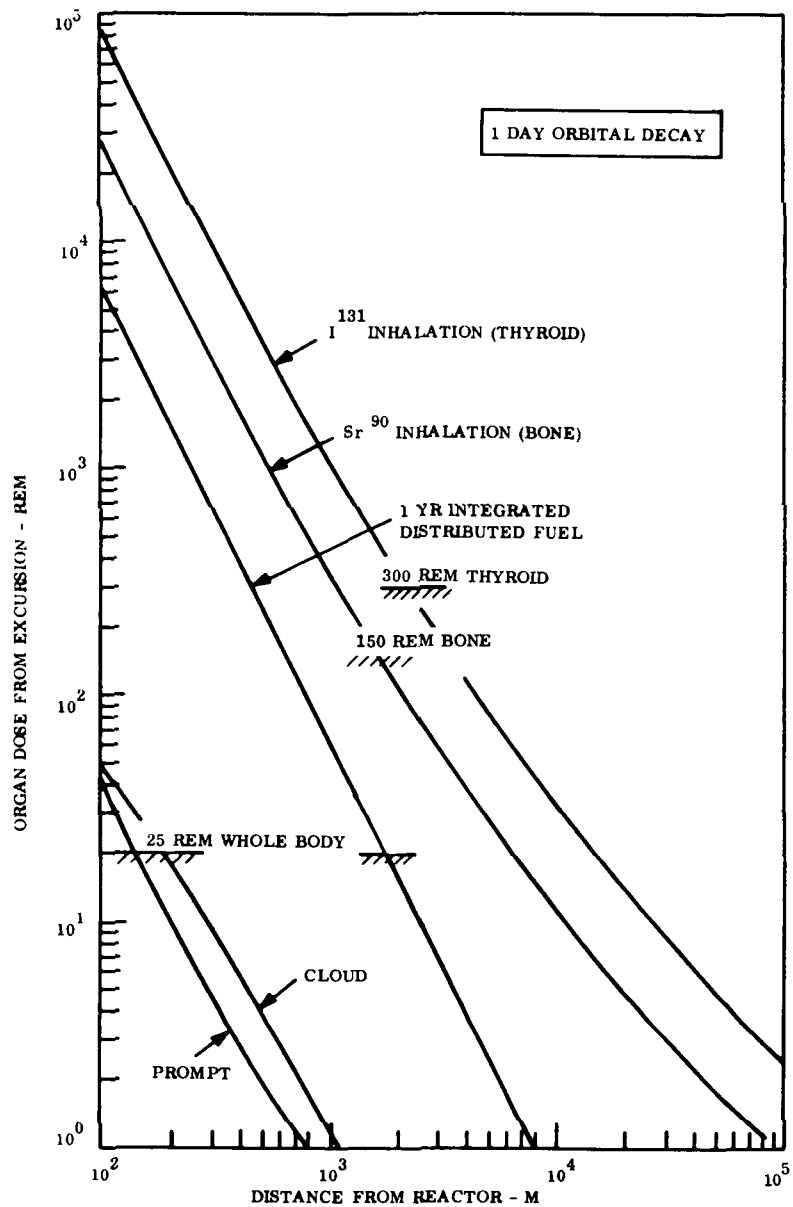


Figure 4-20. Total Exposures Resulting from Destructive Excursion for 1 Day Orbital Decay Time

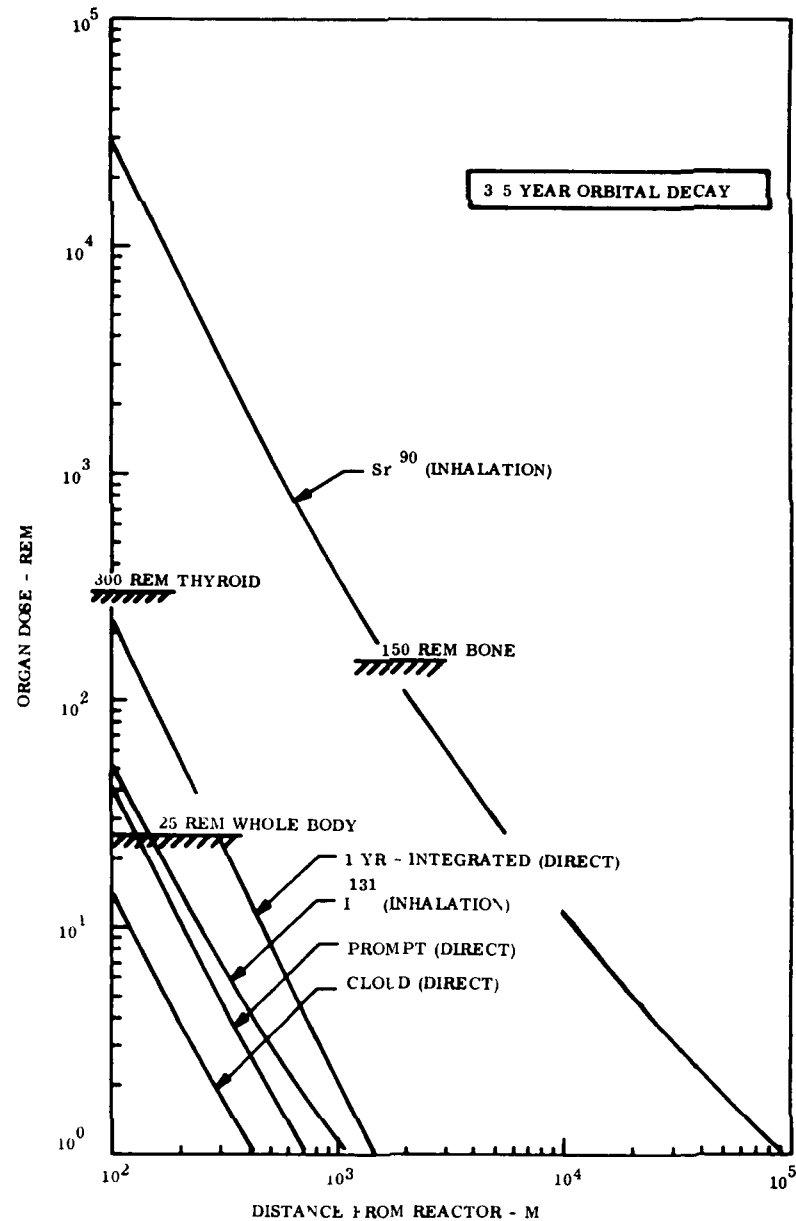
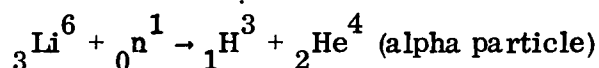


Figure 4-21. Total Exposures Resulting from Destructive Excursion for 3.5 Year Decay Case

4.3.4.4 Exposure Due to Reactor Excursion/Disassembly in Reservoir

Another potential accident considered is a reactor disassembly in a reservoir due to a high velocity water immersion destructive excursion. The most severe accident would be following a one-day orbital decay of a reactor that had operated at 330 kWt for five years. At this time, the release of 7.95×10^3 curies I^{131} and 1.02×10^2 curies Sr^{90} would be considered maximum for the phase as well as for the mission. In comparison, the 100 MW-sec excursion generated I^{131} and Sr^{90} are insignificant. Assuming an instantaneous release with complete mixing to the reservoir volume, the I^{131} thyroid and Sr^{90} bone dose from the ingestion of the contaminated water is shown in Figure 4-22, for either an impact disassembly or a destructive excursion after a one-day orbital decay of the shutdown reactor. The fission product release fractions are assumed to be the same for both assembly cases. For a destructive excursion following a 377-year orbital decay time, the water ingestion doses would be about three orders of magnitude lower than those indicated in Figure 4-22.

Tritium can also be released to the potable water supply by disassembly of the reactor shield on impact. The tritium is generated by neutron interaction with the LiH shielding material:



For the most severe accident where 100 percent of the tritium (3×10^4 curies) is released to the reservoir following a one-day orbital decay of a reactor which has operated at 330 kWt for five years, the tritium whole body dose from the consumption of the contaminated water is shown in Figure 4-22.

As indicated in the figures, only reservoirs with relatively small volumes provide concentrations high enough to exceed the dose guideline values. Guideline values would not be exceeded in a large majority of the reservoirs used for potable water supplies. Early detection and isolation would reduce the exposure even further.

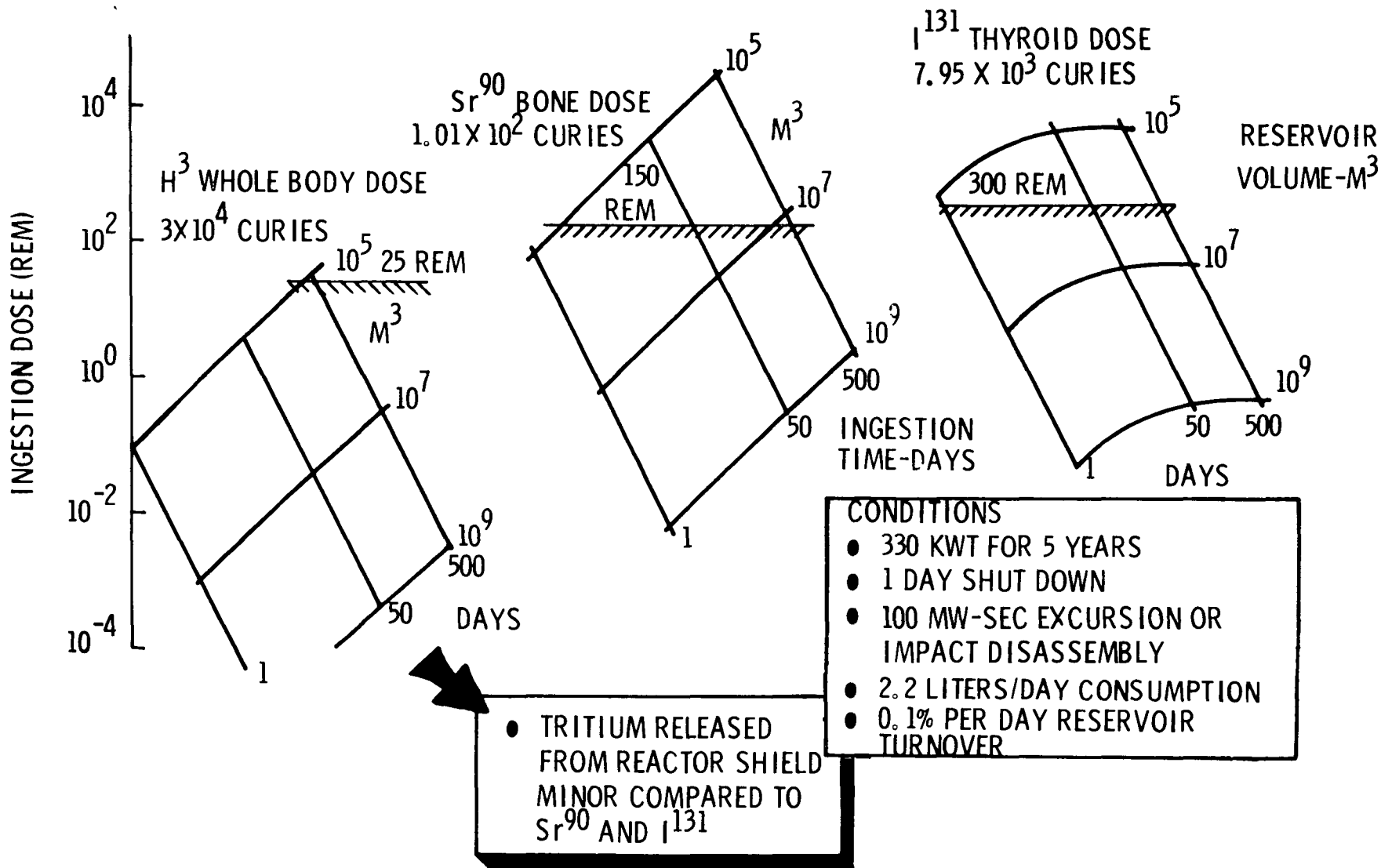


Figure 4-22. Ingestion Exposure from Contaminated Reservoir Water

4.3.4.5 Exposure Due to Reactor Impact on or Near Pasture Land

Another remote possibility is a reactor impact upwind of pasture land. A release of fission products may contaminate herbage downwind of the accident site and a dairy herd grazing on this land will produce milk contaminated with I^{131} and Sr^{90} . Within a day or two this contaminated milk can be consumed by the general public. If the reactor accident is promptly located, the exposure can be minimized. As in the water reservoir accident, the most severe case would be a one-day orbital decay followed by a high velocity impact disassembly or a destructive excursion. The results are shown in Figures 4-23 and 4-24.

4.3.4.6 Fission Product Release From Reentry Burnup

The release of fission products during reentry will result in a widespread dispersal of activity within the hemisphere in which the release took place with little effect due to gravitational settling. This is based on the assumption that all the fission products are reduced in size to the respirable size range (< 10 microns) through vaporization and breakup due to hypersonic reentry conditions. The Total Integrated Concentration (TIC) at sea level (assumed to be uniformly distributed within the troposphere) will be a function of the altitude at which the fission products are injected into the atmosphere. Figures 4-25 and 4-26 indicate the variation of TIC and inhalation dose for a Sr^{90} and I^{131} release to the stratosphere or mesosphere. As would be expected, fuel releases to the stratosphere (region below mesosphere) initially results in higher values of TIC and inhalation dose with time. For the short-lived I^{131} (8-day half-life), this difference persists with time after release (Figure 4-26). For the long lived Sr^{90} (28-year half-life), the stratospheric and mesospheric values converge after about 20 years (Figure 4-25). The TIC and lung dose from a Ta^{182} activation product release to the stratosphere and mesosphere are shown in Figure 4-27. The releases considered in Figures 4-25, 4-26 and 4-27 are the maximum values for five years operation at 330 kWt with zero shutdown time.

4.3.4.7 Exposure From Impacted Bare Core

A reactor impacting land may possibly survive intact, but the shielding may be demolished. The one-year integrated dose for a bare core for all reentry cases for the disposal phase are indicated in Figures 4-28 and 4-29. Again, the reactor operating history prior to

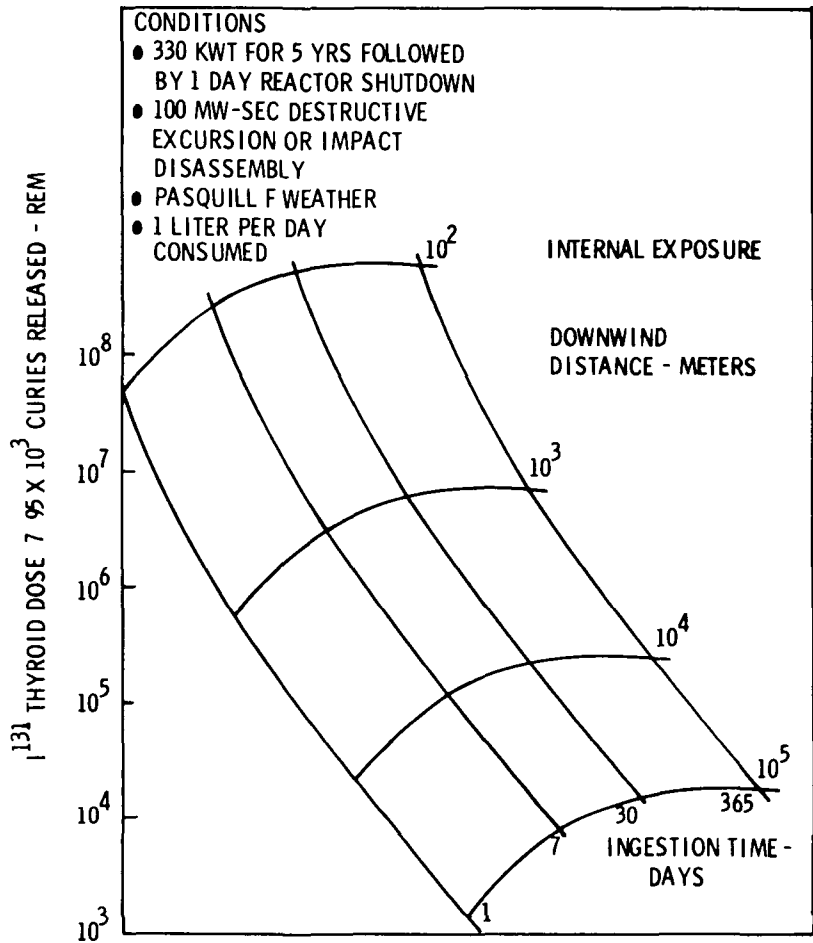


Figure 4-23. ¹³¹I Thyroid Dose from Ingestion of Contaminated Milk

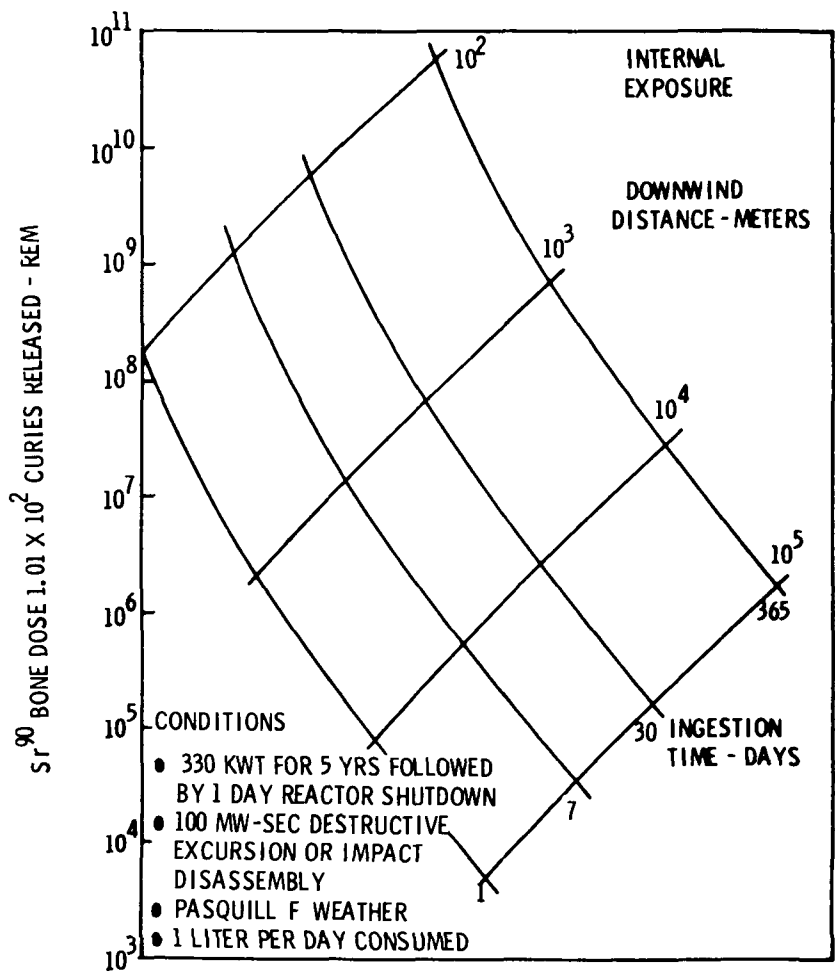


Figure 4-24. ⁹⁰Sr Bone Dose from Ingestion of Contaminated Milk

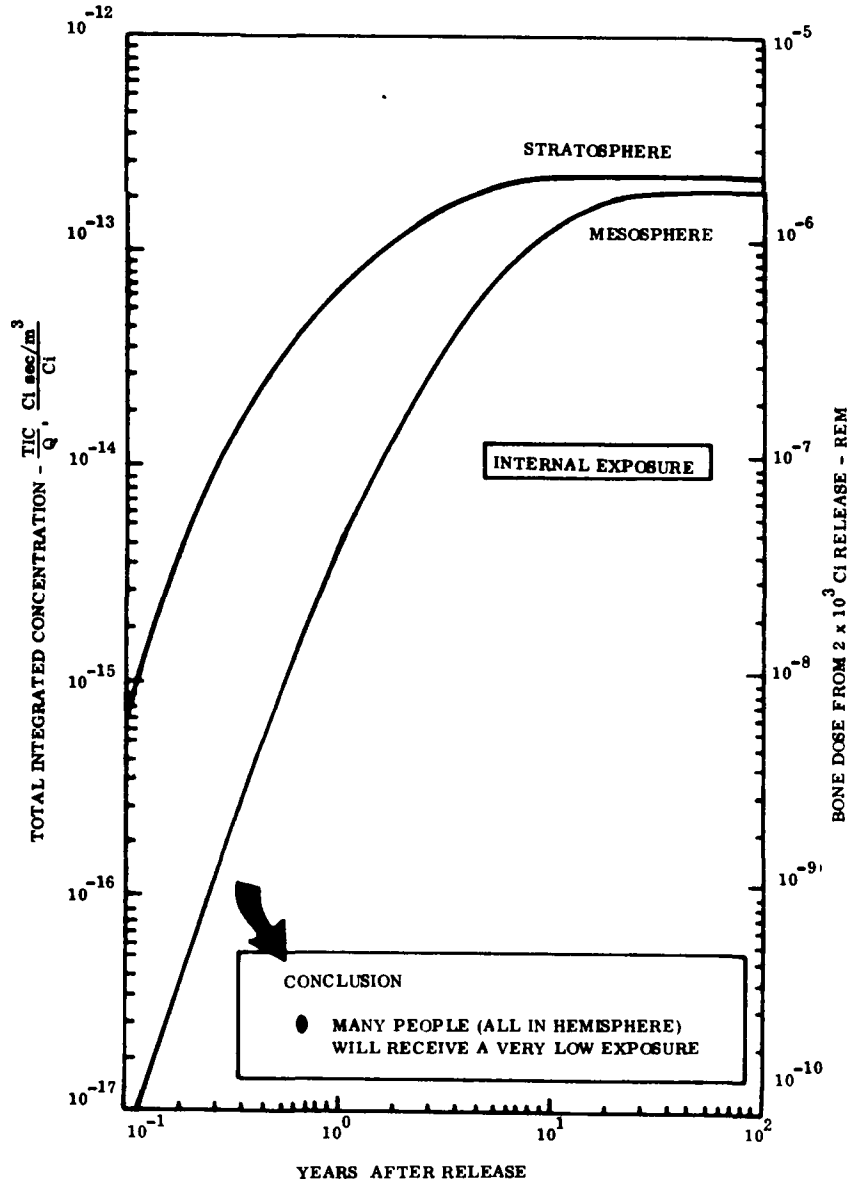


Figure 4-25. Sea Level Total Integrated Concentration and Bone Dose from Mesospheric and Stratospheric Release of Sr^{90}

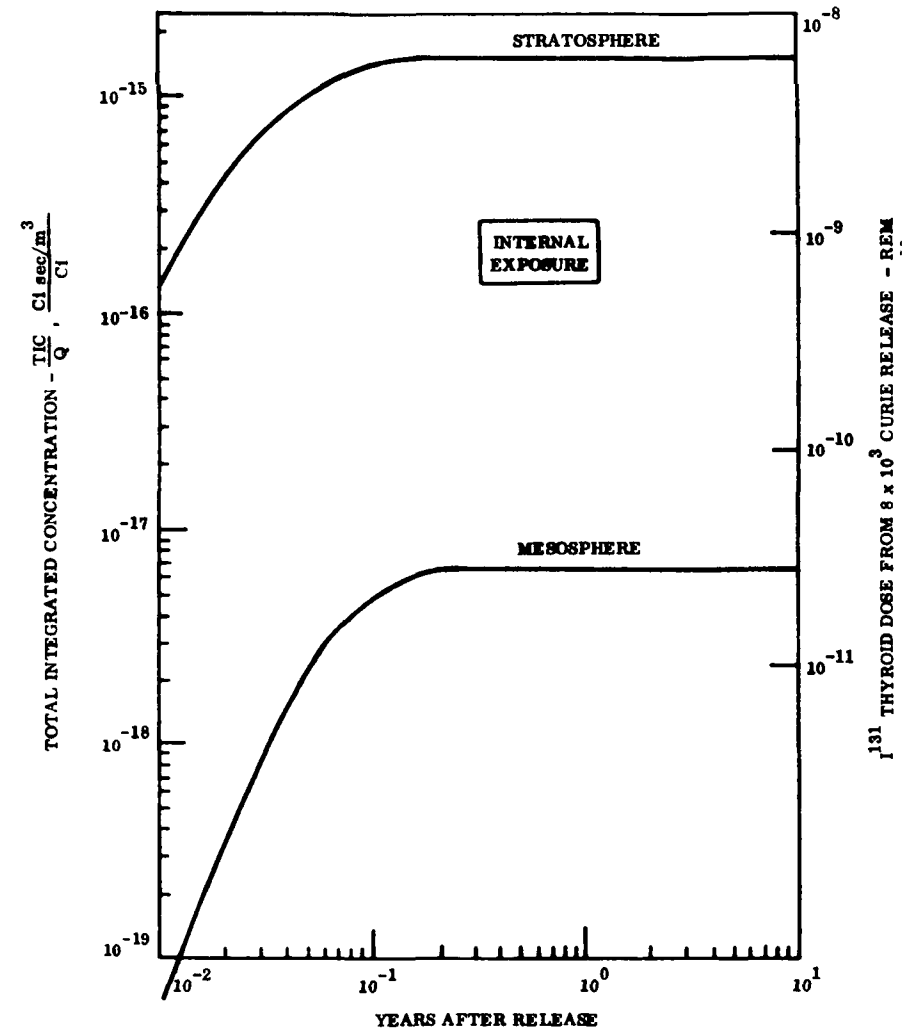


Figure 4-26. Sea Level Total Integrated Concentration and Thyroid Dose from Mesospheric and Stratospheric Release of I^{131}

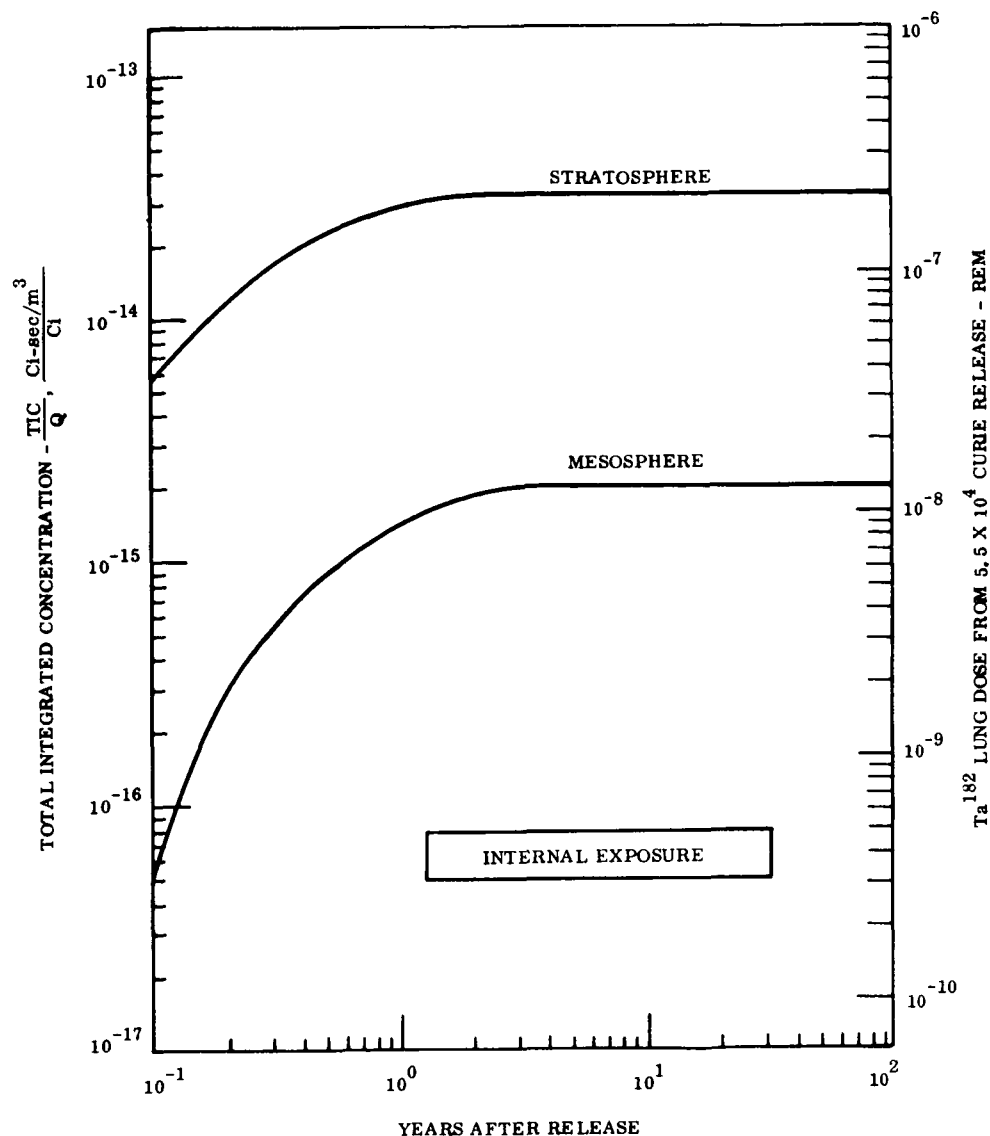


Figure 4-27. Sea Level Total Integrated Concentration and Lung Dose From Mesospheric and Stratospheric Release of Ta^{182}

reentry was taken as five years at a 330 kWt power level. The one-year integrated bare core dose at 100 meters is indicated in Figure 4-30 as a function of shutdown time.

4.3.4.8 Exposure From Single Fuel Elements

Individuals may also be exposed to single fuel elements. The one-year integrated doses from a single fuel element are shown in Figures 4-31 and 4-32. At 10 meters from a single fuel element, the one-year integrated dose is presented in Figure 4-33 as a function of orbital decay time.

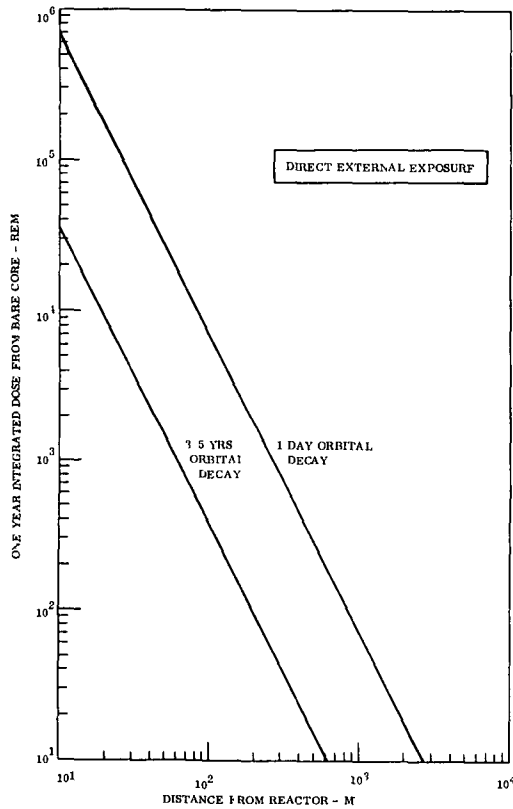


Figure 4-28. One Year Integrated Dose from Bare Core for 1 Day and 3.5 Years Orbital Decay

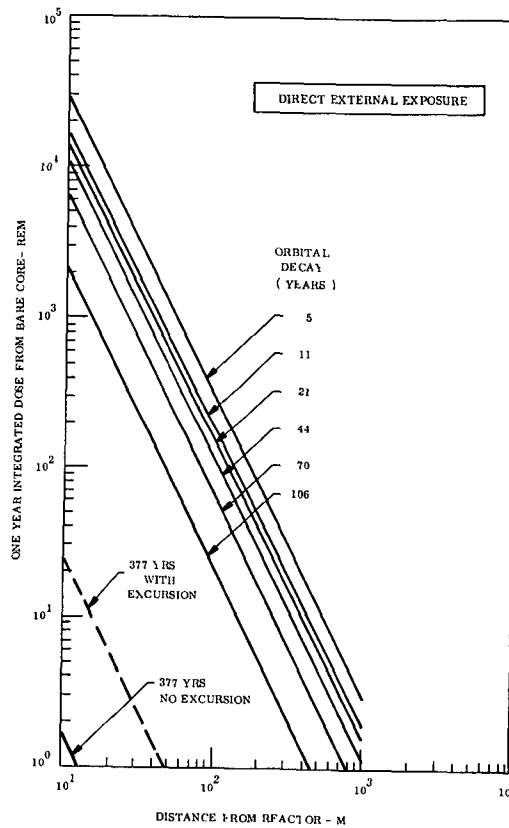


Figure 4-29. One Year Integrated Dose from Bare Core for 5 to 377 Years Orbital Decay

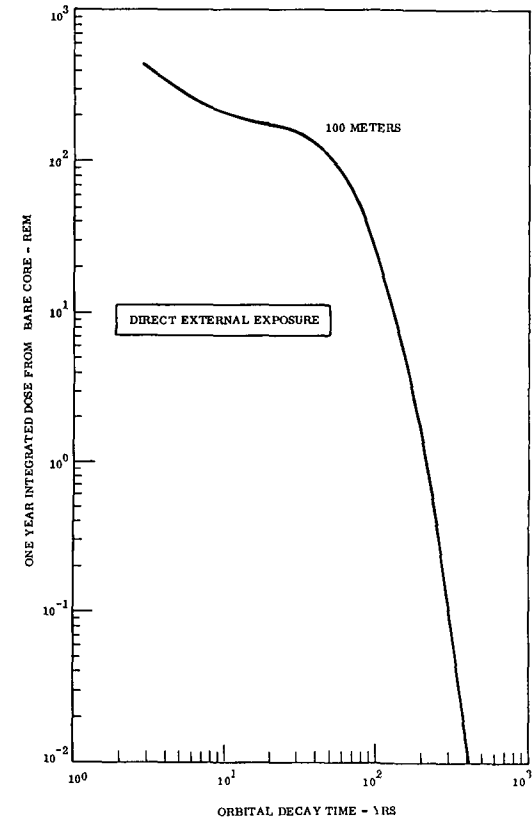


Figure 4-30. One Year Integrated Dose from Bare Core at 100 Meters as a Function of Orbital Decay

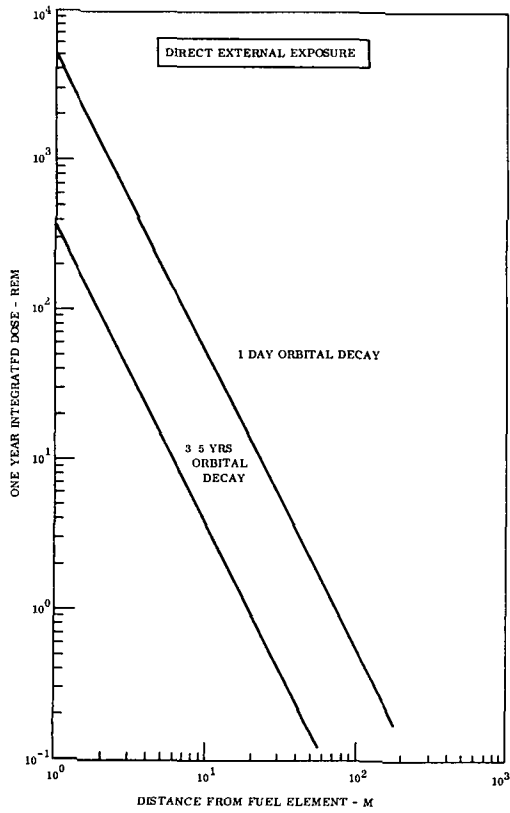


Figure 4-31. Single Fuel Element Integrated Dose for 1 Day and 3.5 Years Orbital Decay

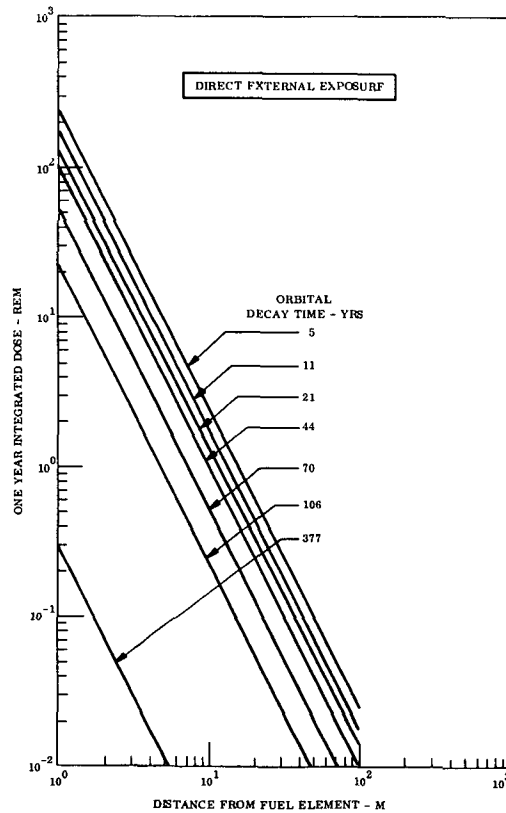


Figure 4-32. Single Fuel Element Integrated Dose for 5 to 377 Years Orbital Decay

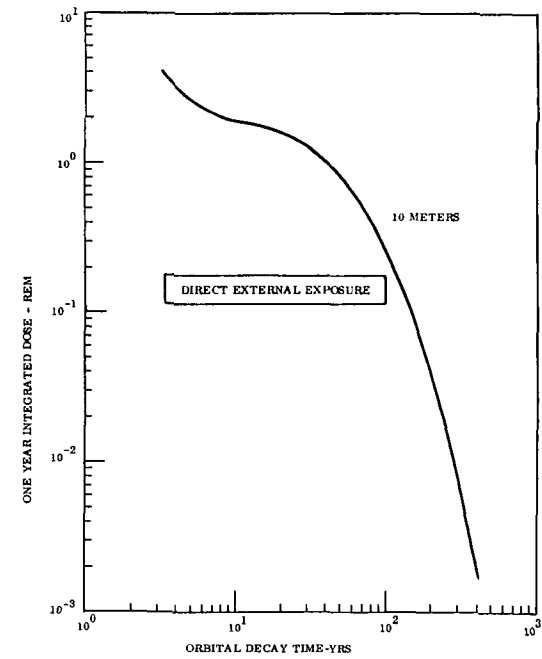


Figure 4-33. Single Fuel Element Integrated Dose at 10 Meters vs. Orbital Decay

4.4 REFERENCES

- 4-1 "Safety Analysis Report SNAPTRAN 2-10A Safety Tests", IDO-17076, Phillips Petroleum Company, October 1965.
- 4-2 "SNAPTRAN-2 Destructive Test Results", IDO-17194, Phillips Petroleum Company, January 1967.

SECTION 5

RADIOLOGICAL RISK ANALYSIS

The "Risk" defined in terms of the average number of people anticipated to be exposed to guideline values and above has been determined for all accident situations, for each mission phase and for the entire mission. Design and operations safeguards should be concentrated in the high risk areas to most effectively increase the safety of the mission.

5.1 CALCULATION OF ACCIDENT RISK

For each fission product release or radiation exposure, the risk to the general public was determined. The risk was assessed through the use of an exposure index which is defined as the average number of people who may be exposed to the dose guideline values defined in Paragraph 2.2.2.1.

The exposure Index (EI) is mathematically defined as:

$$EI = \sum P N \quad (5-1)$$

where:

N = number of people exposed to dose guideline values.

P = probability of people being exposed to dose guideline values.

The summation was made over all identified exposure modes for all accidents in the entire mission. Results are presented in Section 5.2.

5.1.1 CALCULATION TECHNIQUE

The logic for calculation of accident radiological risk is shown in Figure 5-1. As an example of calculation technique, an accident in the Orbital Operations Phase is selected. Case 3.3 (see Table B-3 in Appendix B) involves an equipment failure on board the Space Base which

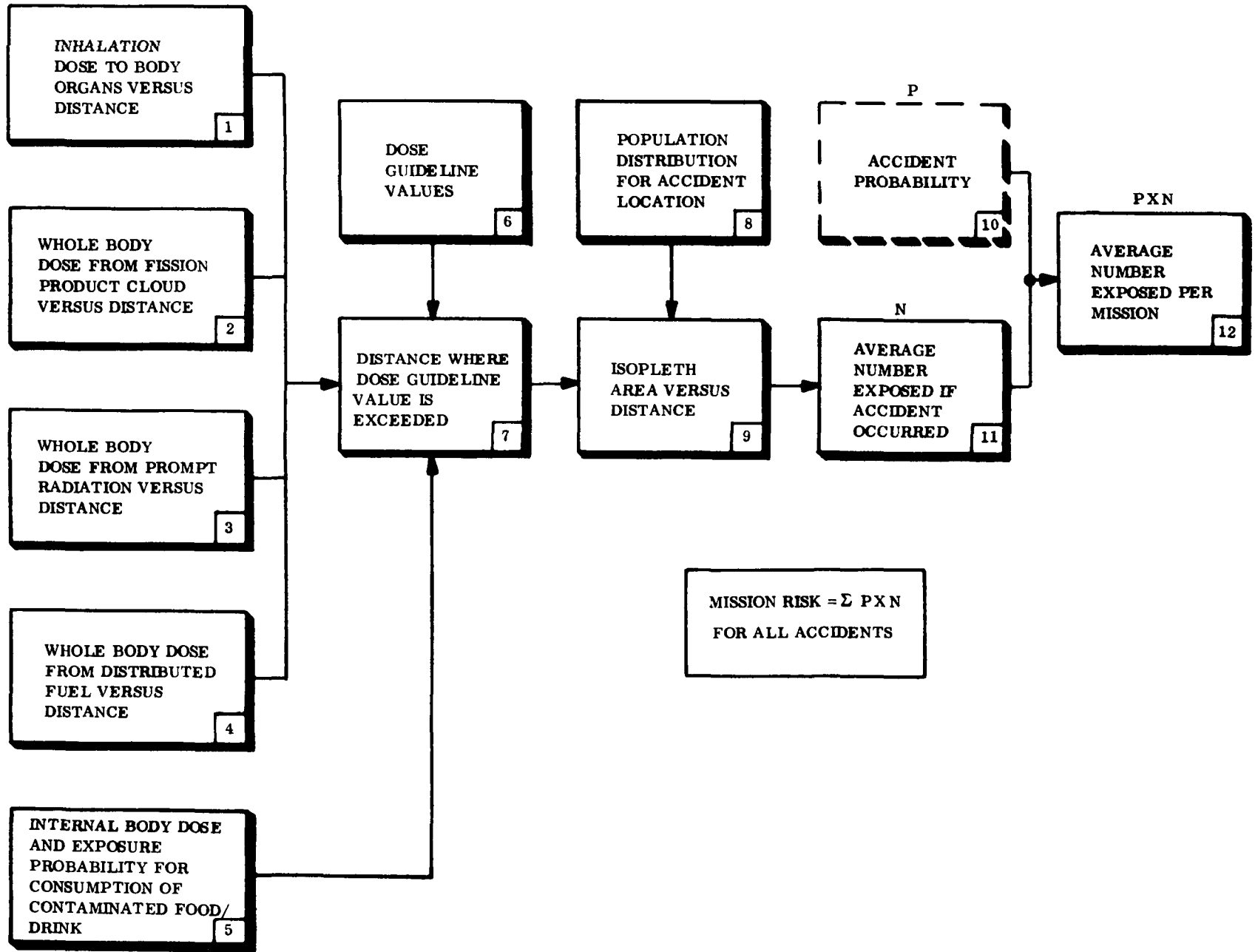


Figure 5-1. Logic for Radiation Exposure Risk Evaluation

eliminates the possibility of reactor disposal and therefore, the power module reenters with the damaged and abandoned Space Base 3.5 years after shutdown. The end result is an impact of the reactor on land, a potential excursion and disassembly followed by a release of fission products. The radiological consequences resulting from the accident are shown in Figure 4-21 and include the organ dose as a function of distance from the reactor impact under Pasquill F weather conditions for:

1. Inhalation Exposure Mode
 - a. Sr^{90} bone dose
 - b. I^{131} thyroid dose
2. Direct Exposure Mode
 - a. Cloud fission products dose
 - b. Prompt neutron and gamma dose
 - c. Distributed fuel - 1 year integrated dose

These radiological consequences are the input for Boxes 1, 2, 3, and 4 of Figure 5-1. Dose values are inserted into the calculational program for incremental distances from zero up to tens of thousands of meters.

The dose guideline values from Section 2, Table 2-2 are used in Box 6. For each exposure shown in Boxes 1-4, the distance where the dose guideline value (Box 6) is exceeded is determined (Box 7). The internal body dose from the ingestion of contaminated food/drink and the exposure probability (Box 5) are determined. The internal body dose (Box 5) is compared to the values in Box 6 to determine if the dose guideline value is exceeded. Population density is now obtained (Box 8). For Case 3.3, the random earth impact data assumed is shown in Table A-3 of Appendix A. The isopleth area as a function of distance for Pasquill F weather (Box 9) is determined from data presented in Appendix A of Reference 5-1. The isopleth areas for direct exposures from prompt neutron and gamma radiation and from distributed fuel are circular. Isopleth areas of inhalation exposures take on the customary elliptical shapes which are dependent on weather conditions and release

heights. Knowing the dose guidelines values (Box 6), the isopleth area (Box 9), the population density (Box 8), the distance where dose guideline values are exceeded for the inhalation and direct exposure modes (Box 7), and the internal body dose and exposure probability for ingestion of contaminated food/drink (Box 5), the average number of people exposed (N), if the accident occurred, is determined (Box 11).

The probability of the accident and a destructive excursion resulting in Case 3.3 is obtained from the probability tables in the AMD (Table 5-2 in Vol III, Part 2). The cumulative probability of such an accident followed by an excursion is 10^{-8} . This value is the input for Box 10 and is the P-value in equation 5-1. The product of N (Box 9) and P (Box 10) is the Exposure Index (EI) for each exposure mode of Case 3.3 expressed in terms of the number of people exposed to or above the guideline value per mission (Box 11). The EI for the accident is the summation of the P x N products for all exposures resulting from the accident. The total mission risk is the summation of each exposure index.

5.2 SUMMARY OF RISK CALCULATIONS

A summary of the risk calculations for each mission phase is presented in Table 5-1. The highest risk accidents can be identified from the table. As shown, the total risk for the entire mission is calculated to be low (3.9×10^{-3}), where only approximately four people are assumed to be exposed to or above dose guideline values for every 1000 missions performed.

The Reactor Disposal Phase is the highest risk with two events being predominant:

1. A reactor disposal system failure prior to circularization ($EI = 2.04 \times 10^{-3}$).
2. The random return from the 990 km disposal orbit ($EI = 1.4 \times 10^{-3}$).

The incorporation of a permanent shutdown device would eliminate the excursion hazard and significantly reduce overall risk.

A reactor recovery by the Shuttle should be considered. Shuttle recovery has been calculated to provide over a 2 order of magnitude reduction in risk during the Disposal Phase.

Table 5-1. Summary of Risk Calculations

Mission Event	Accident	Exposure Index	Mission Event	Accident	Exposure Index	Mission Event	Accident	Exposure Index
Prelaunch			Reactor Disposal			Circularization Burn (Cont)		
Reactor/LV Integration	Reactor dropped while being mated to launch vehicle	0	Pre-separation	G&C equipment failure detected during pre-separation, G&C checkout and failure to repair	2.04×10^{-6}	End-of-Mission/Reentry	Misaligned thrust vector following 1 rocket failure at the circularization burn (following a 1 rocket transfer burn)	2.0×10^{-10}
Transportation to Pad	Tip over of the reactor/launch vehicle during transport to the launch pad	0	Separation, Stabilization and Alignment	Failure to separate power module from Space Base	2.04×10^{-7}		Successful ignition of both rockets for the circularization burn following a 1 rocket transfer burn	1.15×10^{-4}
Launch Preparations	Explosion and fire on the launch pad during launch vehicle fueling	0		G&C disposal system equipment failure detected during post-separation stabilization and alignment and failure to repair	2.04×10^{-4}		Random return from 990 km disposal orbit	1.4×10^{-3}
Prelaunch Operations	Liquid metal fire	0	Transfer Burn	Misaligned thrust vector, normal 2-rocket burn	2.22×10^{-6}			
	Phase Total	0		Misaligned thrust vector, 1-rocket burn	2.04×10^{-8}		Phase Total	3.86×10^{-3}
				Complete failure of the primary propulsion system and failure to repair	2.04×10^{-7}			
Launch/Ascent				Accidental collision with Space Base or related systems following successful ignition of the primary propulsion system	2.24×10^{-9}			
Launch	Launch pad abort, explosion and fire	0		Collision with Space Base or related systems and separation of the reactor/shield configuration from the power module (resulting from the collision) following successful ignition of the primary propulsion system	1.36×10^{-10}			
SIC Boost	Abort, explosion and fire (at altitude)	0						
SIC Boost	Abort, no explosion and fire (at altitude)	0						
S II Boost	Abort, explosion and fire (at altitude)	4.9×10^{-6}						
S II Boost	Abort, no explosion and fire (at altitude)	4.9×10^{-5}						
Rendezvous and Docking	Accidental collision while attempting to dock (repair not possible)	2.0×10^{-6}						
Rendezvous and Docking	Failure to dock with Space Base (repair not possible)	2.0×10^{-6}						
Rendezvous and Docking	Failure to remove thermal shroud (repair not possible)	2.0×10^{-6}						
Rendezvous and Docking	Failure to rendezvous with Space Base	2.0×10^{-6}						
	Phase Total	6.19×10^{-5}						
Orbital Operations								
	Equipment failure aboard Space Base necessitating early abandonment	2.22×10^{-5}						
	Accidental collision or explosion in orbit necessitating early abandonment of Space Base	2.42×10^{-8}						
	Accidental collision or explosion in orbit (Power module damaged)	5.14×10^{-5}						
	Reactor control system malfunction or reactor operational procedure error	1.4×10^{-5}						
	Phase Total	7.50×10^{-5}						

TOTALS	Mission Phase	Exposure Index
	Prelaunch	0
	Launch/Ascent	6.2×10^{-5}
	Orbital Operations	7.5×10^{-5}
	Reactor Disposal	3.9×10^{-3}
	Total Mission	$*3.9 \times 10^{-3}$

*3.9 people exposed to or above dose guideline values for every 1000 missions performed.

A graphical comparison of phase and mission risk is shown in Figure 5-2. The expected risk reductions due to the incorporation of a permanent shutdown device and Shuttle recovery are shown. As noted on the log scale graph, the single highest risk accident for the Disposal Phase constitutes a major portion of the risk.

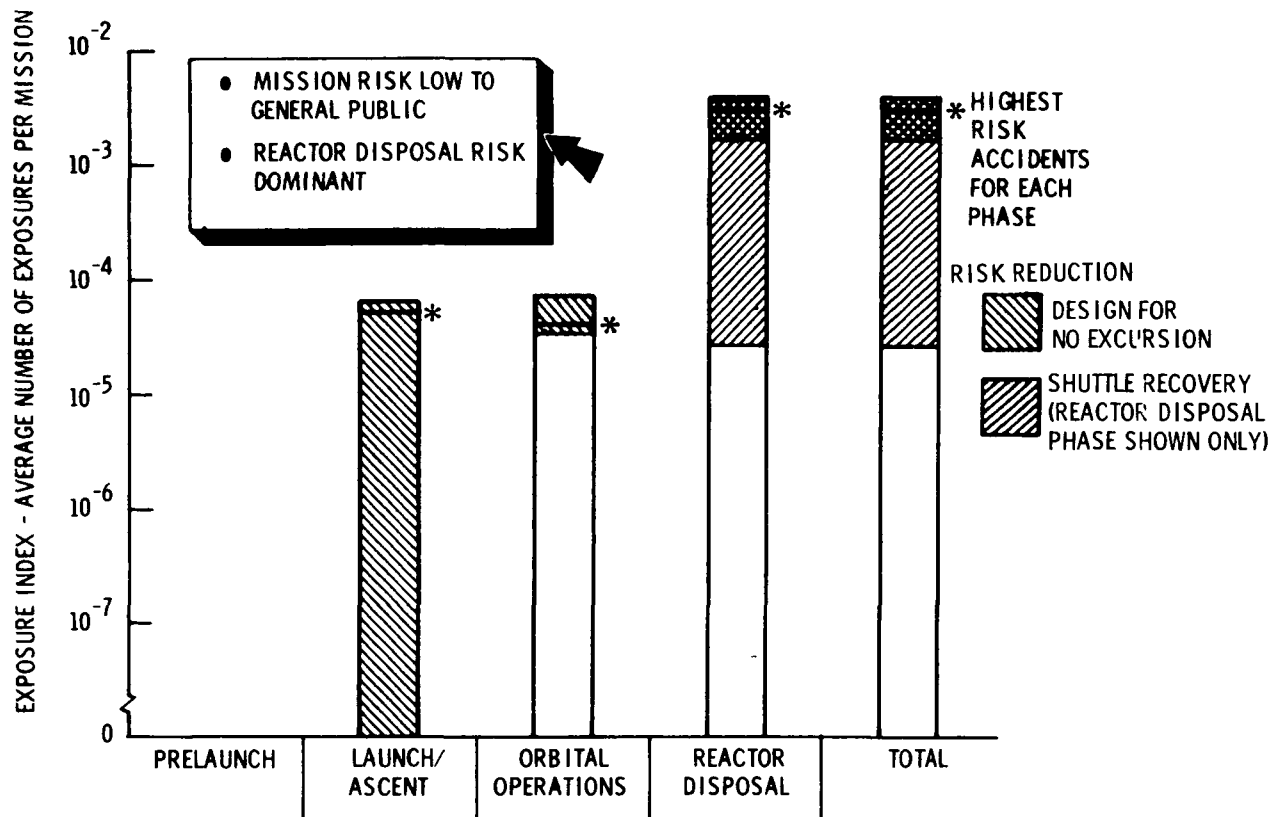


Figure 5-2. Risk Analysis Summary

The highest risk accidents in each phase are individually examined in the following Subsection.

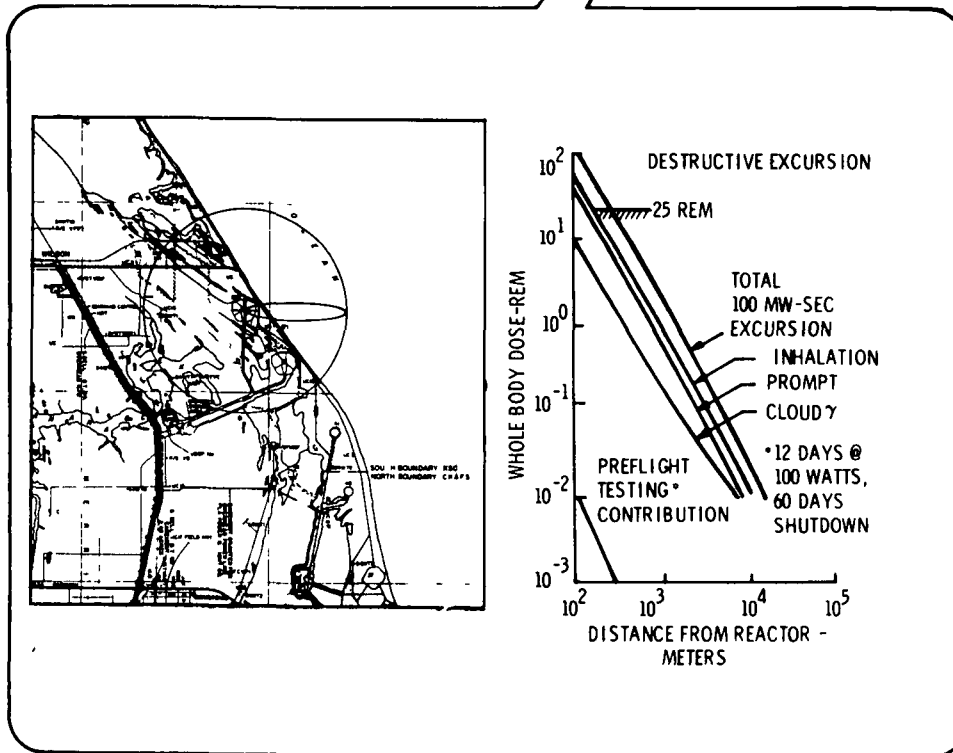
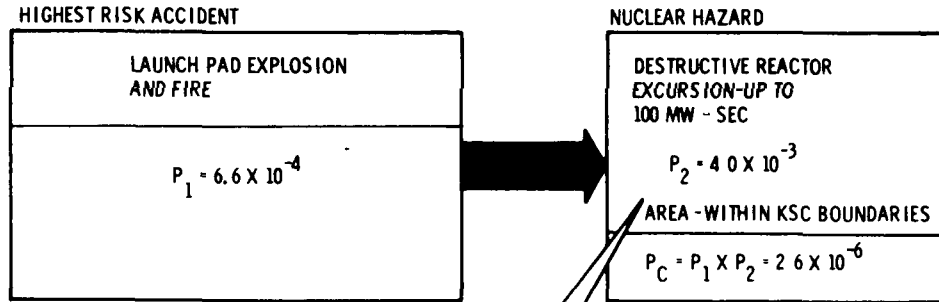
5.3 ACCIDENT EVALUATION

This section defines the most hazardous accidents which may occur in each of the mission phases. The most hazardous accident is defined as the accident with the highest exposure index.

5.3.1 PHASE 1 - PRELAUNCH

The highest probability accident is shown in Figure 5-3. During the Prelaunch Phase, there is no apparent risk to the general public since the radiological consequences of any accident

4 INITIATING ACCIDENTS/EVENTS EVALUATED



SUMMARY

- EXPOSURE INDEX
DOSE GUIDELINE = 0
- NO SIGNIFICANT RISK TO GENERAL PUBLIC
 - TOTAL BODY DOSE < BACKGROUND WITHIN KSC BOUNDARY
 - SMALL AFFECTED AREA (0.7 KM²)
- SAFEGUARDS
 - CONTROL DRUM LOCKOUT DEVICE

TOTAL PHASE
 EXPOSURE INDEX
 DOSE GUIDELINE = 0

Figure 5-3. Prelaunch Phase High Risk Accident Evaluation

are confined within the KSC boundary. There also is no risk to the ground crew or spectators of the launch from a pad abort, since dose guideline values will not be exceeded at the normal vantage points. Should an accident occur during assembly or checkout, some members of the ground crew may become exposed. However, the administrative procedures, handling equipment and shipping containers used during the Prelaunch Phase should prevent or definitely minimize the release of fission products or activated material in most if not all credible accident situations.

5.3.2 PHASE 2 - LAUNCH/ASCENT

During the Launch/Ascent Phase, the highest risk with an exposure index of 4.9×10^{-5} results from a reactor land impact in Eurasia (see Figure 5-4). This accident may occur during the launch trajectory which passes over Eurasia from one of the following initiating events:

1. Premature S-II thrust termination
2. Guidance and control failure
3. Launch vehicle structural failure

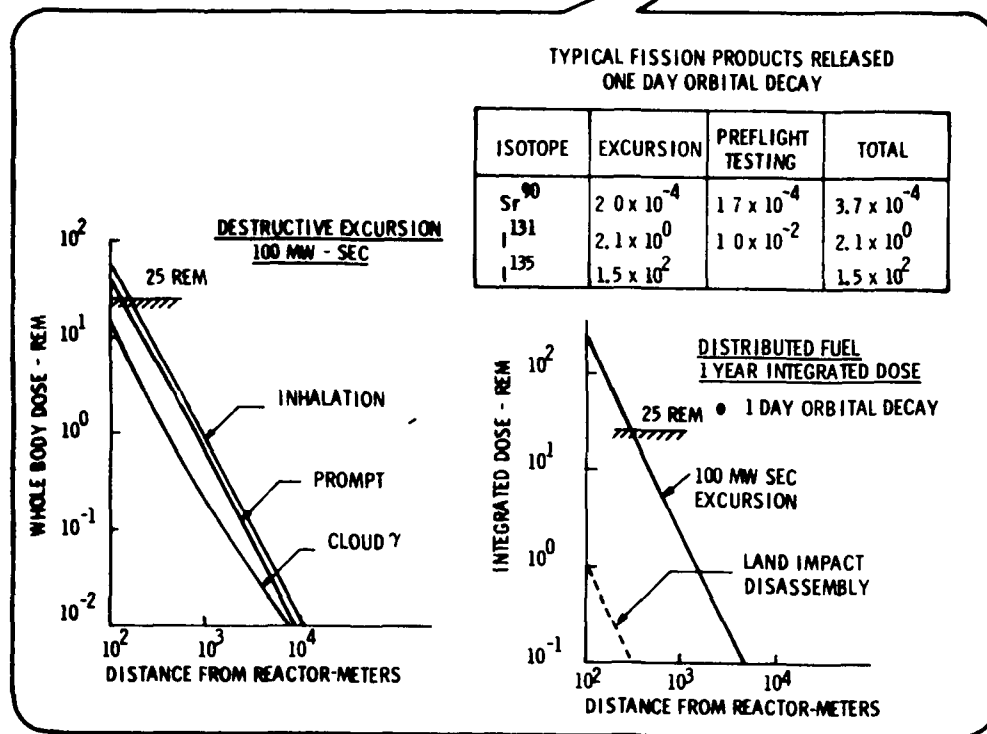
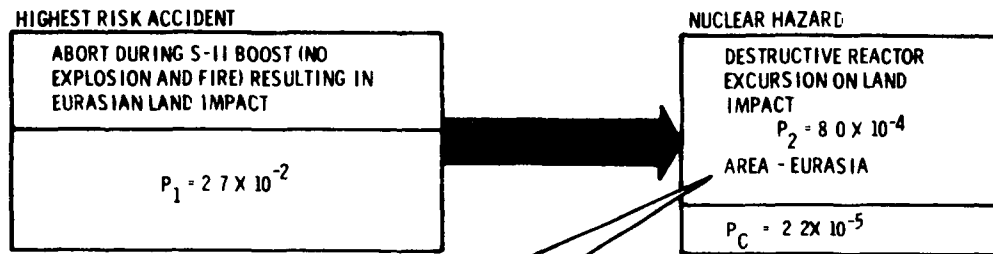
On land impact, the 4.9×10^{-5} exposure index results from a destructive excursion due to control drum rotation/core compaction. This particular accident could be minimized and possibly eliminated by a control drum lockout device which is not removed until after the reactors have been successfully docked and deployed on the Space Base. The remainder of the risk for this phase results from overmoderation accidents where the reactor is immersed in water.

5.3.3 PHASE 3 - ORBITAL OPERATIONS

During the Orbital Operations Phase, two accidents which constitute the highest risk are:

1. Accidental explosion or collision in orbit (5.1×10^{-5})
2. Equipment failure aboard Space Base necessitating early abandonment (2.2×10^{-5})

9 INITIATING ACCIDENTS/EVENTS EVALUATED



SUMMARY

- EXPOSURE INDEX DOSE GUIDELINE - 4.9×10^{-5} (4.9 PEOPLE EXPOSED TO OR ABOVE GUIDELINE FOR EVERY 100,000 MISSIONS)
- LOW RISK TO GENERAL PUBLIC - SMALL AFFECTED AREA ($\approx 0.7 \text{ KM}^2 > \text{BACKGROUND}$)
- SAFEGUARDS
 - CONTROL DRUM LOCKOUT DEVICE
 - TRACKING/RECOVERY

TOTAL PHASE EXPOSURE INDEX DOSE GUIDELINE - 6.2×10^{-5}

Figure 5-4. Launch/Ascent Phase High Risk Accident Evaluation

The first accident involves an explosion or accidental collision in orbit (Figure 5-5). The consequence of concern from an accident of this type is possible permanent damage to the disposal system precluding early disposal of the damaged power module. Successful separation from the Space Base results in a 5-year orbital lifetime whereas remaining with an inoperative base will provide a reduced orbital lifetime of approximately 3.5 years.

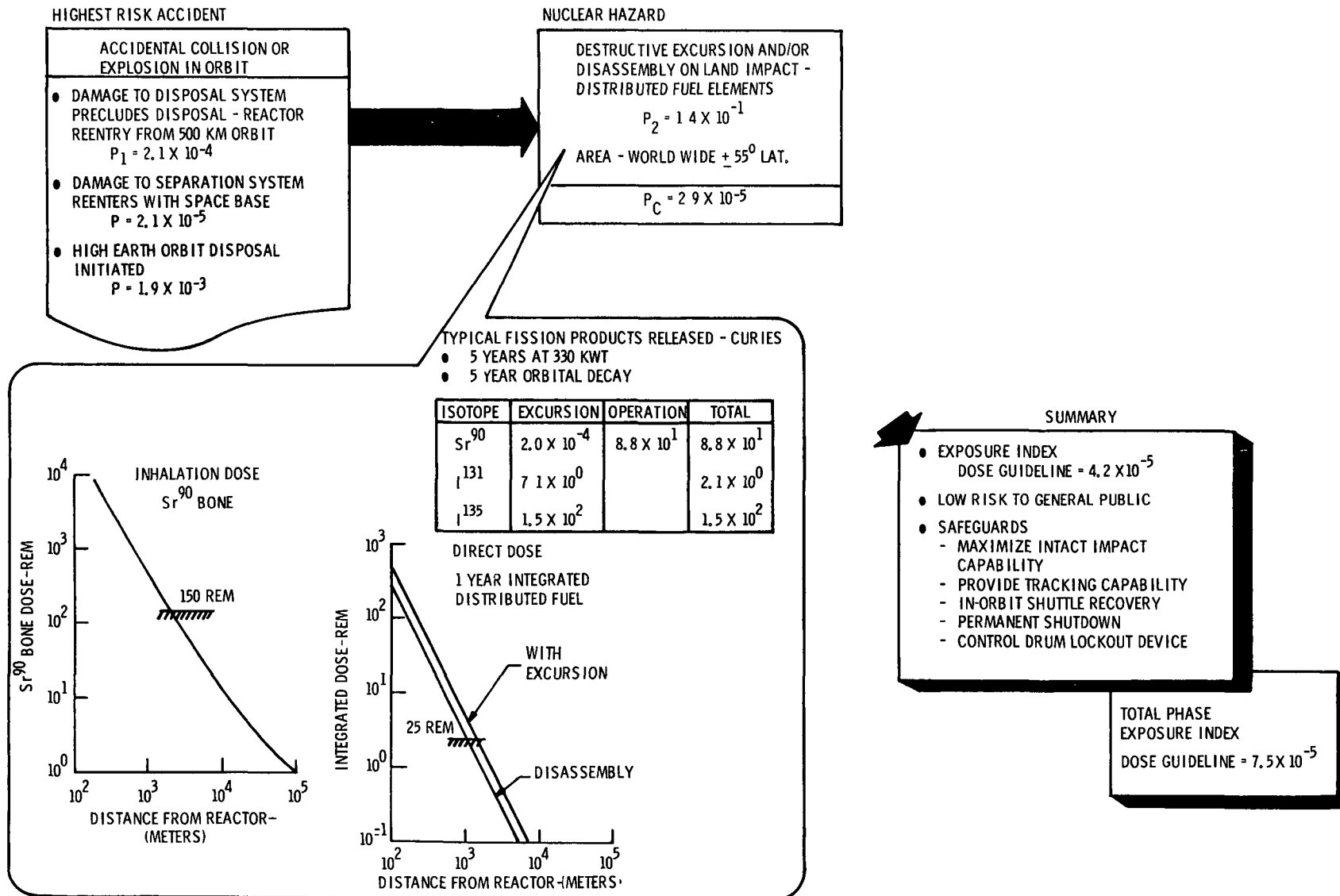
The power module can be damaged to such an extent that the fuel cladding is breached due to loss of cooling or the loss of reactor control. The loss of hydrogen from the core would prevent a reactor excursion on land impact. However, land impact may result in disassembly due to high velocity impact. Due to the high fission product inventory in the core (orbital lifetime of 5 years), the resulting risk is 4.2×10^{-5} people exposed to dose guidelines or above per mission. The risk could be minimized by improving the impact resistance of the core pressure vessel and shielding. An in-orbit recovery by the Shuttle would substantially reduce the hazard.

The possible causes of Accident 2 may be loss of guidance and control, or loss of the environmental control system of the Space Base which would cause an early abandonment. Successful separation of the reactor power modules were achieved in this case which permitted an orbital lifetime of 5 years. The failure aboard the Space Base was assumed to preclude successful high altitude disposal. The risk results from a reactor disassembly on impact without an excursion. A reduction in risk can be achieved by providing increased impact integrity, tracking capability on reentry, and possible backup disposal control from the ground. Shuttle recovery should also be considered; however, the power module may be in a free flying tumbling mode.

5.3.4 PHASE 4 - REACTOR DISPOSAL

During the Reactor Disposal Phase, the highest risk accident has an exposure index of 2.0×10^{-3} which is also the highest single risk for the entire mission. The accident that is of concern is a disposal system guidance and control failure following the transfer burn to the intermediate disposal orbit (Figure 5-6). As a consequence, the power module will reenter from an elliptical orbit with a lifetime of 21 years. The risk is associated with a

4 INITIATING ACCIDENTS/EVENTS EVALUATED



SUMMARY

- EXPOSURE INDEX
DOSE GUIDELINE = 4.2×10^{-5}
- LOW RISK TO GENERAL PUBLIC
- SAFEGUARDS
 - MAXIMIZE INTACT IMPACT CAPABILITY
 - PROVIDE TRACKING CAPABILITY
 - IN-ORBIT SHUTTLE RECOVERY
 - PERMANENT SHUTDOWN
 - CONTROL DRUM LOCKOUT DEVICE

TOTAL PHASE EXPOSURE INDEX
DOSE GUIDELINE = 7.5×10^{-5}

Figure 5-5. Orbital Operations Phase High Risk Accident Evaluation

HIGHEST RISK ACCIDENT

FAILURE TO STABILIZE AND REALIGN AFTER TRANSFER BURN, REENTRY OF REACTOR AFTER 21 YEARS ORBITAL DECAY

- REACTOR SURVIVES REENTRY
 $P_1 = 2 \times 10^{-3}$
- REACTOR FAILS TO SURVIVE REENTRY
 $P = 2 \times 10^{-3}$

NUCLEAR HAZARD

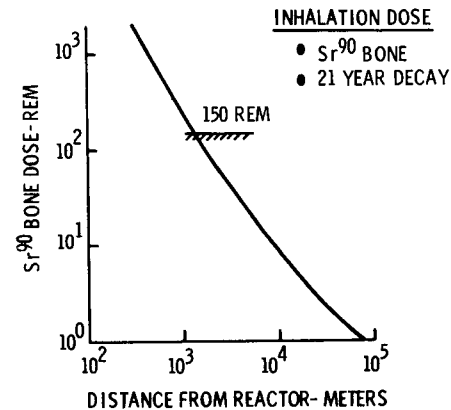
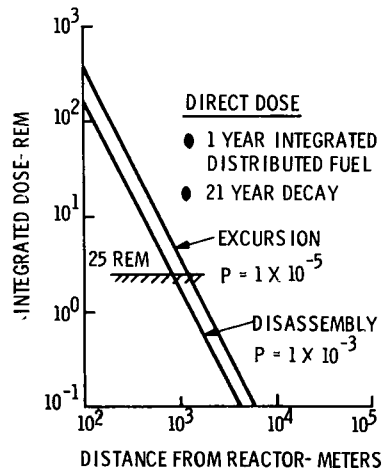
DESTRUCTIVE EXCURSION AND/OR DISASSEMBLY ON LAND IMPACT RESULTING IN DISTRIBUTED FUEL
 $P_2 = 2.7 \times 10^{-1}$

AREA - WORLD WIDE $\pm 55^\circ$ LAT.
 $P_C = 5.3 \times 10^{-4}$

TYPICAL FISSION PRODUCTS RELEASED-CURIES

- 5 YEARS AT 330 KWT
- 21 YEAR ORBITAL DECAY
- 100 MW-SEC EXCURSION

ISOTOPE	EXCURSION	POWER OPERATION	TOTAL
Sr ⁹⁰	2.0×10^{-4}	5.7×10^1	5.7×10^1
I ¹³¹	2.1×10^0		2.1×10^0
I ¹³⁵	1.5×10^2		1.5×10^2



SUMMARY

- EXPOSURE INDEX
DOSE GUIDELINE = 2.0×10^{-3}
- LOW RISK TO GENERAL PUBLIC (HIGH ACCIDENT PROBABILITY)
- SAFEGUARDS
 - MAXIMIZE INTACT IMPACT CAPABILITY
 - PROVIDE TRACKING
 - PERMANENT SHUTDOWN
 - SHUTTLE RECOVERY

TOTAL PHASE EXPOSURE INDEX
DOSE GUIDELINE = 3.9×10^{-3}

Figure 5-6. Reactor Disposal Phase High Risk Accident Evaluation

land impact disassembly caused by the high velocity impact loads. Although the core fission product activity will experience substantial decay before land impact and disassembly, the probability of the accident is high (3.9×10^{-3}); the overall result being a high risk value. The radiological consequence of this accident again can be minimized by improving the impact capability of the reactor and shield and by providing a tracking device for early detection.

Another event worthy of mention is the risk involved in the successful disposal to the desired orbit altitude of 990 km (535 nm) with a calculated power module lifetime of 1167 years. At the end of this lifetime the fission products and activation products will have decayed to non-hazardous levels. However, this does not preclude a hazard from a land impact initiated excursion. If the fuel elements retain the hydrogen moderator during the orbital lifetime a destruction excursion could occur on land impact due to control drum rotation/core compaction. Although a destructive excursion with a very low core activity inventory will affect a relatively small area, the probability of occurrence is high, since the reactor must impact earth after 1167 years. Hence, the resulting exposure index is 1.4×10^{-3} . This risk can be reduced substantially by a permanent shutdown of the reactor prior to insertion into the disposal orbit. The permanent shutdown method can be a combination of control drum lockout devices and neutron poison insertion into the core. Again, a recovery by the Shuttle rather than a boost to high earth orbit can reduce the risk and may be politically more acceptable than eventual random reentry of a reactor power module (possibly radiologically non-hazardous).

5.4 REFERENCES

- 5-1 "Meteorology and Atomic Energy," TID-24190, US Department of Commerce for US Atomic Energy Commission, 1968.

SECTION 6

PARAMETRIC RADIOLOGICAL EXPOSURE ANALYSIS

Parametric analyses play a key role in the terrestrial nuclear safety evaluation. Reactor operational histories and key accident conditions are varied over a range of possible values to illustrate the sensitivity of the resulting radiological hazard to each of the parameters. This analysis can therefore be used to provide additional data should future power module design and operational conditions differ from the reference mission.

The AISITE II program (Reference 6-1) is a particularly useful tool for this parametric investigation. The program automatically varies any one of forty-six parameters such as reactor power, operating time, shutdown time, fission product release heights and release fractions, etc. As many as ten values of the variable parameter can be calculated for each run. Dose versus distance values for internal inhalation and external (immersion) cloud dose to the whole body are indicated in the following figures.

Figure No.	Parametric Evaluation
6-1	Effect of Weather Conditions
6-2	Effect of Release Weight
6-3	Effect of Solid Fission Product Release Function
6-4	Effect of Reactor Operating Time
6-5	Effect of Reactor Power Level
6-6	Effect of Reactor Shutdown Time
6-7	Interrelationships of Reactor Operating Time and Reactor Shutdown Time

In addition, the internal organ doses from the ingestion of contaminated milk and water are given in:

Figure No.	Parametric Evaluation
6-8 and 6-9	Ingestion Dose from Contaminated Milk (Sr^{90} , I^{131})
6-10 and 6-11	Ingestion Dose from Contaminated Water (Sr^{90} , I^{131})

One of the basic questions is how sensitive are the results to the uncertainties of the parameters. The results of a parametric evaluation can indicate the degree of uncertainty and the design requirements or areas where additional research or development may be needed. In addition to providing direction, studies of this nature provide data on the effect that design decisions have on safety. For example, should the inclusion of a specific safeguard to reduce the fission product release rate result in an insignificant decrease in public safety, the added expense is not worthwhile. Conversely, investigations of this type can indicate which engineering safeguards are critical and to what extent. It is important to the reactor designer to understand how design changes will affect safety.

Figure 6-1 indicates the cloud dose and the internal inhalation whole body dose as a function of distance from the reactor for various weather conditions. The release considered is the result of a high velocity impact disassembly. It is evident that the weather conditions prevailing at the time of the accident have a significant effect on the dispersion pattern downwind of the accident site. As an example, at a 1 km distance from the accident location there is a factor of 100 spread in inhalation dose for the various weather conditions. For very unstable conditions, Pasquill A, the isopleth will be shaped like a short stubby cigar. The downwind distance for an equivalent exposure isopleth for stable conditions, Pasquill F, will extend much farther than that for Pasquill A. The isopleth shape will also differ in that it will be long and thin like a Panetela cigar. To be conservative, Pasquill F parameters are used in subsequent NSAD analyses. Figure 6-1 also shows that the inhalation dose is dominant.

An increase in above ground release height significantly reduces the ground level dose to an individual downwind of the release as seen in Figure 6-2 for a high velocity impact disassembly. Because of the uncertainty of the height of the instantaneous puff release from a reactor disassembly by either high velocity impact loads or destructive excursion, the releases are conservatively assumed to be at ground level in the subsequent analyses.

Fission product gases and volatile iodines are assumed to be released completely in a reactor disassembly. However, the nonvolatile solid particle fission products, such as Sr^{90} and Ca^{137} , are released to a lesser extent. Figure 6-3 indicates that the external cloud and internal inhalation dose is directly proportional to the solid release fraction. A fractional release of 0.05 is utilized in the NSAD.

The external cloud and internal inhalation dose is presented in Figure 6-4 as a function of reactor operating time. As expected, the doses increase with operating time due to the buildup of the reactor core fission product inventory. However, the integrated dose increases at a slower rate as the reactor operating history increases since shorter lived fission products have attained saturated values. At these levels, the rate of generation of short lived fission products is balanced by the rate of decay.

The integrated dose levels for cloud and inhalation dose are directly related to reactor power level as indicated in Figure 6-5.

The external cloud dose is primarily due to short-lived fission gases and the internal inhalation whole body dose is primarily a consequence of long-lived fission products. Therefore, their response to reactor cooling time differs as depicted in Figure 6-6.

The whole body inhalation dose is not greatly affected by reactor operating and cooling time as indicated in the carpet plot in Figure 6-7. On the other hand, the whole body cloud dose is significantly affected by reactor cooling time since this exposure mode is primarily a consequence of short-lived fission product gases.

The ingestion of milk contaminated with Sr^{90} and I^{131} has been evaluated as a function of ingestion time and downwind distance from reactor impact location (see Figures 6-8 and 6-9) for Pasquill F weather conditions. The curves are plotted per curie of radioisotope released. Since the I^{131} has a relatively short half-life (8 days) there is essentially no thyroid dose buildup after a 30-day ingestion period. The long-lived Sr^{90} (28-year half-life) continues to build up after a 365-day ingestion period.

The Sr^{90} and I^{131} doses from ingestion of contaminated reservoir water are shown in Figures 6-10 and 6-11 as a function of days ingested and reservoir volume. The thyroid and bone doses are given per curie Sr^{90} and I^{131} released respectively.

REFERENCES

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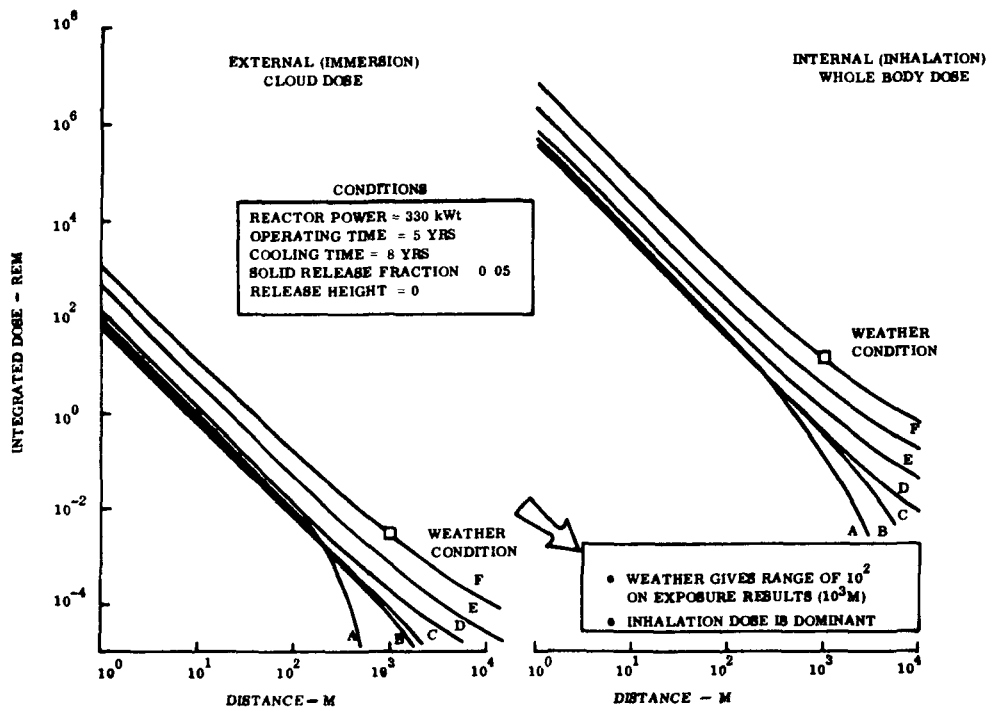


Figure 6-1. Cloud and Inhalation Whole Body Dose as a Function of Weather Condition for High Velocity Impact Disassembly

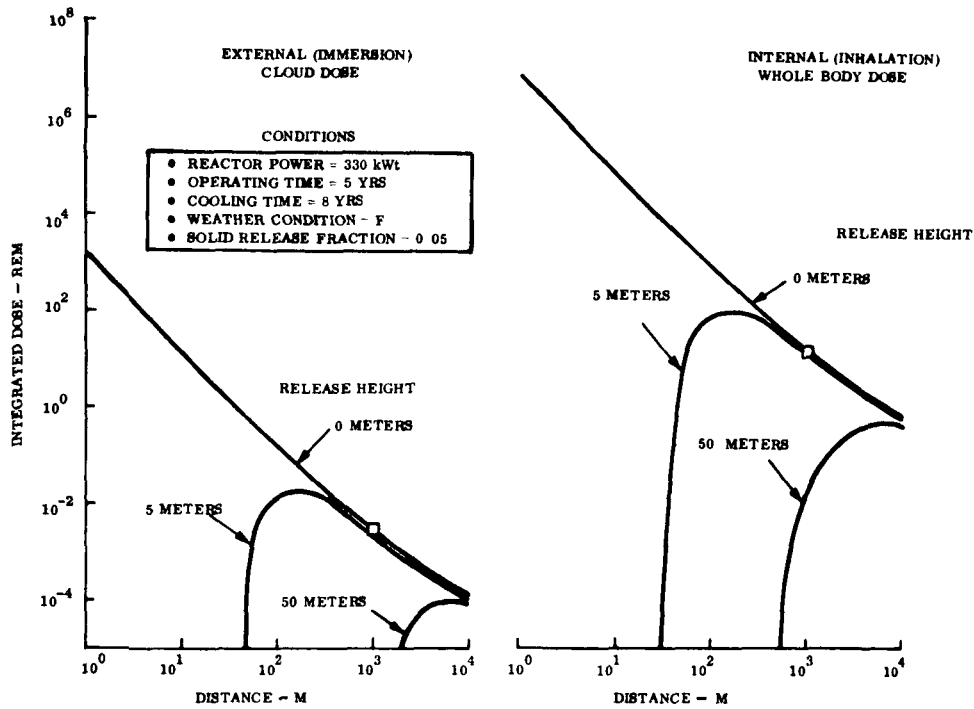


Figure 6-2. Cloud and Inhalation Whole Body Dose as a Function of Release Height

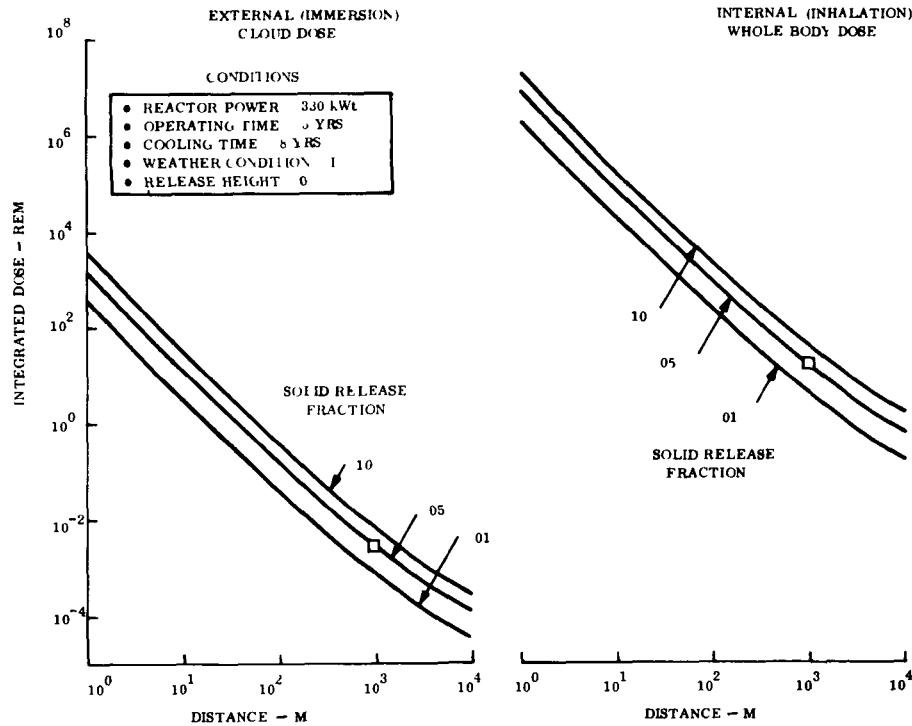


Figure 6-3. Cloud and Inhalation Whole Body Dose as a Function of Solid Release Fraction for High Velocity Impact Disassembly

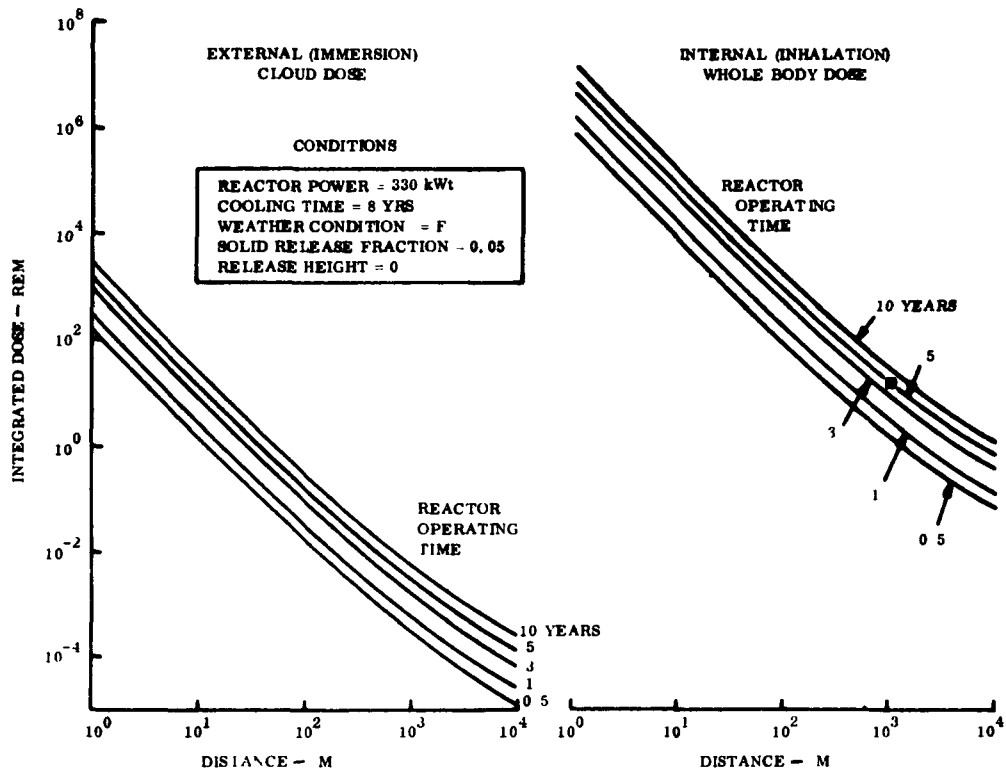


Figure 6-4. Cloud and Inhalation Whole Body Dose as a Function of Reactor Operating Time for High Velocity Impact Disassembly

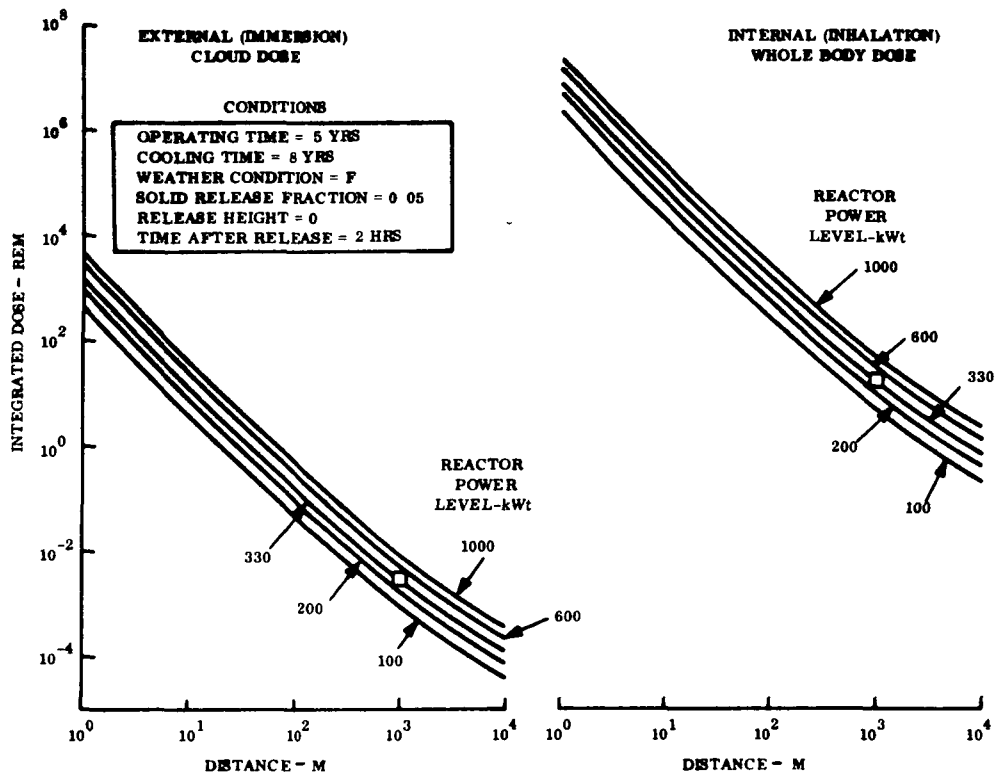


Figure 6-5. Cloud and Inhalation Whole Body Dose as a Function of Reactor Power Level for High Velocity Impact Disassembly

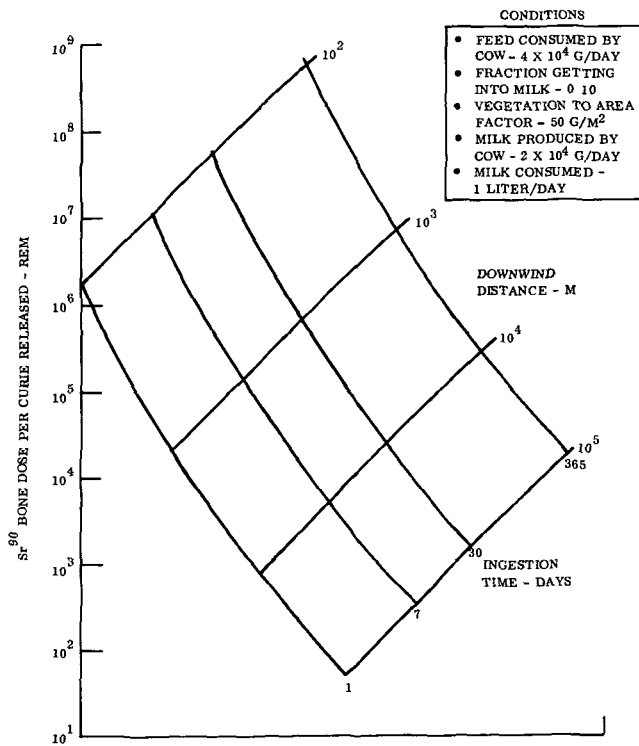


Figure 6-8. Ingestion Dose from Sr⁹⁰ Contaminated Milk

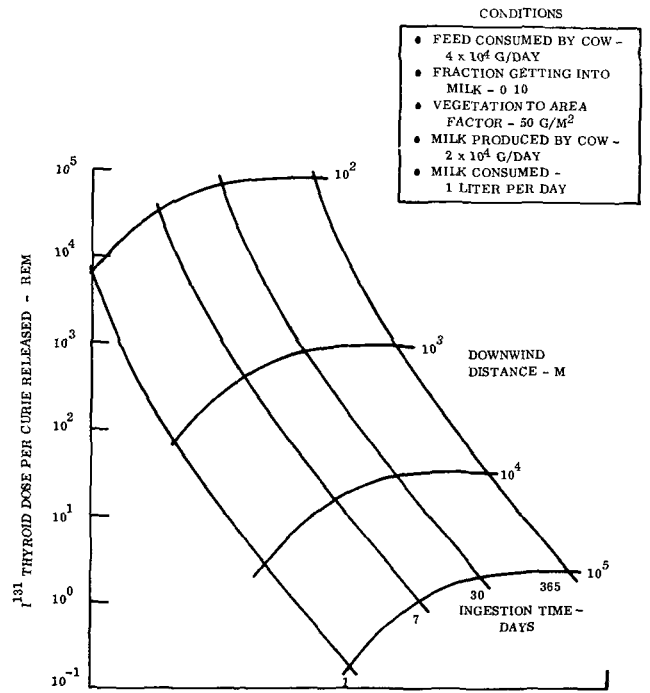


Figure 6-9. Ingestion Dose from I¹³¹ Contaminated Milk

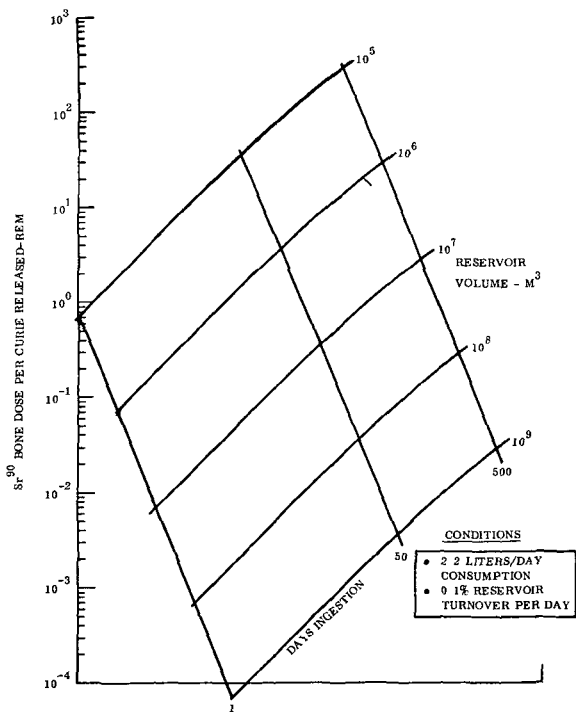


Figure 6-10. Ingestion Dose from Sr⁹⁰ Contaminated Reservoir Water

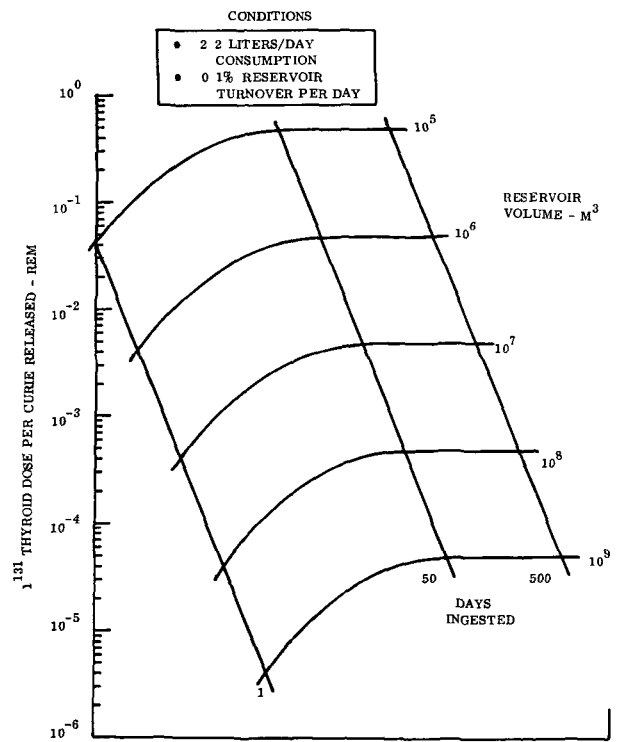


Figure 6-11. Ingestion Dose from I¹³¹ Contaminated Reservoir Water

SECTION 7

CONCLUSIONS AND RECOMMENDATIONS

The terrestrial nuclear safety analysis has shown that the overall mission risk to the general public is low; it is estimated that less than 4×10^{-3} individuals will receive more than 25 rem of radiation per mission (less than 4 individuals per 1000 missions performed). The implementation of additional safeguards can reduce the risk even further.

The analysis and results presented are preliminary and some of the probability and risk values and failure modes identified apply specifically to the reference ZrH reactor and operating conditions. However, much of the analysis, conclusions and recommendations are applicable to all space reactor powerplants. For the most part, revised probabilities, source terms and failure modes can be factored into the analysis (abort sequence trees, etc.) to determine the effect on mission risk due to changes in design or operating conditions.

7.1 CONCLUSIONS

Several of the specific conclusions resulting from the analysis are identified in Table 7-1.

Table 7-1. Conclusions

1	Low power testing of the reactor at the factory (100 watts for 12 days maximum) followed by delivery to the launch center some 60 days hence, provides a very low radiation environment and fission product inventory during pre-launch and launch activities.
2.	There will be no radiological risk to the general public resulting from a prelaunch or launch accident at KSC since the radioactive contamination is below specified dose guideline values (25 rem) outside the KSC boundary
3.	The most significant risk is from prolonged exposure to reactor debris following land impact - generally associated with the disposal phase of the mission where fission product inventories can be high.
4.	Contamination of reservoir water and pasture land can lead to an ingestion exposure problem if the supply water or milk is not expeditiously detected and then quarantined
5.	The end of mission reactor disposal phase constitutes the dominant risk. The most significant reductions in risk can be obtained by implementation of operational and design safeguards associated with this phase.
6.	ZrH reactor fission product inventories are considered negligible after 100 years of decay. Disposal orbits for the reference power module should provide a minimum 100 year lifetime.
7.	The use of the Space Shuttle for reactor recovery as contrasted to a high earth orbit disposal by a disposal system can reduce the risk attributed to the disposal phase by approximately 2 orders of magnitude
8.	Design for no excursion and the incorporation of a permanent shutdown system can provide an approximate 50 percent reduction in mission risk. The risk attributed to the launch/ascent phase would be essentially zero.

7.2 SAFEGUARDS

Nuclear Safety guidelines and requirements for the ZrH reactor power module are identified in Volume V, Part 1. Key recommended safeguards (design and operational features) fundamental to the reduction of radiological risk to the general public are summarized in Table 7-2. It should be noted that these recommendations are based on a safety evaluation and do not reflect or consider design, performance or cost trade-offs.

Table 7-2. Recommended Safeguards

1. Provide a shipping container which is designed to exclude hydrogenous media.
2. Provide positive mechanical control drum lockout devices which can be utilized up to reactor startup and will permit partial removal for individual drum rotation checks during prelaunch.
3. Provide a positive method of determining control drum position.
4. Provide a reactor startup command initiation sequence and control system which precludes accidental execution.
5. Provide a rapid control drum set-back capability (i. e. , SCRAM) for the reactor which is also operable in loss of power situations.
6. Provide a means of safing and recovering a reactor which is or has undergone quasi-steady state operation.
7. Provide for a positive and permanent shutdown (no excursion) capability at the end of mission.
8. Provide a reactor reentry and impact protection system capable of performing effectively after 5 years in a high radiation, high temperature, vacuum environment.
9. Provide reactor tracking and locating capability to enhance impact determination and dispersal of recovery and safing teams.
10. Provide a reliable disposal or recovery system capable of accommodating contingency situations. Random reentry should not be permitted.
11. Consider use of the Space Shuttle as a prime or secondary means of reactor recovery.

7.3 AREAS REQUIRING ADDITIONAL INVESTIGATION

Many of the assumptions made, failure modes identified, source terms calculated and probabilities assigned in this preliminary study are based on preliminary design, experimental data and engineering judgement.

The analysis has identified areas where additional study and experimentation are required prior to the conduct of a more detailed safety analysis, and the development of flight hardware and definitive mission plans. Key areas requiring additional investigation are included in Table 7-3.

Table 7-3. Areas Requiring Further Investigation

1. The adequacy of the LiH shield to function as a reentry protection shield and crush up structure has yet to be proven. A thorough assessment of the reentry behavior after several years in a high temperature, vacuum and radiation environment is required to determine the necessity for a separate reentry protection system. The conclusions of this investigation may have a significant bearing on future design concepts.
2. Experimental tests should be conducted to determine the response of a reactor to various accidents/events such as a launch vehicle fireball (i. e. , the potential total energy release associated with a destructive excursion).
3. Experimental tests should be conducted to determine the mechanisms and energy level associated with reactor quasi-steady state operation. Tests should be conducted to quantitatively measure the rate of water introduction into the core under different accident conditions.
4. Improvement and development of models for the determination of radiation doses associated with the ingestion of contaminated food and water is required.
5. Refinement of probabilities associated with reactor responses, boost, disposal and recovery vehicles is required.
6. An evaluation should be made of the use of and limits established for the dose guideline radiological risk technique including methods of standardization.
7. The desirability of the high earth orbit disposal of nuclear hardware should be evaluated where eventual random reentry with negligible radiological risk is a planned result.
8. Launch vehicle blast and fragmentation data should be refined.
9. Inadvertent control drum rotation prior to and after reactor operation may be prevented by the use of mechanical interlocks. The provision of mechanical interlocks in the reactor control drum design should receive more emphasis.

APPENDIX A

RADIOLOGICAL EXPOSURE MODELS

A.1. HIGH ALTITUDE RELEASE

A reactor disassembly during reentry may result in the release of gaseous and volatile fission products and the production of small particles composed of nonvolatile fission products and activated materials. The small particles released are formed under hypersonic reentry conditions through vaporization and shattering. Small particles are defined as those with terminal velocities less than about 0.03 m/sec. Actual particle size distributions may be quite variable, but as long as all the particles are small (< 10 microns), there will be little direct influence of size on their resulting atmospheric distribution.

It is assumed that particulate materials released to the upper atmosphere (mesosphere or stratosphere) will be dispersed solely by atmospheric motions with little effect due to gravitational settling.

Data obtained from nuclear tests indicate that residence half-times in the mesosphere and stratosphere are five years and two years, respectively. Material which enters the troposphere is subject to more rapid removal because of rainout and direct deposition. The tropospheric residence half-time is approximately six days. The estimated regional boundaries, air masses and small particle elimination constants are given in Table A-1.

Table A-1. Atmospheric Regional Boundaries, Masses, and Small Particle Elimination Constants

Region	Altitude Boundaries (m)	Air Mass (kg)	Elimination Constant (years ⁻¹)
Mesosphere	Above 4.5×10^4	1.5×10^{16}	$\lambda_1 = 0.1386$
Stratosphere	1×10^4 to 4.5×10^4	1.41×10^{18}	$\lambda_2 = 0.3465$
Troposphere	0 to 1×10^4	3.74×10^{18}	$\lambda_3 = 42.15$

The total integrated concentration on the troposphere for a mesospheric release is (Reference A-1).

$$\text{TIC} = 1.031 \times 10^{-11} \lambda_2 \lambda_1 Q_0 \left[\frac{1-e^{-(\lambda_3+\lambda)t}}{(\lambda_3+\lambda)(\lambda_3-\lambda_2)(\lambda_3-\lambda_1)} - \frac{1-e^{-(\lambda_2+\lambda)t}}{(\lambda_2+\lambda)(\lambda_3-\lambda_2)(\lambda_2-\lambda_1)} + \frac{1-e^{-(\lambda_1+\lambda)t}}{(\lambda_1+\lambda)(\lambda_3-\lambda_1)(\lambda_2-\lambda_1)} \right] \quad (\text{A-1})$$

and for a stratospheric release the expression is:

$$\text{TIC} = 1.031 \times 10^{-11} \lambda_2 Q_0 \left[\frac{1-e^{-(\lambda_2+\lambda)t}}{(\lambda_3-\lambda_2)(\lambda_2+\lambda)} - \frac{1-e^{-(\lambda_3+\lambda)t}}{(\lambda_3-\lambda_2)(\lambda_3+\lambda)} \right] \quad (\text{A-2})$$

where:

- TIC = total integrated concentration, Ci-sec/m³
- Q = curies released
- λ_1 = mesospheric elimination constant, year⁻¹
- λ_2 = stratospheric elimination constant, year⁻¹
- λ_3 = tropospheric elimination constant, year⁻¹
- λ = radioactive decay constant, year⁻¹
- t = time since activity release, year

A. 2. INHALATION OF AIRBORNE FISSION PRODUCTS

The transport and subsequent diffusion of a cloud of released fission products is determined by Pasquill diffusion parameters. The equation derived for radioisotope inhalations is (Reference A-2):

$$A_{\tau} = \frac{0.168R Q_{\tau}}{\mu d \theta (d) h (d)} e \left[- \frac{2.303 H^2}{h^2(d)} - \frac{d \lambda r^{\lambda}}{\mu} \right] \quad (A-3)$$

where:

A_{λ} = amount of radioisotope inhaled from cloud during exposure for τ seconds, curies

Q_{τ} = radioisotope released to the air up to time τ , curies

H = effective release height

d = downwind distance, m

μ = windspeed, m/sec

h (d) = vertical cloud spread at distance d, meters

θ (d) = lateral cloud spread at distance d, degrees

R = breathing rate, m³/sec

The plume concentration distribution (vertical and angular cloud spread) can be defined in terms of their standard deviations (Reference A-3):

$$h (d) = 2.14 \sigma_z \quad (A-4)$$

$$\theta (d) = \frac{4.28 \sigma_y}{x} \quad (A-5)$$

The values of h(d) and θ (d) are obtained from the above relationships where the lateral and vertical diffusion standard deviations are obtained from Figures A-1 and A-2. Type F stable dispersion (inversion case) has been used in the analyses since this meteorological condition results in conservative estimates of the inhalation hazard. The values of vertical and angular cloud spread for Type F used in the analyses are shown in Table A-2.

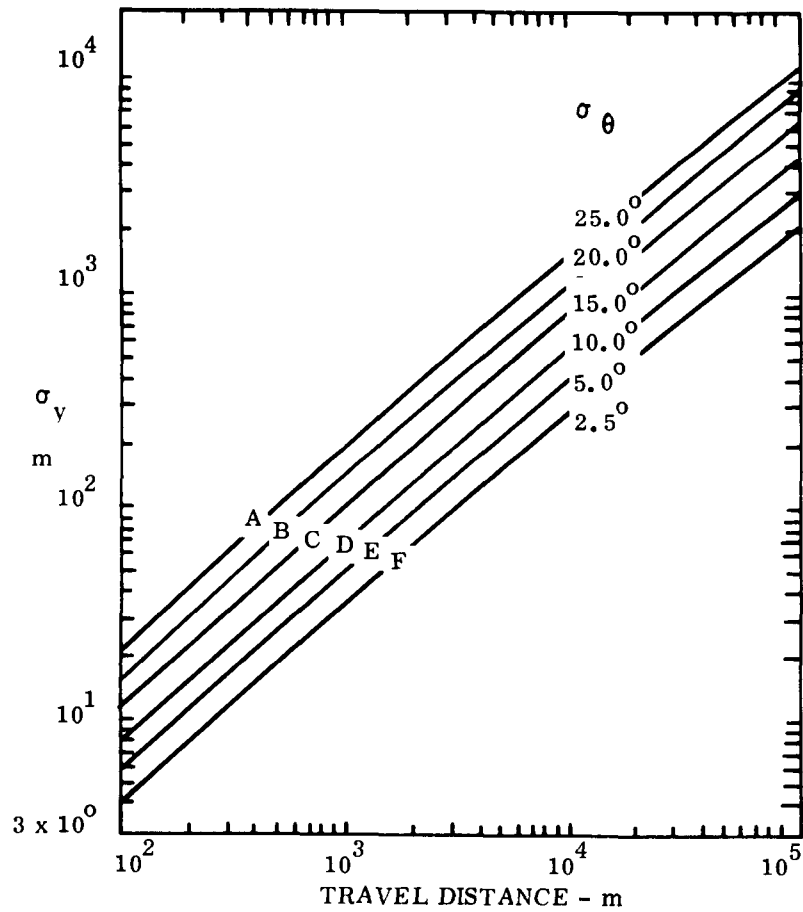


Figure A-1. Standard Deviation of the Lateral Concentration Distribution, σ_y

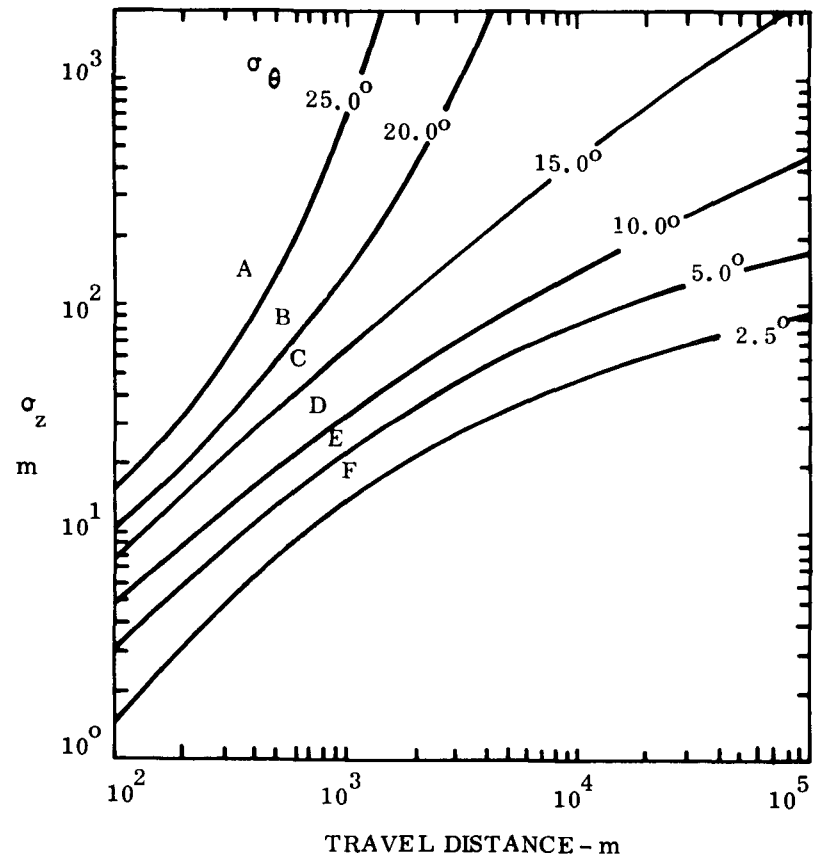


Figure A-2. Standard Deviation of the Vertical Concentration Distribution, σ_z

Table A-2. Pasquill Type F Meteorological Data

Downwind Distance, d - meters	Vertical Cloud Spread, h(d) - meters	Lateral Cloud Spread, θ (d) - Degrees (radians)
1	0.0492	11.0
10	0.492	11.0
100	4.92	11.0
200	7.8	10.7
500	17.0	10.0
1,000	29.0	9.38
5,000	73.8	7.52
15,000	112.6	6.40
25,000	151.4	5.28
50,000	248.4	2.48

The calculation takes into account the radioactive decay of the radioisotopes during transit downwind. The breathing rate utilized was $3.47 \times 10^{-4} \text{ m}^3/\text{sec}$.

A.3. ORGAN DOSE RESULTING FROM SINGLE INHALATION

The isotope inhalation dose by an organ for infinite residence time is given by (Reference A-4):

$$D = \frac{8.54 \times 10^2 A_{\tau} f_a \bar{E} T_e}{m} \quad (\text{A-6})$$

where

A_{τ} is given by equation (A-3), curies

f_a = fraction of the amount inhaled which is deposited in the critical organ

\bar{E} = effective energy absorbed by the critical organ per disintegration, Mev

T_e = effective half-life for the isotope in the body, sec

m = mass of the critical organ, g

A. 4 IMMERSION DOSE FROM THE CLOUD

The direct dose to the whole body from immersion in a cloud considers only gammas and assumes a semi-infinite cloud. The direct dose from the cloud at a distance, d , from an exposure interval, τ , is determined by summing the gamma dose received from each isotope in the cloud as follows:

$$D_{\text{cloud}}(d) = 0.246 \sum_i \frac{A_{\tau}^i(d) E_{\gamma}^i}{R_{\tau}}, \text{ rads} \quad (\text{A-7})$$

where

$A_{\tau}^i(d)$ is given by equation (A-3), curies

E_{γ}^i = gamma energy for isotope i , Mev

R_{τ} = breathing rate, m^3/sec

This formulation is from References A-2 and A-5. The model overestimates the direct dose from the cloud for ground release because it is assumed that the cloud is semi-infinite and uses the centerline isotope concentration.

A. 5 INGESTION DOSE TO MAN FROM IODINE-131

The relationship between the integrated air concentration in milk can be expressed by the following equation (Reference A-6):

$$CM = \frac{(TIC)V_g F_i F_m M_d}{F_w V_m}, \text{ Curies/liter} \quad (\text{A-8})$$

where

- TIC = total integrated concentration, Ci-sec/m³
V_g = deposition velocity, m/sec
F_i = amount of feed consumed by the cow, g/day
F_m = fraction of iodine getting into milk
M_d = density of milk, g/l
F_w = vegetation to area factor, g/m²
V_m = daily volume of milk produced by a cow, l
CM = 8 x 10⁻² TIC, Ci/liter of I¹³¹ in milk

It was assumed that the time from deposition on the pasture until the milk concentration is at a maximum is about 2 days. With this decay, the dominant radioiodine is I¹³¹. The dose to the thyroid from I¹³¹ ingestion is given by:

$$D = \frac{CM(TIC) V F}{\lambda_{eff}} \left[\frac{1 - e^{-\lambda_r t_1}}{\lambda_r} + \frac{e^{-\lambda t_2} (1 - e^{+\lambda_b t_1})}{\lambda_b} \right] \quad (A-9)$$

where

- CM(TIC) = milk concentration, Ci/l
V = milk consumption, l/day
λ_{eff} = effective decay constant = λ_r + λ_b, days⁻¹
λ_r = radioactive decay constant, days⁻¹
λ_b = biological decay constant, days⁻¹
t₁ = days of ingestion
t₂ = dose integration time, days

A. 6 INGESTION OF CONTAMINATED DRINKING WATER

The impact of a reactor into a potable water supply has been evaluated. If it were assumed that the fission products released to a reservoir were rapidly dispersed in the entire volume, the dose from ingestion of the contaminated water is given by (Reference A-7):

$$D_I = \frac{C_{fw} S_o V}{\lambda} \left[\frac{1 - e^{-(\lambda_r + \lambda_{res}) t_1}}{(\lambda_r + \lambda_{res})} + \frac{e^{-\lambda t_2} \left(\frac{(\lambda_b - \lambda_{res}) t_1}{1 - e^{-(\lambda_b - \lambda_{res}) t_1}} \right)}{(\lambda_b - \lambda_{res})} \right]$$

where

D_I = bone dose received in time, t_2 , ingestion over period, t_1 , rem

C_{fw} = rem/day to the bone due to 1 μ ci of Sr^{90} taken in at time, $t = 0$

S_o = initial equilibrium reservoir concentration, Q_o/V_{res}

Q_o = μ Curies released

V_{res} = reservoir volume, m^3

λ_r = radiological decay constant, day^{-1}

λ_b = biological decay constant, day^{-1}

λ = effective decay constant, day^{-1}

λ_{res} = reservoir turnover, day^{-1}

$$C_{fw} = \frac{R}{q} \frac{Rm/day}{\mu ci} = \frac{3.7 \times 10^4 \times 1.6 \times 10^{-6} \times 8.64 \times 10^4 f_2 \epsilon}{100 m}$$

where

$$3.7 \times 10^4 = \text{dis/sec-}\mu\text{ci}$$

$$1.6 \times 10^{-6} = \text{ergs/Mev}$$

$$8.64 \times 10^4 = \text{sec/day}$$

- 100 = ergs/g rad
- R = rem/day
- q = body burden, μci
- f_2 = fraction of body burden in organ of reference
- ϵ = effective absorbed energy per disintegration = $\sum EF(\text{RBE})n$
- m = mass of organ of reference, g

For some representative radioisotopes the values for Cfw in rem/day - μci are:

Sr^{90}	3.62×10^{-3}
Sr^{89}	4.39×10^{-3}
I^{131}	1.76×10^{-1}
I^{132}	4.99×10^{-1}
I^{133}	4.15×10^{-1}
I^{134}	6.30×10^1
I^{135}	3.98×10^{-2}
H^3	7.31×10^{-6}

A.7 POPULATION DENSITY DISTRIBUTION

In evaluating the risk to the general public from potential Space Base accidents, the population density distribution is associated with random reentry and earth impact. Reference A-8 presents the composite population distribution data for the entire world's surface as well as the surface contained between 35 degrees S and 35 degrees N latitude. This data was primarily obtained from the Defense Communication Agency of the DOD.

The data used for the Space Base study was for the entire world's surface since this was considered more representative of the 55 degrees S and 55 degrees N latitude area which is of concern for an orbit with an inclination of 55 degrees to the equatorial plane of the earth.

The population density distribution for the 90 degrees S to 90 degrees N latitude case is shown in Table A-3.

Table A-3. Population Density Distribution Data for 90 Degrees S to 90 Degrees N Latitude

Population Density People/km ²	Fraction of Earth's Surface with Density Within Boundary of Interval
0 - 0.39	1.92×10^{-1}
0.39 - 1.93	1.78×10^{-1}
1.93 - 9.65	1.45×10^{-1}
9.65 - 38.6	7.5×10^{-2}
38.6 - 193	3.2×10^{-2}
193 - 386	5.8×10^{-3}
386 - 772	1.69×10^{-3}
772 - 1,158	4.8×10^{-4}
1,158 - 1,544	3.6×10^{-4}
1,544 - 1,931	3.1×10^{-4}
1,931 - 2,703	2.6×10^{-4}
2,703 - 3,861	2.1×10^{-4}
3,861 - 5,792	1.29×10^{-4}
5,792 - 7,722	6.5×10^{-5}
7,722 - 9,653	4.0×10^{-5}
9,653 - 19,310	2.6×10^{-5}
19,310 - 28,960	6.2×10^{-6}
28,960 - 38,610	1.27×10^{-6}
38,610 - 48,260	3.0×10^{-7}
48,260 - 57,920	1.24×10^{-7}
57,920 - 65,640	3.4×10^{-8}
65,640 - 77,220	1.95×10^{-8}
> 77,220	1.1×10^{-8}

During the Launch/Ascent Phase, the Space Base mission requires insertion of the payload into a 500 km (273 nm) circular orbit inclined 55 degrees to the earth equatorial plane. The trajectory for this flight takes the payload over Eurasia. Table A-4 indicates the population density distribution for Eurasia (Reference A-9) for a 185 km (100 nm) wide track along the reference mission instantaneous impact points.

Table A-4. Population Density Distribution Data, for Eurasia

Population Density People/km ²			Fraction of Eurasian Surface with Density Within Boundary of Interval
0	-	0.39	$3.90 \times 10^{-1} *$
0.39	-	1.93	2.54×10^{-1}
1.93	-	9.65	-
9.65	-	38.6	3.69×10^{-2}
38.6	-	193	2.78×10^{-1}
193	-	386	3.93×10^{-2}
386	-	772	-
772	-	1,158	-
1,158	-	1,544	-
1,544	-	1,931	-
1,931	-	2,703	-
2,703	-	3,861	-
3,861	-	5,792	1.2×10^{-3}

* Includes Eurasian water with population density of ~ 0 people/km²

A. 8. REFERENCES

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Table B-1. Characteristics of Key Mission Accidents - Prelaunch

Mission Phase Prelaunch

Reactor Power History Low power criticality testing
(100 watts for 12 days, 60 days prior to launch)

Accident Description		Possible Consequences & Probabilities			Nuclear Hazard		
Accident	Possible Causes	Accident Probability	Possible Consequences & Probabilities	Case No.	Hazard Sources & Probabilities	Location	Risk
Reactor dropped while being mated to launch vehicle	<ul style="list-style-type: none"> Crane failure Crane operator error Structural failure 	2.49×10^{-4}	Destructive reactor excursion on land impact <ul style="list-style-type: none"> Control drum motion 100 MW-sec ($P = 2.49 \times 10^{-7}$) 	1.1	Table 5-15 (AMD)	KSC	0
			Non-destructive reactor excursion on land impact <ul style="list-style-type: none"> Control drum motion Unshielded reactor (assumed for conservatism) ($P = 2.24 \times 10^{-6}$) 	1.2	Table 5-15 (AMD)	KSC	0
			Radiation shield damaged upon land impact ($P = 2.44 \times 10^{-4}$)	1.3	Table 5-15 (AMD)	KSC	0
Tip Over of the reactor/launch vehicle during transport to the launch pad.	<ul style="list-style-type: none"> Malfunction of transporter Structural failure Mobile Launcher (ML) 	2.49×10^{-4}	Destructive reactor excursion on land impact <ul style="list-style-type: none"> Control drum motion 100 MW-sec. ($P = 2.47 \times 10^{-7}$) 	1.4	Table 5-15 (AMD)	KSC	0
			Non-destructive reactor excursion on land impact <ul style="list-style-type: none"> Control drum motion Unshielded reactor (assumed for conservatism) ($P = 2.22 \times 10^{-6}$) 	1.5	Table 5-15 (AMD)	KSC	0
			Radiation shield damaged upon earth impact ($P = 2.47 \times 10^{-4}$)	1.6	Table 5-15 (AMD)	KSC	0
			Destructive reactor excursion following water immersion <ul style="list-style-type: none"> Over moderation 100 MW-sec. ($P = 2.24 \times 10^{-7}$) 	1.7	Table 5-15 (AMD)	KSC	0
			Non-destructive reactor excursion following water immersion <ul style="list-style-type: none"> Over moderation Quasi-steady state operation Unshielded reactor (assumed for conservatism) ($P = 2.02 \times 10^{-6}$) 	1.8	Table 5-15 (AMD)	KSC	0
Explosion and fire on the launch pad during launch vehicle fueling (reactor falls back on launch pad)	<ul style="list-style-type: none"> Mixing of propellants during fueling Fuel tanks rupture 	6.64×10^{-4}	Reactor disassembly <ul style="list-style-type: none"> Damaged fuel elements released from core ($P = 6.64 \times 10^{-6}$) 	1.9	Table 5-15 (AMD)	Launch Pad	0
			Destructive reactor excursion due to over moderation <ul style="list-style-type: none"> Reactor immersion in deluge water or liquid propellants 100 MW-sec ($P = 1.99 \times 10^{-6}$) 	1.10	Table 5-15 (AMD)	Launch Pad	0
			Non-destructive reactor excursion due to over moderation <ul style="list-style-type: none"> Reactor immersion in deluge water or liquid propellants Quasi-steady state operation Unshielded reactor (assumed for conservatism) ($P = 1.79 \times 10^{-5}$) 	1.11	Table 5-15 (AMD)	Launch Pad	0
			Destructive reactor excursion on land impact <ul style="list-style-type: none"> Control drum motion 100 MW-sec ($P = 6.64 \times 10^{-7}$) 	1.12	Table 5-15 (AMD)	Launch Pad	0
			Non-destructive reactor excursion on land impact <ul style="list-style-type: none"> Control drum motion Unshielded reactor (assumed for conservatism) ($P = 5.98 \times 10^{-6}$) 	1.13	Table 5-15 (AMD)	Launch Pad	0
			Radiation shield damaged <ul style="list-style-type: none"> Fragmentation and/or earth impact ($P = 6.24 \times 10^{-4}$) 	1.14	Table 5-15 (AMD)	Launch Pad	0
Liquid metal fire	<ul style="list-style-type: none"> Rupture of Radiator Intermediate Coolant Loop Primary System 	4.98×10^{-4}	Fuel cladding breached & primary system ruptured ($P = 4.98 \times 10^{-5}$)	1.15	Table 5-15 (AMD)	KSC	0
			Radiation shield damaged ($P = 3.98 \times 10^{-4}$)	1.16	Table 5-15 (AMD)	KSC	0

FOLDOUT FRAME 1

FOLDOUT FRAME 2

6-3

Table B-2. Characteristics of Key Mission Accidents-Launch/Ascent

Mission Phase Launch/Ascent
 Reactor Power History Low Power Criticality Testing

	Accident Description		Possible Consequences & Probabilities		Nuclear Hazard			
	Accident	Possible Causes	Accident Probability	Possible Consequences and Probabilities	Case No	Hazard Sources & Probabilities	Location	Risk
Launch (-9 ≤ t ≤ 0 Sec)	Launch Pad Abort, Explosion & Fire	<ul style="list-style-type: none"> S-IC/S-II explosion Inadvertent command destruct LV structural failure 	2 18x10 ⁻⁴	Reactor disassembly (P = 2 18x10 ⁻⁶)	2 1	Table 5-16 (AMD)	Launch Pad	0
				Destructive reactor excursion due to over moderation <ul style="list-style-type: none"> Reactor immersion in deluge water or liquid propellants 100 MW-sec (P = 6 54x10⁻⁷) 	2 2	Table 5-16 (AMD)	Launch Pad	0
				Non-destructive reactor excursion due to over moderation <ul style="list-style-type: none"> Reactor immersion in deluge water or liquid propellants Quasi-steady state operation Unshielded reactor (assumed for conservatism) (P = 5, 89x10⁻⁶) 	2 3	Table 5-16 (AMD)	Launch Pad	0
				Destructive reactor excursion on land impact <ul style="list-style-type: none"> Control drum motion 100 MW-sec (P = 2 18x10⁻⁷) 	2 4	Table 5-16 (AMD)	Launch Pad	0
				Non-destructive reactor excursion on land impact <ul style="list-style-type: none"> Control drum motion Unshielded reactor (assumed for conservatism) (P = 1 96x10⁻⁶) 	2 5	Table 5-16 (AMD)	Launch Pad	0
				Radiation shield damaged <ul style="list-style-type: none"> Fragmentation and/or earth impact (P = 2, 05x10⁻⁴) 	2 6	Table 5-16 (AMD)	Launch Pad	0
S-IC Boost (0 ≤ t ≤ 160 Sec)	Abort, Explosion & Fire (At Altitude)	<ul style="list-style-type: none"> S-IC/S-II explosion Command destruct 	3 65x10 ⁻³	Disassembly of reactor at altitude <ul style="list-style-type: none"> Damaged fuel elements released from core (P = 3 65x10⁻⁵) 	2 7	Table 5-17 (AMD)	Over KSC (at 1 km), 5 km, 40 km	0
				Land impact of reactor <ul style="list-style-type: none"> Reactor may be damaged but core remains intact (P = 2 90x10⁻⁴) 	2 8	Table 5-17 (AMD)	KSC	0
				Water impact of reactor <ul style="list-style-type: none"> Reactor may be damaged but core remains intact (P = 1 30 x 10⁻³) 	2 9	Table 5-18 (AMD)	KSC, U S Continental Shelf	0
S-IC Boost (0 ≤ t ≤ 160 Sec)	Abort, No Explosion & Fire (At Altitude)	<ul style="list-style-type: none"> Premature S-IC thrust termination LV guidance and control failure LV structural failure (No command destruct) 	2 24x10 ⁻²	Land impact of reactor (P = 1 79x10 ⁻³)	2 10	Table 5-17 (AMD)	KSC	0
				Water impact of reactor (P = 8 06x10 ⁻³)	2 11	Table 5-18 (AMD)	KSC, U S Continental Shelf	0
S-II Boost (160 ≤ t ≤ 557 Sec)	Abort, Explosion & Fire (At Altitude)	<ul style="list-style-type: none"> S-II explosion Command destruct 	2 32x10 ⁻³	Land impact of reactor <ul style="list-style-type: none"> Reactor may be damaged but core remains intact (P = 1 84 x 10⁻⁴) 	2 12	Table 5-19 (AMD)	<ul style="list-style-type: none"> Europe Middle East 	4 9x10 ⁻⁶
				Water impact of reactor <ul style="list-style-type: none"> Reactor may be damaged but core remains intact (P = 6 92x10⁻⁵) 	2,13	Table 5-19 (AMD)	<ul style="list-style-type: none"> Europe Middle East European Continental Shelf Adriatic Sea Aegean Sea Mediterranean Sea Arabian Sea 	0
	Abort, No Explosion & Fire (At Altitude)	<ul style="list-style-type: none"> Premature S-II thrust termination Thrust and control failure LV structural failure (No command destruct) 	2 66x10 ⁻²	Land impact of reactor (P = 2 13 x 10 ⁻³)	2 14	Table 5-19 (AMD)	<ul style="list-style-type: none"> Europe Middle East 	4 9x10 ⁻⁵
				Water impact of reactor (P = 7 99x10 ⁻⁴)	2 15	Table 5-19 (AMD)	<ul style="list-style-type: none"> European Continental Shelf Europe Middle East Adriatic Sea Aegean Sea Mediterranean Sea Arabian Sea 	0
Rendezvous & Docking	Accidental Collision While Attempting to Dock (Repair not Possible)	<ul style="list-style-type: none"> Guidance and control failure Excessive closing velocity 	2 34x10 ⁻³	Power Module left in low earth orbit <ul style="list-style-type: none"> Orbital decay 500 km, circular 5 year orbital lifetime Radiation shield damaged in some cases (P = 2, 34x10⁻³) 	2 16	Tables 5-19, 20 (AMD)	Earth (random)	2 0x10 ⁻⁶
	Failure to Dock with Space Base (Repair not possible)	<ul style="list-style-type: none"> Mechanical or electrical failure 	2 34x10 ⁻³	Power Module left in low earth orbit <ul style="list-style-type: none"> Orbital decay 500 km, circular 5 year orbital lifetime (P = 2 34x10⁻³) 	2 17	Tables 5-19, 20 (AMD)	Earth (random)	2 0x10 ⁻⁶
	Failure to Remove Thermal Shroud (Repair not possible)	<ul style="list-style-type: none"> Pyrotechnic failure 	2 34x10 ⁻³	Power Module left in low earth orbit <ul style="list-style-type: none"> Orbital decay 500 km, circular 5 year orbital lifetime (P = 2 34x10⁻³) 	2 18	Tables 5-19, 20 (AMD)	Earth (random)	2 0x10 ⁻⁶
	Failure to Rendezvous with Space Base	<ul style="list-style-type: none"> Guidance and control failure Propulsion failure 	2 34x10 ⁻³	Power Module left in low earth orbit <ul style="list-style-type: none"> Orbital decay 500 km, circular 5 year orbital lifetime (P = 2 34x10⁻³) 	2 19	Tables 5-19, 20 (AMD)	Earth (random)	2, 0x10 ⁻⁶

FOLDOUT FRAME

FOLDOUT FRAME

Table B-3. Characteristics of Key Mission Accidents-Orbital Operations

MISSION PHASE Orbital Operations

Cumulative In-Orbit Accident Probability = 4.6×10^{-2}

REACTOR POWER HISTORY 5 year power operation at
330 kw assumed for conservatism

← Accident Description		Possible Consequences and Probabilities			Nuclear Hazard →			
Accident	Possible Causes	Accident Probability	Possible Consequences and Probabilities	Case No	Hazard Sources and Probabilities	Location	Risk	
Equipment Failure Aboard Space Base Necessitating Early Abandonment	<ul style="list-style-type: none"> Loss of guidance and control Loss of ECLS 	4.6×10^{-4}	Initiate early reactor disposal sequence (no damage to power module) ($P = 4.1 \times 10^{-4}$)	3.1	This case similar to case 3.4. Probabilities are therefore combined. Total probability is $P = 4.15 \times 10^{-4}$. These cases are combined with EOL Reactor Disposal Refer to Table 5-13			
			Equipment failure aboard SB precludes early reactor disposal (successful separation from SB achieved to increase orbit lifetime) <ul style="list-style-type: none"> Orbital decay 500 km 5 year orbital lifetime ($P = 4.6 \times 10^{-5}$)	3.2		Tables 5-21, 22 (AMD)	Earth (Random)	2.02×10^{-5}
			Equipment failure aboard SB precludes early PM separation and disposal <ul style="list-style-type: none"> Orbital decay (PM/SB configuration) 500 km, circular 3.5 year orbital lifetime ($P = 4.6 \times 10^{-6}$)	3.3		Tables 5-21, 22 (AMD)	Earth (Random)	2.02×10^{-6}
Accidental Collision or Explosion in Orbit Necessitating Early Abandonment of Space Base	Accidental Collision <ul style="list-style-type: none"> Orbital debris Logistic vehicles Detached modules Meteors Spent or damaged PM (Misaligned thrust vector during reactor disposal) 	9.2×10^{-6}	Initiate early reactor disposal sequence (no damage to power module) ($P = 5.5 \times 10^{-6}$)	3.4		Refer to Case 3.1		
			Permanent damage to disposal package precludes early reactor disposal (successful separation from SB achieved to increase orbit lifetime) <ul style="list-style-type: none"> Orbital decay 500 km, circular 5 year orbital lifetime Radiation shield permanently damaged ($P = 3.8 \times 10^{-7}$)	3.5	Tables 5-21, 22 (AMD)	Earth (Random)	2.20×10^{-8}	

Table B-3. Characteristics of Key Mission Accidents-Orbital Operations (Cont)

MISSION PHASE Orbital Operations

REACTOR POWER HISTORY 5 year power operation at
330 kw assumed for conservatism

← Accident Description		Possible Consequences and Probabilities			Nuclear Hazard →		
Accident	Possible Causes	Accident Probability	Possible Consequences and Probabilities	Case No	Hazard Sources and Probabilities	Location	Risk
	Explosion <ul style="list-style-type: none"> • Power Module • Gas management system • TAC • Disposal propulsion system • Space Base • ECLS tanks • Propulsion system • Logistic vehicle • Propellant tanks 		Permanent damage to separation system precludes early PM separation from SB <ul style="list-style-type: none"> • Orbital decay (PM/SB configuration) • 500 km, circular • 3.5 year orbital lifetime • Radiation shield permanently damaged ($P = 3.8 \times 10^{-8}$) 	3.6	Tables 5-21, 22 (AMD)	Earth (Random)	2.20×10^{-9}
			Initiate pre-separation G&C checkout for early reactor disposal. <ul style="list-style-type: none"> • Reactor successfully shutdown • Radiation shield permanently damaged (3.4×10^{-6}) 	3.7	This case similar to cases 3.19, 3.26, and 3.29. Probabilities therefore combined. Total probability is 1.7×10^{-3} . These cases are combined with EOL Reactor Disposal. Refer to Table 5-13.		
Accidental Collision or Explosion in Orbit	Accidental Collision <ul style="list-style-type: none"> • Orbital debris • Logistic vehicles • Detached modules • Meteors • Spent or damaged PM (misaligned thrust vector during reactor disposal) 	2.8×10^{-3}	PM is torn from SB, reactor safely shuts itself down prior to re-entry (fission products are not released to the primary coolant) <ul style="list-style-type: none"> • Orbital decay • 500 km, circular • 5 year orbital lifetime ($P = 5.5 \times 10^{-8}$) 	3.8	Tables 5-21, 22 (AMD)	Earth (Random)	2.02×10^{-8}
			PM is torn from SB, fuel cladding breached due to loss of cooling <ul style="list-style-type: none"> • Orbital decay • 500 km, circular • 5 year orbital lifetime • Fission products in primary coolant • Radiation shield damaged in some cases ($P = 6 \times 10^{-6}$) 	3.9	Tables 5-21, 22 (AMD)	Earth (Random)	3.0×10^{-6}

Table B-3. Characteristics of Key Mission Accidents-Orbital Operations (Cont)

MISSION PHASE Orbital Operations

REACTOR POWER HISTORY 5 year power operation at
330 kw assumed for conservatism

← Accident Description		Possible Consequences and Probabilities			Nuclear Hazard →		
Accident	Possible Causes	Accident Probability	Possible Consequences and Probabilities	Case No	Hazard Sources and Probabilities	Location	Risk
	Explosion <ul style="list-style-type: none"> • Power Module • Gas management system • TAC • Disposal propulsion system • Space Base • ECLS tanks • Propulsion system • Logistic vehicle • Propellant tanks 		PM is torn from SB, (a) fuel cladding and primary system breached due to loss of cooling, (b) primary system breached due to collision or explosion, fuel cladding breached due to loss of cooling <ul style="list-style-type: none"> • Orbital decay • 500 km, circular • 5 year orbital lifetime • Fission product gases and activated NaK released in orbit • Radiation shield damaged in some cases (P = 2.2×10^{-5})	3 10	Tables 5-21, 22, 23 (AMD)	Earth (Random)	2.0×10^{-6}
			R/S configuration torn from PM, fuel cladding breached due to loss of cooling <ul style="list-style-type: none"> • Orbital decay • 500 km, circular • 44 year orbital lifetime • Fission products in primary coolant • Radiation shield damaged (P = 5.5×10^{-6})	3 11	Tables 5-21, 22 (AMD)	Earth (Random)	6.2×10^{-7}
			R/S configuration torn from PM, (a) fuel cladding and primary system breached due to loss of cooling, (b) primary system breached due to collision or explosion, fuel cladding breached due to loss of cooling <ul style="list-style-type: none"> • Orbital decay • 500 km, circular • 44 year orbital lifetime • Fission product gases and activated NaK released in orbit • Radiation shield damaged (P = 1.7×10^{-5})	3 12	Tables 5-21, 22, 23 (AMD)	Earth (Random)	6.2×10^{-7}

Table B-3. Characteristics of Key Mission Accidents-Orbital Operations (Cont)

MISSION PHASE Orbital Operations

REACTOR POWER HISTORY 5 year power operation at
330 kw assumed for conservatism

← Accident Description			Possible Consequences and Probabilities	Nuclear Hazard →			
Accident	Possible Causes	Accident Probability	Possible Consequences and Probabilities	Case No	Hazard Sources and Probabilities	Location	Risk
			<p>Initiate pre-separation G&C checkout for early reactor disposal (No damage to disposal package and/or separation system)</p> <p>(a) Radiation shield, primary system, and fuel cladding breached due to collision or explosion</p> <p>(b) Radiation shield and primary system breached due to collision or explosion, fuel cladding breached due to loss of cooling</p> <p>(c) Loss of cooling or loss of reactor control, fuel cladding and primary system breached due to excessive core temperatures, radiation shield damaged</p> <p>(d) Failure to remove decay heat after emergency shutdown, fuel cladding and primary system breached due to loss of cooling, radiation shield damaged</p> <ul style="list-style-type: none"> • Fission product gases and activated NaK released in orbit • Radiation shield damaged. (P = 1.1 x 10⁻³) 	3.13	<p>This case similar to cases 3.16, 3.24, 3.25, 3.30, and 3.31. Probabilities for this class of accidents are therefore combined. Total probability is P = 3.1 x 10⁻². Description of reactor disposal accidents for this class of mission abort accidents is given in Table 5-12, (AMD).</p>		
			<p>Permanent damage to disposal package precludes early disposal of damaged PM (successful separation from SB achieved to increase orbit lifetime)</p> <p>(a) Radiation shield, primary system, and fuel cladding breached due to collision or explosion</p>	3.14		<p>Tables 5-21, 22, 23 (AMD)</p>	Earth (Random)

Table B-3. Characteristics of Key Mission Accidents—Orbital Operations (Cont)

MISSION PHASE Orbital Operations

REACTOR POWER HISTORY 5 year power operation at
330 kw assumed for conservatism

← Accident Description			← Possible Consequences and Probabilities		← Nuclear Hazard →		
Accident	Possible Causes	Accident Probability	Possible Consequences and Probabilities	Case No	Hazard Sources and Probabilities	Location	Risk
			(b) Radiation shield and primary system breached due to collision or explosion, fuel cladding breached due to loss of cooling (c) Loss of cooling or loss of reactor control, fuel cladding and primary system breached due to excessive core temperatures, radiation shield damaged (d) Failure to remove decay heat after emergency shutdown, fuel cladding and primary system breached due to loss of cooling, radiation shield damaged <ul style="list-style-type: none"> • Orbital decay • 500 km, circular • 5 year orbital lifetime • Fission product gases and activated NaK released in orbit • Radiation shield damaged ($P = 1.2 \times 10^{-4}$) 				
			Permanent damage to separation system precludes early PM separation from SB and disposal (a) Radiation shield, primary system, and fuel cladding breached due to collision or explosion (b) Radiation shield and primary system breached due to collision or explosion, fuel cladding breached due to loss of cooling	3 15	Table 5-21, 22, 23 (AMD)	Earth (Random)	2.0×10^{-6}

Table B-3. Characteristics of Key Mission Accidents-Orbital Operations (Cont)

MISSION PHASE Orbital Operations

REACTOR POWER HISTORY 5 year power operation at
330 kw assumed for conservatism

← Accident Description			Possible Consequences and Probabilities	Nuclear Hazard →			
Accident	Possible Causes	Accident Probability	Possible Consequences and Probabilities	Case No	Hazard Sources and Probabilities	Location	Risk
			(c) Loss of cooling or loss of reactor control, fuel cladding and primary system breached due to excessive core temperatures, radiation shield damaged (d) Failure to remove decay heat after emergency shutdown, fuel cladding and primary system breached due to loss of cooling, radiation shield damaged • Orbital decay (PM/SB configuration) • 500 km, circular • 3.5 year orbital lifetime • Fission product gases and activated NaK released in orbit • Radiation shield damaged (P = 1.2 x 10 ⁻⁵)				
			Initiate pre-separation G&C checkout for early reactor disposal (no damage to disposal package and/or separation system) (a) Loss of cooling or loss of reactor control, fuel cladding breached due to excessive core temperatures, radiation shield damaged (b) Failure to remove decay heat after emergency shutdown, fuel cladding breached due to loss of cooling, radiation shield damaged • Fission products in primary coolant • Radiation shield damaged (P = 5 x 10 ⁻⁴)	3 16		Refer to Case 3.13	

Table B-3. Characteristics of Key Mission Accidents-Orbital Operations (Cont)

MISSION PHASE Orbital Operations

REACTOR POWER HISTORY 5 year power operation at
330 kw assumed for conservatism

← Accident Description			Possible Consequences and Probabilities	Nuclear Hazard →			
Accident	Possible Causes	Accident Probability	Possible Consequences and Probabilities	Case No	Hazard Sources and Probabilities	Location	Risk
			Permanent damage to disposal package precludes early reactor disposal (successful separation from SB achieved to increase orbit lifetime) (a) Loss of cooling or loss of reactor control, fuel cladding breached due to excessive core temperatures, radiation shield damaged (b) Failure to remove decay heat after emergency shutdown, fuel cladding breached due to loss of cooling, radiation shield damaged <ul style="list-style-type: none"> • Orbital decay • 500 km, circular • 5 year orbital lifetime • Fission products in primary coolant • Radiation shield damaged (P = 5.6 x 10⁻⁵) 	3 17	Tables 5-21, 22 (AMD)	Earth (Random)	2.0 x 10 ⁻⁵
			Permanent damage to separation system precludes early PM separation from SB and disposal (a) Loss of cooling or loss of reactor control, fuel cladding breached due to excessive core temperatures, radiation shield damaged. (b) Failure to remove decay heat after emergency shutdown, fuel cladding breached due to loss of cooling, radiation shield damaged	3 18	Tables 5-21, 22 (AMD)	Earth (Random)	2.0 x 10 ⁻⁶

Table B-3. Characteristics of Key Mission Accidents-Orbital Operations (Cont)

MISSION PHASE Orbital Operations

REACTOR POWER HISTORY 5 year power operation at
330 kw assumed for conservatism

← Accident Description			← Possible Consequences and Probabilities		← Nuclear Hazard →		
Accident	Possible Causes	Accident Probability	Possible Consequences and Probabilities	Case No	Hazard Sources and Probabilities	Location	Risk
			<ul style="list-style-type: none"> Orbital decay (PM/SB configuration) 500 km, circular 3 5 year orbital lifetime Fission products in primary coolant Radiation shield damaged (P = 5, 6 x 10⁻⁶) 				
			Initiate pre-separation G&C checkout for early reactor disposal (no damage to disposal package and/or separation system) <ul style="list-style-type: none"> Radiation shield permanently damaged (P= 3, 3 x 10⁻⁴) 	3.19		Refer to Case 3.7	
			Permanent damage to disposal package precludes <p>(a) Early reactor disposal</p> <p>(b) EOL reactor disposal (successful separation from SB achieved to increase orbital lifetime)</p> <ul style="list-style-type: none"> Orbital decay 500 km, circular 5 year orbital lifetime Radiation shield damaged in some cases (P = 3, 7 x 10⁻⁵) 	3.20	Tables 5-21, 22 (AMD)	Earth (Random)	2 0 x 10 ⁻⁶

Table B-3. Characteristics of Key Mission Accidents-Orbital Operations (Cont)

MISSION PHASE Orbital Operations

REACTOR POWER HISTORY 5 year power operation at 330 kw assumed for conservatism

← Accident Description			← Possible Consequences and Probabilities		← Nuclear Hazard →		
Accident	Possible Causes	Accident Probability	Possible Consequences and Probabilities	Case No	Hazard Sources and Probabilities	Location	Risk
			Permanent damage to separation system precludes (a) Early PM separation and disposal (b) EOL PM separation and disposal <ul style="list-style-type: none"> • Orbital decay (PM/SB configuration) • 500 km, circular • 3 5 year orbital lifetime • Radiation shield damaged in some cases (P = 3 7 x 10⁻⁶) 	3 21	Tables 5-21, 22 (AMD)	Earth (Random)	2 0 x 10 ⁻⁷
			Disassembly of the reactor in orbit (P = 2 2 x 10 ⁻⁵)	3 22	Table 5-23 (AMD)	Earth (Random)	-
			Destructive excursion in orbit resulting from accidental collision <ul style="list-style-type: none"> • Control drum motion • 100 MW-sec (P = 1 8 x 10⁻⁵) 	3 23	Table 5-23 (AMD)	Earth (Random)	-
Reactor Control System Malfunction or Reactor Operational Procedure Error	<ul style="list-style-type: none"> • Automatic controller fails • Drum position error • Stuck drums • Sensor errors • Human errors 	1 98 x 10 ⁻²	Initiate pre-separation G&C checkout for early reactor disposal (a) Fuel cladding breached due to a non-destructive reactor excursion (b) Failure to remove decay heat after inadvertent reactor shutdown, fuel cladding breached <ul style="list-style-type: none"> • Fission products in primary coolant (P = 8 8 x 10⁻³) 	3 24		Refer to case 3.13	

Table B-3. Characteristics of Key Mission Accidents-Orbital Operations (Cont)

MISSION PHASE Orbital Operations

REACTOR POWER HISTORY * 5 year power operation at 330 kw assumed for conservatism

← Accident Description			Possible Consequences and Probabilities		Nuclear Hazard →		
Accident	Possible Causes	Accident Probability	Possible Consequences and Probabilities	Case No	Hazard Sources and Probabilities	Location	Risk
			Initiate pre-separation G&C checkout for early reactor disposal (a) Non-destructive reactor excursion, fuel elements and primary system breached (b) Failure to remove decay heat after inadvertent reactor shutdown, fuel cladding and primary system breached • Fission products and activated NaK released in orbit (P = 8.8×10^{-3})	3.25		Refer to Case 3.13	
			Initiate pre-separation G&C checkout for early reactor disposal, inadvertent reactor shutdown, repair not possible, R/S configuration undamaged (P = 9.9×10^{-6})	3.26		Refer to Case 3.7	
			Failure to startup reactor at BOL, Power Module left in low earth orbit • Reactor power history • Low power criticality testing • Orbital decay • 500 km, circular • 5 year orbital lifetime (P = 2×10^{-3})	3.27	Tables 5-21, 22 (AMD)	Earth (Random)	1.4×10^{-6}
			Destructive reactor excursion in orbit • 100 MW-Sec (P = 2×10^{-4})	3.28	Table 5-23 (AMD)	Earth (Random)	-

* Case 3.27 100 watts for 12 days, 60 days prior to launch

Table B-3. Characteristics of Key Mission Accidents-Orbital Operations (Cont)

MISSION PHASE Orbital Operations

REACTOR POWER HISTORY 5 year power operation at
330 kw assumed for conservatism

← Accident Description			Possible Consequences and Probabilities	Nuclear Hazard →			
Accident	Possible Causes	Accident Probability	Possible Consequences and Probabilities	Case No	Hazard Sources and Probabilities	Location	Risk
Loss of Critical Electrical Power System Component	<ul style="list-style-type: none"> • Flow blockage of coolant loop/heat rejection loop • Failure of Nak isolation valves around HSHX • Alternator failure • Loss of parasitic load resistors • Failure of gas bearings in the TAC unit • Loss of hydrogen in LiH shield due to failure of the SS container caused by <ul style="list-style-type: none"> - Manufacturing defect - Aging - Thermal cycling 	2.3×10^{-2}	Initiate pre-separation G&C checkout for early reactor disposal (a) Loss of heat removal, repair not possible (b) Reduction in nuclear radiation shielding, repair not possible <ul style="list-style-type: none"> • Damaged radiation shield in some cases ($P = 1.4 \times 10^{-3}$) 	3 29		Refer to Case 3 7	
			Initiate pre-separation G&C checkout for early reactor disposal. (a) Loss of heat removal, fuel cladding breached (b) Failure to remove decay heat after emergency shutdown, fuel cladding breached <ul style="list-style-type: none"> • Fission products in primary coolant • Radiation shield damaged in some cases ($P = 5.7 \times 10^{-3}$) 	3 30		Refer to Case 3 13	
			Initiate pre-separation G&C checkout for early reactor disposal (a) Loss of heat removal, fuel cladding and primary system breached (b) Failure to remove decay heat after emergency shutdown, fuel cladding and primary system breached <ul style="list-style-type: none"> • Fission products and activated NaK released in orbit • Radiation shield damaged in some cases ($P = 5.7 \times 10^{-3}$) 	3 31		Refer to Case 3.13	

Table B-4. Characteristics of Key Mission Accidents-Reactor Disposal

MISSION PHASE Reactor Disposal

REACTOR POWER HISTORY 5 year power operation
at 330 kw (normal shutdown)

	← Accident Description		← Possible Consequences and Probabilities		← Nuclear Hazard			
	Accident	Possible Causes	Accident Probability	Possible Consequences and Probabilities	Case No	Hazard Sources and Probabilities	Location	Risk
Pre-separation	Inadvertent control drum rotation to most reactive position (during reactor shutdown)	<ul style="list-style-type: none"> Control system malfunction Human error 	10^{-3}	Destructive reactor excursion in orbit ($P = 10^{-3}$)	4 1	Table 5-26 (AMD)	Earth (random)	-
	G&C equipment failure detected during separation G&C checkout, and failure to repair		9.9×10^{-6}	Power Module left in low earth orbit following separation from the Space Base <ul style="list-style-type: none"> Orbital decay 500 km, circular 5 year orbital lifetime ($P = 9.9 \times 10^{-6}$)	4 2	Tables 5-24, 25 (AMD)	Earth (random)	2.02×10^{-6}
Separation, Stabilization, & Alignment	Failure to separate power module from Space Base	<ul style="list-style-type: none"> Stuck compression springs Mechanical failure Electrical failure 	4×10^{-7}	Re-entry of Power Module with Space Base <ul style="list-style-type: none"> Orbital decay 500 km, circular 3.5 year orbital lifetime ($P = 4 \times 10^{-7}$)	4 3	Tables 5-24, 25 (AMD)	Earth (random)	2.02×10^{-7}
	G&C equipment failure detected during post-separation stabilization and alignment, and failure to repair		4.9×10^{-4}	Power Module left in low earth orbit <ul style="list-style-type: none"> Orbital decay 500 km, circular 5 year orbital lifetime ($P = 4.9 \times 10^{-4}$)	4 4	Tables 5-24, 25 (AMD)	Earth (random)	2.02×10^{-4}
Transfer Burn	Misaligned thrust vector, normal 2-rocket burn	Undetected G&C failure	2×10^{-5}	Power Module placed in short-lived orbit. <ul style="list-style-type: none"> Orbital decay 890 x 455 km, elliptical 12 year orbital lifetime ($P = 2 \times 10^{-5}$)	4 5	Tables 5-24, 25 (AMD)	Earth (random)	2.02×10^{-6}
				Immediate re-entry of Power Module from 500 km, circular orbit <ul style="list-style-type: none"> Initial $\Delta V = 128$ m/sec Retrograde firing ($P = 2 \times 10^{-9}$)	4 6	Tables 5-24, 25 (AMD)	Earth (random)	1.0×10^{-9}

Table B-4. Characteristics of Key Mission Accidents-Reactor Disposal (Cont)

MISSION PHASE Reactor Disposal

REACTOR POWER HISTORY 5 year power operation
at 330 kw (normal shutdown)

← Accident Description		Possible Consequences and Probabilities			Nuclear Hazard →			
Accident	Possible Causes	Accident Probability	Possible Consequences and Probabilities	Case No	Hazard Sources and Probabilities	Location	Risk	
Transfer Burn	Misaligned thrust vector, 1 rocket burn	8×10^{-8}	<ul style="list-style-type: none"> ● Undetected G&C failure ● Malfunction of the primary propulsion system 	Power Module placed in short-lived orbit <ul style="list-style-type: none"> ● Orbital decay ● 670 km x 455 km, elliptical ● 6 year orbital lifetime ($P = 8 \times 10^{-8}$) 	4 7	Tables 5-24, 25 (AMD)	Earth (random)	2.02×10^{-8}
			Re-entry of Power Module from short-lived orbit <ul style="list-style-type: none"> ● Orbital decay ● 305 km x 500 km, elliptical ● 1 year orbital lifetime ($P < 10^{-12}$) 	4 8	Non-credible	--	-	
	Complete failure of the primary propulsion system and failure to repair		1×10^{-6}	Power Module left in low earth orbit <ul style="list-style-type: none"> ● Orbital decay ● 500 km, circular ● 5 year orbital lifetime ($P = 1 \times 10^{-6}$) 	4 9	Tables 5-24, 25 (AMD)	Earth (random)	2.02×10^{-7}
	Accidental collision with Space Base or related systems following successful ignition of the primary propulsion system	Undetected G&C failure	1.5×10^{-8}	Disassembly in orbit due to collision ($P = 10^{-10}$)	4 10	Table 5-26 (AMD)	Earth (random)	-
				Destructive reactor excursion in orbit (control drum motion) ($P = 10^{-10}$)	4 11	Table 5-26 (AMD)	Earth (random)	-
				Damaged Power Module left in low earth orbit following collision <ul style="list-style-type: none"> ● Orbital decay ● 500 km, circular ● 5 year orbital lifetime ● Structural damage to radiation shield and primary NaK loop prior to re-entry ($P = 2.4 \times 10^{-9}$) 	4 12	Tables 5-24, 25 (AMD)	Earth (random)	2.02×10^{-10}

Table B-4. Characteristics of Key Mission Accidents-Reactor Disposal (Cont)

MISSION PHASE Reactor Disposal

REACTOR POWER HISTORY 5 year power operation
at 330 kw (normal shutdown)

← Accident Description			Possible Consequences and Probabilities		Nuclear Hazard →			
Accident	Possible Causes	Accident Probability	Possible Consequences and Probabilities	Case No	Hazard Sources and Probabilities	Location	Risk	
Transfer Burn			PM left in low earth orbit following collision <ul style="list-style-type: none"> ● Orbital decay ● 500 km circular ● 5 year orbital lifetime ● Radiation shield damaged in some cases (P = 1.2 x 10⁻⁸) 	4 13	Tables 5-24, 25 (AMD)	Earth (random)	2.02 x 10 ⁻⁹	
			Immediate re-entry of damaged Power Module <ul style="list-style-type: none"> ● Initial ΔV = 128 m/sec ● 500 km, circular ● Structural damage to radiation shield and primary NaK loop prior to re-entry (P < 10⁻¹²) 	4 14	Non-credible	--	-	
			Immediate re-entry of PM <ul style="list-style-type: none"> ● Initial ΔV = 128 m/sec ● 500 km, circular ● Radiation shield damaged in some cases (P < 10⁻¹²) 	4 15	Non-credible	--	-	
	Accidental collision with Space Base or related systems following ignition of 1 rocket for the transfer burn <ul style="list-style-type: none"> ● Reactor/shield configuration remains attached to Power Module following collision 	<ul style="list-style-type: none"> ● Undetected G&C failure ● Malfunction of the primary propulsion system 	5.8 x 10 ⁻¹¹	Disassembly in orbit due to collision (P < 10 ⁻¹²)	4 16	Non-credible	--	--
				Destructive reactor excursion in orbit (control drum motion) (P < 10 ⁻¹²)	4 17	Non-credible	-	-

Table B-4. Characteristics of Key Mission Accidents-Reactor Disposal (Cont)

MISSION PHASE Reactor Disposal

REACTOR POWER HISTORY 5 year power operation
at 330 kw (normal shutdown)

← Accident Description			← Possible Consequences and Probabilities		← Nuclear Hazard →		
Accident	Possible Causes	Accident Probability	Possible Consequences and Probabilities	Case No	Hazard Sources and Probabilities	Location	Risk
Transfer Burn			Damaged Power Module left in low earth orbit following collision <ul style="list-style-type: none"> ● Orbital decay ● 500 km, circular ● 5 year orbital lifetime ● Structural damage to radiation shield and primary NaK loop prior to re-entry ($P < 10^{-12}$) 	4 18	Non-credible	--	-
			Power Module left in low earth orbit following collision <ul style="list-style-type: none"> ● Orbital decay ● 500 km, circular ● 5 year orbital lifetime ● Radiation shield damaged in some cases ($P = 3.8 \times 10^{-11}$) 	4 19	Tables 5-24, 25 (AMD)	Earth (random)	-
			Re-entry of Power Module from short-lived orbit <ul style="list-style-type: none"> ● Orbital decay ● 305 x 500 km elliptical ● 1 year orbital lifetime ● Structural damage to radiation shield and primary NaK loop prior to re-entry ($P < 10^{-12}$) 	4 20	Non-credible	--	-
			Re-entry of Power Module from short-lived orbit <ul style="list-style-type: none"> ● Orbital decay ● 305 x 500 km, elliptical ● 1 year orbital lifetime ● Radiation shield damaged in some cases ($P < 10^{-12}$) 	4 21	Non-credible	--	-

Table B-4. Characteristics of Key Mission Accidents-Reactor Disposal (Cont)

MISSION PHASE Reactor Disposal

REACTOR POWER HISTORY 5 year power operation
at 330 kw (normal shutdown)

← Accident Description			Possible Consequences and Probabilities		Nuclear Hazard →			
Accident	Possible Causes	Accident Probability	Possible Consequences and Probabilities	Case No	Hazard Sources and Probabilities	Location	Risk	
Transfer Burn	Collision with Space Base or related systems and separation of the reactor/shield configuration from the Power Module (resulting from collision) following successful ignition of the primary propulsion system	5.4×10^{-9}	Damaged reactor/shield configuration left in low earth orbit <ul style="list-style-type: none"> ● Orbital decay ● 500 km, circular ● 44 year orbital lifetime ● Structural damage to radiation shield and primary NaK loop prior to re-entry ($P = 2.4 \times 10^{-9}$) 	4 22	Tables 5-24, 25 (AMD)	Earth (random)	6.2×10^{-11}	
			Reactor/Shield configuration left in low earth orbit <ul style="list-style-type: none"> ● Orbital decay ● 500 km, circular ● 44 year orbital lifetime ● Radiation shield damaged in some cases ($P = 2.9 \times 10^{-9}$) 	4 23	Tables 5-24, 25 (AMD)	Earth (random)	6.2×10^{-11}	
	Collision with Space Base or related systems and separation of the reactor/shield from the Power Module (resulting from collision) following ignition of 1 rocket for the transfer burn	<ul style="list-style-type: none"> ● Undetected G&C failure ● Malfunction of the primary propulsion system 	$< 10^{-12}$ (Non-credible)	Damaged reactor/shield configuration left in low earth orbit <ul style="list-style-type: none"> ● Orbital decay ● 500 km, circular ● 44 year orbital lifetime ● Structural damage to radiation shield and primary NaK loop ($P < 10^{-12}$) 	4 24	Non-credible	--	-
				Reactor/shield configuration left in low earth orbit <ul style="list-style-type: none"> ● Orbital decay ● 500 km, circular ● 44 year orbital lifetime ● Radiation shield damaged in some cases ($P < 10^{-12}$) 	4 25	Non-credible	--	-

Table B-4. Characteristics of Key Mission Accidents-Reactor Disposal (Cont)

MISSION PHASE Reactor Disposal

REACTOR POWER HISTORY 5 year power operation
at 330 kw (normal shutdown)

	← Accident Description		Possible Consequences and Probabilities		Nuclear Hazard →			
	Accident	Possible Causes	Accident Probability	Possible Consequences and Probabilities	Case No	Hazard Sources and Probabilities	Location	Risk
Coast to Apogee, Stabilization, & Realignment	G&C equipment failure detected following successful transfer burn, and failure to repair	G&C equipment failure	3.9×10^{-3}	Re-entry of Power Module from short-lived elliptical orbit <ul style="list-style-type: none"> • Orbital decay • 990 x 500 km, elliptical • 21 year orbital lifetime (P = 3.9×10^{-3}) 	4 26	Tables 5-24, 25 (AMD)	Earth (random)	2.02×10^{-3}
	G&C equipment failure detected following a 1 rocket transfer burn, and failure to repair	G&C equipment failure	1.6×10^{-5}	Re-entry of power module from short-lived elliptical orbit <ul style="list-style-type: none"> • Orbital decay • 745 x 500 km elliptical • 11 year orbital lifetime (P = 1.6×10^{-5}) 	4 27	Tables 5-24, 25 (AMD)	Earth (random)	2.02×10^{-6}
Circularization Burn	1 rocket failure during circularization burn following a successful transfer burn	Malfunction of the primary propulsion system	4×10^{-3}	Premature re-entry of Power Module <ul style="list-style-type: none"> • Orbital decay • 990 x 745 km, elliptical • 108 year orbital lifetime (P = 4×10^{-3}) 	4 28	Tables 5-24, 25 (AMD)	Earth (random)	1.14×10^{-4}
	Complete failure of the primary propulsion system for the circularization burn following a successful transfer burn	Malfunction of the primary propulsion system	4×10^{-6}	Premature re-entry of Power Module from short-lived elliptical orbit <ul style="list-style-type: none"> • Orbital decay • 990 x 500 km, elliptical • 21 year orbital lifetime (P = 4×10^{-6}) 	4 29	Tables 5-24, 25 (AMD)	Earth (random)	2.02×10^{-6}
	Misaligned thrust vector following ignition of 2 rockets for the circularization burn (successful transfer burn)	Undetected G&C failure	3×10^{-5}	Premature re-entry of Power Module <ul style="list-style-type: none"> • Orbital decay • 890 km, circular • 377 year orbital lifetime (P = 3×10^{-5}) 	4 30	Tables 5-24, 25 (AMD)	Earth (random)	1.41×10^{-8}

Table B-4. Characteristics of Key Mission Accidents-Reactor Disposal (Cont)

MISSION PHASE Reactor Disposal
 REACTOR POWER HISTORY 5 year power operation
 at 330 kw (normal shutdown)

← Accident Description			Possible Consequences and Probabilities		Nuclear Hazard →			
Accident	Possible Causes	Accident Probability	Possible Consequences and Probabilities	Case No	Hazard Sources and Probabilities	Location	Risk	
Circularization Burn			Immediate re-entry of Power Module from 990 km ● Retrograde firing ● Initial $\Delta V = 126$ m/sec (P = 3×10^{-9})	4 31	Tables 5-24, 25 (AMD)	Earth (random)	1.1×10^{-9}	
	Misaligned thrust vector following ignition of 1 rocket for the circularization burn (following successful transfer burn)	● Undetected G&C failure ● Malfunction of the primary propulsion system	Premature re-entry of Power Module ● Orbital decay ● 890 x 455 km, elliptical ● 48 year orbital lifetime (P = 1.2×10^{-7})	4 32	Tables 5-24, 25 (AMD)	Earth (random)	6.37×10^{-9}	
				4 33	Non-credible	--	-	
	Failure of 1 rocket during circularization burn following a 1 rocket transfer burn	● Malfunction of the primary propulsion system	1.6×10^{-5}	Premature re-entry of Power Module ● Orbital decay ● 745 x 743 km orbit ● 70 year orbital lifetime (P = 1.6×10^{-5})	4 34	Tables 5-24, 25 (AMD)	Earth (random)	4.25×10^{-7}
	Complete failure of the primary propulsion system for the circularization burn following a 1 rocket transfer burn	● Malfunction of the primary propulsion system	1.6×10^{-8}	Re-entry of the Power Module from short-lived orbit ● Orbital decay ● 745 x 395 km, elliptical ● 11 year orbital lifetime (P = 1.6×10^{-8})	4 35	Tables 5-24, 25 (AMD)	Earth (random)	2.02×10^{-9}

Table B-4. Characteristics of Key Mission Accidents-Reactor Disposal (Cont)

MISSION PHASE Reactor Disposal

REACTOR POWER HISTORY 5 year power operation
at 330 kw (normal shutdown)

← Accident Description			Possible Consequences and Probabilities		Nuclear Hazard →		
Accident	Possible Causes	Accident Probability	Possible Consequences and Probabilities	Case No	Hazard Sources and Probabilities	Location	Risk
Circularization Burn	Misaligned thrust vector following a successful ignition of the primary propulsion system for the circularization burn (following a 1 rocket transfer burn)	1.2×10^{-7}	Premature re-entry of Power Module <ul style="list-style-type: none"> Orbital decay 890 x 670 km, elliptical 48 year orbital lifetime ($P = 1.2 \times 10^{-7}$) 	4 36	Tables 5-24, 25 (AMD)	Earth (random)	-
			Immediate re-entry of Power Module from 745 km <ul style="list-style-type: none"> Initial $\Delta V = 126$ m/sec Retrograde firing ($P = 1.2 \times 10^{-11}$) 	4 37	Non-credible	--	-
	Misaligned thrust vector following 1 rocket failure at the circularization burn (following a 1 rocket transfer burn)	4.8×10^{-10}	Premature re-entry of the Power Module <ul style="list-style-type: none"> Orbital decay 670 x 668 km orbit 30 year orbital lifetime ($P = 4.8 \times 10^{-10}$) 	4 38	Tables 5-24, 25 (AMD)	Earth (random)	-
			Re-entry of the Power Module from short-lived orbit <ul style="list-style-type: none"> Orbital decay 305 x 745 km, elliptical 5 year orbital lifetime Retrograde firing ($P < 10^{-12}$) 	4 39	Non-credible	--	-
Successful ignition of both rockets for the circularization burn following a 1 rocket transfer burn	Malfunction of the primary propulsion system (during the transfer burn)	4×10^{-3}	Premature re-entry of Power Module <ul style="list-style-type: none"> Orbital decay 985 x 745 km, elliptical 106 year orbital lifetime ($P = 4 \times 10^{-3}$) 	4 40	Tables 5-24, 25 (AMD)	Earth (random)	-

Table B-5. Characteristics of Key Mission Accidents-Early Reactor Disposal (Fission Products in Primary Coolant)

MISSION PHASE Reactor Disposal*

REACTOR POWER HISTORY 5 year power operation at 330 kw,
(Reactor permanently shutdown prior to re-entry)

*Fission products in primary coolant
(ΣP = 3.1 x 10⁻²)

		← Accident Description		← Possible Consequences and Probabilities		← Nuclear Hazard			
		Accident	Possible Causes	Accident Probability	Possible Consequences and Probabilities	Case No	Hazard Sources and Probabilities	Location	Risk
Pre-Separation	Inadvertent control drum rotation to most reactive position (during reactor shutdown)	<ul style="list-style-type: none"> Control system malfunction Human error 	0	Destructive reactor excursion in orbit (P=0)	5.1	This case does not apply in the disposal phase for this class of mission abort accidents. Reactor has been permanently shutdown prior to entering this disposal phase.			
	G&C equipment failure detected during pre-separation G&C checkout, and failure to repair		3.1 x 10 ⁻⁷	Power Module left in low earth orbit following separation from the Space Base <ul style="list-style-type: none"> Orbital decay 500 km, circular 5 year orbital lifetime (P = 3.1 x 10⁻⁷) 	5.2	Tables 5-27, 28 (AMD)	Earth (random)	2.0 x 10 ⁻⁸	
Separation, Stabilization, & Alignment	Failure to separate power module from Space Base	<ul style="list-style-type: none"> Stuck compression springs Mechanical failure Electrical failure 	1.2 x 10 ⁻⁸	Reentry of Power Module with Space Base <ul style="list-style-type: none"> Orbital decay 500 km, circular 3.5 year orbital lifetime (P = 1.2 x 10⁻⁸) 	5.3	Tables 5-27, 28 (AMD)	Earth (random)	2.0 x 10 ⁻⁹	
	G&C Equipment failure detected during post-separation stabilization & alignment, and failure to repair		1.5 x 10 ⁻⁵	Power Module left in low earth orbit <ul style="list-style-type: none"> Orbital decay 500 km, circular 5 year orbital lifetime (P = 1.5 x 10⁻⁵) 	5.4	Tables 5-27, 28 (AMD)	Earth (random)	2.0 x 10 ⁻⁶	

Table B-5. Characteristics of Key Mission Accidents-Early
Reactor Disposal (Fission Products in Primary Coolant) (Cont)

MISSION PHASE Reactor Disposal*

REACTOR POWER HISTORY 5 year power operation at 330 kw_t
(Reactor permanently shutdown prior to re-entry)

*Fission products in primary coolant

← Accident Description			← Possible Consequences and Probabilities		← Nuclear Hazard →			
Accident	Possible Causes	Accident Probability	Possible Consequences and Probabilities	Case No	Hazard Sources and Probabilities	Location	Risk	
Transfer Burn	Misaligned thrust vector, normal 2-rocket burn	Undetected G&C failure	6.2 x 10 ⁻⁷	Power Module placed in short-lived orbit <ul style="list-style-type: none"> Orbital decay 890 x 455 km, elliptical 12 year orbital lifetime (P = 6.2 x 10⁻⁷) 	5 5	Tables 5-27, 28 (AMD)	Earth (random)	2.0 x 10 ⁻⁷
				Immediate re-entry of Power Module from 500 km circular orbit <ul style="list-style-type: none"> Initial ΔV = 128 m/sec Retrograde firing (P = 6.2 x 10⁻¹¹) 	5 6	Tables 5-27, 28 (AMD)	Earth (random)	~0
	Misaligned thrust vector, 1 rocket burn	<ul style="list-style-type: none"> Undetected G&C failure Malfunction of the primary propulsion system 	2.5 x 10 ⁻⁹	Power Module placed in short-lived orbit <ul style="list-style-type: none"> Orbital decay 670 x 455 km, elliptical 6 year orbital lifetime (P = 2.5 x 10⁻⁹) 	5 7	Tables 5-27, 28 (AMD)	Earth (random)	2.0 x 10 ⁻¹⁰
				Re-entry of Power Module from short-lived orbit <ul style="list-style-type: none"> Orbital decay 305 x 500 km, elliptical 1 year orbital lifetime (P < 10⁻¹²) 	5 8	Non-Credible	-	-
Complete failure of the primary propulsion system & failure to repair		3.1 x 10 ⁻⁸	Power Module Left in low earth orbit <ul style="list-style-type: none"> Orbital decay 500 km, circular 5 year orbital lifetime (P = 3.1 x 10⁻⁸) 	5 9	Tables 5-27, 28 (AMD)	Earth (random)	2.0 x 10 ⁻⁹	

Table B-5. Characteristics of Key Mission Accidents-Early Reactor Disposal (Fission Products in Primary Coolant) (Cont)

MISSION PHASE Reactor Disposal*

REACTOR POWER HISTORY 5 year power operation of 330 kw_t
(Reactor permanently shutdown prior to re-entry)

*Fission products in primary coolant

Accident Description			Possible Consequences and Probabilities		Nuclear Hazard		
Accident	Possible Causes	Accident Probability	Possible Consequences and Probabilities	Case No	Hazard Sources and Probabilities	Location	Risk
Transfer Burn	Accidental collision with Space Base or related systems following successful ignition of the primary propulsion system. <ul style="list-style-type: none"> Reactor/Shield configuration remains attached to Power Module following collision 	4.7×10^{-10}	Disassembly in orbit due to collision. ($P < 10^{-12}$)	5.10	Non-Credible	-	-
			Destructive reactor excursion in orbit (control drum motion) ($P = 0$)	5.11	-	-	-
			Damaged Power Module left in low earth orbit following collision. <ul style="list-style-type: none"> Orbital decay 500 km, circular 5 year orbital lifetime Structural damage to radiation shield & primary NaK loop prior to reentry. ($P = 7.6 \times 10^{-11}$) 	5.12	Tables 5-27, 28, 29 (AMD)	Earth (random)	0
			PM left in low earth orbit following collision. <ul style="list-style-type: none"> Orbital decay 500 km, circular 5 year orbital lifetime Radiation shield damaged in some cases. ($P = 3.7 \times 10^{-10}$) 	5.13	Tables 5-27, 28, 29 (AMD)	Earth (random)	2.0×10^{-11}
			Immediate re-entry of damaged Power Module <ul style="list-style-type: none"> Initial $\Delta V = 128$ m/sec 500 km, circular Structural damage to radiation shield & primary NaK loop prior to re-entry ($P < 10^{-12}$) 	5.14	Non-Credible	-	-

Table B-5. Characteristics of Key Mission Accidents-Early Reactor Disposal (Fission Products in Primary Coolant) (Cont)

MISSION PHASE Reactor Disposal*

REACTOR POWER HISTORY 5 year power operation at 330 kW_t
(Reactor permanently shutdown prior to re-entry)

*Fission products in primary coolant

← Accident Description			← Possible Consequences and Probabilities		← Nuclear Hazard			
Accident	Possible Causes	Accident Probability	Possible Consequences and Probabilities	Case No	Hazard Sources and Probabilities	Location	Risk	
Transfer Burn			Immediate re-entry of PM <ul style="list-style-type: none"> • Initial $\Delta V = 128$ m/sec • 500 km, Circular • Radiation shield damaged in some cases ($P = 10^{-12}$) 	5.15	Non-Credible	-	-	
	Accidental collision with Space Base or related systems following ignition of 1 rocket for the transfer burn. <ul style="list-style-type: none"> • Reactor/Shield configuration remains attached to Power Module following collision 	<ul style="list-style-type: none"> • Undetected G&C failure • Malfunction of the primary propulsion system 	Non-Credible ($P < 10^{-12}$)	Disassembly in orbit due to collision ($P < 10^{-12}$)	5.16	Non-Credible	-	-
				Destructive reactor excursion in orbit (control drum motion) ($P=0$)	5.17	-	-	-
				Damaged Power Module left in low earth orbit following collision. <ul style="list-style-type: none"> • Orbital decay • 500 km, circular • 5 year orbital lifetime • Structural damage to radiation shield & primary NaK loop prior to re-entry ($P < 10^{-12}$) 	5.18	Non-Credible	-	-
				Power Module left in low earth orbit following collision <ul style="list-style-type: none"> • Orbital decay • 500 km, circular • 5 year orbital lifetime • Radiation shield damaged in some cases ($P < 10^{-12}$) 	5.19	Non-Credible	-	-

Table B-5. Characteristics of Key Mission Accidents-Early Reactor Disposal (Fission Products in Primary Coolant) (Cont)

MISSION PHASE Reactor Disposal*

REACTOR POWER HISTORY 5 year power operation at 330 kw_t
(Reactor permanently shutdown prior to re-entry)

*Fission products in primary coolant

← Accident Description			Possible Consequences and Probabilities		Nuclear Hazard →			
Accident	Possible Causes	Accident Probability	Possible Consequences and Probabilities	Case No	Hazard Sources and Probabilities	Location	Risk	
Transfer Burn			Re-entry of Power Module from short-lived orbit <ul style="list-style-type: none"> • Orbital decay • 305 x 500 km, elliptical • 1 year orbital lifetime • Structural damage to radiation shield & primary NaK loop prior to re-entry. (P < 10⁻¹²) 	5.20	Non-Credible	-	-	
			Re-entry of Power Module from short-lived orbit. <ul style="list-style-type: none"> • Orbital decay • 305 x 500 km, elliptical • 1 year orbital lifetime • Radiation shield damaged in some cases (P < 10⁻¹²) 	5.21	Non-Credible	-	-	
	Collision with Space Base or related systems & separation of the reactor/shield configuration from the Power Module (resulting from collision) following successful ignition of the primary propulsion system.	Undetected G&C failure	1.7 x 10 ⁻¹⁰	Damaged reactor/shield configuration left in low earth orbit <ul style="list-style-type: none"> • Orbital decay • 500 km, circular • 44 year orbital lifetime • Structural damage to radiation shield and primary NaK loop prior to re-entry (P = 7.6 x 10⁻¹¹) 	5.22	Tables 5-27, 28, 29 (AMD)	Earth (random)	6.2 x 10 ⁻¹²
				Reactor/Shield configuration left in low earth orbit <ul style="list-style-type: none"> • Orbital decay • 500 km, circular • 44 year orbital lifetime • Radiation shield damaged in some cases. (P = 9.2 x 10⁻¹¹) 	5.23	Tables 5-27, 28 (AMD)	Earth (random)	6.2 x 10 ⁻¹²

Table B-5. Characteristics of Key Mission Accidents-Early Reactor Disposal (Fission Products in Primary Coolant) (Cont)

MISSION PHASE Reactor Disposal*

REACTOR POWER HISTORY 5 year power operation at 330 kw_t
(Reactor permanently shutdown prior to re-entry)

*Fission products in primary coolant

← Accident Description			Possible Consequences and Probabilities		Nuclear Hazard →			
Accident	Possible Causes	Accident Probability	Possible Consequences and Probabilities	Case No	Hazard Sources and Probabilities	Location	Risk	
Transfer Burn	Collision with Space Base or related systems & separation of the reactor/shield from the Power Module (resulting from collision) following ignition of 1 rocket for the transfer burn.	<ul style="list-style-type: none"> Undetected G&C failure Malfunction of the primary propulsion system. 	10^{-12} (Non-Credible)	Damaged reactor/shield configuration left in low earth orbit <ul style="list-style-type: none"> Orbital decay 500 km, circular 44 year orbital lifetime Structural damage to radiation shield and primary NaK loop. ($P < 10^{-12}$) 	5.24	Non-Credible	-	-
			Reactor/Shield configuration left in low earth orbit <ul style="list-style-type: none"> Orbital decay 500 km, circular 44 year orbital lifetime Radiation shield damaged in some cases ($P < 10^{-12}$) 	5.25	Non-Credible	-	-	
Coast to Apogee, Stabilization & Realignment	G&C equipment failure detected following successful transfer burn, & failure to repair.	G&C equipment failure	1.2×10^{-4}	Re-entry of Power Module from short-lived elliptical orbit <ul style="list-style-type: none"> Orbital decay 990 x 500 km, elliptical 21 year orbital lifetime ($P = 1.2 \times 10^{-4}$) 	5.26	Tables 5-27, 28 (AMD)	Earth (random)	2.0×10^{-5}
	G&C Equipment failure detected following a 1 rocket transfer burn, and failure to repair	G&C equipment failure	4.5×10^{-7}	Re-entry of Power Module from short-lived elliptical orbit <ul style="list-style-type: none"> Orbital decay 745 x 500 km, elliptical 11 year orbital lifetime ($P = 4.5 \times 10^{-7}$) 	5.27	Tables 5-27, 28 (AMD)	Earth (random)	2.0×10^{-7}

Table B-5. Characteristics of Key Mission Accidents-Early Reactor Disposal (Fission Products in Primary Coolant) (Cont)

MISSION PHASE Reactor Disposal*

REACTOR POWER HISTORY 5 year power operation at 330 kw_t
(Reactor permanently shutdown prior to re-entry)

*Fission products in primary coolant

← Accident Description		Possible Consequences and Probabilities			Nuclear Hazard →			
Accident	Possible Causes	Accident Probability	Possible Consequences and Probabilities	Case No	Hazard Sources and Probabilities	Location	Risk	
Circularization Burn	1 rocket failure during circularization burn following a successful transfer burn.	Malfunction of the primary propulsion system	1.2×10^{-4}	Premature re-entry of Power Module <ul style="list-style-type: none"> Orbital Decay 990 x 245 km, elliptical 108 year orbital lifetime (P = 4.5×10^{-7}) 	5 28	Tables 5-27, 28 (AMD)	Earth (random)	1.0×10^{-6}
	Complete failure of the primary propulsion system for the circularization burn following a successful transfer burn.	Malfunction of the primary propulsion system	1.2×10^{-7}	Premature re-entry of Power Module from short-lived elliptical orbit <ul style="list-style-type: none"> Orbital decay 990 x 500 km, elliptical 21 year orbital lifetime (P = 4.5×10^{-7}) 	5 29	Tables 5-27, 28 (AMD)	Earth (random)	2.0×10^{-8}
	Misaligned thrust vector following ignition of 2 rockets for the circularization burn (successful transfer burn).	Undetected G&C failure.	9.3×10^{-7}	Premature re-entry of Power Module <ul style="list-style-type: none"> Orbital decay 890 km, circular 377 year orbital lifetime (P = 9.3×10^{-7}) 	5 30	Tables 5-27, 28 (AMD)	Earth (random)	7.0×10^{-12}
				Immediate re-entry of Power Module from 990 km. <ul style="list-style-type: none"> Retrograde firing Initial $\Delta V = 126$ m/sec (P = 9.3×10^{-11}) 	5 31	Tables 5-27, 28 (AMD)	Earth (random)	1.1×10^{-10}
	Misaligned thrust vector following ignition of 1 rocket for the circularization burn (following successful transfer burn)	<ul style="list-style-type: none"> Undetected G&C failure Malfunction of the primary propulsion system. 	3.7×10^{-9}	Premature re-entry of Power Module <ul style="list-style-type: none"> Orbital decay 890 x 455 km, elliptical 48 year orbital lifetime (P = 3.7×10^{-9}) 	5 32	Tables 5-27, 28 (AMD)	Earth (random)	6.2×10^{-11}

Table B-5. Characteristics of Key Mission Accidents-Early Reactor Disposal (Fission Products in Primary Coolant) (Cont)

MISSION PHASE Reactor Disposal*

REACTOR POWER HISTORY 5 year power operation at 330 kw,
(Reactor permanently shutdown prior to re-entry)

*Fission products in primary coolant

← Accident Description			← Possible Consequences and Probabilities		← Nuclear Hazard →		
Accident	Possible Causes	Accident Probability	Possible Consequences and Probabilities	Case No	Hazard Sources and Probabilities	Location	Risk
			Re-entry of the Power Module from short-lived elliptical orbit. <ul style="list-style-type: none"> Orbital decay 305 x 990 km, elliptical 6 year orbital lifetime Retrograde firing ($P < 10^{-12}$) 	5.33	Non-Credible	-	-
Failure of 1 rocket during circularization burn following a 1 rocket transfer burn.	<ul style="list-style-type: none"> Malfunction of the primary propulsion system. 	5×10^{-7}	Premature re-entry of Power Module <ul style="list-style-type: none"> Orbital decay 745 x 743 km orbit 70 year orbital lifetime ($P = 5 \times 10^{-7}$) 	5.34	Tables 5-27, 28 (AMD)	Earth (random)	4.1×10^{-8}
Complete failure of the primary propulsion system for the circularization burn following as 1 rocket transfer burn.	<ul style="list-style-type: none"> Malfunction of the primary propulsion system 	5×10^{-10}	Re-entry of the Power Module from short-lived orbit <ul style="list-style-type: none"> Orbital decay 745 x 395 km, elliptical 11 year orbital lifetime ($P = 5 \times 10^{-10}$) 	5.35	Tables 5-27, 28 (AMD)	Earth (random)	2.0×10^{-10}
Misaligned thrust vector following a successful ignition of the primary propulsion system for the circularization burn (following a 1 rocket transfer burn)	<ul style="list-style-type: none"> Undetected G&C failure 	3.7×10^{-9}	Premature re-entry of Power Module <ul style="list-style-type: none"> Orbital decay 890 x 670 km, elliptical 48 year orbital lifetime ($P = 3.7 \times 10^{-9}$) 	5.36	Tables 5-27, 28 (AMD)	Earth (random)	6.2×10^{-11}
			Immediate re-entry of Power Module from 745 km <ul style="list-style-type: none"> Initial $\Delta V = 126$ m/sec Retrograde firing ($P < 10^{-12}$) 	5.37	Non-Credible	-	-

Circularization Burn

Table B-5. Characteristics of Key Mission Accidents—Early Reactor Disposal (Fission Products in Primary Coolant) (Cont)

MISSION PHASE Reactor Disposal*

REACTOR POWER HISTORY 5 year power operation at 330 kw,
(Reactor permanently shutdown prior to re-entry)

*Fission products in primary coolant

← Accident Description		Possible Consequences and Probabilities			Nuclear Hazard →		
Accident	Possible Causes	Accident Probability	Possible Consequences and Probabilities	Case No	Hazard Sources and Probabilities	Location	Risk
Circularization Burn	<ul style="list-style-type: none"> Undetected G&C failure Malfunction of the primary propulsion system. 	1.5 x 10 ⁻¹¹	Premature re-entry of the Power Module <ul style="list-style-type: none"> Orbital decay 670 x 668 km orbit 30 year orbital lifetime (P = 1.5 x 10⁻¹¹) 	5.38	Non-Credible	-	-
			Re-entry of the Power Module from short-lived orbit. <ul style="list-style-type: none"> Orbital decay 305 x 745 km, elliptical 5 year orbital lifetime Retrograde firing (P < 10⁻¹²) 	5.39	Non-Credible	-	-
Successful ignition of both rockets for the circularization burn following a 1 rocket transfer burn	<ul style="list-style-type: none"> Malfunction of the primary propulsion system 	1.2 x 10 ⁻⁴	Premature re-entry of Power Module <ul style="list-style-type: none"> Orbital decay 985 x 745 km, elliptical 106 year orbital lifetime. (P = 1.2 x 10⁻⁴) 	5.40	Tables 5-27, 28 (AMD)	Earth (random)	1.0 x 10 ⁻⁶

CONVERSION FACTORS INTERNATIONAL TO ENGLISH UNITS

<u>Physical Quantity</u>	<u>International Units</u>	<u>English Units</u>	<u>Conversion Factor Multiply By</u>
Acceleration	m/sec ²	ft/sec ²	3.281
Area	m ²	ft ²	10.764
		in ²	1550.39
Density	Kg/m ²	lb/ft ³	6.242 x 10 ⁻²
		lb/in ³	3.610 x 10 ⁻⁵
Energy	Joule	Btu	9.479 x 10 ⁻⁴
Force	Newton	lbf	2.248 x 10 ⁻¹
Length	m	ft	3.281
		nm	5.399 x 10 ⁻⁴
Mass	Kg	lbm	2.205
Power	watt	Btu/sec	9.488 x 10 ⁻⁴
		Btu/min	5.691 x 10 ⁻²
		Btu/hr	3.413
Pressure	Newton/m ²	Atmosphere	3.413
		lbf/in ²	1.451 x 10 ⁻⁴
		lbf/ft ²	2.088 x 10 ⁻²
Speed	m/sec	ft/sec (fps)	3.281
Temperature	K	F	(9/5 - 459.67/t _K)
Volume	m ³	in ³	6.097 x 10 ⁴
		ft ³	35.335

GLOSSARY OF TERMS

Abort	Premature and abrupt termination of an event or mission because of existing or imminent degradation or failure of hardware. (In the safety analysis, no distinction is made between an accident and abort.)
Accident	An undesirable unplanned event which may or may not result from a system failure or malfunction.
Airborne Material	Radioactive gases, vapors and particulates released to the air
Breached	Fuel elements, coolant loops, pressure vessel, core, or radiation shield are (a) physically torn by thermal or mechanical stresses, (b) cut open by fragmentation or (c) split open by internal pressures
Bulk Damage (Radiation)	Radiation causing atomic displacement in semiconductor devices - sometimes commonly referred to as "crystal" damage
Contamination	A condition where a radioactive material is mixed or adheres to a desirable substance or where radioactivity has spread to places where it may harm persons, experiments or make areas unsafe
Control Drum Motion	Rotation of the control drums or drum toward or away from the most reactive position within a reactor. (As used in safety analysis results in a reactor excursion)
Core Compaction	The act of increasing the density of the core which results in increased reactivity and possible criticality
Cover Gas	A gas blanket used to provide an inert atmospheric environment around hardware to minimize potential reactions which can give rise to accident situations.
Credible	An event having a relative or cumulative probability of occurrence of $> 10^{-12}$
Criticality	The act of obtaining and sustaining a chain reaction
Critical Mass	The mass of fissionable material necessary to obtain criticality
Cumulative Probability	Sometimes referred to as "Mission probability" is the overall probability of a sequence of events occurring (product of "relative probabilities" of the individual events along a path of an abort sequence tree).
Damaged	Same as "Breached"
Decontamination	The removal of undesired dispersed radioactive substances from material, personnel, rooms, equipment, air, etc (e g , washing, filtering, chipping).
Destructive Excursion	An excursion (safety analysis assumes ~ 100 MW-sec) accompanied by a complete disassembly of the reactor, a prompt radiation emission and release of fission product gases, vapors and particulates
Disassembly/Disassembled	Nuclear hardware (e g , reactor) which has been violently broken or separated into parts and not capable of forming a critical mass
Disposal	The planned discarding or recovery of nuclear hardware
Distributed Material	The spread of nuclear fuel and radioactive debris on the earth's surface following impact or destructive excursion
Dose Guidelines	Established radiation levels used in the nuclear safety analysis for evaluating number of exposures and in determining operating limits and boundaries
Dosimetry	Techniques used in the measurement of radiation

GLOSSARY OF TERMS (CONT)

Dynamic Interference	An experiment radiation effect where the flux rate above some threshold (a fraction of the experiment signal-to-noise ratio at maximum sensitivity, for electronic detectors) causes noticeable degradation of data quality
Early Reactor Disposal	Attempted disposal of the reactor prior to its successful completion of 5 years operational lifetime
Electrical Power System	All components (heat source, regulation, control, power conversion and radiators) necessary for the development of electrical power. The reactor electrical power system includes all hardware associated with the Power Module with the exception of the Disposal System
End of Mission	Generally associated with the termination of the mission or flight. Is also used to define those activities involved with disposal and recovery of hardware after intended lifetime
Excursion	A rapid and usually unplanned increase in thermal power associated with the operation of a power reactor
Exposure Limit	Total accumulated or time dependent radiation exposure limits imposed on personnel by regulatory agencies or limits which preclude equipment damage
Fission Products	The nuclides (quite often radioactive) produced by the fission of a heavy element nuclide such as U-235 or Pu-239
Fuel	Fissionable material in a reactor or radioisotopes in a heat source used in producing energy
Fuel Element/Capsule	A shaped body of nuclear fuel prepared for use in a reactor or heat source. Common usage involves some form of encapsulation
Fuel Element Ablation	Fuel element clad and/or fuel removed by reentry heating, releasing fission products to the atmosphere
Fuel Element Burial	Individual fuel elements beneath the ground surface completely covered by soil
Gallery	The compartment of the reactor shield which houses the major primary loop components
Ground Deposited Particles	Particles deposited on the ground from radioactive fallout
Hazard	An existing situation caused by an unsafe act or condition which can result in harm or damage to personnel and equipment
Hazard Source	The location and/or origin of the hazard
Immediate Reentry	Very early reentry of the reactor (e.g., misaligned thrust vector which causes firing of the reactor disposal rockets toward earth resulting in 1-2 day reentry)
Impact in Deep Ocean	Reentering and/or impact of nuclear material in the ocean, beyond the Continental Shelf where contamination of the food chain is extremely remote
Impact in Reservoir	Reentering and/or impact of nuclear material in reservoir containing potable drinking water
Impact in Water Containing Edible Marine Life	Reentering and/or impact of nuclear material on the Continental Shelf or in a body of water such as a lake, river or stream where contamination of the food chain is likely
Intact Reentry/Reactor	A nuclear system that retains its integrity upon impact and in the case of a reactor is capable of undergoing an excursion
Integrated/Cumulative Dose	The total dose resulting from all or repeated exposures to radiation
Interfacing Vehicle	Any defined module, spacecraft, booster or logistic vehicle which may have an interaction with the Manned Space Base

GLOSSARY OF TERMS (CONT)

Ionization Damage	Radiation causing surface damage in materials (e g., the fogging of film)
Land Impact	Nuclear hardware which impacts land at terminal velocities following reentry and lower velocities during prelaunch or early in the launch/ascent phase.
Loss of Coolant	Loss of organic or liquid metal coolant in reactor coolant loops due to failure/accident
Mission Support	Supporting functions provided the Space Base Program by ground personnel and interfacing vehicles throughout all mission phases
Moderator	Material used in a nuclear reactor to slow down neutrons from the high energies at which they are released to increase the probability of neutron capture Water and hydrogen are moderators in a thermal reactor
NaK-78	An alloy of sodium (22% by weight) and potassium (78%) used as a liquid metal heat transfer fluid.
No Discernible Hazard	Represents no hazard to the general populace
Non-credible	An event having a relative or cumulative probability of occurrence of $< 10^{-12}$ Considered not worthy of concern
Non-destructive Excursion	A temperature excursion which may rupture the primary coolant loop and release fission products to the environment but - leaves the reactor shield essentially intact
Normal Operations	Planned and anticipated mission activities and events
Over Moderation	Immersion of reactor in an hydrogenous medium (moderator) resulting in increased neutron reflection into the core causing a reactor excursion
Permanent Shutdown	Enacting provisions which preclude reactor criticality under all foreseeable circumstances.
Poison	A material that absorbs neutrons and reduces the reactivity of a reactor
Power Module	The complete reactor/shield, radiator, power conversion system and disposal system unit as provided on the Space Base
Premature Reentry	Any reentry of the reactor from Earth orbit with orbital lifetimes less than the planned (1167 year) orbital decay time of the 990 km disposal altitude
Pre-poison	A poison which is added to the reactor fuel for purposes of controlling reactivity Sometimes referred to as "burnable poison".
Prompt Radiation	The neutron and gamma radiation released coincident with the fission process as opposed to the radiation from fission product decay Commonly associated with an excursion event
Quasi-Steady State	A term used to describe the condition when a reactor periodically goes critical and then sub-critical due to water surging in and out of the core
Radiological Consequences	The radiation exposure effect on personnel and the ecology from a radiation release accident or event
Radiological Hazards	Hazards associated with radiation as differentiated from other sources
Radiological Risk	The term used to define the average number of people anticipated to be affected by radiation in a given mission or phase thereof
Random Reentry	The uncontrolled non-directed reentry of a vehicle from orbit
Reactivity	A measure of the departure of a reactor from critical such that positive values correspond to reactors super-critical and negative values to reactors which are sub-critical (Usually expressed in multiples of a dollar)

GLOSSARY OF TERMS (CONT)

Reactor Fails to Survive Reentry	Reactor/shield is completely disassembled by reentry heating, releasing individual fuel elements and structural debris to the atmosphere
Reactor Survives Reentry	Reactor is not disassembled by reentry heating, radiation shield may be damaged
Reactor/Shield	A system containing the reactor, control drums, gallery and surrounding LiH and Tungsten shield.
Relative Probability	Probability of the occurrence of a particular event given a defined set of choices.
Repair/Replacement	Consists of (a) physically repairing all faulty systems, or (b) complete replacement of the faulty system(s)
Ruptured	Same as "Breached".
Safety	Freedom from chance of injury or loss to personnel, equipment or property
Safety Catastrophic	Condition(s) such that environment, personnel error, design characteristics, procedural deficiencies, or subsystem or component malfunction will severely degrade system performance, and cause subsequent system loss, death, or multiple injuries to personnel (SPD-1A).
Safety Critical	Condition(s) such that environment, personnel error, design characteristics, procedural deficiencies, or subsystem or component malfunction will cause equipment damage or personnel injury, or will result in a hazard requiring immediate corrective action for personnel or system survival (SPD-1A).
Safety Marginal	Condition(s) such that environment, personnel error, design characteristics, procedural deficiencies, or subsystem failure or component malfunction will degrade system performance but which can be counteracted or controlled without major damage or any injury to personnel (SPD-1A)
Safety Negligible	Condition(s) such that personnel error, design characteristics, procedural deficiencies, or subsystem failure or component malfunction will not result in minor system degradation and will not produce system functional damage or personnel injury (SPD-1A)
Scram System	A separate, possibly automatic, mechanism used to rapidly shut down a reactor.
System Safety	The optimum degree of risk management within the constraints of operational effectiveness, time and cost attained through the application of management and engineering principles throughout all phases of a program.
Space Base Program	All aspects of the Space Base mission including all prime and support hardware and personnel both on the ground, at sea or in orbit, which are required throughout all mission phases.
Space Debris	Uncontrolled radioactive or non-radioactive man-made objects in space, these objects may present collision and radiation hazards to earth orbital missions.
Space Shuttle	The manned vehicle used for the transportation of cargo to and from earth orbit. A separately launched vehicle (booster) on which the Shuttle is placed provides the initial first stage thrust
Source Terms	Characterization of a radiation hazard with regard to (a) location, (b) magnitude, and (c) exposure mode
Tracer	Material in which isotopes of an element may be incorporated to make possible observation of the course of the element through a chemical, biological or physical process



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