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BATTELLE

Report To

National Aeronautics and Space Administration

Marshall Space Flight Center Huntsville, Alabama

VOLUME I

EXECUTIVE SUMMARY
OF TECHNICAL REPORT

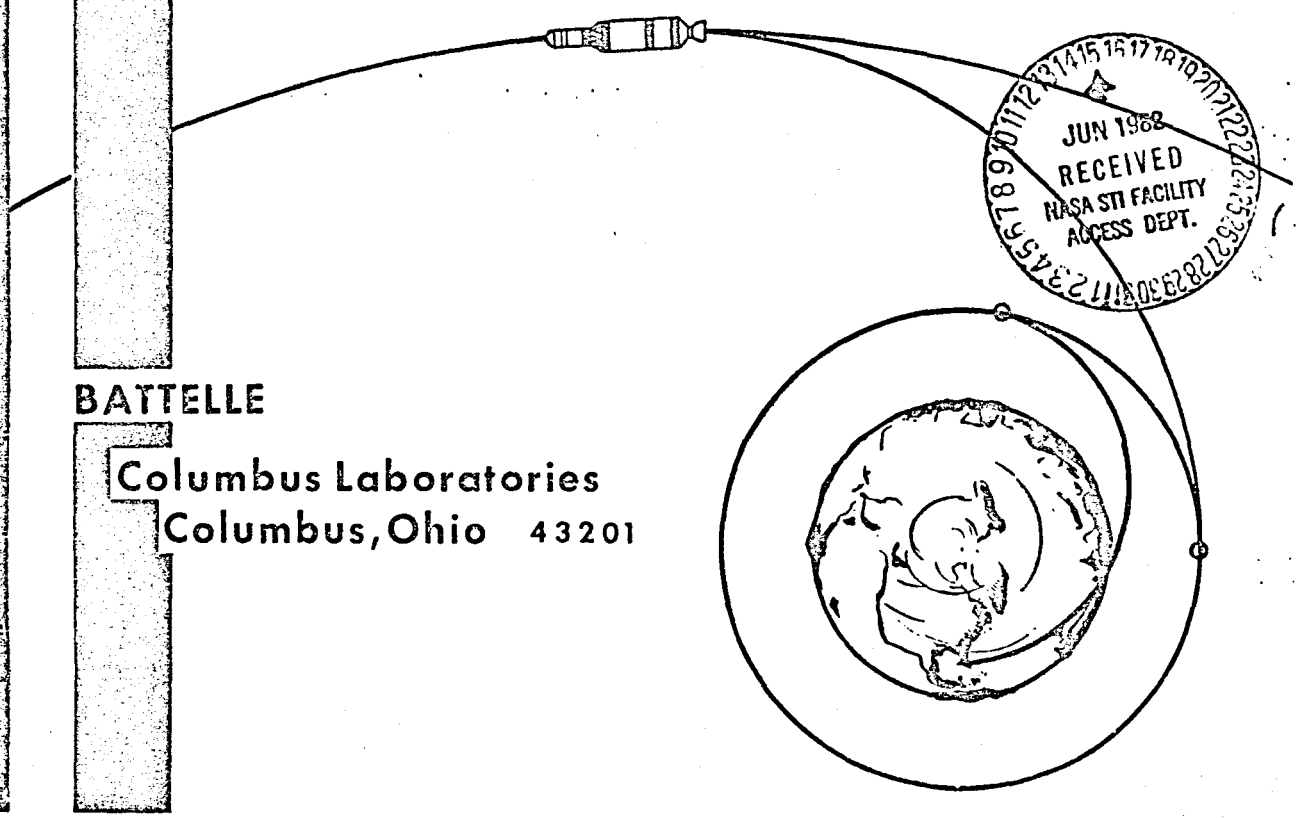
on

PRELIMINARY RISK ASSESSMENT FOR
NUCLEAR WASTE DISPOSAL IN SPACE

to

NATIONAL AERONAUTICS AND
SPACE ADMINISTRATION
MARSHALL SPACE FLIGHT CENTER
(Contract Number NAS8-34512)
DPD No. 608, DR No. 4

February 28, 1982



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Columbus Laboratories
Columbus, Ohio 43201

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VOLUME I

EXECUTIVE SUMMARY OF TECHNICAL REPORT

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February 28, 1982

by

Eric E. Rice, BCL
Richard S. Denning, BCL
Alan L. Friedlander, SAI

E. E. Rice

E. E. Rice, Project Manager
Battelle Columbus Laboratories
Columbus, Ohio

C. C. Priest

C. C. Priest, COR
NASA/Marshall Space Flight Center
Huntsville, Alabama

BATTELLE
Columbus Laboratories
505 King Avenue
Columbus, Ohio 43201

FOREWORD

The study summarized in this report was a part of an analysis to determine the feasibility, desirability, and preferred approaches for disposal of selected high-level nuclear wastes in space. The Battelle Columbus Laboratories (BCL) study was an integral part of the Office of Nuclear Waste Isolation (ONWI)-managed DOE/NASA program for study of nuclear waste disposal in space, and was conducted in parallel with efforts at Battelle Pacific Northwest Laboratory; Boeing Aerospace Company; and Science Applications, Inc. (SAI - under subcontract to Battelle and reported here). The research effort reported here was performed by Battelle Columbus Laboratories (with SAI being a subcontractor) under NASA Contract NAS8-34512 from June 1981 through February 1982. The study objective was to provide NASA and DOE with preliminary space disposal risk estimates and estimates of risk uncertainty, such that potential total system risk benefits of space disposal of certain waste components could be evaluated.

The information developed during the study period is contained in this two-volume final report. The title of each volume is listed below.

Volume I Executive Summary
Volume II Technical Report

Inquiries regarding this study should be addressed to:

C. C. (Pete) Priest, COR
NASA/Marshall Space Flight Center
Attention: PS01
Huntsville, Alabama 35812
Telephone: (205) 453-0413

Eric E. Rice, Project Manager
Battelle Columbus Laboratories
505 King Avenue
Columbus, Ohio 43201
Telephone: (614) 424-5103

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James B. Baeker (Wiggins Co.)
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Donald J. Kessler (NASA/JSC)
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Lisa A. Miller
A. George Mourad
William S. Pope
Fred G. Rea
Richard P. Reinert (Boeing)
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Dwight L. Suiter (NASA/JSC)
Chen-sayh Tsay
G. Walker (Univ. of Hawaii)
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Acknowledgment is also made to the outstanding guidance and cooperation by the NASA/MSFC study monitor, Claude C. (Pete) Priest. Also, special thanks must go to Ralph E. Best, Program Manager at the U.S. Department of Energy (DOE) Office of Nuclear Waste Isolation (ONWI), Columbus, Ohio, and Philip R. Compton, Energy Systems Division, Office of Aeronautics and Space Technology, NASA/Headquarters, Washington, DC, for their thoughtful guidance throughout the study.

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1.0 INTRODUCTION

This volume (Volume I) provides a brief summary of the work performed during the 1981-1982 Battelle Columbus Laboratories (BCL) preliminary study of the risk of nuclear waste disposal in space. This volume summarizes the following: study objectives, approach, assumptions, and limitations; the relationship of this effort to other NASA and DOE efforts; the basic technical data and results derived from the study (contained in detail in Volume II); conclusions; and recommendations. References for this volume are listed in Appendix A. Abbreviations and acronyms used in this volume are defined in Appendix B.

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3.0 RELATIONSHIP TO OTHER NASA AND DOE EFFORTS

This study, performed by Battelle Columbus Laboratories with SAI subcontract support (for long-term risk estimates), was sponsored and monitored by NASA/MSFC, and funded through an interagency agreement with ONWI/DOE. The 1981-1982 program effort is summarized in Figure 1.

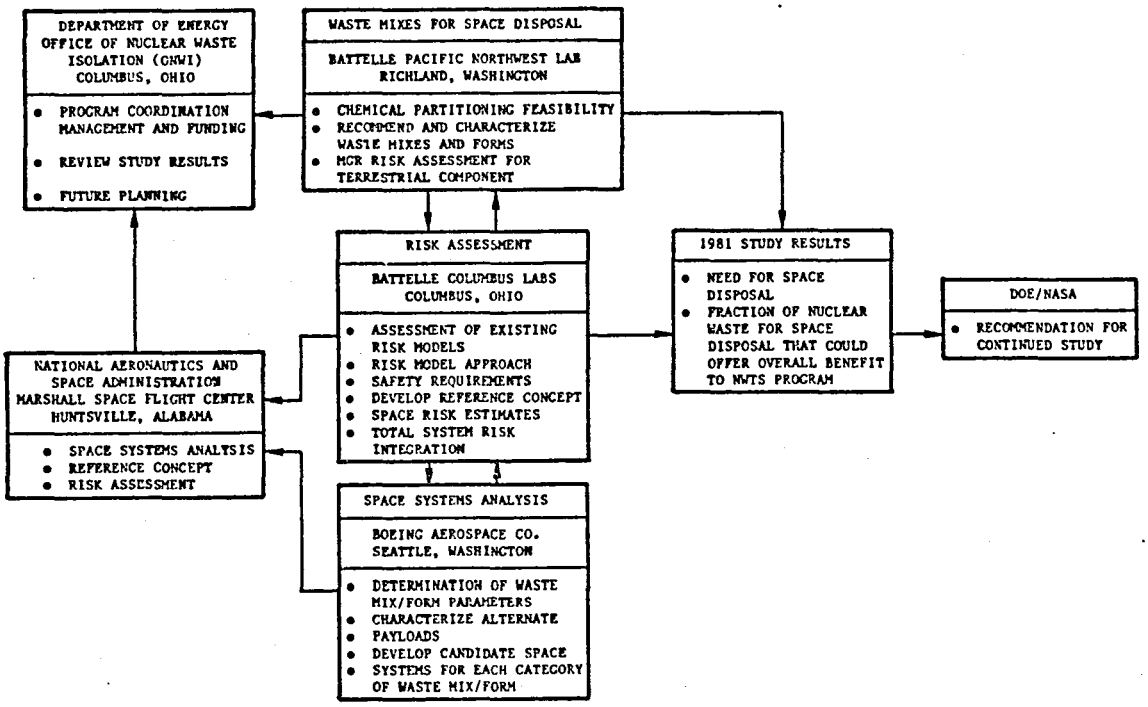

FIGURE 1. RELATIONSHIP OF STUDY TO OTHER SPACE DISPOSAL ACTIVITIES

The Department of Energy, Office of Nuclear Waste Isolation (ONWI), Columbus, Ohio, sponsored and managed the overall program. ONWI contracted with: (1) Battelle Pacific Northwest Laboratory (PNL) to perform the "Waste Mixes Study" (see McCallum et al, 1982), and (2) NASA to perform the "Risk Assessment and Space Systems Analysis Studies". Battelle Columbus Laboratories, Columbus, Ohio, with support from Science Applications, Inc., Schaumburg, Illinois, was assigned the "Risk Assessment", and Boeing Aerospace Company, Seattle, Washington, was assigned the "Space Systems Analysis" (see Reinert et al, 1982).

The following discussion provides a brief overview of the work performed during the 1981-1982 studies by the various contributors.

The Pacific Northwest Laboratory (PNL) study defined promising waste mixes for space disposal along with their appropriate waste forms. PNL characterized the physical properties of the waste mixes and forms, as well as side waste streams that are generated by processing the waste. PNL also characterized the short-term public health risks (in man-rems) of waste processing and the payload fabrication plant. Also, PNL assessed the isotopic release risk into the biosphere as a result of mined geologic repository (MGR) accidents involving natural processes (earthquakes) and human intrusion (drilling). The risks from natural events, such as an earthquake, are assumed to occur after mined geologic repository (MGR) closure and are defined as long-term risks. The information from the PNL study was input to the space systems contractor (Boeing Aerospace Company).

The Boeing study (Reinert et al, 1982) defined all the space systems required to support the waste mixes and waste forms defined by PNL. The systems were defined in accordance with safety requirements defined in this study (Battelle Columbus). Boeing assisted PNL in defining waste fabrication procerses and procedures.

The Battelle Columbus Laboratories (BCL) study effort drew upon both the PNL and Boeing studies for input data. The BCL effort included the evaluation of both long- and short-term risk of the space disposal mission, starting with the receipt of the payload package at the launch pad. BCL has integrated the PNL results with BCL results to form preliminary estimates of total system risks for disposing of certain waste mixes.

4.0 PRINCIPAL STUDY ASSUMPTIONS AND GUIDELINES

The principal assumptions and guidelines that govern the results of this study are given below:

- For the purpose of defining the waste mixes available for disposal, only high-level waste (HLW) from commercial processing of light water reactor fuels was considered.

- The Reference mined geologic repository is assumed to be in bedded salt and represented by the geology present at Paradox Basin. Terrestrial disposal data to be provided by Pacific Northwest Laboratory.

- The overall risk comparison was made by normalizing to a 100,000 metric tons of heavy metal (MTHM) repository size.

- A reprocessing rate of about 4500 MTHM per year by the year 2000 was used for the Reference case.

- Only one space disposal mission scenario and one payload design was considered for the major part of the risk analysis. Risks for disposing of alternate payloads to be estimated based upon the risks developed for the Reference mission concept.

- BCL's preliminary estimates of space disposal risk include: (1) activity phases that begin with the receipt of the payload at the launch pad and end with final delivery at the space destination; (2) consideration of events that could occur after delivery to the final destination; and (3) the assumption of wastes decaying with time.

- The preliminary BCL risk estimates are to be in terms of isotopic cumulative release to the biosphere, for the purpose of "compatible" integration of risk data.

- Risks to occupational workers are not included in the study.

- Only single-point failures for space transportation booster systems (Space Shuttle) are included in failure rates. Data to be provided by the Wiggins study (Baeker, 1981 and Hudson, 1979).

- Data on the overall space systems to be provided by the Boeing study (Reinert et al, 1982).

- Preliminary space disposal risk estimates to be provided within funding limitations for the study.

5.0 TECHNICAL SUMMARY OF SIGNIFICANT RESULTS

This section summarizes the findings of the study that are contained in total in Volume II of the final report. Section 5.0 is organized into the following subsections:

5.1 General System Safety Design Guidelines for Reference Concept

5.2 Space Disposal Concept Definition in Summary

5.3 Overall Risk Model Approach

5.4 Space Disposal Risk Estimates

5.5 Integrated Risk Benefit/Disbenefit for Waste Management Systems Complemented by Space Disposal of Nuclear Waste.

5.1 System Safety Design Guidelines for Reference Concept

One of the most important factors in the ultimate decision-making process for the space disposal concept is public health safety. For space disposal to be an acceptable approach, it is likely that the total long-term health risk of a space disposal concept coupled with terrestrial disposal must be at a comparable or preferably at a much lower level than that of terrestrial disposal of all the waste. The short-term health risk must be at an acceptable level.

Over the years of studying space disposal, a "safety concept" has been developing. Work done on safety specifications for radioisotope thermal generators (U.S. DOE, 1977) was included in the development of safety guidelines for space disposal. As a result of the current study, the safety guidelines were modified to guide Boeing's study.

The system safety guidelines for the nuclear waste disposal in space missions help to assure that nuclear waste payloads and their associated handling may be considered acceptable and radiologically safe.

The general system safety guidelines are based upon the assumption that the waste payload is carried into space by the uprated, liquid rocket boosted Space Shuttle vehicle and is processed at the launch site in a facility named the Nuclear Payload Preparation Facility (NPPF).

The general safety objectives for the nuclear waste disposal in space mission are: (1) to contain the solid radioactive waste materials, and (2) to limit the exposure of humans and the environment to the radioactive waste materials. For normal operations, complete containment and minimum radiological exposure are required. For potential accident situations, the degrees of containment and interaction shall result in an acceptable risk to humans and the environment and be as low as reasonably achievable (ALARA). Many of the

general safety guidelines have been selected using our best judgment and do not have the benefit of detailed analysis.

The general system safety guidelines for the nuclear waste disposal in space mission involve the following safety aspects:

(1) Radiation Exposure and Shielding
(2) Containment
(3) Accident Environments
(4) Criticality
(5) Postaccident Recovery
(6) Monitoring Systems
(7) Isolation.

The details of the general safety guidelines are given in Section 2.0 of Volume II of this report.

5.2 Space Disposal Concept Definition in Summary

The current Reference Concept has evolved based upon the study results of PNL (McCallum et al, 1982) and Boeing (Reinert et al, 1982) and developed further by BCL. The ground and space operations are shown in Figure 2. Aspects of the overall disposal mission are discussed below.

5.2.1 Waste Source and Mix

The primary waste source would be high-level nuclear waste generated by the operation of commercial nuclear power plants and recovered by reprocessing. The waste mix to be disposed of in space is reprocessed high-level waste (containing 0.5 percent of the plutonium and 0.1 percent of the uranium that is present in the fuel rods at the time of reprocessing) that has been out of the reactor for approximately 50 years. Also, at the time of reprocessing, 95 percent of the strontium and cesium is removed. Gases and transuranic (TRU) wastes, plus 95 percent of strontium and cesium, would go to disposal in the mined geologic repository. Plutonium would be processed out of the TRU wastes; this fraction would be added to the mix and go into space for disposal. The combination of cesium and strontium removal and the 50-year aging of the waste is needed to avoid postburial meltdown for the "Reference-sized" sphere packages flown on a given mission. (Smaller spheres or dilution of the waste form would allow the transport of 10-year-old waste.)

5.2.2 Waste Form

The Reference waste form for space disposal is the Oak Ridge National Laboratory (ORNL) iron/nickel-based cermet (ceramic/metal matrix), a dispersion of ceramic particles in a continuous metallic phase. This waste form has been chosen over others because of its expected responses to possible accident environments. The cermet is expected to have a waste loading of the order of 67.4 percent, where 100 percent is defined as high-level waste in

oxide form. The thermal conductivity is expected to be about 9.5 W/m°C, and the density is about 6.5 g/cc.

5.2.3 Payload Fabrication

The cermet waste form would be made into cylindrical billets approximately 6 cm in diameter. They would be placed into a 316 stainless steel spherical waste form support structure or core. The core has 241 parallel holes bored in it to accommodate the stacked cylindrical billets (see Figure 3). At the payload fabrication facility the billets would be installed in the core using an automatic loading machine. Covers at both ends of each bore would be installed to retain the billets. The loaded core would then be lowered into the lower half of the container/integral shield. The upper half of the integral shield would then be lowered into place and the upper and lower shield halves electron-beam welded together. Almost all of the graphite/steel "tiles" would be preinstalled on the shield halves. A "belt" around the equator would be left free of tiles to allow the electron-beam weld. Following the weld, the remaining tiles would be installed using remote handling equipment. The waste payload is then ready to be placed in a shipping cask for transport to the launch site.

5.2.4 Shipping Casks and Ground Transport Vehicles

For transport from the waste processing and fabrication facilities, the waste package would be housed in a shipping cask. The cask would be licensed by the U.S. Nuclear Regulatory Commission (NRC) and would be transported by rail to the launch site.

5.2.5 Launch Site Facilities and Operations

Upon arrival at the launch site, the waste package would be removed from the cask and placed into its flight support structure system and stored for launch.

5.2.6 Uprated Shuttle Vehicle

The Uprated Space Shuttle vehicle is defined as having oxygen/RP-1 Liquid Rocket Boosters (LRBs) replacing the Solid Rocket Boosters (SRBs). This not only provides for a 45,400-kg payload, but allows increased safety for the launch ascent phase and a lower launch cost.

5.2.7 Shuttle Derived Vehicle (SDV)

The Shuttle Derived Vehicle (SDV) would be derived from the basic Uprated Space Shuttle, where the Orbiter is replaced by the Space Shuttle Main Engine (SSME) propulsion pod and a large aerodynamic payload shroud (see Figure 2). This vehicle would be used to launch Orbit Transfer Vehicles

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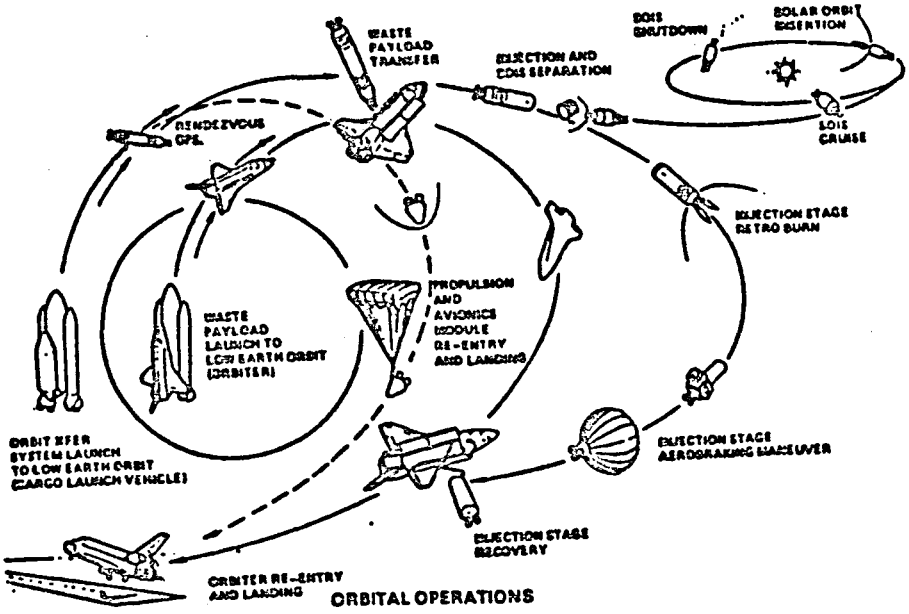
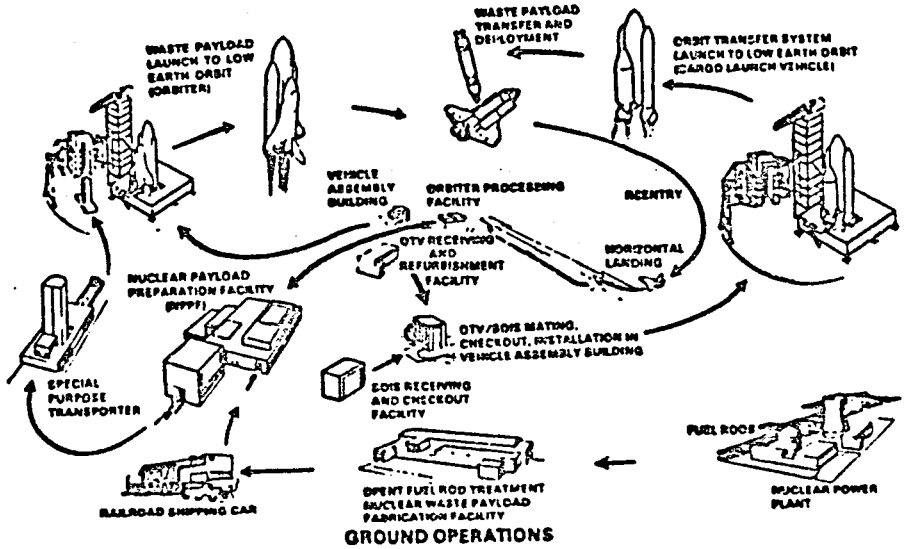


ORBITAL OPERATIONS



GROUND OPERATIONS

FIGURE 2. GROUND AND SPACE OPERATIONS FOR REFERENCE SPACE DISPOSAL MISSION

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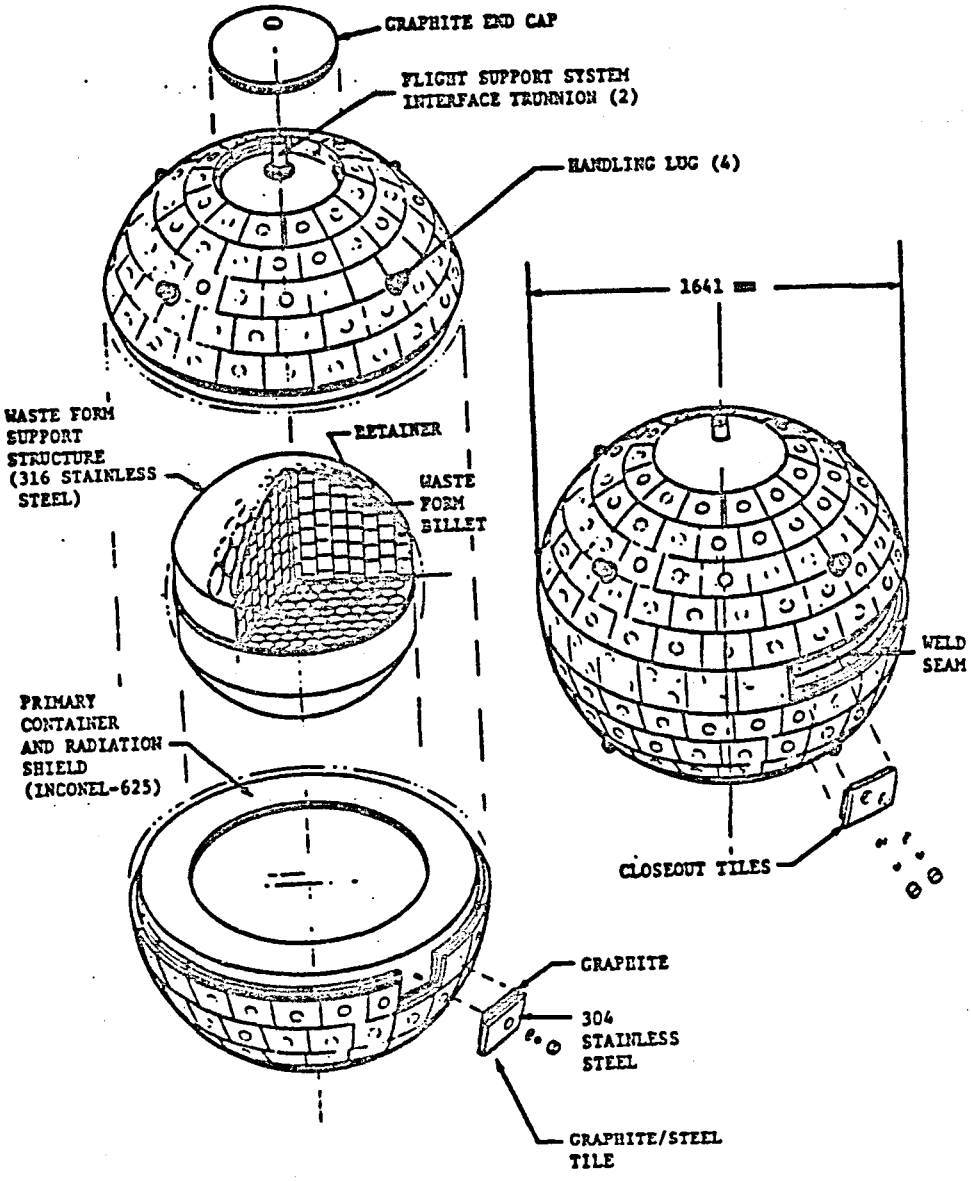

FIGURE 3. WASTE PAYLOAD PACKAGE FOR SPACE DISPOSAL

(OTVs) and the Solar Orbit Insertion Stage (SOIS) into low-Earth orbit. The vehicle would also use Liquid Rocket Boosters.

5.2.8 Orbit Transfer Vehicle and Solar Orbit Insertion Stage

The OTV would be a large hydrogen/oxygen cryogenic stage, employing current technology. The SOIS would be a cryogenic propellant vehicle with long-life subsystems.

5.2.9 Orbital Operations

The SDV would be launched first to place the OTV/SOIS on orbit (38 degrees, 370 km). Two waste packages would then be launched by the Uprated Space Shuttle to rendezvous with the OTV/SOIS. The OTV/SOIS would then dock with the payload in the cargo bay of the shuttle Orbiter. The payload package would be removed, and the OTV/SOIS would carry out the proper maneuvers to deliver the payload package to its destination. The OTV would be recoverable. The expendable SOIS would provide the velocity increment at perihelion (0.85 A.U.) needed to circularize the solar orbit.

5.2.10 Space Destination

The space destination for the Reference Concept is the orbital region between the orbits of Earth and Venus. The nominal circular orbit is defined as 0.85 $\pm$ 0.01 A.U., with a 1-degree inclination from the ecliptic plane.

5.3 Overall Risk Model Approach

The overall risk model approach that has been developed for the current study is to estimate the nonrecoverable, cumulative, expected radionuclide release in curies to the Earth's biosphere for different options of the disposal of nuclear waste.

The risk estimates for the disposal of the waste in a mined geologic repository (MGR) are based upon analyses of accident sequences performed by Battelle Pacific Northwest Laboratory (McCallum et al, 1982). The space risk estimates were developed by Battelle Columbus Laboratories.

Although it would have been preferable to represent the consequences of accidental releases in terms of direct health effects to the human population, funding limitations did not permit this level of analysis. Instead, the consequences of accidents are characterized in terms of the release of radionuclides in curies to the biosphere (air, ground, and sea). In those cases where release might occur from the waste package, but for which cleanup operations would be anticipated (in the near term), credit was taken for the recovery of material.

Four sets of radionuclide groups have been selected to illustrate the results: (1) the sum of 15 important long-lived radionuclides (as given in the draft EPA release limit guidelines - see U.S. EPA, 1981), (2) the sum of important actinide elements (AC), (3) Tc-99, and (4) I-129. The time span considered in the study is one million years. Not only could events occur at various times in the future, the release of radioactive material to the biosphere could be distributed over extended time periods following an accident. In the presentation of the results, the expected release rate of radionuclides is integrated over time to obtain the cumulative expected release in curies, and this integral is plotted versus time. Short- and long-term risks are provided in the same figures.

For comparative purposes, the risks from (1) the Reference MGR, (2) the MGR complemented for each space disposal option without space disposal accidents, and (3) accidents directly associated with space disposal are each displayed separately. By adding the space disposal risk to the complemented MGR risk and comparing the reference case, the potential benefits/disbenefits of the space waste disposal options could be determined.

5.4 Space Disposal Risk Estimates

This section briefly describes the approach used to estimate the rate of space disposal. Details are provided in Volume II. The basic approach to determining preliminary estimates of space disposal release risk, as defined in Section 5.3, was developed by considering what would be the most cost-effective method (because of limited funding for this effort). Basically the approach used drew on: (1) past data bases developed for space disposal (Pardue et al, 1977; Edgecombe et al, 1978; and Rice et al, 1980a); (2) Space Transportation System (STS) failure rates developed by the Wiggins Company (Baeker, 1981; Hudson, 1979); (3) previous works by A. Friedlander on long-term risk (see Rice et al, 1980a); (4) expert opinion where easily obtainable; (5) new response analysis, where practical; (6) engineering estimates; and (7) technical data provided by Boeing (Reinert et al, 1982). The desired format for "space risk" was determined by the format developed by McCallum et al (1982) for geologic disposal, both the Reference case and the various "complemented" cases. The major goal was to develop "space risk" in terms of probabilistic cumulative releases (unrecoverable) to the biosphere from launch through to one million years. It was assumed that short-term risks could be mitigated by accident recovery and rescue, although these would not always be either successful or complete. For longer time frames (beyond 100 years after launch), recovery and rescue were not included in the analysis. Figure 4 provides an overview of the approach used for estimating space disposal risks.

5.4.1 Space Accident Identification

Accidents that involve the nuclear waste payload were the only ones considered. Previous analyses (Edgecombe et al, 1978) presented a list of possible accidents for a space disposal mission. Since that work and other follow-on work (Rice et al, 1980a) have been completed, significant changes in the Reference space disposal concept have been made (see current summary of

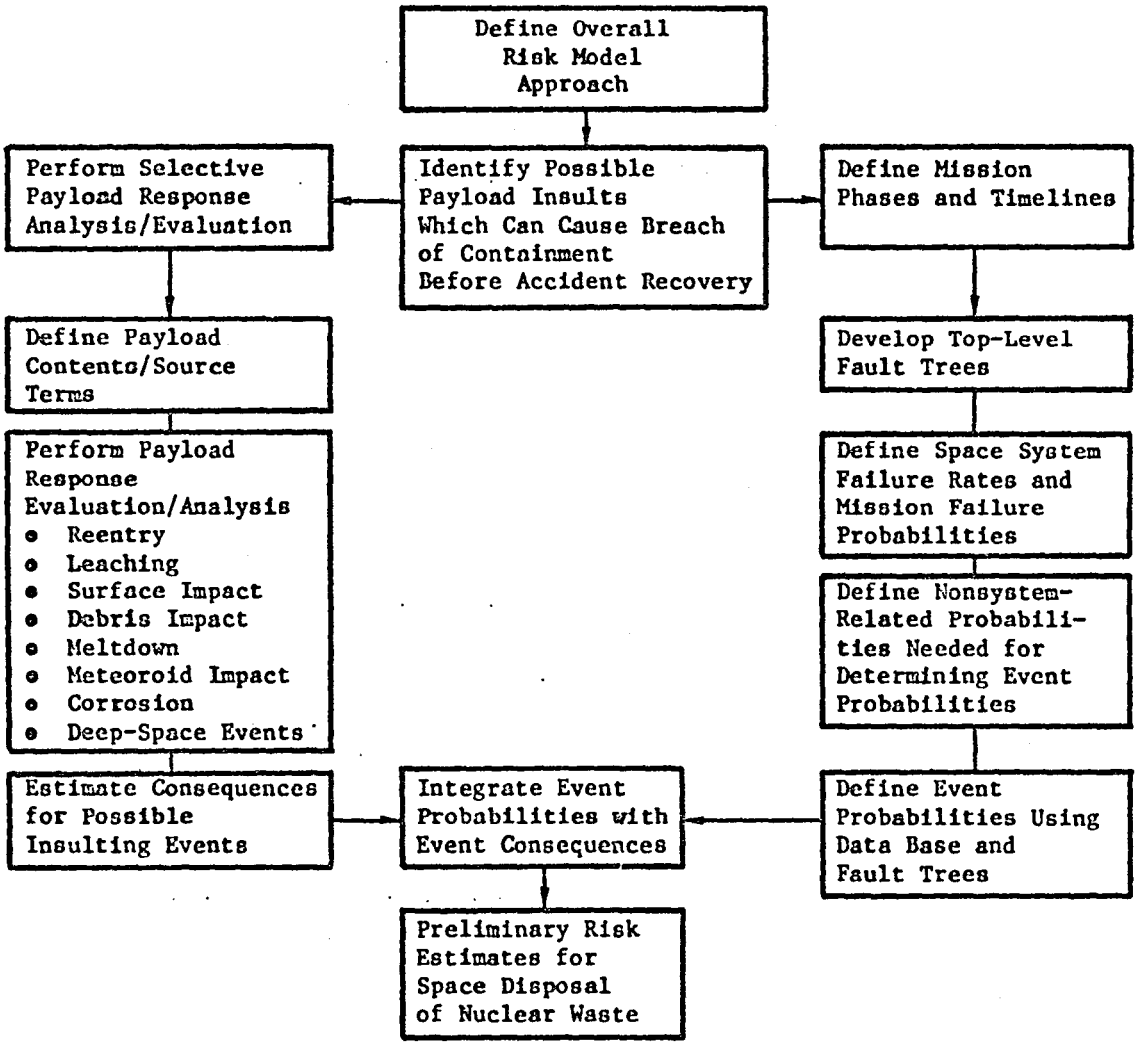

FIGURE 4. APPROACH FOR ESTIMATING SPACE DISPOSAL RISK

Reference Concept, Section 5.2). Because accidents involving the release of radioactive material are the only ones of current interest, many previously studied accidents/events involving the payload have not been included here.

Table 1 provides a summary of the possible insults to the currently defined Reference nuclear waste payload. The probability of occurrence of the events listed was not considered in the construction of this table. This list of possible insults to the payload was used to define the events that could lead to breach of containment during and after launch. This is discussed further in the next section.

5.4.2 Mission Phase and Fault Tree Development

After the list of possible payload insults was developed (see Table 1) the space disposal mission was divided up into mission phases which allowed the treatment of certain types of accidents. This was necessary because the character of accidents changed with the time during the mission. The payload altitude and velocity, instantaneous impact point location, potential for damage by STS explosion, potential reentry velocity, and the potential for deep-space events are constantly changing throughout the mission.

Previous study results (Rice et al, 1980a) have indicated that an on-pad accident involving the catastrophic failure of the launch vehicle [Uprated (LRB) Space Shuttle] will not result in a breach of the current Reference payload concept. Environments considered include: (1) the on-pad fireball, (2) on-pad residual propellant fire, (3) blast overpressure, (4) fragment impact, and (5) hard surface impact. Intact aborts (non-catastrophic) have been eliminated from consideration here, as well as Orbiter crash landings (total recovery anticipated for this event). Payload impacts onto chemical, munitions, or steel plants have also been eliminated because it is believed that their probability is very small and that the payload would not be insulted by the chemical or thermal environment, that it would "fly through it" and end up below it in the ground.

The phases and timelines for the disposal mission are listed in Table 2. The timelines were developed from data presented in the Boeing report (Reinert et al, 1982).

The fault tree analysis method was selected as most appropriate for use in this study. Application of the technique yields combinations of basic events whose occurrences cause the undesired failure events (containment breaches). These event combinations can then be evaluated by various screening techniques to determine the high-risk scenarios and their probability of occurrence. The fault trees allowed the generation of the required probability information about all of the individual failures or events. A sample fault tree (for Phase 1) is given in Figure 5. Data for the fault trees are given in detail in Volume II and are not discussed further here.

TABLE 1. POSSIBLE INSULTS TO THE SPACE DISPOSAL PAYLOAD

Impact	Melting	Corrosion
On Ground	**On Ground**	**On Ground**
• Rock • Man-Made Structures • Soils • Ice • Water • Explosion Fragments	• Impact Related - Insulation ($K < K_{limit}$) - Certain Soils - Certain Minerals • Volcano • Chemical Plant/Storage • Tank Farm • Processing Furnaces • On-Pad Accident/Fire	• Aqueous - Fresh Water - Ocean Water - Severe (Brines, H_2S, etc.) - Reducing • Nonaqueous - Salt Beds • Special - Chemical Plant/ Storage • Soils
In Space	**In Flight**	**In Space**
• Meteoroids • On-Orbit Debris • On-Orbit Vehicles • Celestial Bodies • Other Waste Payloads • Explosion Fragments • Comet	• Reentry - Intact - Damaged - Aged/Degraded - Fragmented	• Sputtering/Erosion

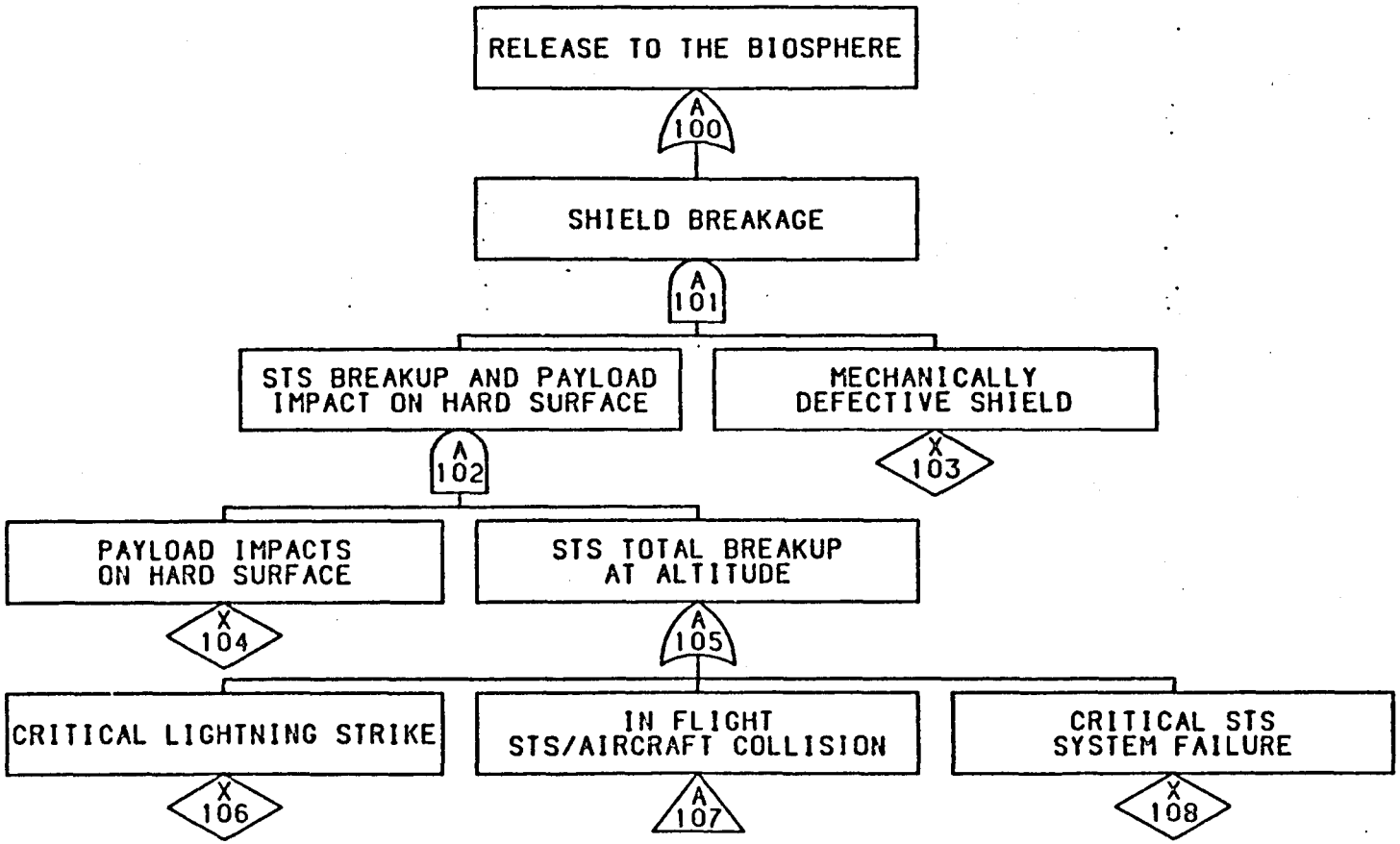

FIGURE 5. PHASE 1 FAULT TREE: IGNITION TO IMPACT POINT CLEARS COASTLINE (T = 0 to 24 s)

TABLE 2. MISSION PHASE AND TIMELINE DEFINITION

Phase Number	Description	Timeline, s[a]
1	Ignition to Impact Point Clears Land	0-24
2	Clear Land Impact to LRB Staging	24-124
3	LRB Staging to MECO[b]	124-518
4	MECO to LEO[b] Orbit Attainment	518-2,734
5	LEO Orbit Attainment to OTV Ignition	2,734-35,024
6	OTV Ignition to Earth Escape	35,024-36,926
7	Earth Escape to OTV Shutdown	36,926-37,005
8	SOIS Coast Through SOIS Burn	37,005-14,295,107
9	Placement	14,295,107-3.15E13

(a) Data derived from Boeing study (Reinert et al, 1982).
(b) MECO is main engine cutoff; LEO is launch-to-Earth orbit.

5.4.3 Payload Response Analysis

Various payload response analyses were needed to verify the expected response of the nuclear waste payload to certain accident environments. Emphasis was placed on areas where it was felt that easy answers could be provided and where accidents, should they occur, were expected to play a predominant role in the risk estimate for space disposal.

Response analysis was conducted for the reentry of the payload under various possible accident conditions. The Battelle RETAC Code was employed. The resulting data were used to estimate releases.

The DYNA2D computer code was used to model (under very simplified and conservative assumptions) the impact of the payload on hard granite. The results were reflected in the release risk estimates.

Various corrosion, leaching, and thermal analyses were also conducted and used to support the estimated risk estimates.

5.4.4 Preliminary "Space" Risk Estimates

Based upon the fault tree and payload response analyses, the risk for space disposal was estimated. Table 3 provides a summary of the probabilities and fractional releases for possible accident events for space disposal. The basis for the fractional release data is described in the right-hand column of the table.

TABLE 3. SUMMARY OF SPACE ACCIDENT CONSEQUENCE ESTIMATES FOR REFERENCE CONCEPT

Event	Expected Probability (750 missions)	Release to Biosphere	Basis
1. Long-Term Corrosion, Ocean	8.2E-6	Total (ocean)	After Corrosion and Leaching
2. Hard Rock Impact	8.3E-3	5E-6 Fraction (atmosphere)	RTG[b] Release Data, Remainder Recovered
3. Impact on Volcano	8.2E-12	Total (volcano/lava)	External Melt Expected
4. Soil Meltdown	1.1E-12[a]	Zero	Event Physically Impossible
5. Meteorite/Debris Impact	1.1E-8	Total (atmosphere)	Burn Up Expected if Reentry Occurs
6. Long-Term Corrosion, Soil	3.2E-7	Total (wet soil)	After Corrosion and Leaching
7. High Velocity on Water	4.7E-7	Total (ocean)	After Leaching
8. High Velocity on Rock	3.6E-7	5E-4 Fraction (atmosphere)	100 x Event 2, Remainder Recovered
9. High Velocity on Soil	1.6E-6	1E-3 Fraction (soil)	200 x Event 2, Remainder Recovered
10. Deep-Space Critical Meteoroid Impact	1.8E-4	Partial	Long-Term Integration
11. Long-Term Payload Return from Deep Space	--	Total	Long-Term Integration

(a) This probability relates to safety limits as defined in General Safety Guidelines, Section 5.1; probability associated with meltdown much lower and practically impossible to contemplate.
(b) RTG is radioisotope thermal generator.

Figures 6 and 7 provide the results of the space risk study. Considerable uncertainty exists in the data. The accomplishment of a Monte Carlo analysis needed to help define uncertainty was beyond the scope of this study. However, based upon mathematically carrying through the high- and low-probability data and estimated uncertainty in source terms, we believe there are at least two orders of magnitude on either side of the "expected" space risk data. Section 5.5 discusses the integration of this risk with the terrestrial disposal risk to form the total system release risk values for space disposal.

5.5 Integrated Risk Benefit/Disbenefit for Disposal System Complemented by Space Disposal of Nuclear Waste

This section integrates the results of both the PNL and BCL release risk assessments for the total nuclear waste disposal systems considered in the current year study program. Risk is defined as cumulative curies released to the accessible environment (what we refer to as the "biosphere"). The terrestrial disposal risk is comprised of the following components: (1) expected waste-processing releases to the biosphere, (2) probabilistic waste releases to the biosphere via a fault event, and (3) probabilistic waste releases to the biosphere due to a drilling scenario. The space disposal risk is comprised of probabilistic releases to the biosphere resulting from credible accidents that can occur from the launch pad to the final destination. Space accidents include:

- Long-term corrosion in the ocean and in wet soil
- Hard rock impact
- Volcano impact
- Meteoroid/debris impact
- High-velocity impacts on soil, rock, and water
- Deep-space meteoroid impacts
- Deep-space payload return over the long term.

Based upon the data in Sections 5.0 and 6.0 of Volume II, we will discuss and compare the various cumulative release risk contributions for the noncomplemented MGR (no space disposal) and the space-complemented MGR systems. The approach for discussing the integrated risk is as follows. For the five scenarios listed below, the risk of the noncomplemented MGR will be discussed first, followed by the complemented MGR risk, assuming that an "ideal" or "zero" risk disposal system could handle the waste removed from the complemented MGR. Then, the total integrated risks (complemented MGR plus space risk) for each scenario will be compared to the noncomplemented MGR. Potential risk benefits or disbenefits based upon the available data will be discussed.

These five scenarios are considered and discussed:

(1) The cumulative release risk for the sum of the 15 EPA isotopes (see McCallum et al, 1982) for HLW disposal in space

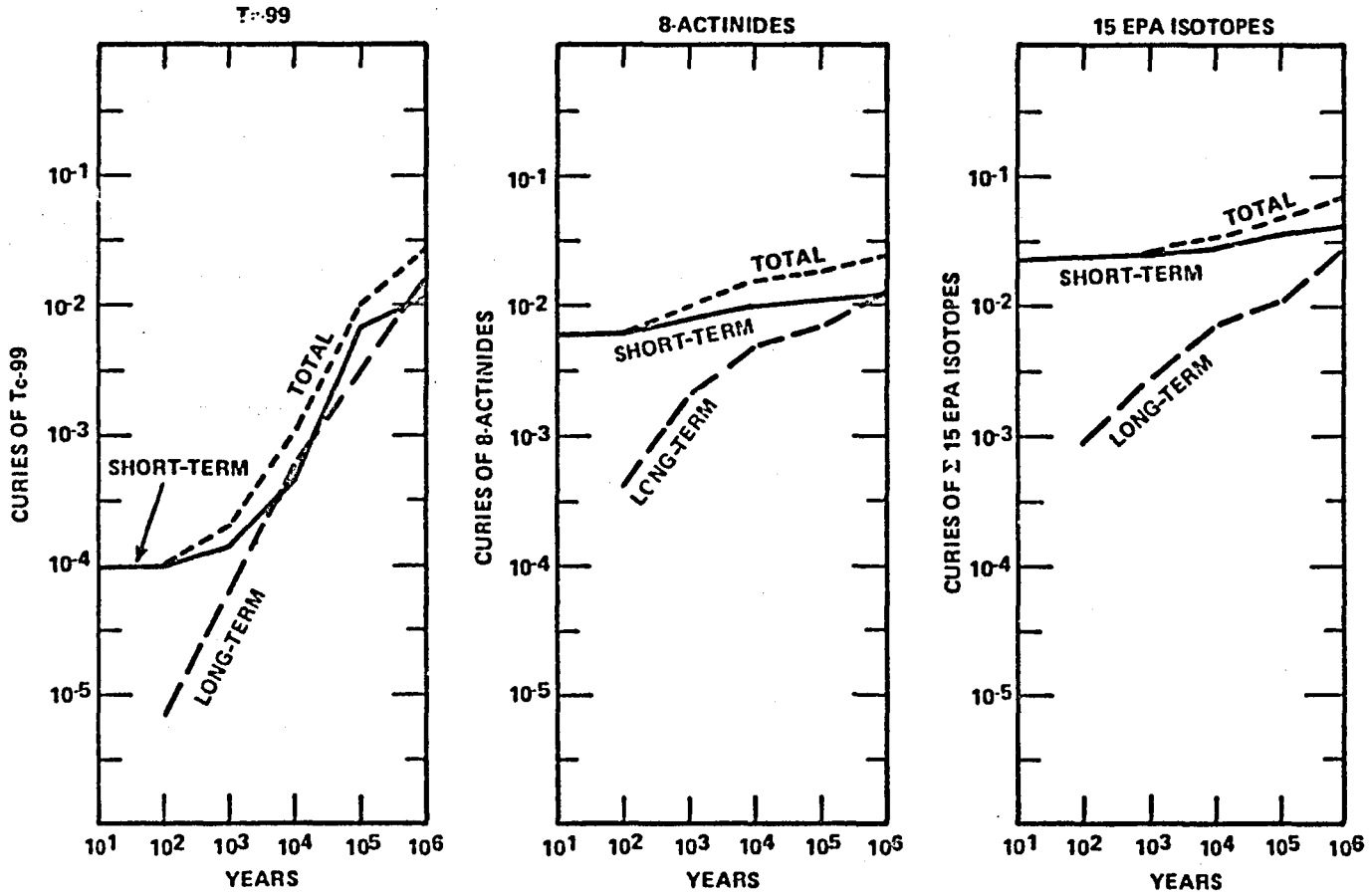

FIGURE 6. EXPECTED CUMULATIVE SPACE RISK COMPARISON FOR HLW DISPOSAL IN SPACE

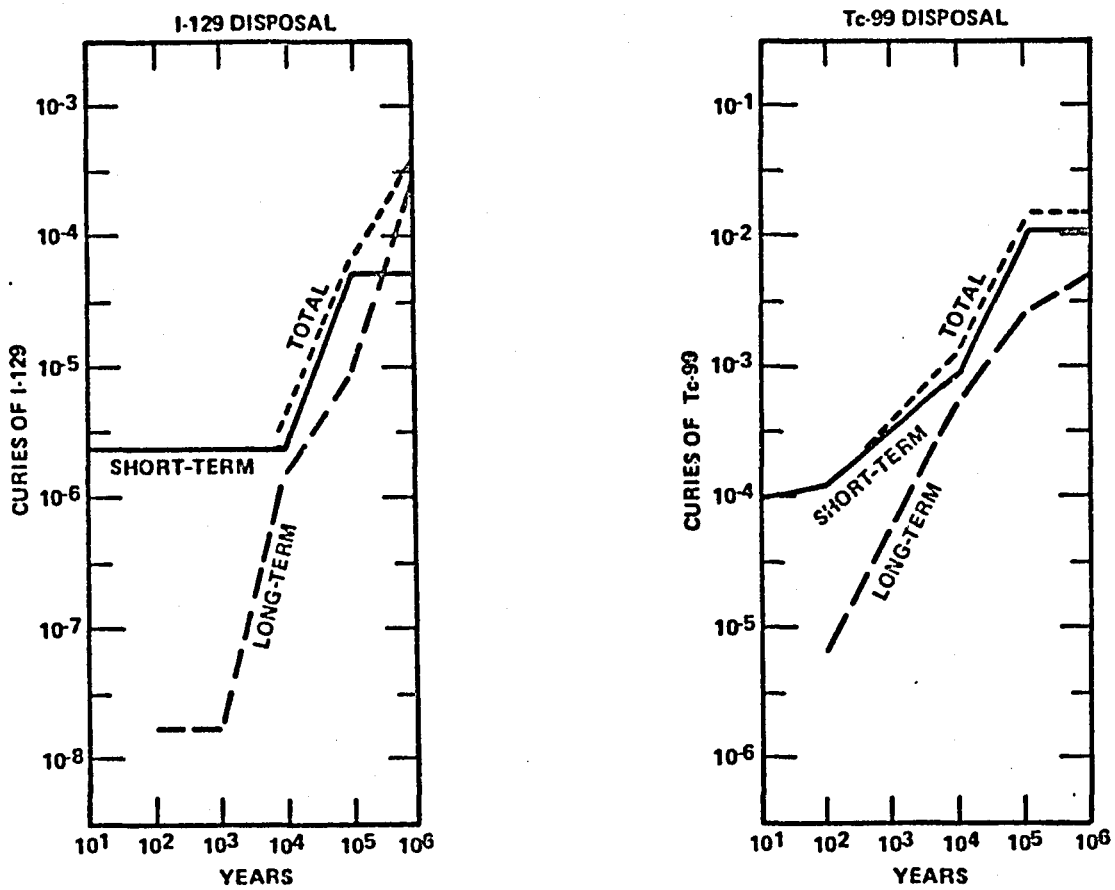

FIGURE 7. EXPECTED CUMULATIVE SPACE RISK COMPARISONS FOR I-129 AND Tc-99 DISPOSAL IN SPACE

(2) The cumulative release risk for the sum of eight actinides (see McCallum et al, 1982) for HLW disposal in space

(3) The cumulative release risk of Tc-99 for HLW disposal in space

(4) The cumulative release risk of I-129 for I-129 disposal in space

(5) The cumulative release risk of Tc-99 for Tc-99 disposal in space.

The integrated results are depicted in Figures 8 through 12. A summary of related findings is presented below.

Based Upon Data Derived in the PNL Study

(1) The risk to future populations from the mined geologic disposal of radioactive waste appears to be extremely small.

(2) In terms of curies released, the escape of fission products during normal reprocessing would be expected to be as large as the total amount released (due to a natural fault or human intrusion) over the subsequent one million years.

(3) The release of actinide elements dominates the escape of radionuclides over the expected period of possible human intervention (drilling events) in the MGR.

(4) The release of Tc-99 appears to dominate the escape of radionuclides in MGR seismic events. Actinide releases are expected to be small.

(5) Since some radioactive material would be disposed of in an MGR for each of the space disposal options examined, space disposal could reduce but not eliminate this element of risk. For some radionuclides, the additional waste processing required for space options would actually increase the waste-reprocessing component of the risk.

(6) The potential for risk benefit is limited by the degree of separation and release in waste processing and the inclusion of TRU wastes in the MGR.

(7) Current technology indicates that there is no potential for release risk benefit for the space disposal of I-129. Potential exists for Tc-99 and the actinides for current waste-processing technology.

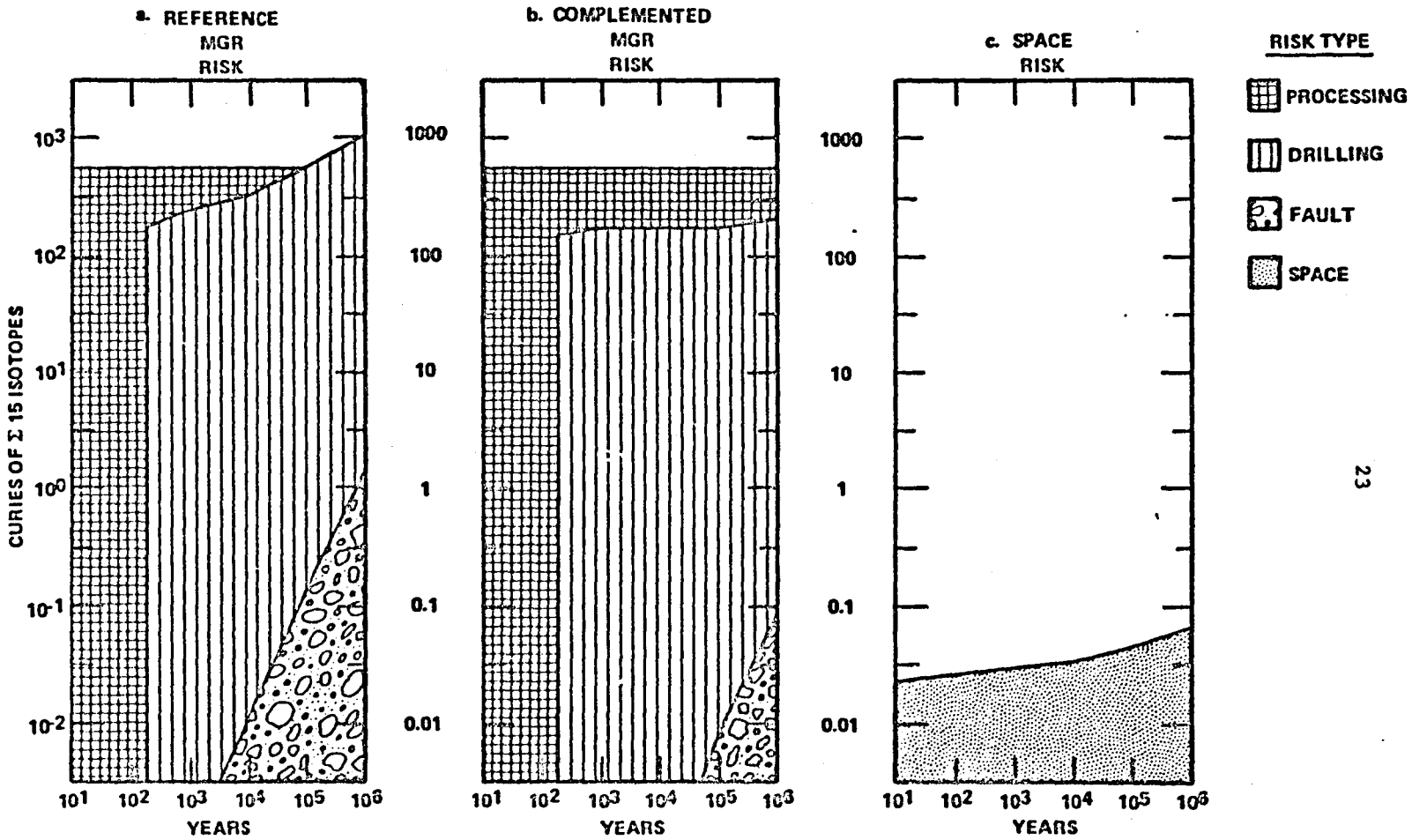

FIGURE 8. INTEGRATED EXPECTED CUMULATIVE RELEASE RISK COMPARISONS (IN CURIE SUM OF 15 EPA ISOTOPES) FOR HLW DISPOSAL IN SPACE

BATTELLE — COLUMBUS

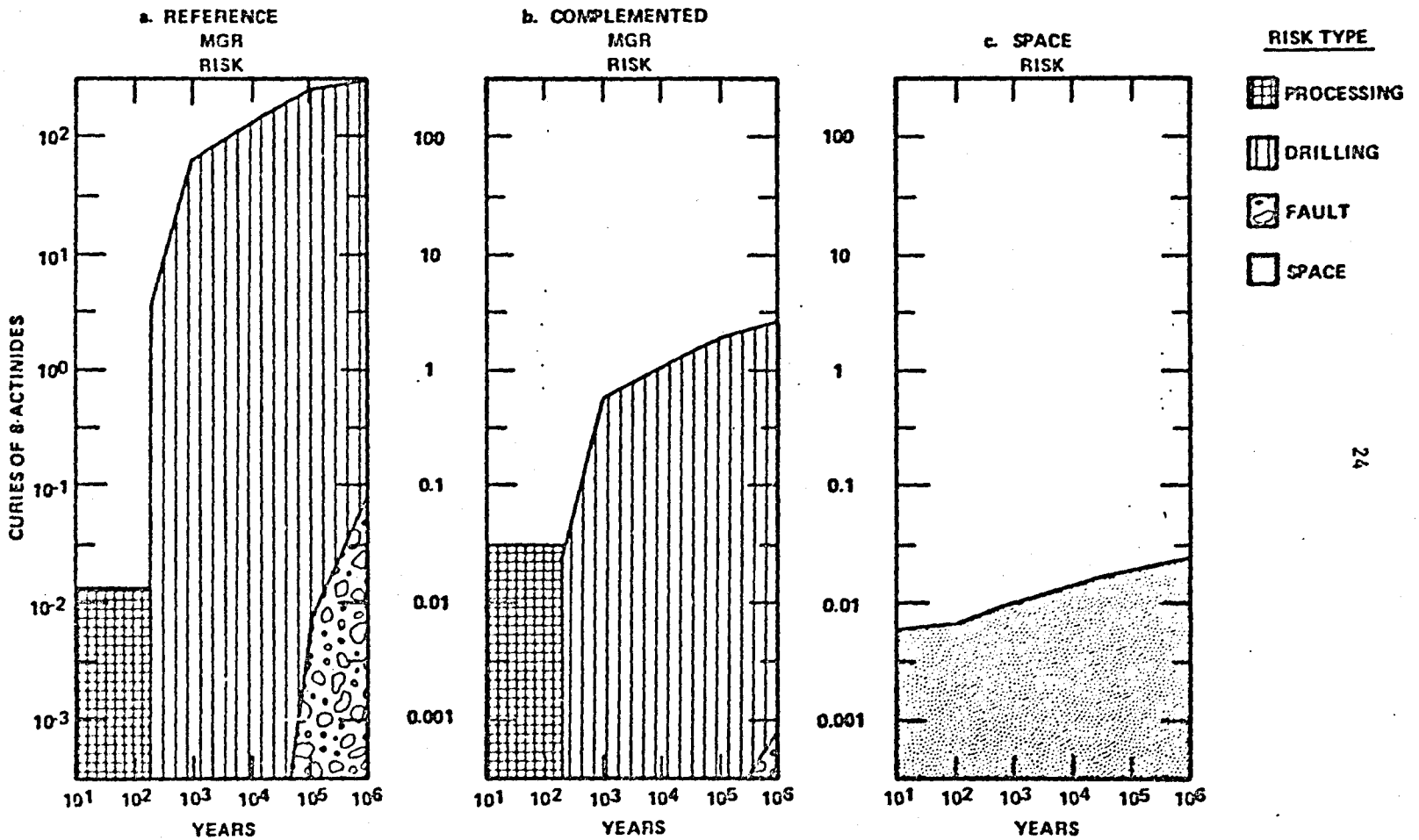

FIGURE 9. INTEGRATED EXPECTED CUMULATIVE RELEASE RISK COMPARISONS (IN CURIE SUM OF EIGHT EPA ACTINIDES) FOR HLW DISPOSAL IN SPACE

BATTELLE — COLUMBUS

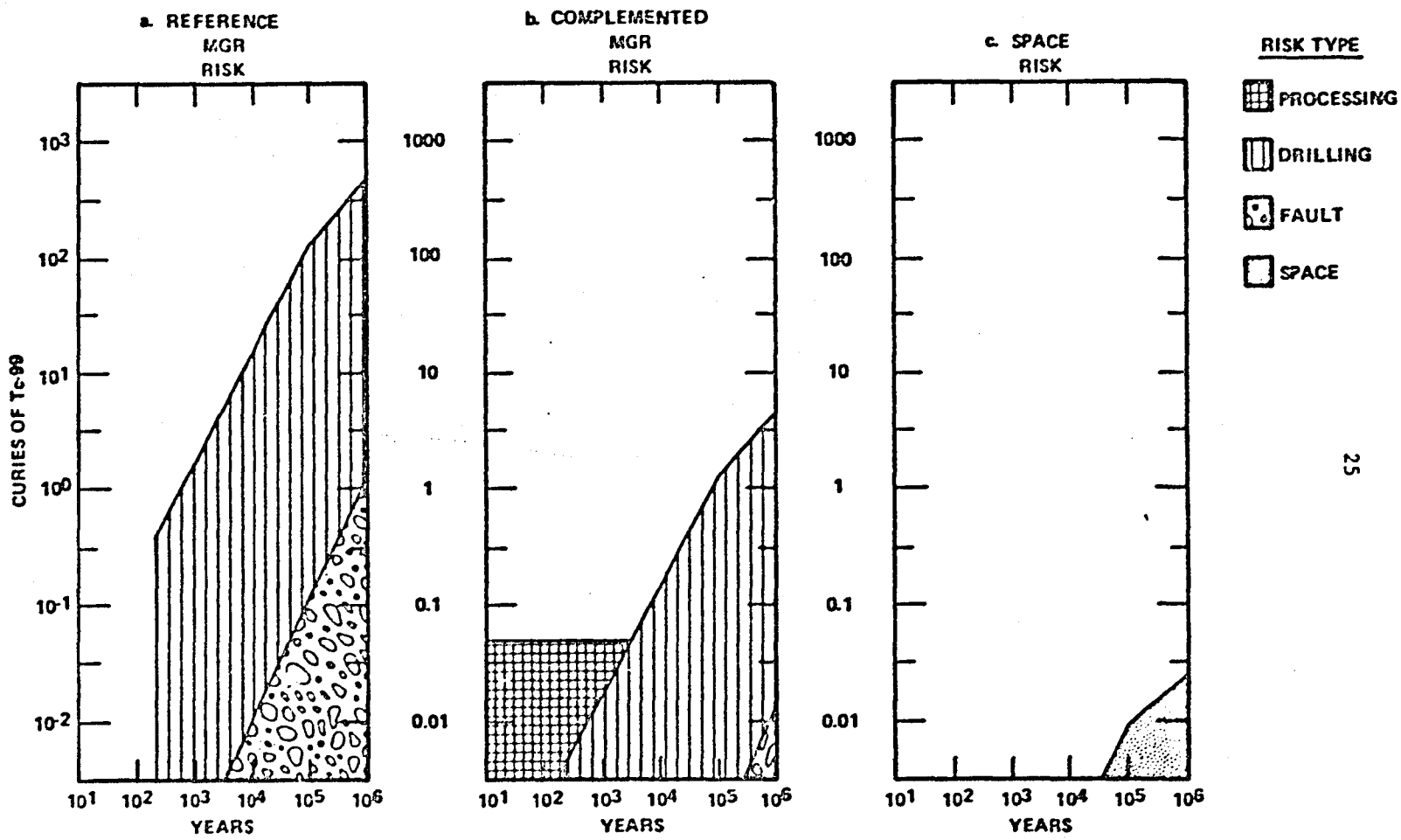

FIGURE 10. INTEGRATED EXPECTED CUMULATIVE RELEASE RISK COMPARISONS (IN CURIES OF Tc-99) FOR HLW DISPOSAL IN SPACE

BATTELLE - COLUMBUS

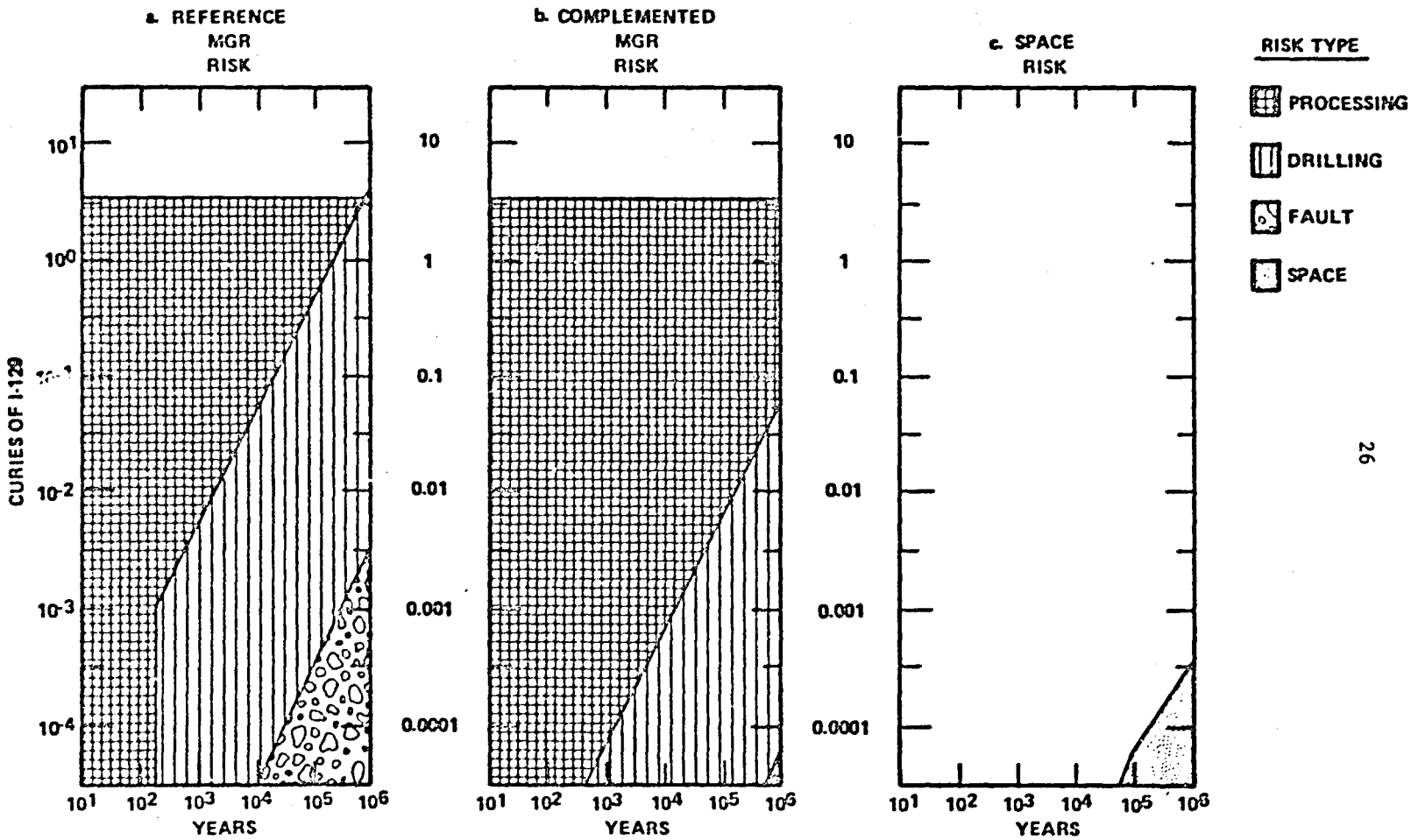

FIGURE 11. INTEGRATED EXPECTED CUMULATIVE RELEASE RISK COMPARISONS (IN CURIES OF I-129) FOR I-129 DISPOSAL IN SPACE

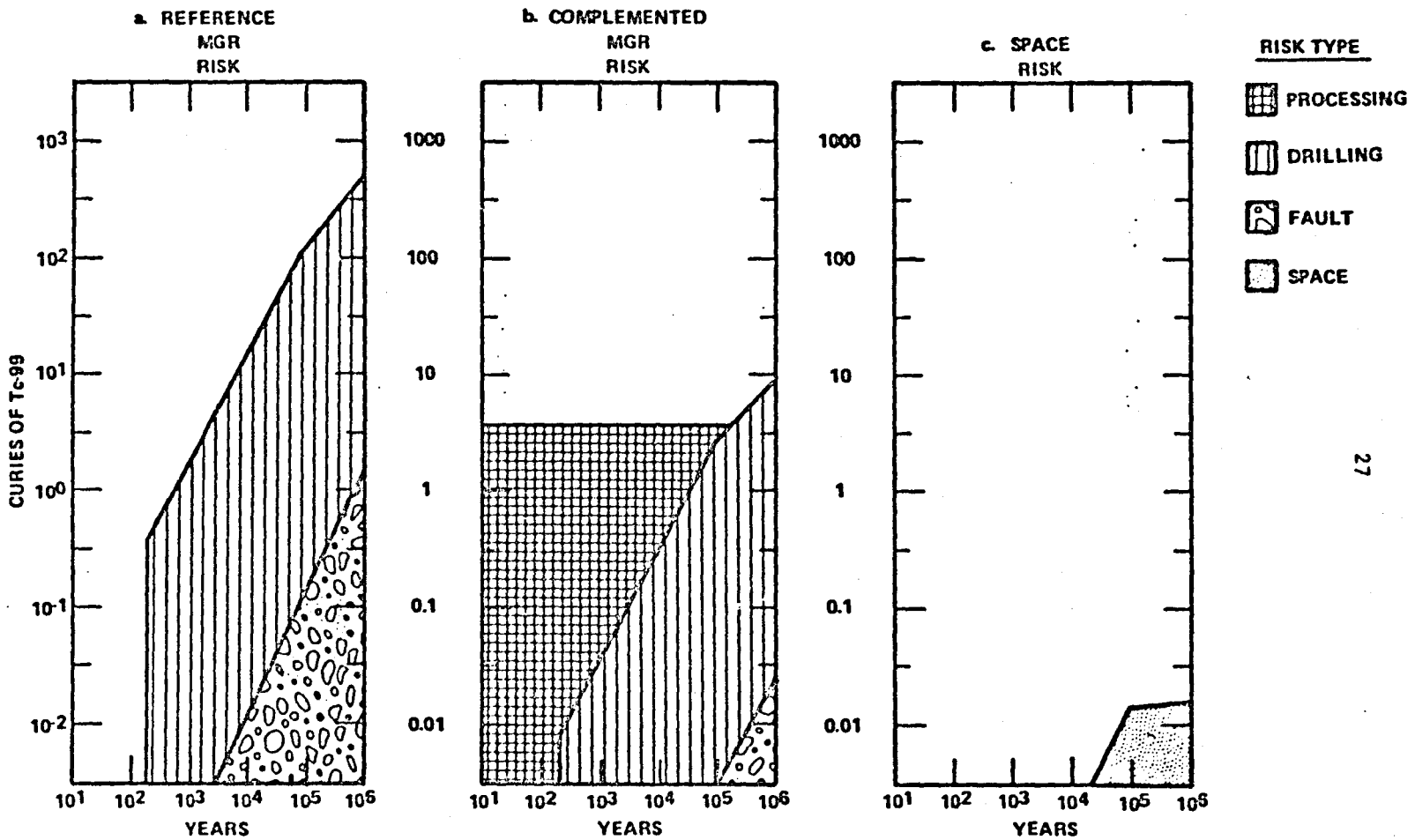

FIGURE 12. INTEGRATED EXPECTED CUMULATIVE RELEASE RISK COMPARISONS (IN CURIES OF Tc-99) FOR Tc-99 DISPOSAL IN SPACE

BATTELLE — COLUMBUS

Based Upon BCL Preliminary Space Risk Estimates

(8) The risk of space disposal appears to be very small.

(9) Short-term space disposal release risk (space component) is dominated by payload reentry, impact on hard rock, and complete breakup and reentry due to direct meteoroid/payload or debris/payload collisions.

(10) Long-term release risk (space component) is dominated by the failure to locate reentered payloads in the ocean, intact payload return from deep-space after rescue attempts fail, and small particle return after deep-space meteoroid collisions.

(11) Short-term accident events dominate the space risk component, but not by much (well within any uncertainty band).

(12) An uncertainty analysis was not possible under the scope of this study; however, the uncertainty for the space disposal risk is believed to be within two orders of magnitude of the expected value.

(13) From examination of the release risk for space disposal (space component), it is evident that a few contributors to the risk would be very difficult to reduce (e.g., meteoroid impact); however, most of the risk contributors can be controlled by proper design.

Based Upon Integrated PNL/BCL Risk Data

(14) Ignoring probabilities, no single accident event examined in the study, for either space disposal or mined geologic disposal, would be catastrophic in terms of an immediate threat to a large number of human lives or an extensive impact on the environment.

(15) Although space disposal appears to offer some potential for reduction in risk, it should be recognized that the uncertainties in the risk estimates are large and that the predicted risk of mined geologic disposal is extremely small to begin with.

(16) The results of this study only indicate possible benefits/disbenefits of space disposal. To obtain more realistic and meaningful results, pathway models resulting in dose estimates are needed.

6.0 CONCLUSIONS

This section summarizes three major conclusions that come from this preliminary risk assessment of nuclear waste disposal in space:

(1) Preliminary estimates of space disposal risk are low, even with the estimated uncertainty bounds.

(2) If calculated MGR release risks remain low, as given in the PNL Waste Mixes Study (McCallum et al, 1982), and the EPA requirements continue to be met, then no additional space disposal study effort is warranted.

(3) If risks perceived by the public are significant in the acceptance of mined geologic repositories, then consideration of space disposal as an MGR complement is warranted.

7.0 RECOMMENDATIONS

As a result of this study, the following recommendations are made to NASA and the U.S. DOE:

(1) During the continued evaluation of the mined geologic repository risk over the years ahead by DOE, if any significant increase in the calculated health risk is predicted for the MGR, then space disposal should be reevaluated at that time.

(2) The risks perceived by the public for the MGR should be evaluated on a broad basis by an independent organization to evaluate acceptance.

(3) If, in the future, MGR risks are found to be significant due to some presently unknown technical or social factor, and space disposal is selected as an alternative that may be useful in mitigating the risks, then the following space disposal study activities are recommended:

- Improvement in chemical processing technology for wastes
- Payload accident response analysis
- Risk uncertainty analysis for both MGR and space disposal
- Health risk modeling that includes pathway and dose estimates

- Space disposal cost modeling
- Assessment of space disposal perceived (by public) risk benefit
- Space systems analysis supporting risk and cost modeling.

APPENDIX A
REFERENCES

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REFERENCES

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APPENDIX B

ACRONYMS AND ABBREVIATIONS

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ACRONYMS AND ABBREVIATIONS

AC - actinide elements
ALARA - as low as reasonably achievable
A.U. - astronomical unit
BCL - Battelle Columbus Laboratories
COR - contracting officer's representative
DOE - U.S. Department of Energy
EPA - U.S. Environmental Protection Agency
HLW - high-level waste
JSC - NASA's Johnson Space Center, Houston, Texas
KSC - NASA's Kennedy Space Center, Florida
LEO - low Earth orbit
LRB - Liquid Rocket Booster
MECO - Main Engine cutoff
MGR - mined geologic repository
MSFC - NASA's Marshall Space Flight Center
MTHM - metric tons of heavy metal
NASA - National Aeronautics and Space Administration
NPPF - Nuclear Payload Preparation Facility
NRC - U.S. Nuclear Regulatory Commission
NWTS - DOE's National Waste Terminal Storage Program
ONWI - Office of Nuclear Waste Isolation (DOE's)
ORNL - Oak Ridge National Laboratories
OTV - Orbit Transfer Vehicle
PNL - Pacific Northwest Laboratories
SAI - Science Applications, Inc., Schaumburg, Illinois
SDV - Shuttle Derived Vehicle
SOIS - Solar Orbit Insertion Stage
SRB - Solid Rocket Booster
SSME - Space Shuttle Main Engine
STS - Space Transportation System
TRU - transuranic waste

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