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VOLUME I

EXECUTIVE SUMMARY OF TECHNICAL REPORT

ON

ANALYSIS OF NUCLEAR WASTE DISPOSAL IN SPACE--PHASE III

TO

NATIONAL AERONAUTICS AND
SPACE ADMINISTRATION
MARSHALL SPACE FLIGHT CENTER
(Contract Number NAS8-32391)
DPD No. 580, DR No. 4

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Eric E. Rice
E. E. Rice, Program Manager
Battelle's 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

BATTELLE - COLUMBUS

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FOREWORD

The study summarized in this report is a part of an ongoing analysis to determine the feasibility and preferred approaches for disposal of selected high-level nuclear wastes in space. The Battelle Columbus Laboratory (BCL) study is an integral part of the ongoing 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 NASA Marshall Space Flight Center (MSFC); Science Applications, Inc. (SAI--under subcontract to Battelle and reported here); Battelle's Human Affairs Research Centers (HARC); Bechtel National, Inc.; and Oak Ridge National Laboratory (ORNL). The research effort reported here (Phase III) was performed by Battelle's Columbus Laboratories (with SAI being a subcontractor for Task 4) under NASA Contract NAS8-32391 from June 1979 through March 1980. The study objective was to provide NASA and DOE with additional technical data and information in specialized areas as a basis for developing space disposal concept definitions, requirements, and program plans.

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: PS04
Huntsville, Alabama 35812
Telephone: (205) 453-2769

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

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1.0 INTRODUCTION

This volume provides a brief summary of the work performed during the 1979-1980 Phase III Battelle Columbus Laboratory (BCL) study of nuclear waste disposal in space. This volume summarizes the following: study objectives, approach, assumptions and limitations; the relationship to nuclear waste disposal in space to other NASA and DOE efforts; the basic technical data and results derived from the study (contained in detail in Volume II); implications for research and technology, and finally, suggested additional effort. Appendix A provides definitions of acronyms and abbreviations used in this volume. Appendix B gives metric to English unit conversion factors. References are listed in Appendix C.

2.0 STUDY OBJECTIVES

The overall objective for the 1979-1980 Phase III BCL study was to provide NASA and DOE with additional technical data and information in specialized areas as a basis for developing space disposal concept definitions, requirements, and program plans. To accomplish this overall study objective the study was broken down into five major study areas, each having its own objectives. These objectives are defined below for each study task:

- Payload Characterization (Task 1)
  - Select a new improved waste form
  - Define commercial and defense waste payloads
  - Define containment requirements
  - Conduct parametric shielding and thermal analysis
  - Define waste processing and payload fabrication systems

- Safety Assessment (Task 2)
  - Perform literature review of space nuclear safety aspects
  - Define major accidents environments for the reference and advanced concepts
  - Perform limited payload accident response analysis (commercial waste)
  - Perform preliminary safety assessment of HLLV (commercial waste)

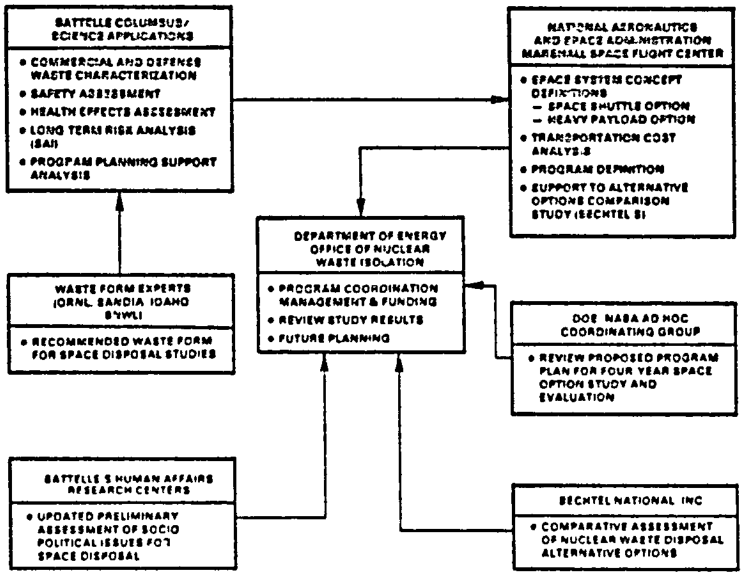
- Health Effects Assessment (Task 3)
  - Evaluate hazard index models to aid in selecting space mix
  - Assess resuspension models and include in analysis
  - Determine health effects from reentry accidents (commercial waste)

- Long-Term Risk Assessment (SAI-Task 4)
  - Perform literature review and technology assessment of automated rendezvous and docking
  - Investigate long-term reentry risk for small particles released in solar orbit

- Program Planning Support Analysis (Task 5)
    - Update concept definition document
    - Prepare concept program plan
    - Assess requirements for licensing, SR&T, and testing.

3.0 RELATIONSHIP TO OTHER NASA AND DOE EFFORTS

This study, performed by Battelle-Columbus Laboratories with SAI subcontract support, was sponsored and monitored by NASA/MSFC, and funded through an interagency agreement with ONWI/DOE. The 1979-1980 program effort is summarized in Figure 1. NASA's Marshall Space Flight Center, Huntsville, Alabama, performed the space-transportation and reentry-system concept definition analysis.(1) Most of the efforts of Battelle's Columbus Laboratories and Science Applications, Inc. (Schaumberg, Illinois) were directed toward providing support to NASA/MSFC in the areas of nuclear-waste payload characterization, the safety and health effects assessments, long-term risk analysis and program planning support. Various DOE laboratories also supported the Battelle-Columbus effort in the area of waste-form definition. Battelle's Human Affairs Research Centers became involved by addressing social issues for ONWI(2). Bechtel performed, for ONWI, a comparative assessment of alternative disposal concepts, including the space option.(3)



Note Arrows indicate information flow

FIGURE 1. RELATIONSHIP OF THIS PHASE III BCL STUDY TO OTHER SPACE DISPOSAL ACTIVITIES

4.0 METHOD OF APPROACH AND PRINCIPAL ASSUMPTIONS

The approach and study logic for this Analysis of Nuclear Waste Disposal in Space Study is outlined in Figure 2. Major inputs, outputs, flow of tasks and interrelationships among the five major tasks are presented. The study consisted of five primary activities: nuclear waste payload characterization; a safety assessment; a health effects assessment; a long-term risk assessment; and program planning support analysis.

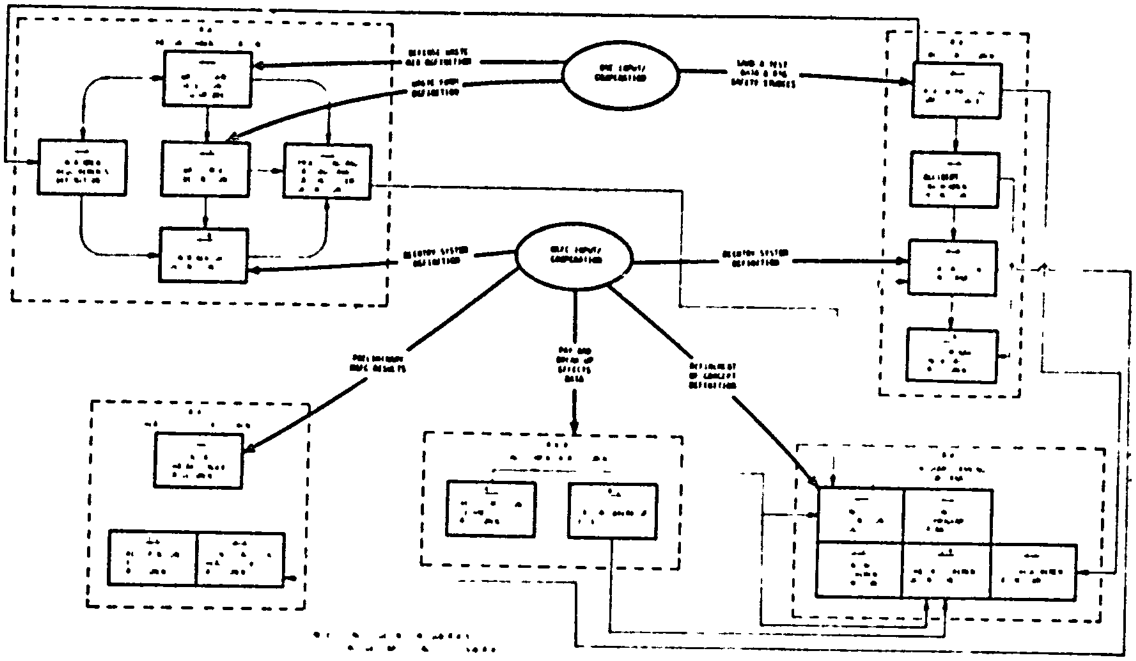


FIGURE 2. STUDY FLOW PROGRAM

Because of the number of technical areas considered and the interactions among the analyses of the various system elements, two methods for insuring concept control were instituted. First, a Concept Definition Working Group consisting of NASA/Headquarters, NASA/MSFC, Battelle and SAI personnel, was organized and met periodically (face to face and telecon) throughout the study. Second, a control document defining the reference space disposal concept and a set of alternatives was developed. This document, called the Concept Definition Document (CDD), was revised three times and published twice under NASA/MSFC cover (see Section 2 of Volume II of this report).(4)

The principal assumptions that guided the Phase III study effort were:

- Make maximum use of related studies and data (especially RTG data)
- Disposal flights were assumed to begin in the 1990-1995 time period
- One waste form was defined for all waste mixes
- Only wastes from U.S. commercial light water reactors and defense waste from Hanford were considered for defining reference waste mixes
- Shuttle-based and SPS heavy lift launch vehicles were assumed for the space launch boosters
- Payload reference designs, safety, and health effects were only based on commercial waste disposal concepts (defense waste excluded)
- Other guidelines, considerations, and assumptions specified in the study plan were followed.

5.0 TECHNICAL SUMMARY OF SIGNIFICANT RESULTS

This section summarizes the significant technical results of the 1979-80 Phase III Battelle Columbus Laboratory study of nuclear waste disposal in space (see Volume II for details). The study objective was to provide NASA and DOE with additional technical data and information in specialized areas as a basis for developing space disposal concept definitions, requirements, and program plans. To accomplish this objective, five basic tasks were defined:

- Nuclear Waste Payload Characterization (Task 1)
- Safety Assessment (Task 2)
- Health Effects Assessment (Task 3)
- Long-Term Risk Assessment (Task 4)
- Program Planning Support Analysis (Task 5)

Tasks 1, 2, 3 and 5 were conducted by Battelle; Task 4 was performed by Science Applications, Inc. (SAI) under subcontract. During the study, a considerable amount of interaction existed among the study tasks and with NASA and DOE (see Figure 2). The following paragraphs briefly outline the contents of this section.

Section 5.1 summarizes the current reference concept for nuclear waste disposal in space, and is based upon the Concept Definition Document developed for NASA/Marshall Space Flight Center as a part of this study. Aspects covered in this summary section include: (1) major concept options; (2) a reference concept mission description; and (3) an advanced space disposal concept that employs a heavy lift launch vehicle.

Section 5.2 reports the work accomplished under the commercial and defense waste payload characterization activity (Task 1). The waste form evaluation and selection process is discussed along with the physical characteristics of the chosen reference waste form (iron/nickel-based cermet matrix). The characteristics of the waste mixes for reference commercial waste (BNWL PW-4b) and defense waste (Hanford) are also presented. A draft Containment Requirements Document was prepared during the study and is summarized. Also, the results of a parametric shielding and cooling analysis are presented for both commercial and defense waste.

The safety assessment (Task 2) is briefly summarized in Section 5.3. The review of various safety studies for space nuclear payloads was conducted. The on-pad catastrophic accident environments for the Uprated Space Shuttle and the heavy lift launch vehicle (HLLV) are summarized. The thermal accident environments for on-pad booster failures formed the basis for: (1) a limited survivability analysis, and (2) the preliminary conclusions related to the HLLV safety assessment. Payload response to inadvertent reentry have resulted in recommended design changes to the reference concept.

Section 5.4 summarizes the results of the health effects assessment. The ORIGEN dilution hazard index model was exercised in an attempt to aid in the determination of the radionuclides that contribute most to the long-term risk of terrestrial disposal. The results from an EPA pathway hazard model were also evaluated. The effects of resuspension of fallout particles from an accidental release of waste material were reviewed. A health effects assessment of upper atmospheric burnup was conducted employing data developed in the payload response analysis. Design changes to the reference concept have been motivated, based upon this health effects assessment.

Section 5.5 presents the results of the payload breakup analysis and rescue technology assessment conducted by SAI, under subcontract. The deep space payload breakup analysis was conducted for both calcine powder and cermet matrix waste forms and two solar orbit disposal regions were considered (only the cermet breakup is discussed in this summary). A preliminary rescue technology assessment for the nuclear waste disposal mission has recommended certain approaches for further consideration.

Section 5.6 describes the effort on the program planning support analysis task. Two working documents were prepared during this effort: (1) the Concept Definition Document (CDD)(4); and (2) the Concept Definition and Evaluation Program Plan(5). Also described are the expected requirements for licensing, and safety testing.

Section 5.7 presents the conclusions that have resulted from this Phase III study.

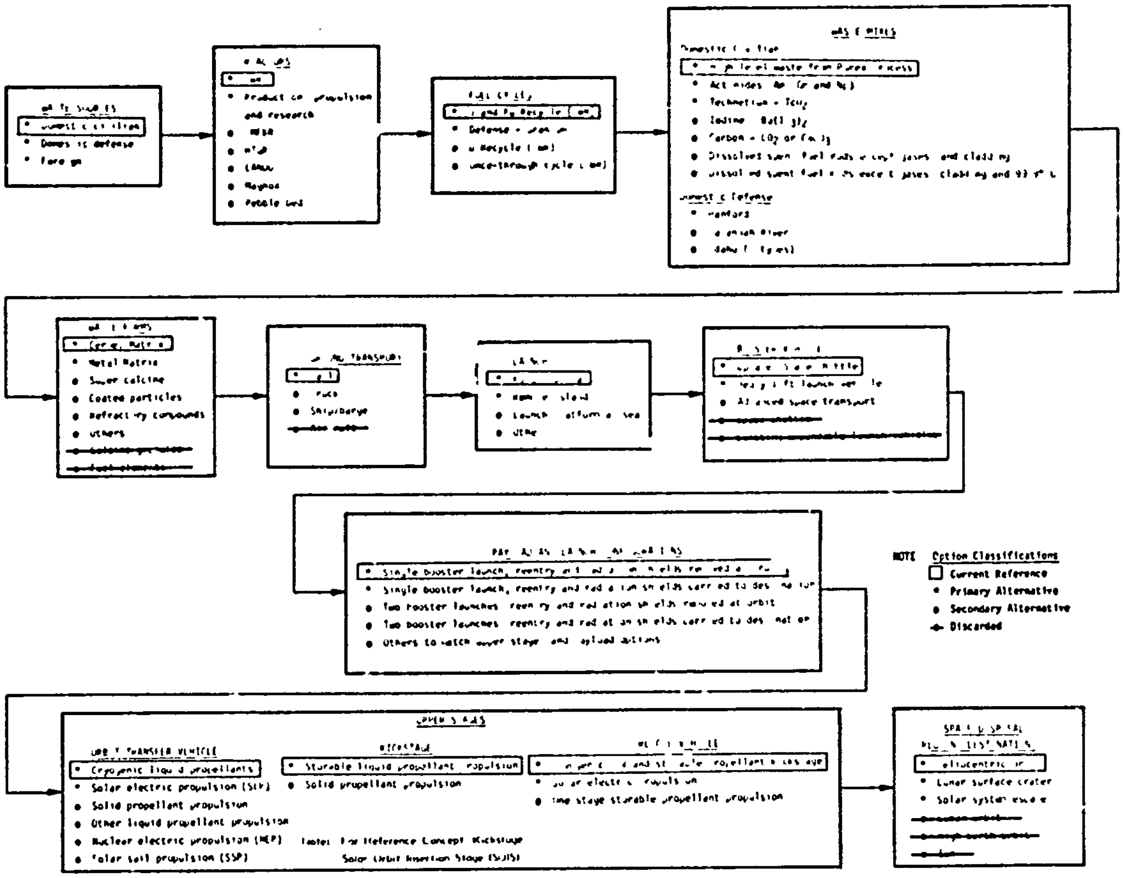
References indicated in the text are listed in Appendix C.

5.1 Reference Concept Definition and Options Summary

This section summarizes the various options (Section 5.1.1), and reference definitions (Section 5.1.2) currently envisioned for the total nuclear waste disposal in space mission(4). The reference concept is believed to be representative of what could be done to rid the Earth of hazardous nuclear wastes and allows trade-off studies to be performed such that the concept can be properly improved. Many reference definitions were employed in the study, but due to the evolving nature of the space disposal option, many have not been used. It is expected that follow-on studies will use and update these reference definitions. It should also be noted that Section 5.1.3 briefly defines an advanced disposal concept which employs the use of a Space Power System (SPS)-derived heavy lift launch vehicle for the space booster to low Earth orbit. This concept is believed to be possible in the 2000 to 2010 time period.

5.1.1 Concept Options

The reference concept for the initial space disposal of nuclear waste has been developed from a considerable number of options available at each step along the way from the reactor to the ultimate space disposal destination. A summary of the various options available is shown in Figure 3. The reference mission options are shown in the blocks; primary alternatives are indicated by an asterisk; and those options no longer considered which have lines drawn through them.



MARCH, 1980

FIGURE 3. MAJOR OPTIONS FOR SPACE DISPOSAL OF NUCLEAR WASTE

5.1.2 Overall Reference Mission

The overall reference mission, described in this section and developed during the course of this study, represents the concept for which most of the analyses in this report and in the NASA/MSFC documentation were conducted. Because of the many possible variations within the space disposal option, one point of reference is necessary. The major aspects of the reference mission are illustrated in Figure 4. This mission profile has been divided into seven major activities. The first two are expected to be the responsibility of the Department of Energy (DOE) and the last five are expected to be NASA's. These are:

(1) Nuclear Waste Processing and Payload Fabrication (DOE)
(2) Nuclear Waste Ground Transport (DOE)
(3) Payload Preparation at Launch Site (NASA)
(4) Prelaunch Activities (NASA)
(5) Uprated Space Shuttle Operations (NASA)
(6) Upper Stage Operations (NASA)
(7) Payload Monitoring (NASA).

5.1.2.1 Nuclear Waste Processing and Payload Fabrication (DOE)

Typically, spent fuel rods from domestic power plants would be transported to the waste processing and payload fabrication sites via conventional shipping casks. Using the Purex process, high-level waste containing fission products and actinides, including 0.1 percent plutonium and 0.1 percent uranium, would be processed from these spent fuel rods. The high-level waste would be formed into a cermet matrix by a calcination and hydrogen reduction process. The waste form would then be fabricated into a 5000 kg spherical payload. Within a remote shielded cell, the waste payload is loaded into a container; the container is then closed and sealed, inspected, decontaminated, and packaged into a flight-weight gamma radiation shield assembly. During these operations and subsequent interim storage at the processing site, the waste payload is cooled by an auxiliary cooling system.

5.1.2.2 Nuclear Waste Ground Transport (DOE)

The shielded waste container would then be loaded into a ground transportation shipping cask (see Figure 4). This cask, which provides additional shielding, thermal, and impact protection for the waste container to comply with the Nuclear Regulatory Commission/Department of Transportation regulations, is then loaded onto a specially designed rail car for transporting the waste container from the waste payload fabrication site to the Kennedy Space Center (KSC), Florida launch site. Once the cask reaches the launch site, it is offloaded into the Nuclear Payload Preparation Facility (NPPF).

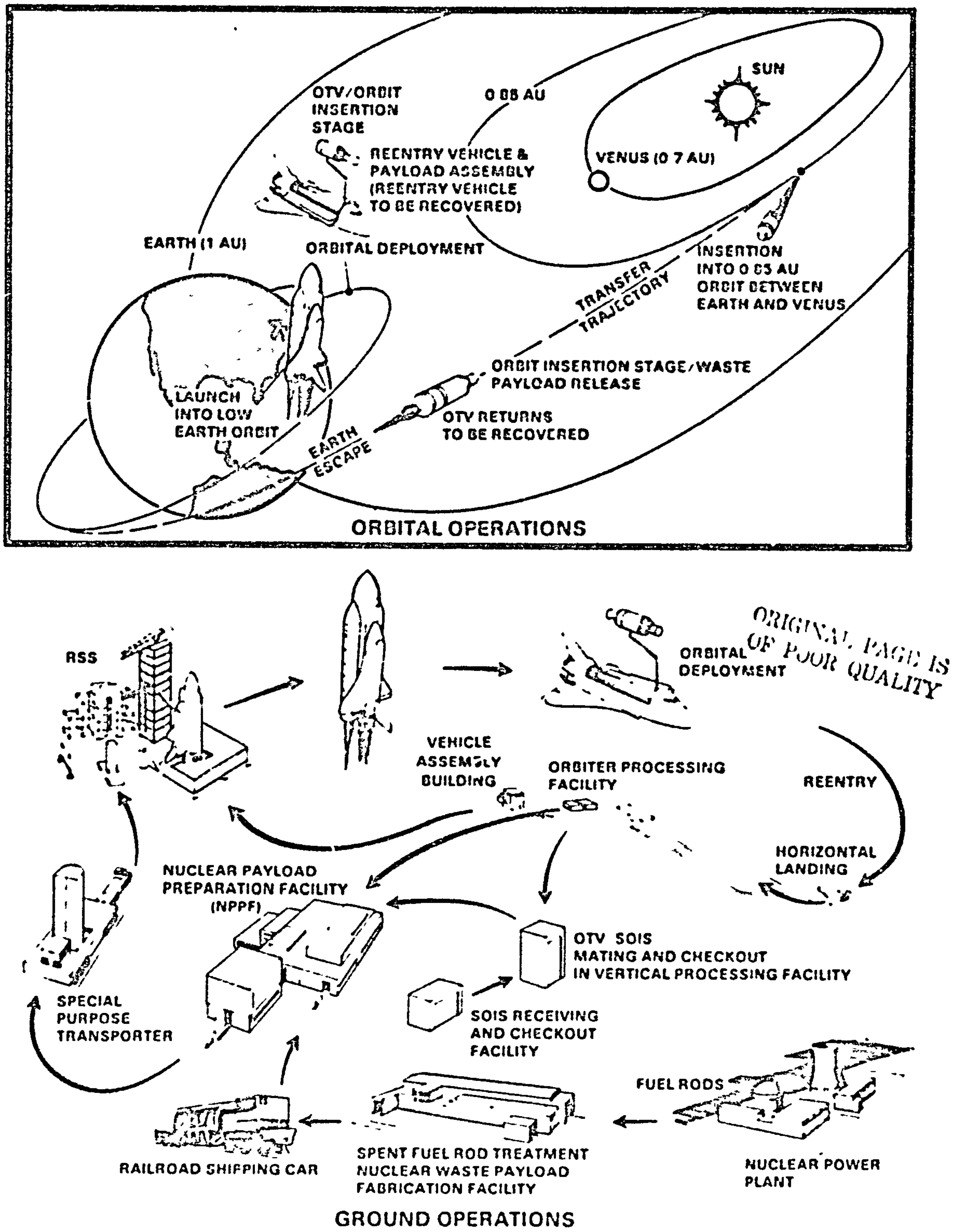


FIGURE 4. GROUND AND SPACE OPERATIONS FOR REFERENCE SPACE DISPOSAL MISSION

5.1.2.3 Payload Preparation at Launch Site (NASA)

The NPPF is expected to provide interim storage capability for up to three shielded waste containers, which affords efficient preparation for launches plus capacity for unplanned delays. During storage, additional radiation shielding, thermal control, monitoring and inspection of the waste container would be provided.

5.1.2.4 Prelaunch Activities (NASA)

In preparation for launch of the nuclear waste into space, the integrated Space Shuttle waste payload is prelaunch checked in the NPPF. The integrated Shuttle payload consists of: the waste form; the container, the radiation shield; the reentry vehicle (RV), which protects and structurally supports the waste in the Orbiter cargo bay (see Figure 5); the Solar Orbit Insertion Stage (SOIS), which circularizes the waste payload into the solar orbit disposal destination; and the Orbit Transfer Vehicle (OTV), which provides escape from low Earth orbit and insertion into the heliocentric transfer trajectory. Transfer of the payload to the launch pad's Rotating Service Structure (RSS), is accomplished by a special purpose transporter which maintains the Shuttle payload in the proper position for installation in the Orbiter cargo bay (see Figure 4). The payload is transferred from the NPPF to the pad after the Shuttle vehicle installation at the launch pad has been completed. The payload is then positioned by the RSS and installed in the Orbiter cargo bay. After payload installation, propellant loading of the OTV, and final systems checkout, the decision to launch is made.

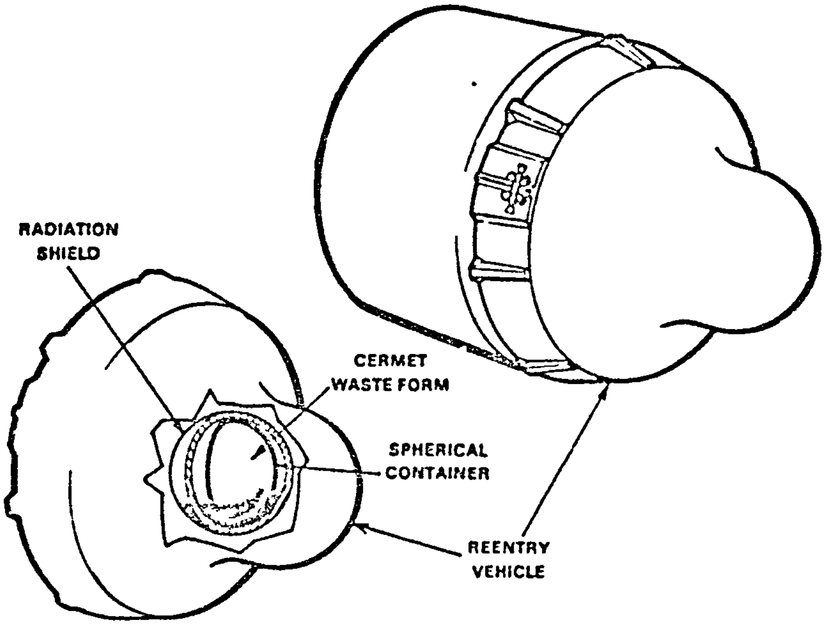


FIGURE 5. REFERENCE CONCEPT OF A LOADED REENTRY VEHICLE

5.1.2.5 Uprated Space Shuttle Operations (NASA)

One Uprated Space Shuttle vehicle (LOX/RP-1 reusable boosters replacing the solid rocket boosters) would be readied for launch for a given disposal mission. The Uprated Space Shuttle (45,400 kg payload to low Earth orbit), that is to perform the disposal mission, is launched from KSC at a 108 degree south azimuth to a 300 km (160 n.mi.) circular orbit inclined 38 degrees to the equator. Once on orbit, the loaded reentry vehicle (RV) in the Shuttle Orbiter cargo bay is remotely translated aft a short distance and structurally latched to the SOIS. Using the OTV payload bay rotation structure, the OTV, SOIS, and loaded RV are deployed from the Orbiter bay. After the configuration has been stabilized in a fixed attitude, the Orbiter will move to a safe distance away to limit the radiation dose to the crew from the unshielded payload. At this time, the waste payload would be mechanically transferred by remote control to the SOIS payload adapter, and the OTV/SOIS/waste payload is oriented for the Earth escape propulsive burn. The reentry vehicle would remain in orbit and be recovered and returned to KSC by the Shuttle Orbiter.

The traffic model for the reference space disposal concept is given below in Table 1.

TABLE 1. PROJECTED UPRATED SPACE SHUTTLE TRAFFIC MODEL FOR COMMERCIAL HIGH-LEVEL NUCLEAR WASTE DISPOSAL MISSIONS (1992-2003)

	Year												
	92	93	94	95	96	97	98	99	00	01	02	03	Total
Uprated Space Shuttle Flights	10	20	50	50	50	50	50	60	60	60	60	60	580

5.1.2.6 Upper Stage Operations (NASA)

After the OTV/SOIS/waste payload system has passed final systems checkouts, the OTV propulsive burn would place the SOIS and its attached waste payload on the proper Earth escape trajectory. Control of the propulsive burn from low Earth orbit would be from the aft deck payload control station on the Orbiter, with backup provided by a ground control station. After the burn is complete, the SOIS/waste payload is then released. In about 160 days the payload and the storable liquid propellant SOIS would travel to its perihelion at 0.85 A.U. about the Sun. (One astronomical unit is equal to the average distance from the Earth to the Sun.) The SOIS would then place the payload in its final space disposal destination by reducing the aphelion from 1.0 to 0.85 A.U. To aid in obtaining the desired orbital lifetimes, this orbit would be inclined to the ecliptic plane by 1 degree. The recovery burns of the OTV would use the remaining OTV propellant to rendezvous with the Shuttle Orbiter for its subsequent recovery, refurbishment, and reuse on a later mission (see Figure 4).

5.1.2.7 Payload Monitoring (NASA)

The Earth escape trajectory of the SOIS/waste payload would be monitored by ground-based radar systems and telemetry from the SOIS and OTV. The final disposal orbit achieved would be monitored by NASA's Deep Space Network. Once the proper disposal orbit has been verified, no additional monitoring is necessary. However, monitoring could be re-established in the future, if required.

5.1.3 Advanced Concept for Space Disposal of Nuclear Waste

The advanced concept for space disposal of nuclear waste is similar in many respects to the reference concept defined previously. The advanced concept is based upon the availability of a heavy lift launch vehicle (HLLV) that may be developed by NASA for future space missions beyond the year 2000 (see Figure 6). The major differences between the advanced and reference concepts are summarized in Table 2.

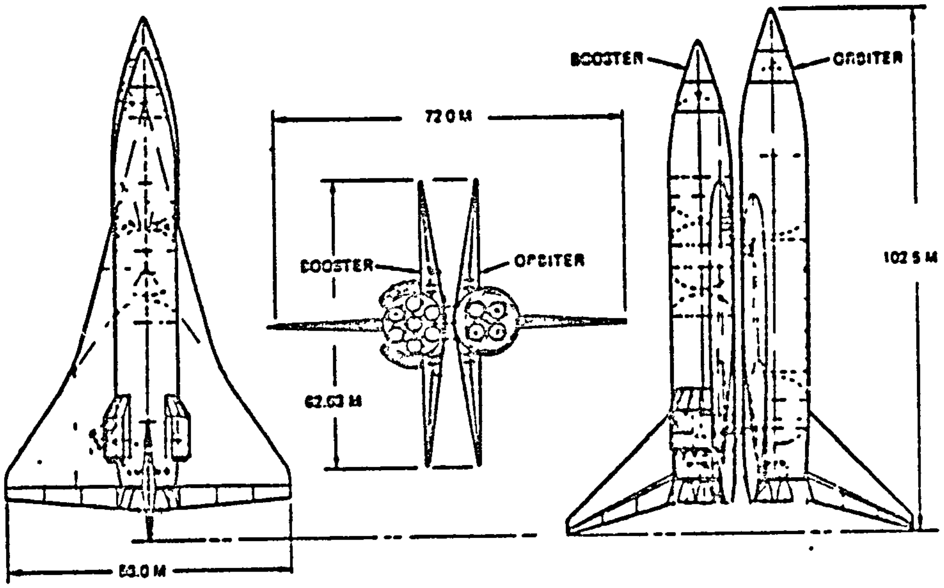


FIGURE 6. HLLV LAUNCH CONFIGURATION

TABLE 2. COMPARISON OF REFERENCE AND ADVANCED SPACE DISPOSAL CONCEPTS

Mission Elements	Reference Concept	Advanced Concept
Waste Mix	PW-4b	Modified PW-4b (90% Cs and Sr removed)
Waste Form Mass/Payload, kg	5000	9500
Number of Payloads/Mission	1	3
Number of OTV's/Mission	1	3
Number of SOIS's/Mission	1	3
Ground Transportation	Rail	Rail/Sea
Launch Site	KSC, Florida	Remote Island
Launch Vehicle	Uprated Space Shuttle	HLLV
Launch Vehicle Payload, kg	45,400	231,000

5.2 Nuclear Waste Payload Characterization

The objective of the Nuclear Waste Payload Characterization Task was to define the commercial and defense nuclear waste payload in terms of waste form, waste mix, containment system requirements, container and shield definitions, and waste processing and payload fabrication operations. The major goal of this activity was to identify a new waste form for commercial and defense high-level waste. In addition, the composition and concentration of each waste type was reevaluated to update the radiation and heat source terms for the waste package. The data were used for parametric studies of the radiation shield definition and thermal design for a range of waste payload sizes from a small RTG-size sphere to a large HLLV package. A 5.5 MT sized payload was defined for the Uprated Space Shuttle case (current reference concept has a 5.0 MT payload).

5.2.1 Waste Form Evaluation, Selection and Characterization

During the Battelle Phase I[6] and Phase II studies of[7] nuclear waste disposal in space, a constraint on waste form to be available in the early 1980's limited the waste form selection to calcine or glass. Because of its higher waste loading, calcine was selected over glass. It was recognized that calcine had problems of its own, i.e., it is easily dispersed and leached, and it has poor thermal conductivity. For the Phase III study, the technology constraint was shifted to the early 1990's. Because of this, advanced waste forms could be evaluated for potential use in space disposal.

A waste form selection meeting was held at BCL on July 19, 1979 to evaluate waste forms for the space disposal of commercial and defense high-level waste (HLW). Participants included ONWI, NASA, BCL, and DOE-Richland

Operations personnel and waste form experts from Battelle Northwest Laboratories, Oak Ridge National Laboratories, Idaho Chemical Processing Plant, and Sandia Laboratories. Ten parameters were determined to be applicable to the waste form evaluation (see Volume II for detailed discussion of each).

(1) High waste loading
(2) High thermal conductivity
(3) Resistance to thermal shock
(4) Thermochemical stability
(5) Resistance to leaching
(6) Toughness
(7) Applicability to both commercial (PW-4b) and defense (Hanford) HLW mixes
(8) Fabrication
(9) Economics and resource utilization
(10) Resistance to oxidation

The waste forms chosen for evaluation were: borosilicate glass, hot-pressed supercalcine, ORNL cermet, ICPP glass ceramic, Sandia titanate ceramic, and metal matrix with coated particles. Calcine and SYNROC were excluded from evaluation. Table 3 presents the qualitative ratings (high, moderate, or low) as agreed to by the waste form experts for the various waste forms.

TABLE 3. COMPARISON OF ADVANCED WASTE FORMS FOR SPACE DISPOSAL

	ORNL CERMET	ICPP GLASS CERAMIC	SANDIA TITANATE CERAMIC	BORO-SILICATE GLASS	METAL MATRIX (COATED PARTICLE)	HOT-PRESSED SUPERCALCINE
HIGH WASTE LOADING	M[a]	M	M	L	L	H
HIGH THERMAL CONDUCTIVITY	H	L	L	L	H	L
RESISTANCE TO THERMAL SHOCK	H	H	H	L	H	H
THERMOCHEMICAL STABILITY (FABRICATION TEMP., C)	1450	1100	1100	1100	1000[b]	1100
RESISTANCE TO LEACHING	H	H	H	H	H	H
TOUGHNESS	H	M	M	L	H	M
APPLICABILITY TO COMMERCIAL (PW-4b) AND DEFENSE (HANFORD) MIXES	H	L	L	L	H	L
FABRICATION OF WASTE FORM INTO DESIRED SHAPE AND SIZE	M	L	L	H	M	L
ECONOMICS	M	M	M	H	L	M
RESISTANCE TO OXIDATION	L	H	H	H	L	H

NOTES: (a) H = HIGH, M = MODERATE, AND L = LOW
(b) COPPER

With respect to the parameters deemed to be of greatest importance, the ORNL cermet (iron-nickel based) appears clearly superior and was selected with the concurrance of the waste form experts, NASA, ONWI and the BCL Project Team, as the reference waste form for use in the study.

ORNL cermet is a metallic appearing waste form in which the majority of the HLW radionuclides are uniformly distributed as micron-sized particles of crystalline ceramic oxides, aluminosilicates, and/or titanates in a hydrogen reducible metal matrix.(8) The metal matrix is composed of chemically reducible metals and fission products already in the waste (Fe, Ni, Cu, Te, etc.) and reducible metal additives necessary to formulate a particular alloy composition. Reference concept cermet compositions have been recommended by ORNL for both commercial (PW-4b) and defense (Hanford) HLW and are presented in Table 4. The densities, waste loadings, thermal conductivities, specific heats, and heat generation rates for commercial and defense HLW are presented in Table 5.

TABLE 4. ORNL REFERENCE CERMET COMPOSITION FOR COMMERCIAL AND DEFENSE HIGH-LEVEL WASTE

	Reference Commercial HLW Cermet (PW-4b), Kg/MTHM	Reference Defense HLW Cermet (Hanford), Mass percent*
Composition at Start of Form Processing		
Oxide	40.8	40.0
Metal Additives (Fe, Ni, and Cu)	25.2	52.2
TiO_2, SiO_2 and Al_2O_3	3.5	7.8
Total	69.5	100.0*
Composition After Reduction in Hydrogen		
Waste Oxides, Including Ti, Si and Al	34.8	43.0
Reduced Waste Metals	9.5	4.8
Metal Additives	25.2	52.2
Total	69.5	100.0*

*Note: Units in mass percent.

TABLE 5. REFERENCE CERMET CHARACTERISTICS (ESTIMATED) FOR COMMERCIAL AND DEFENSE HIGH-LEVEL WASTE

Characteristic	Reference Commercial HLW Cermet (PW-4b)	Reference Defense HLW Cermet (Hanford)
Density, g/cc	6.7	5.7
Waste Loading, percent**	58.7	40.0
Thermal Conductivity, W/m-C	14	20.5
Specific Heat, cal/g-C	0.14	0.20
Heat Generation, kW/MT	19.2	0.23

**Note. Calcine powder defined as 100 percent.

5.2.2 Waste Mix Definition

A realistic evaluation of the thermophysical conditions and possible environmental impact for the waste form package during a space disposal mission required a fairly detailed composition definition of both commercial and defense HLW mixes. The following paragraphs review the data developed for these mixes.

It is important that the commercial HLW mix used for the space disposal mission concept be referenced and understood by members of the waste management community. The waste form experts agreed that the PW-4b(9) mix would be the most appropriate commercial HLW mix for space disposal studies. It corresponds to reprocessed HLW of 33,000 megawatt-days per ton burnup from an optimized reprocessing plant, and in general, represents the type of waste which would be generated from the General Electric Morris Plant and the proposed Exxon Plant. Furthermore, PW-4b contains low quantities of inerts and reprocessing chemicals, assumes 99.9 percent U and Pu removal, and has the lowest mass/MTHM reprocessed. Table 6 presents the elemental composition of the PW-4b mix.(9) A detailed radionuclide inventory is given in Volume II of this report.

TABLE 6. REFERENCE COMMERCIAL ELEMENTAL WASTE MIX COMPOSITION (PW-4b)

	Constituent	Amount, kg/MTHM		Constituent	Amount, kg/MTHM
Inerts	Na_2O	--	Fission Products (Cont'd.)	TeO_2	0.725
	Fe_2O_3	1.511		Cs_2O	2.880
	Cr_2O_3	0.345		BaO	1.567
	NiO	0.141		La_2O_3	1.480
	P_2O_5	0.672		CeO_2	3.323
	Gd_2O_3	--		Pr_6O_{11}	1.482
				Nd_2O_3	4.522
Fission Products	Rb_2O	0.354		Pm_2O_3	0.123
	SrO	1.059		Sm_2O_3	0.924
	Y_2O_3	0.598		Eu_2O_3	0.200
	ZrO_2	4.944		Gd_2O_3	0.137
	MoO_3	5.176			
	Tc_2O_7	1.291	Actinides	U_3O_8	1.169
	RuO_2	2.972		NpO_2	0.865
	Rh_2O_3	0.480		PuO_2	0.010
	PdO	1.483		Am_2O_3	0.181
	Ag_2O	0.088		Cm_2O_3	0.040
	CdO	0.097			
				TOTAL	40.839

Source Reference 9.

An important consideration for the space disposal of commercial HLW is the number of launches required for disposal. Recent estimates(10) project a nuclear electric generation capacity of 200 GWe by the year 2000. Based on this projection it is possible to project the quantity of spent fuel discharged from reactors and reprocessed. It has been assumed that the first reprocessing plant attains full capacity (1500 MTHM/year) by 1986, that a second reprocessing plant attains full capacity (2000 MTHM/year) by 1991, and a third plant will reach full capacity of 2000 MTHM/year by 1999. An additional assumption made regarding the cooling time necessary between discharge and processing is that waste will be available for space disposal 10 years after discharge from the reactor. The annual spent fuel available for disposal, and the annual HLW in cermet form available for space disposal are presented in Table 7.

TABLE 7. PROJECTED NUCLEAR POWER GENERATION AND COMMERCIAL HIGH-LEVEL WASTE AVAILABLE FOR SPACE DISPOSAL

	Cumulative(a)		Annual Nuclear Waste Available for Disposal, MTHM/yr	Annual High-Level PW-4b Waste in Cermet Form(d) Available for Space Disposal, MT/yr
Year	Power, GWe	Waste, MTHM(b)		
1979	61.9	5890(c)	0	0
1980	74.8	7690	0	0
1981	87.3	9790	0	0
1982	101.1	12,220	0	0
1983	115.4	14,990	0	0
1984	131.4	18,140	0	0
1985	144.3	21,600	0	0
1986	157.1	25,370	0	0
1987	164.9	29,330	0	0
1988	174.0	33,510	0	0
1989	180.9	37,850	5890(c)	410(e)
1990	186.5	42,330	1800	125
1991	188.9	46,860	2100	146
1992	190.1	51,420	2430	169
1993	192.5	56,040	2770	193
1994	194.0	60,700	3150	219
1995	195.0	65,380	3460	241
1996	196.0	70,080	3500	244
1997	197.0	74,810	3960	275
1998	198.0	79,560	4180	290
1999	199.0	84,340	4340	301
2000	200.0	89,140	4480	310

(a) From: Yates, K. R., and Park, U. Y., "Projections of Commercial Nuclear Capacity and Spent-Fuel Accumulation in the United States", Transaction American Nuclear Society, pp. 350-352 (June 1979).

(b) MTHM is metric tons heavy metal.

(c) Includes 4400 MTHM PW-4b existing as of 1978.

(d) Assumes 40.8 kg/MT waste for space disposal and a cermet waste form loading of 58.7 percent.

(e) Computed by multiplying 5890 MTHM by 0.0408 MT/MTHM and dividing by 0.587.

The Hanford site, located near Richland, Washington, has been producing plutonium and other special nuclear materials since 1944. Detailed information was presented in last year's final report on the Hanford HLW mix. During this year's study, updated radionuclide removal runsheets were supplied by Rockwell Hanford along with ORIGEN computer printouts of the radionuclide composition for present waste, future waste and a mixture of both. The radionuclide composition of the present waste is currently the most useful data for study purposes and it is presented in Volume II, Section 3.2.2 of this report. The total mass of Hanford waste that could be carried to space, assuming the chemistry described in Volume II of this report, is given in Table 8 for both previous and updated mass estimates. The reference waste concentration factor (WCF) has also changed to 25.5 (from 27.2) because of the updated information.

TABLE 8. REFERENCE DEFENSE WASTE MIX INVENTORY (HANFORD HLW) FOR SPACE DISPOSAL

Component	Last Year's Study (1978-1979)(7)	Current Reference(a) (1979-1980)
	Metric Tons	
Inert Material	154	145
Fission Product Oxides	66	7.2
Thorium (ThO_2)	0.3-0.8	0.3-0.8
Uranium (UO_2)	21-52	21-51
Isolated Products from Salt Cake and Liquor	3-14	4
Zirconium Sludge	0-318	0-412
Total	244.3-604.8	177.5-620
Waste Concentraction Factor(b)	27.2	25.5

(a) Assumes same chemistry as last year's study (Reference 7)

(b) Based upon total masses of Hanford Waste of 16,379 and 15,830, respectively (from radionuclide removal process).

5.2.3 Containment Requirements Definition

The space disposal option introduces the need to define containment requirements and/or allowable limits for the waste payload configurations considered for use during the various mission phases. Current federal regulations cover little beyond ground transportation aspects. Additional information that must be developed from follow-on studies includes the handling, storage, transportation, and final disposition requirements for both commercial and defense HLW. Preliminary containment requirements developed in this study are presented in Volume II, Section 3.3. Three independent components of containment requirements are: (1) specific parameters indicative of the response of various containment systems; (2) specific systems for containing the waste (waste form, containment vessels, etc.); and (3) various mission phases during which specific levels of containment are required. Table 9 lists the components of these categories. The three levels containment requirements can be used to define any aspect of containment.

TABLE 9. SPECIFIC COMPONENTS OF CONTAINMENT REQUIREMENTS

Parameters	Components	Mission Phases
• Thermal • Mechanical • Chemical • Nuclear	• Waste Form • Primary Container • Radiation Shield • Impact Absorber • Ablation Shield • Shipping Cask	• Fabrication/Assembly • Terrestrial Transport • Launch Site Handling • Launch to Earth Orbit • Orbit Transfer to Destination

5.2.4 Container, Shield, and Cooling Requirements Definition

The objective of this effort was to define basic concepts for the primary container and radiation shield, over a range of payload masses for both commercial (PW-4b) and defense (Hanford) waste mixes. The reference commercial (PW-4b) and Hanford defense wastes were evaluated for three spherical waste masses ranging from an RTG-type payload [approximately 1/3 the diameter of the 5.5 metric ton (MT) payload] up to a heavy life launch vehicle (HLLV) capability (defined by a waste payload diameter upper limit of 3 meters due to ground transport constraints). A primary container wall was assumed to enclose the cermet waste form. A radiation shield surrounding the container consists of depleted uranium with an inner and outer cladding of stainless steel. The shielding thickness was determined as a function of payload waste form mass using standard shield codes. For space flight, the shielded package is enclosed by a spherical honeycomb steel impact absorber and a thermal protection layer of insulation and ablation material.

5.2.4.1 Shielding Analysis

The shielding analysis consisted of determining the thickness of uranium required to reduce the gamma and neutron radiation dose rates to within the designated limits. This procedure began with development of a shielding source term for commercial and Hanford waste mixes using the ORIGEN code.(11) Both commercial and Hanford shielding results were computed using the ANISN(12) code. In addition to gamma and neutron source terms, the waste decay heat is also predicted by ORIGEN. These values were input to the thermal analysis. The results of these analyses are presented in Table 10. The shielding analyses show several interesting characteristics. First, the phenomena of self-shielding of gamma rays is significant. The package materials, even the waste form itself, are effective gamma shielding materials. Consequently, only the gamma radiation from the outer region of the waste requires shielding; the central portions are shielded by the outer package materials themselves. Second, the neutrons emitted by the waste are fast neutrons. Effective self-shielding of fast neutrons does not occur in the waste material. Thus, the neutron dose rate at the surface of a waste payload increases as the radius increases.

TABLE 10. SUMMARY OF SPACE DISPOSAL SHIELDING REQUIREMENTS FOR COMMERCIAL (PW-4b) AND HANFORD (WCF = 25) WASTE

Type of Waste	Dose Rate rem/hour(a)	Payload Waste Form Mass, kg								
		204			5500			99,300		
		$\gamma\left(\frac{rem}{hr}\right)^{(b)}$	$n\left(\frac{rem}{hr}\right)^{(c)}$	$U_t(cm)^{(d)}$	$\gamma\left(\frac{rem}{hr}\right)^{(b)}$	$n\left(\frac{rem}{hr}\right)^{(c)}$	$U_t(cm)^{(d)}$	$\gamma\left(\frac{rem}{hr}\right)^{(b)}$	$n\left(\frac{rem}{hr}\right)^{(c)}$	$U_t(cm)^{(d)}$
PW-4b	0.5	0.22	0.28	5.6	0.01	0.49	8.4	(e)	0.50	10.9
PW-4b	1.0	0.61	0.39	4.8	0.09	0.91	7.2	0.02	0.98	9.6
PW-4b	2.0	1.51	0.49	4.1	0.46	1.54	6.0	0.08	1.92	8.2
Hanford	0.5	0.5	--	1.86	0.5	--	2.31	0.5	--	3.41
Hanford	1.0	1.0	--	1.51	1.0	--	2.44	1.0	--	3.03
Hanford	2.0	2.0	--	1.18	2.0	--	2.06	2.0	--	2.67

Notes:
(a) Dose rate at 1 meter from surface of shield.
(b) Gamma radiation component.
(c) Neutron radiation component.
(d) Calculated uranium thicknesses, U_t, include consideration of the shielding available due to 2.54 cm steel (shield liner and waste container).
(e) Less than 0.005.

The mass of the waste, primary container, and radiation shield as a function of waste mass and dose rate is presented graphically in Figure 7.

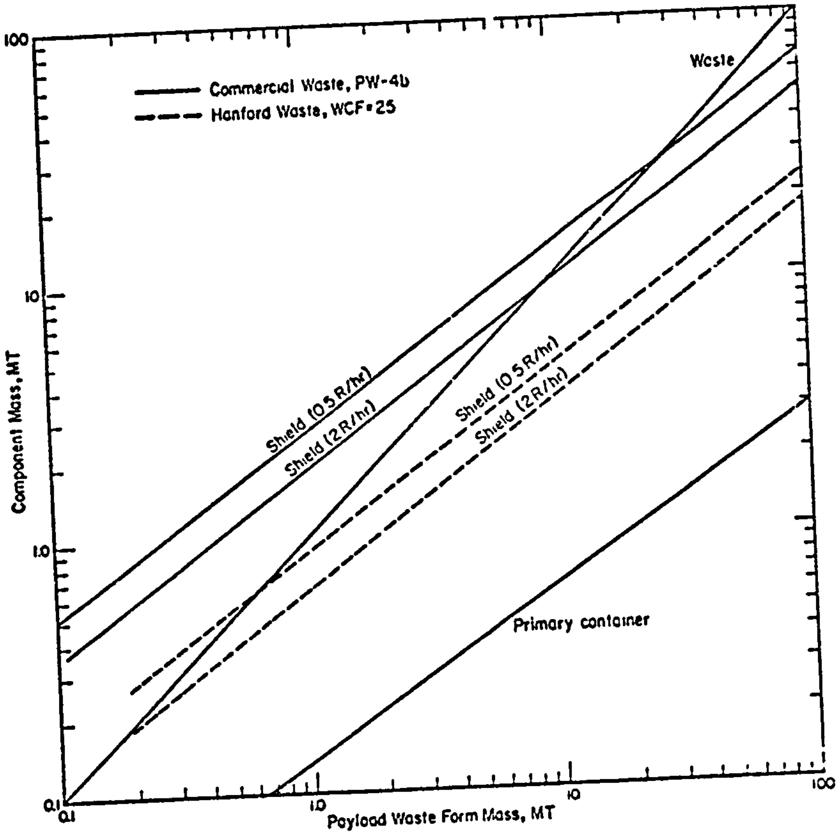


FIGURE 7. CONTAINER AND SHIELD MASS AS A FUNCTION OF PAYLOAD WASTE FORM MASS FOR COMMERCIAL (PW-4b) AND HANFORD (WCF=25) HIGH-LEVEL WASTE

5.2.4.2 Thermal Analysis

In addition to shielding requirements, temperature limits are important considerations in establishing conceptual payload designs. For example, design trade-offs are necessary to compromise the conflicting goals of minimizing waste volume (by concentration) and minimizing dose rate and thermal requirements. The purpose of this analysis was to provide data that can be used to assess the importance of various parameters, and thereby evaluate trade-offs in designs.

For the space disposal option, in addition to the thermal requirements stated in Volume II, Section 3.3, a design constraint is that the final destination thermal equilibrium condition (by passive cooling) results in acceptable temperatures. Although this is not the most severe thermal condition for the waste package, the design philosophy must meet this criterion while relying on auxiliary cooling only for more severe, short-term conditions. Consequently, the deep space environment was chosen as the design basis condition for the unshielded primary container. The results of the thermal analysis are summarized in Figure 8.

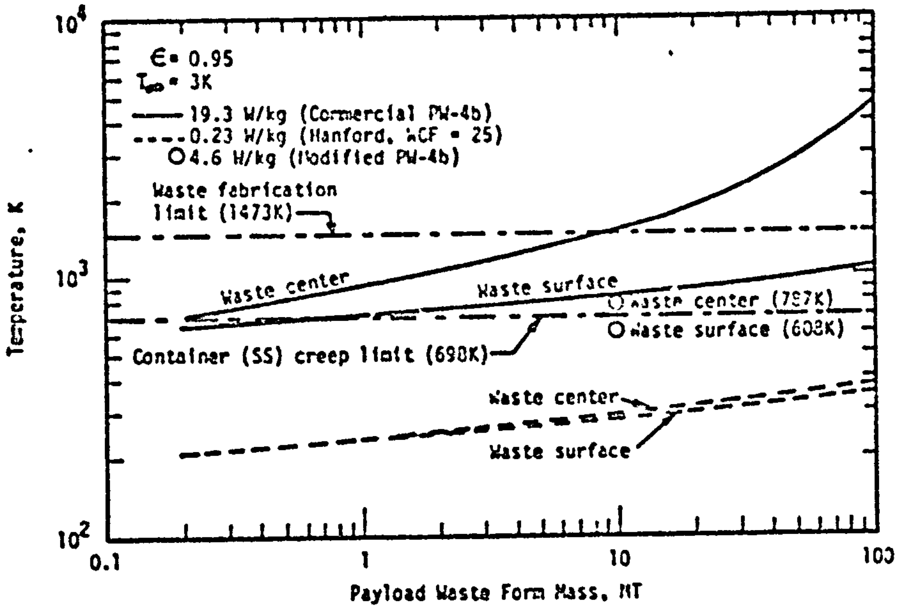


FIGURE 8. TEMPERATURE AS A FUNCTION OF PAYLOAD WASTE FORM MASS FOR VARIOUS LOCATIONS, WITHOUT RADIATION SHIELD, SPACE ENVIRONMENT

Results indicate that no thermal problems exist for any waste payloads analyzed for the Hanford waste (concentrations up to WCF=25). For commercial (PW-4b) waste payloads with masses greater than about 8 MT, the waste temperature exceeds the normal limit (waste fabrication temperature). For the container wall, the conservative temperature limit established (mechanical limit for stainless steel) is exceeded for commercial waste masses exceeding 700 kg. To achieve acceptable temperatures for larger payloads, an attractive option is the removal of the "hottest" nuclides. For example, if 90 percent of the strontium and cesium nuclides (and their daughters) were removed, the decay heat load would decrease to about one-quarter its original value. Calculations for a 9.5 MT Modified PW-4b waste payload yield maximum waste center and surface temperatures of 514 and 335 C, respectively, for the deep space equilibrium condition. Both of these values are within the present thermal limits for a stainless steel container.

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5.2.4.3 Auxiliary Cooling Analysis

A design based on passive cooling in a space environment will require active cooling to meet the same limits in an earth environment. This is because of the large radiation heat loss created by the low temperatures in space and the insulating effect of protection systems. The auxiliary cooling required is in the range of 15-69 percent of the heat generated for the 204 kg waste form mass, 88-98 percent for the 5500 kg waste form mass, and 39-75 percent for the 9500 kg (using the Modified PW-4b) waste form mass, depending on the temperature margin desired.

After auxiliary cooling is removed, the temperatures throughout the package will rise. For commercial waste, the waste and container temperatures will eventually reach and surpass their respective limits for even the lower masses (204 kg). As the temperature rises, the amount of heat transferred through the shield and reentry vehicle increases, resulting in an asymptotic approach to equilibrium, i.e., the rate of temperature increase is not constant, but diminishes with time. Results indicate that, for a given waste concentration the larger the waste mass, the shorter the heat-up time.

5.2.4.4 Parametric Analysis of Dose Rate as a Function of Shielding Thickness and Distance

During orbital handling operations of the waste payload, especially after the shield is removed, the crew and other vital components will be exposed to radiation from the waste package. To assess the potential radiation dose to personnel and equipment during this phase of the operation, the dose rate as a function of distance and thickness of intervening material was determined as a function of payload waste mass. For the 5500 kg commercial waste mass payload, without radiation shield, a distance of about 1000 meters is required to reduce the dose rate to 2 rem/hr. If 2.5 cm of aluminum shielding were intervening, a distance of 860 meters would be required. By contrast, a bare container of 5500 kg Hanford waste (WCF = 25) would produce a dose rate of 2 rem/hr at a distance of only 12 meters from the surface.

5.2.4.5 Conclusions

The parametric evaluation conducted in this study of the nuclear shielding and thermal effects of various sizes of commercial and defense high-level waste is intended to demonstrate those combinations of design parameters that are feasible for the space disposal option. Overall, there do not appear to be any shielding or steady-state thermal limitations to even the larger payloads of Hanford waste. In fact, none of the defense waste mass payloads examined required auxiliary cooling in near-earth environments. Commercial waste (PW-4b) can be adequately shielded for all waste masses studied. However, constraints in allowable temperatures in the waste and reference container material severely limit the waste mass per payload. Assuming that certain nuclides can be removed from the PW-4b mix, it has been shown that a 9500 kg waste mass can meet thermal requirements, with a minimum amount of auxiliary cooling required.

5.3 Safety Assessment

The major objective of this Phase III Safety Assessment was to define the major accident environments and study the response of the reference commercial nuclear waste payload to these accident environments, and to predict the degree of containment that might be expected. The response analysis was limited in this report to the thermal (fire) and reentry environs. Payload response to the blast wave, shrapnel, and impact needs to be accomplished in follow-on studies. Information generated by this assessment was supplied to the Health Effects Assessment Task (see Section 5.4).

5.3.1 Safety Study Review

The objective of the BCL safety study review was to incorporate appropriate concepts, approaches and testing procedures for the RTG, General Purpose Heat Source (GPHS), and previous nuclear waste disposal studies into the current space option safety considerations and program plans. (NASA/MSFC also conducted an independent review of previous studies; their emphasis was to relate the "RTG" design and materials choices to the space option conceptual designs.) Appropriate information available from the BCL safety review was provided to other study activities.

As a result of this review of safety documents, appropriate information was supplied to other study activities. It was recommended to NASA/MSFC that the GPHS carbon/carbon AVCO fine-weave, pierced fabric reentry and impact material be used for the reentry vehicle. Also, it was recommended for use as a thermal protection material on the outside of the primary container. The safety index approach used for the GPHS/RTG should be considered for use in payload response studies for the space option. The concept of sequential safety testing in the GPHS and RTG programs has been applied to the safety requirements for the space option. For actinide payloads, He vents should be considered.

Various works resulting from the LeRC study of nuclear waste disposal in space are considered valuable in the current study. It is recommended that, prior to any new work in related areas, critical in-depth reviews be conducted of past works to establish what results and computer codes are appropriate for future efforts. The conclusion that the larger and slower fragments (shrapnel) pose a greater potential for payload damage than the smaller high-speed fragments coupled with the results of Section 4.2.4 (Volume II) imply that more work is needed. It is recommended that experimental work be conducted to determine the fragment velocity and size distributions for exploding propellant tanks.

5.3.2 Accident Environment Definition

The System Safety Design Requirements for the reference space disposal concept (see Volume II, Section 2.5), that have been developed as a part of this study, call for the survivability of the nuclear waste payload in low-probability launch pad accidents. Before the survivability (payload response) can be assessed, the worst-case credible accident environments must be defined. Although not done in this study, it is recommended that future efforts establish probability distribution for accident environments such that total risk estimates are realistic. This section describes the first analysis of the major accident environments for the Uprated Space Shuttle(13) and the heavy lift launch vehicle (HLLV)(14). The categories of environments analyzed are: (1) liquid propellant fireball; (2) liquid propellant residual fire; (3) blast wave overpressure; and (4) fragment. These are discussed below.

Should the fully loaded, liquid hydrogen/liquid oxygen/RP-1, Uprated Space Shuttle or HLLV explode on the launch pad, the nuclear waste payload could be exposed to a severe short-term thermal environment. Figure 9 is a schematic defining the assumed fireball features and fireball development with time. An example of the resulting relationship between temperature and time, as well as heat flux and time, is provided in Figure 10 for the Uprated Space Shuttle case.

Liquid propellant residual fires have been observed with the catastrophic failures of Atlas launch vehicles (which utilize RP-1 as a fuel).(15) Reference 16 indicates that residual fires are mostly expected to occur when high-boiling-point liquid fuels are present (e.g., RP-1). Also, Reference 16 indicates that residual fires involving RP-1 for the Atlas have been observed to last up to or exceeding one hour. The liquid propellant residual fire environment was parameterized by assuming a radiant heat flux of 198 kW/m^2, corresponding to a temperature of 1366 K (2000 F), and a burn rate of 0.439 cm/min for RP-1. To have a fire last over 1 hour, assuming no wind, the RP-1 pool depth would have to be greater than about 26 cm. Figure 11 provides the recommended combined fireball and residual fire environments for the Uprated Space Shuttle which were used in the payload response analysis. It is worth noting that this liquid propellant residual fire environment is much less severe than the solid propellant residual fires that have been predicted for the Space Shuttle.(7)

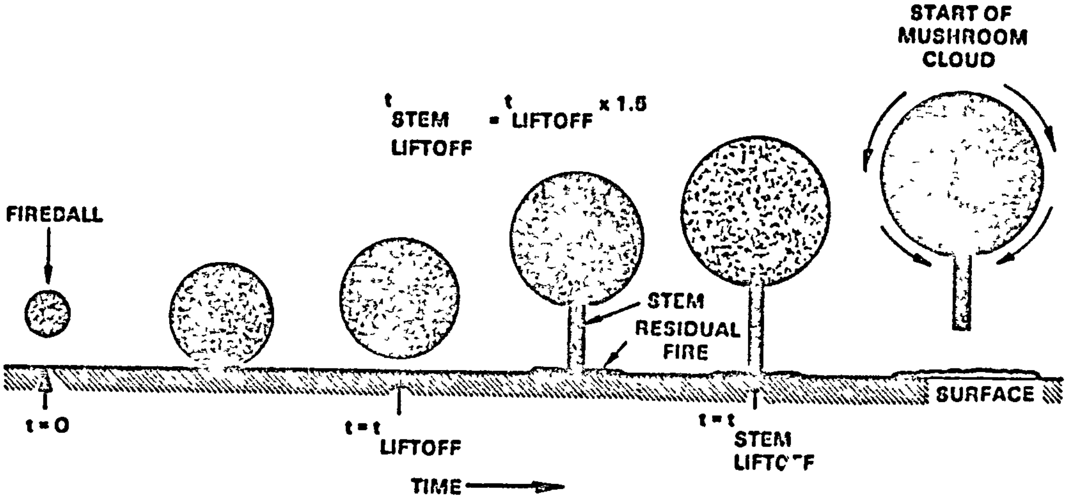

FIGURE 9. MODELED FIREBALL DEVELOPMENT

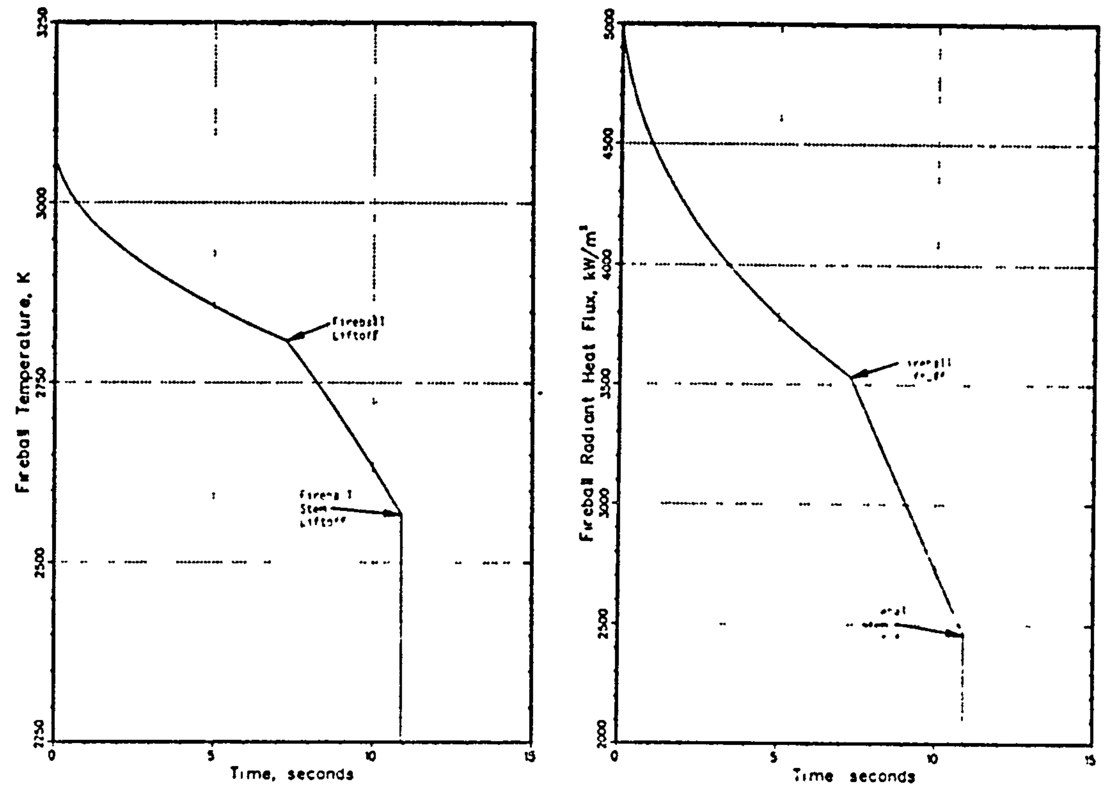

FIGURE 10. TEMPERATURE AND RADIANT HEAT FLUX AS A FUNCTION OF TIME FOR THE UPRATED SPACE SHUTTLE HYDROGEN/OXYGEN/RP-1 FIREBALL ENVIRONMENT

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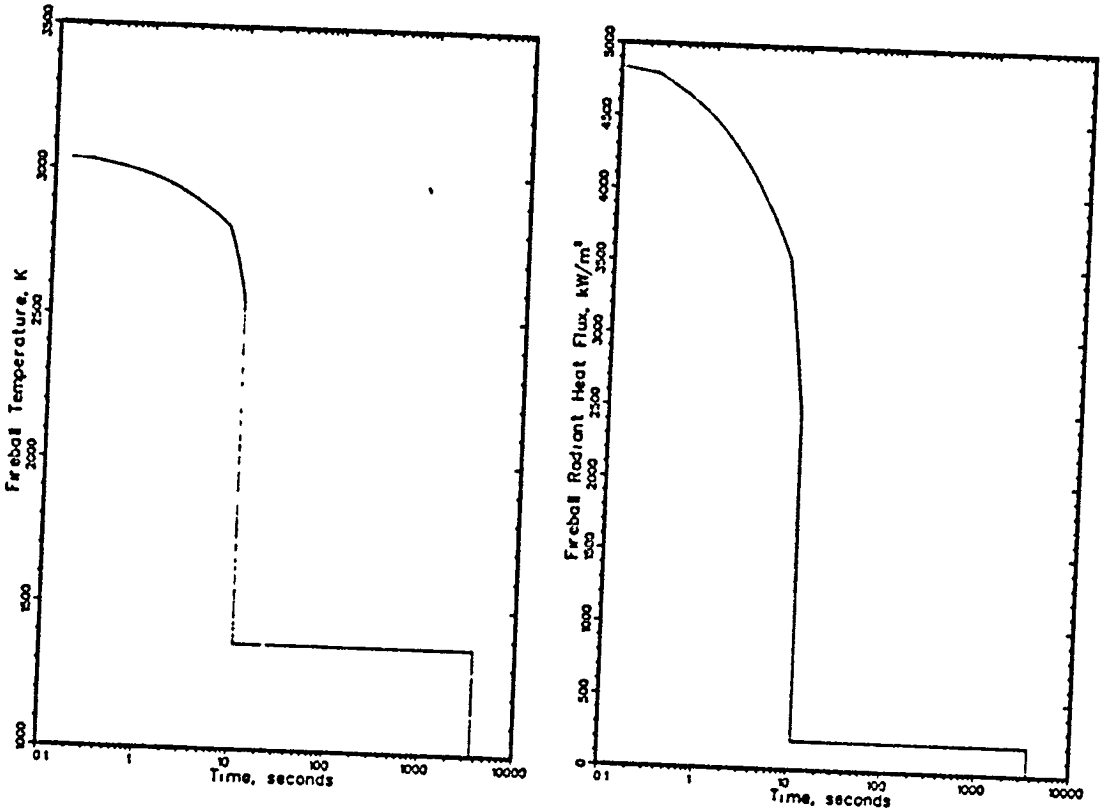

FIGURE 11. TEMPERATURE AND RADIANT HEAT FLUX AS A FUNCTION OF TIME FOR UPRATED SPACE SHUTTLE HYDROGEN/OXYGEN/RP-1 FIREBALL AND RP-1 RESIDUAL FIRE ENVIRONMENTS

Most recently, NASA/MSFC has recommended that a 10 percent yield be assumed for a failure of the Shuttle ET intertank structure during ascent.(17) Also recommended was that the resulting blast overpressure from an on-pad catastrophic failure (tipover), although at a higher estimated yield, would produce similar overpressures as the 10 percent yield during accent.(17) Procedures outlined in "Workbook for Predicting Pressure Wave and Fragment Effects of Exploding Propellant Tanks and Gas Storage Vessels", Reference 18, were used to calculate the overpressure and impulse data. Side-on and reflected overpressures and impulses are predicted as a function of percent explosive yield (0.1 to 160) and distance (15, 20, 30, 50, and 100 m) from the COE to the point of interest. Table 11 provides a summary of the data. Data are given for 1 and 10 percent yields with a COE assumed to be 20 m distant. These are the reference cases chosen for the safety design requirements and are recommended for future payload response analyses.

TABLE 11. TYPICAL BLAST WAVE ENVIRONMENT VALUES[a]

	Propellant Tank Configurations							
	OTV		LRB		ET		HLLV	
Characteristic	1%[b]	10%	1%	10%	1%	10%	1%	10%
Side-On Over-Pressure, N/cm^2	6.3	23	50	180	51	250	150	410
Reflected Over-Pressure, N/cm^2	16	82	220	1350	230	1700	1130	3050
Side-On Impulse, N-s/cm^2	0.05	0.21	0.35	1.5	0.45	2.0	1.2	4.6
Reflected Impulse, N-s/cm^2	0.12	0.73	1.5	11	1.9	15	8.7	35

Notes: (a) All data for distance of 20 m.
(b) Percent yield, TNT equivalent.

Prediction of the fragment environment at the payload position in the cargo bay resulting from the explosion of propellants in a rocket booster is an extremely complex problem. The fragments of primary interest, but perhaps not exclusively, are believed to originate from the propellant tankage and associated components. Figure 12 shows the relationship and the data quoted to support the correlation of explosive yield and fragment velocity, as developed in NASA CR 134906(18). This reference, on the basis of data pooled from a number of tests, suggests using a log-normal distribution of fragment velocities. The log-normal distribution is a very poor fit to the data. Figure 13 shows the data plotted as a normal distribution. The mean velocity is chosen from Figure 12. Figure 14 presents a plot of the fragment projected area distributions from the five events. This plot suggests that, at least as a reasonable upper bound, the mean fragment projected area and area distribution are independent of event parameters (yield and quantity of propellant involved).

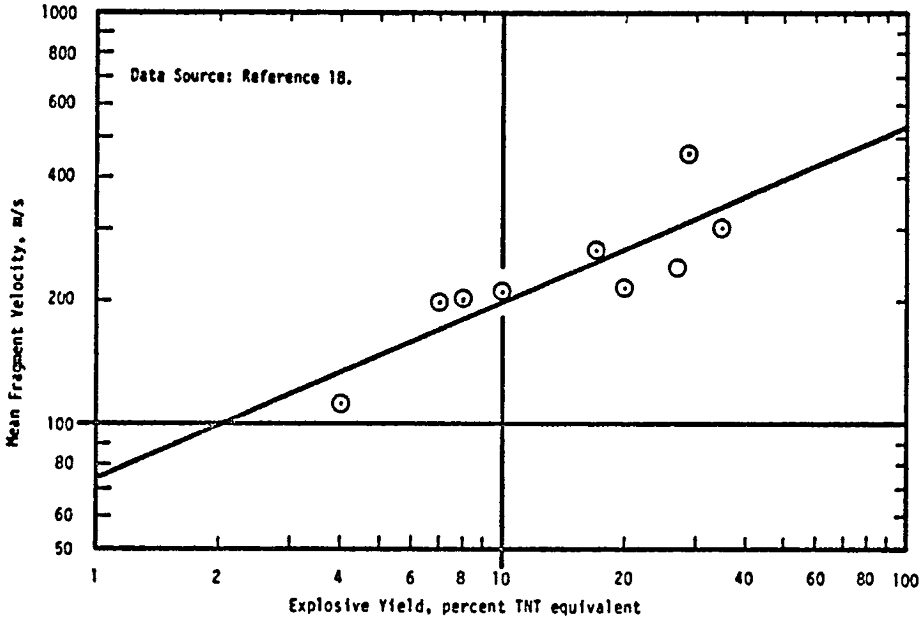

FIGURE 12. MEAN FRAGMENT VELOCITY AS A FUNCTION OF PERCENT EXPLOSIVE YIELD

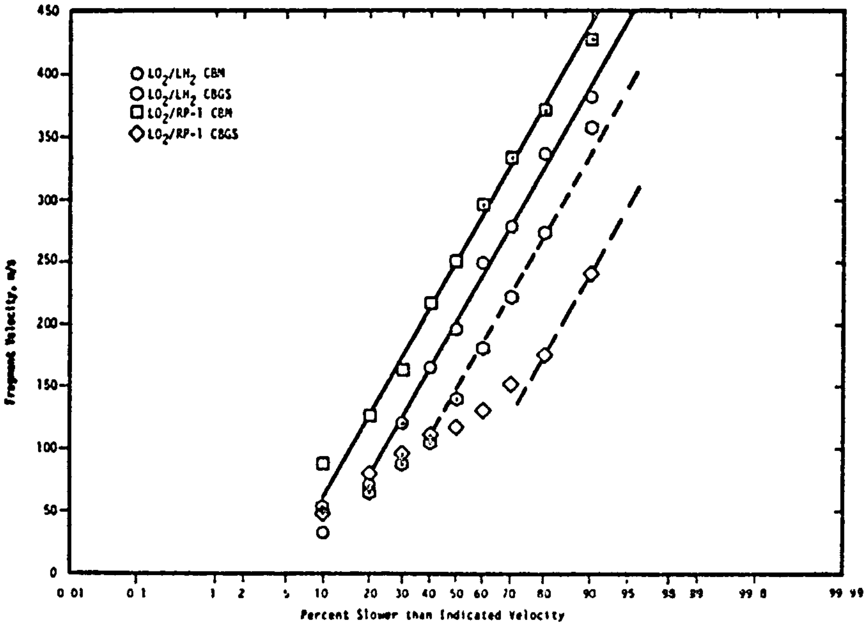

FIGURE 13. MEAN VELOCITY DISTRIBUTIONS FOR CONFINED-BY-MISSILE (CBM) AND CONFINED-BY-GROUND SURFACE (CBGS) FOR LOX/LH_2 AND LOX/RP-1

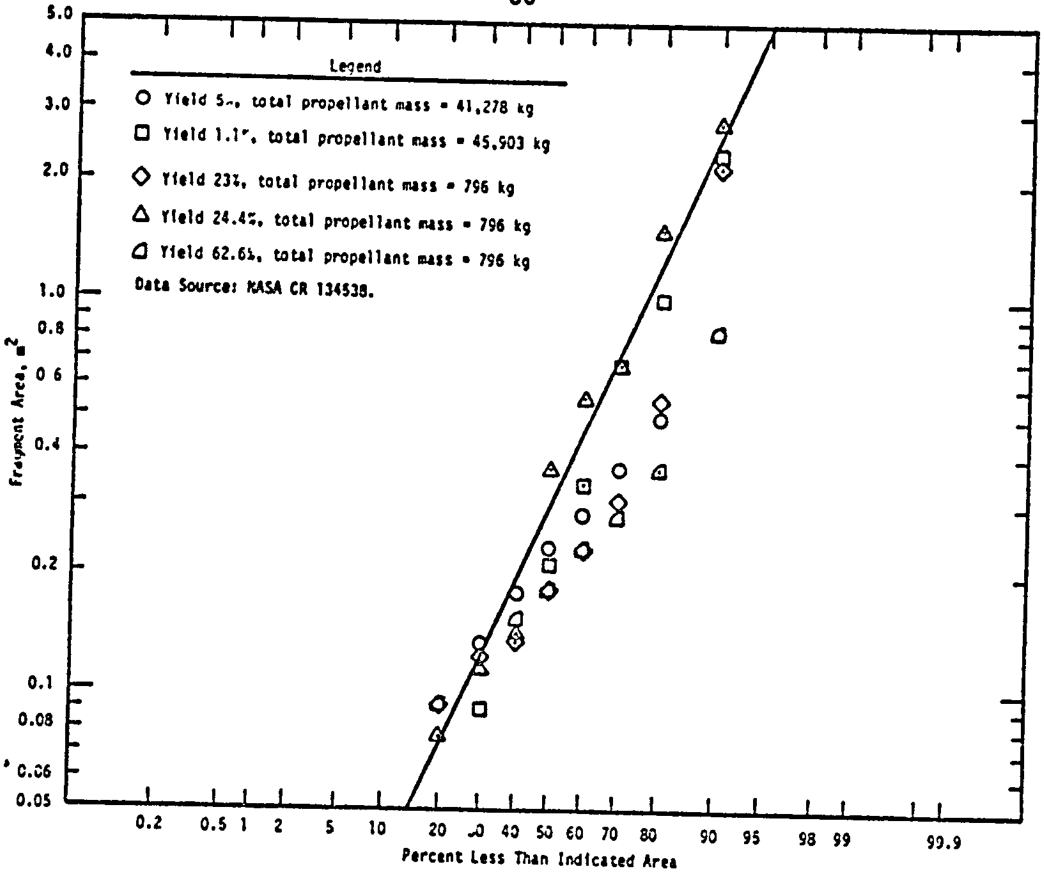

FIGURE 14. FRAGMENT SIZE DISTRIBUTION

5.3.3 Payload Response Analysis

There is a wide range of accident payload response analyses which need to be evaluated for the space option of waste disposal. A limited response analysis was conducted in this study. Future safety studies need to include a more in-depth analysis of the mechanical environment (impact, earth surface impact, etc.). The nuclear waste payload can be subjected to several possible severe accident conditions, including an on-pad launch vehicle fire, or an inadvertent reentry following an orbital malfunction. The major objectives of this effort were to determine the quantity of waste mass released due to the thermal environments alone and to recommend design modifications which would prevent the predicted releases.

For an inadvertent reentry and an on-pad launch vehicle fire, the thermal analysis indicated that no waste form release is expected to occur for the fully protected reentry vehicle configuration. However, for an unprotected container, severe stagnation point recession was predicted to occur during stable-mode atmospheric reentry. The resultant change in waste form shape due to recession following a stable reentry occurs on the entire forward portion of the body. A summary of mass released into the Earth's atmosphere due to the inadvertent reentry of various unprotected containers is given in Table 12.

TABLE 12. WASTE MASS RELEASE DURING UNPROTECTED WASTE FORM PLUS CONTAINER REENTRY

Reentry Mode	Mass/ Area, kg/m^2	Waste Mix	Initial Waste Form Wall Temperature, K	Initial Waste Form Mass$^{(a)}$, kg	Percent Released	Mass Released, kg
Stable	5193	PW-4b	800	5000	23.8	1190
Stable	5193	Modified PW-4b	573	5000	11.2	560
Spinning	5193	PW-4b	800	5000	2.4	120
Spinning	5193	Modified PW-4b	573	5000	0.0	0
Stable	6622	Modified PW-4b	608	9500	10.6	1007
Spinning	6622	Modified PW-4b	608	9500	0.0	0

Note: (a) Iron/nickel-based cermet waste form.

Based upon the release analysis, design changes are suggested to improve the accident response of the reference waste payload configuration. In the case of the on-pad launch vehicle fire environment, no design changes are recommended at this time, since no release is predicted. However, the Modified PW-4b cermet waste form will have a decreased probability of over heating due to loss of coolant, so, it is recommended that this waste form mix be utilized based upon this safety concern.

For an inadvertent reentry of the waste form plus container, it was found that large amounts (approximately 1 MT) of waste could be released into the Earth's atmosphere under certain conditions. Therefore, some design recommendations have been made, which would reduce and/or eliminate waste mass loss in the atmosphere during inadvertent reentry. These are:

- Aerodynamic devices to insure vehicle spinning during reentry
- Reduction in initial surface temperature
- Reduction in the vehicle ballistic coefficient
- Addition of a reentry protection shell on the container wall
- New container material.

5.3.4 Preliminary HLLV Safety Assessment

The HLLV concept considered is a design proposed in Satellite Power System (SPS) studies. It is shown in Figure 6. Principal differences between the HLLV and reference concept, as applied to the waste disposal operation,are summarized in Table 2. From a safety standpoint, use of the HLLV should not be significantly different from use of the Uprated Space Shuttle. Flight operations and payload handling techniques would be very similar, and the overall reliability of the HLLV should be comparable to that of the Uprated Space Shuttle. However, the HLLV is a much larger vehicle with greater payload capability (231,000 kg versus 45,400 kg for the Uprated Space Shuttle). Hence, the potential for more severe accident environments exists, as does the potential for more serious consequences of protection system failure--larger HLLV waste packages have a higher release potential. Two accident events were considered: (1) on-pad failures; and (2) inadvertent reentry of unprotected containers.

The HLLV uses the same propellents (RP-1, hydrogen, oxygen) as does the Uprated Space Shuttle, and in approximately the same proportions. However, the HLLV requires over three times the total propellent load of the Uprated Space Shuttle. Thus, in the event of an on-pad or near-pad failure a larger explosion and fire environment could result. Table 13 compares typical on-pad accident environments of the HLLV and Uprated Space Shuttle, that have been compiled from data developed in this study. The data in the table indicate that the accident environments for these two vehicles are predicted to be very similar. The blast wave environment for the HLLV is significantly higher; however, in reality this is not expected to be the case. The percent yield for the HLLV is expected to be lower than the percent yield for the Uprated Shuttle for a similar event. One can conclude, from reviewing these data, and with the assumption that the reentry vehicles are properly designed, that adequate margin exists for surviving the on-pad accident and, that there is little difference in the overall risk. On the other hand, if the reentry vehicle/protection system does fail, the amount of radioactive material released in a single incident is potentially much greater for the HLLV (28,500 kg) than for the Uprated Space Shuttle (5000 kg) case. This fact is of little concern; however, since proper design (and overall concept) can all but eliminate the probability of such a release.

Each HLLV launch will orbit three OTV/SOIS/waste package configurations. Each waste/package contains a spherical 9,500 kg cermet waste form (Modified PW-4b). Thus, failure of an OTV, following removal of the payload protection system could result in the reentry of a 9,500 kg waste mass. In the equivalent event for the Uprated Space Shuttle case, 5,000 kg of waste mass could reenter. For one event, the larger mass will result in about twice the upper atmospheric release of radioactive material (see Table 12) and would double the health effects (see Section 5.4). However, because OTV reliability is expected to be the same for both cases, and the HLLV option requires fewer OTV flights for the total program, the overall program risk and potential health effects can be expected to be approximately the same for both options. The HLLV cost is less than one-third the Shuttle cost. If risk becomes a more critical issue, then some (or all) of the transportation cost savings could be sacrificed to further reduce risks by increasing protective packaging/shielding. Therefore, it may be concluded that the HLLV option holds significant potential for reducing cost and/or reducing risk.

TABLE 13. COMPARISON OF HLLV AND UPRATED SPACE SHUTTLE ON-PAD ACCIDENT ENVIRONMENTS

Environment[a]	Uprated Space Shuttle	HLLV
Fireball		
Initial Fireball Temperature, K	3057	3058
Time to Fireball Liftoff, s	7.27	8.90
Time to Stem Liftoff, s	10.9	13.4
Heat Flux at Stem Liftoff, kW/m^2	2470	2700
Residual Fire		
Fire Temperature, K	1366	1366
Duration, sec[b]	3600	3600
Blast Wave[c]		
Side-on Overpressure, N/cm^2	250	410
Reflected Overpressure, N/cm^2	1700	3050
Side-on Impulse, N-s/cm^2	2.0	4.6
Reflected Impulse, N-s/cm^2	15.0	35.0
Fragments		
Mean Fragment Velocity, m/s	200	250
Mean Fragment Size, m^2	0.3	0.3
Fragment Flux, number/m^2	0.8	0.9

Notes: (a) Data from work performed in this study.
(b) Proper dike design is assumed to limit residual fires to 1 hour.
(c) Assumes a distance from COE of 20 meters and a 10 percent explosive yield for both cases. In reality, the percent yield is likely to be less for the HLLV than the Uprated Space Shuttle.

5.4 Health Effects Assessment

The overall objective of the continuing Health Effects Assessment is to provide estimates of radiation doses and health effects from major space disposal accidents, where nuclear wastes are postulated to be released to the biosphere, an additional subobjective of this activity is to support the selection process for the nuclear waste mix composition for space disposal. Studies conducted during this Phase III effort provide: (1) an assessment of various generalized indices for comparing the potential hazard associated with different nuclear waste mixes; (2) a critical review of methods available for dealing with the resuspension problem; and (3) an assessment of the upper atmospheric burnup of commercial waste payloads, by the estimation of the potential world population dose, including the consideration of inhalation of resuspended fallout particles. Analysis performed was based upon the use of Modified PW-4b waste mix. The health effects assessment conducted here is not intended to be used in comparisons with other waste disposal options or used in environmental assessments of the space option. Its sole purpose is to influence the design selection and operational alternatives, such that, a safe space disposal concept is evolved.

5.4.1 Hazard Index Evaluation

To assess the possible risk/benefits derived from space disposal, two hazard models were evaluated. The two models selected for study were ORIGEN(11) and AMRAW-A.(19) ORIGEN is an isotope generation and depletion code which can calculate the quantity of air or water necessary to dilute each radionuclide contained in HLW to the maximum permissible concentration (MPC) at various points in time. It does not account for geologic transport of radionuclides, their subsequent uptake in food chains, nor estimate the subsequent dose rate to individuals in the vicinity of the repository. In contrast, AMRAW-A has a source term model similar to ORIGEN to calculate radionuclide concentrations at various points in time, a release model which simulates geologic transport, an environmental model which simulates radionuclide uptake in food chains, and can estimate the resultant dose rate to individuals in the vicinity of the repository at various points in time (see Figure 15).

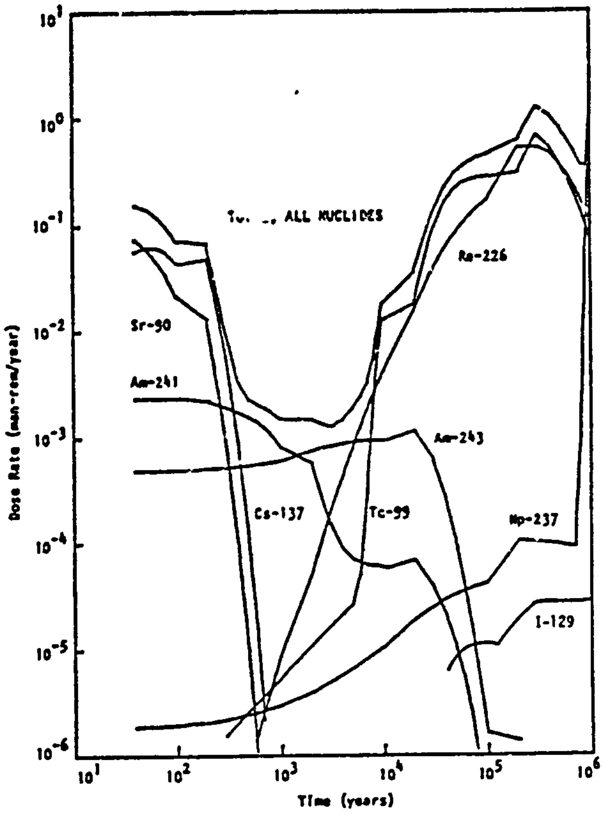

FIGURE 15. RESULTS FROM AMRAW-A MODEL

The ORIGEN hazard analysis for commercial waste concluded that: (1) the only mix which significantly lessens the hazard of terrestrial disposal is sending the entire HLW fraction to space and keeping the structural materials, cladding, and volatile fission products on Earth; (2) "hazard" as defined in the ORIGEN model is a naive approach which should not be taken seriously; and (3) the model is overly simplistic and does not provide a realistic evaluation of the problem.

The AMRAW-A analysis for commercial waste concluded that: (1) a potential mix for space disposal, useful in effectively reducing the hazard associated with terrestrial disposal, is the actinide fraction of HLW plus technetium (Tc), and (2) it is important to note that ^{129}I, often considered as a major problem for terrestrial disposal, does not contribute significantly to the dose rate for the time span shown.

In summary, the continuation of this type of analysis is vital to the proper selection of the nuclide mix for space disposal. Models, like the AMRAW-A code, should be applied to the space disposal option. The 4-year Concept Definition and Evaluation Program Plan developed during the course of this Phase III effort emphasized the importance of this activity.

5.4.2 Resuspension Effects

Assessment of the impact on world health of the accidental reentry and possible partial burnup of a nuclear waste payload is based on a model designed to provide estimates of world population doses due to inhalation of particulate burnup debris. During the Phase II study, inhalation of resuspended particles was ignored. Numerous studies have demonstrated that radioactive particles deposited on soil or other environmental surfaces are susceptible to resuspension by wind action and/or mechanical disturbance. Studies conducted in fallout fields at the Nevada Test Site and elsewhere indicate that the resuspension factor in relatively undisturbed environments decreases with time after deposition and tends to an asymptotic value of about 10^{-9} m^{-1}. Finding no satisfactory general model of the resuspension process and lacking an adequate data base for implementation of the empirical models currently available, it was decided to use the mass loading approximation suggested by Anspaugh(20, 21), to provide a reasonable basis for approximating the effect of resuspension on the estimation of world population doses which would follow the accidental release of a nuclear waste to the biosphere.

5.4.3 Burnup Accident Analysis

The basic assumptions, general formulation, and mathematical development of the model used to estimate world population doses due to the accidental reentry and burnup in the upper atmosphere of a nuclear waste payload are described in Reference 7. The burnup accident assessment results for the Modified PW-4b commercial waste mix are given here, and include estimates of both fallout and resuspension dose. Results indicate that the major component of the world dose results from fallout prior to resuspension.

Using a predicted 11.2 percent Modified PW-4b payload burnup (see Table 12 for a 5 MT cermet waste form) with an assumed particle size of 0.2 microns, the maximum individual lifetime doses would be about 0.043 rem to the lungs, 0.016 rem to bone and 0.0011 rem to the total body. These estimates are well below the annual dose-rate limits for individuals of the public. The world-wide health effects predicted for Modified PW-4b cermet payloads, are given in Table 14. The results shown support the recommendations that thermal reentry protection should be added to the container surface, and that the stainless steel container material be replaced by a higher melting point alloy. It should also be noted that the health risk is proportional to the amount of high-level waste dispersed accidentally into the upper atmosphere and that the upper and lower bounds of risk are strongly influenced by assumed particle size.

TABLE 14. RANGES OF EXPECTED HEALTH EFFECTS FOR INADVERTENT PAYLOAD REENTRY BURNUP, AS PREDICTED BY PAYLOAD BREAKUP ANALYSIS (MODIFIED PW-4b IN CERMET)

Type of Risk(a)	Releases, kg			
	1	1007(b)	560(c)	0(d)
Cancer deaths from:				
Total Body Exposure	0.0031 - 0.078	3-79	1-44	0
Lung Exposure	0.0059 - 0.296	5-299	3-166	0
Bone Exposure	0.0036 - 0.065	3-66	2-37	0
Genetic effects from:				
Total Body Exposure	0.0031 - 0.078	3-79	1-44	0

Notes: (a) Risk factors used were taken from Reference 7.
(b) 9.5 MT Payload, stable reentry, no thermal protection.
(c) 5.0 MT Payload, stable reentry, no thermal protection.
(d) 5.0 MT Payload, spinning reentry, no thermal protection.

5.5 Long-Term Risk Assessment*

Safety risk may be separated into two categories on the basis of timeline consequences and response. Short-term risk, measured in hours or days, is associated with accidents occurring prior to deep space injection. Included in this cateogry are the sequential phases of waste payload ground phase of the injection burn while the payload is still bound to Earth's gravitational field. Long-term risk measured in hundreds or thousands of years, commences after the payload has attained Earth-escape conditions. For the reference concept of a solar orbit destination, this category encompasses deployment system (propulsion and control) failures which prevent the payload from achieving its stable orbit destination, and accidental explosion or other fragmentation events (meteor encounters) which break up the payload and upset the long-term orbit stability. These failures or events could result in the waste material being stray objects in planet-crossing orbits with subsequent future risk of reentry in Earth's biosphere. Some of the short-term safety problems are addressed in Sections 5.3 and 5.4. This section addresses two new aspects of the long-term problem.

A key result of earlier studies is that it may be possible to attain acceptably low levels of long-term risk only through the mechanism of

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*Note: This section was prepared by "Science Applications, Incorporated, Schaumburg, Illinois, under subcontract to Battelle's Columbus Laboratories.

retrieval and final disposal of failed payloads. Rescue mission capability is defined as the ability to send another propulsion system to rendezvous with the failed payload in orbit and to place it into the desired disposal orbit. Suppose, however, that the payload has fragmented, making rescue impossible. Section 5.5.1 addresses the fragmentation problem and its consequences with the objective of describing the orbital evolution characteristics of small particles in solar orbit and the probability of eventual Earth reentry of this material. Section 5.5.2 then takes up the more likely disposition of failure wherein the payload remains intact and is subject to rescue attempts. The objective here was to provide a technology assessment of the (critical) automated rendezvous and docking phase of the rescue mission with emphasis on noncooperative or only partially cooperative rendezvous due to failure of crucial payload subsystems such as communications and attitude control.

5.5.1 Payload Breakup Effects

Small remnant particles on the order the 1000 microns or less are subject to various nongravitational forces in the space environment, such as solar radiation pressure and the electromagnetic field carried by the solar wind. Physical processes such as photoionization and surface erosion can induce changes in the state of material that enhance the nongravitational effects. The orbital evolutionary consequences for small particles are very different from those applying to objects influenced by gravitational forces alone. Gravitational forces act on all bodies independent of size. The perturbing effects of these forces have been described in detail in previous analyses of long-term risk, but they are noted again here because of their interaction with nongravitational force effects which are strongly dependent on particle size. In particular, the close planetary encounters which could arise as a result of the latter perturbations is one of the principal mechanisms for waste particle interception by Earth. The two most significant nongravitational perturbations are Poynting-Robertson drag and electromagnetic Lorentz scattering.

Figure 16 describes the mass-time distribution of cermet small particles for initially circular orbits at both 0.85 A.U. and 1.19 A.U. distance from the Sun. For the 0.85 A.U. case (Curve A), the resulting disposition stated as a fraction of the total initial mass in small particles is as follows: (1) 0.12 percent falls on Earth; (2) 2.57 percent falls on Venus; (3) 0.28 percent falls on Mercury; and (4) 97 percent survives to the close vicinity of the Sun. The mean time of the material returned to Earth is about 10^5 years after the payload breakup event. Of the particles surviving to the Sun, 20 percent of the mass arrives within 10^5 years, 63 percent within 10^6 years, and 97 percent within 3 x 10^6 years after payload breakup. It is expected that the surviving mass will be quickly ejected toward the outer solar system by the solar wind and radiation pressure forces following vaporization, sputtering and/or photoionization. During the ejection process, which occurs at different times for individual particles, the probability of interception and capture of charged particles by the Earth's magnetosphere is very small--less than three chances in a million. Curve B applies to an initial circular orbit at 1.19 A.U. In this case, because the Earth's orbit is first crossed as the particles spiral inward, the material that could be expected to return to Earth increases to 6.7 percent of the initial mass in small particle distribution. The mean time of this occurrence is about 45,000 years after payload breakup.

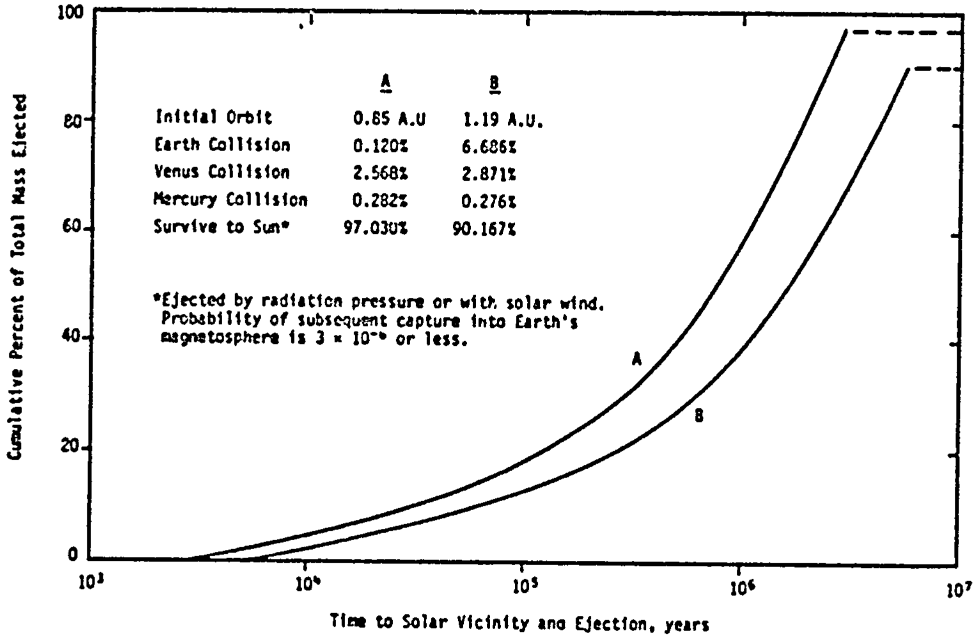

FIGURE 16. DISPOSITION OF SMALL PARTICLE MASS DISTRIBUTION (CERMET WASTE FORM) UNDER POYNTING-ROBERTSON AND LORENTZ FORCES, INITIALLY CIRCULAR ORBITS INCLINED 1° to ECLIPTIC PLANE

It is important to place the results of the small particle effects analysis in perspective. The mass return fraction associated with a payload breakup event needs to be tagged with the probability of occurrence of such an event. For the reference waste cermet form, the threshold energy level of catastrophic fragmentation due to a 0.24 kg meteoriod impact would release only 0.2 percent of the total material in small particles. The probability of this threshold impact event is about 4 x 10^{-9} per year. Complete fragmentation by a meteoriod mass of 30 kg is 6 x 10^{-11} per year.

The data shown below assume a 5000 kg cermet payload placed in the nominally stable 0.85 A.U. circular orbit. The data show the probable amount of mass return to Earth as a function of time under the condition of immediate total fragmentation. For times up to 6.7 million years after fragmentation (or launch), the probably mass return is only 0.017 kg. The maximum mass return is 6 kg (0.12 percent of 5000 kg), but this requires a time interval of 3 million years.

Time After Fragmentation, Years	Probable Mass Return to Earth, kg
10^3	0.014
10^4	0.015
10^5	0.017
10^6	1.3
3×10^6	6.0 (Maximum)

With the assumption of a 5000 kg cermet payload in a 0.85 A.U. circular orbit, the consequences of material release, distributed over time in orbit, are given below. An integrated release rate of 1.6×10^{-6} kg/year applies in this case; i.e., the probable material release by meteroid impact over 1 million years is only 1.6 kg. Since the probable amount of mass return to Earth is a small fraction of the mass released, this amount is quite negligible even up to several million years after launch. The probable maximum of 6 kg requires an interval of 3 billion years.

Time After Fragmentation, Years	Probable Mass Return to Earth, kg
2×10^3	4.5×10^{-9}
2×10^4	4.8×10^{-8}
2×10^3	4.5×10^{-9}
2×10^4	4.8×10^{-8}
2×10^5	5.4×10^{-7}
2×10^6	4.2×10^{-4}
3×10^9	6.0 (Maximum)

Unless evidence to the contrary is uncovered, we would conclude that program planners need not be concerned about the risk associated with small particle release from a cermet payload in solar orbit. A much more likely failure event is that the payload would not achieve the desired orbit because of vehicle system malfunction. In such a case a rescue mission could be attempted, and the chance of payload breakup during the relatively short time before rescue is virtually nil.

5.5.2 Rescue Mission Technology Assessment

The objective of the subtask was to provide a more detailed technology assessment of the (critical) automated rendezvous and docking phase of the rescue mission. Of particular interest is the case of noncooperative or only partially cooperative rendezvous due to failure of crucial payload vehicle subsystems such as communications and attitude control. The approach taken was to review and summarize the current status of the technology, including ongoing programs, as ascertained by a literature search and personal contact with NASA and contractor staff members working in this field. This information provides a basis for new directives in supporting research and technology (SR&T) programs.

The implementation of automated rendezvous and docking operations as would be required for rescue of disabled nuclear waste payloads can by no means be viewed as an easy problem. This technology is in its early stages. However, there is no need to prove "off-the-shelf" availability of such systems today. What is needed is reasonable confidence that this capability can be developed in the near future, and an implementation plan to assure this development. Cooperative, unmanned rendezvous between two spacecraft can be accomplished with current technology. The demonstration of this by the U.S. is simply a matter of priorities, funding, and engineering design. Once this is accomplished there should be a steady progression to rendezvous and recovery of targets that have not been predesigned to aid these operations, i.e., partially cooperative or noncooperative targets.

If rescue capability is necessary in nuclear waste disposal, then it follows that cooperative rendezvous must not be relied on as the only mode of rescue operations. Fallback options must exist in the event of failure of target vehicle's communication link or attitude control capability. The following classification of rescue scenarios along with possible design criteria will place some perspective on the problems:

Class 1 Rescue. Cooperative rendezvous and docking is the nominal mode of operation and is reflected in the design of both rescue and target vehicles. Some level of redundancy is built in the target's subsystems to assure high reliability of nominal function.

Class 2 Rescue. Failure has occurred in the target's communications tracking link and/or 3-axis stabilization function. In the first instance, the rescue vehicle employs a backup sensor mode during the terminal rendezvous phase to acquire the target at long range, e.g., IR or higher powered RF radar. Possibly the target can aid this search by automatically deploying devices or material to increase its RF target cross section. In the second failure instance, the target automatically reverts to backup energy dissipation devices to convert tumbling motion into spin-stabilized motion. The rescue vehicle design accommodates docking with a spinning target as a backup mode. The target vehicle likewise accommodates this mode by design.

Class 3 Rescue. The target vehicle is completely noncooperative as a result of failure or absence of backup systems. The rescue vehicle is designed to accommodate all possible contingencies and still capture the target.

It is clear that each of these scenarios, ordered by increasing technical difficulty, will drive the design configuration of both rescue and target vehicle systems in different ways. Premature selection of fallback options may even affect the viability of the entire rescue concept. Tradeoffs need to be made regarding questions of: (1) technology feasibility and development risk; (2) cost implications; (3) system reliability; and (4) rescue policy and ground rules related to acceptable level of risk of not succeeding. The data base that would eventually allow such trade-offs to be made needs to be improved. It is recommended that future study activity on the space disposal concept address this objective some place in the statement of work for both NASA in-house planning efforts and contracted systems engineering efforts.

In specific areas of supporting research and technology, the following directions are indicated:

1. Sensor Technology

a. Long-Range Target Acquisition Device--conceptual design and analysis of candidate sensors (e.g., IR or RF) that could locate a passive target at ranges exceeding several thousand kilometers.

b. Automated Video Trackers--a phased development program to include data requirements definition, algorithm development, component design, laboratory breadboarding and testing, and flight tests.

2. Docking/Capture Technology

a. Energy Dissipation Mechanisms--a conceptual design study and analysis of candidate mechanisms (on-board target vehicle) for backup attitude control. Study input is current definition of waste payload/SOIS configuration. Study output is data base on derived system requirements, control response, estimated development cost and risk, and comparative evaluation.

b. External Torque Mechanisms--study scope similar to above but confined to techniques and devices (on-board rescue vehicle for capture of unstable targets).

5.6 Program Planning Support Analysis

The objective of the program planning support analysis was two fold. First, BCL assisted NASA/MSFC and ONWI in providing appropriate input data for generating two specific working documents: (1) the Concept Definition Document (see Section 5.1 of this report)(4); and (2) the 4-year Concept Definition and Evaluation Program Plan for the space option(5). Second, the requirements for licensing, SR&T, and testing were assessed. Discussion relating to SR&T requirements is given in Section 7.0 of this summary report.

Six different drafts of a 4-year program plan for determining the feasibility of the space option were prepared by BCL for NASA/MSFC and ONWI. Drafts of the plan considered information from last year's study, new input from NASA/MSFC and ONWI, and review/comments from the newly formed DOE/NASA Ad Hoc Coordinating Group.* The plan identified the following program objectives:

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*Note: The purpose of this group was to coordinate program planning for the space option. The group is made up of personnel from ONWI, NASA/MSFC, Sandia, Savannah River Laboratories, NUS Corporation, Battelle Northwest Laboratories, Applied Physics Laboratory and DOE/Headquarters.

- Risk - To identify and quantify the risk benefits that may be achieved through use of space disposal of certain radioactive wastes as an augmentation for geologic waste disposal.

- Cost - To establish the costs of the space disposal augmentation for a reference risk level. Also, to establish the incremental costs of risk improvement.

The work breakdown structure for the January 28, 1980, plan is shown in Figure 17. For other details concerning the plan the reader is referred to Reference 5.

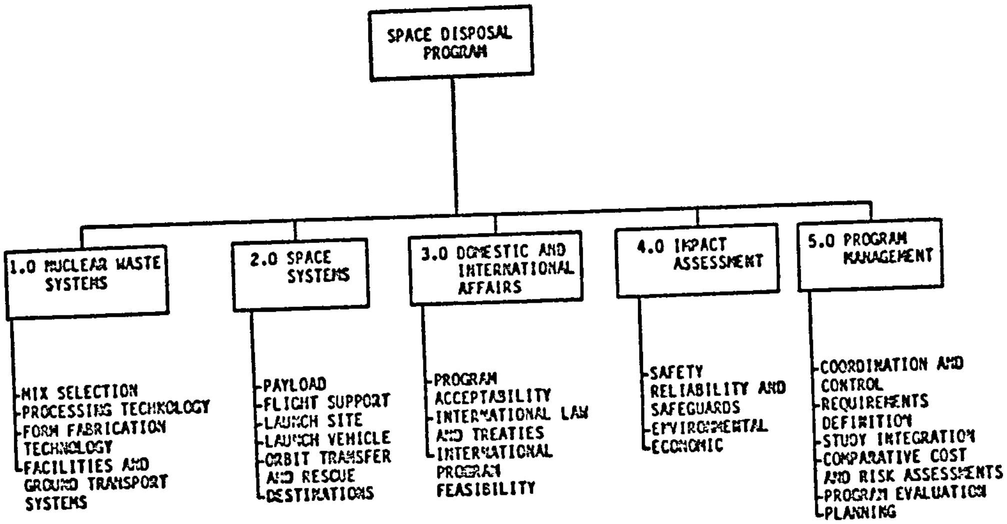

FIGURE 17. WORK BREAKDOWN STRUCTURE FOR SPACE OPTION PROGRAM PLAN

5.6.1 Licensing Requirements Definition

This section discusses the licensing and policy questions which must be answered before proceeding with the space disposal option. The four primary areas of concern in developing the space disposal option are:

(1) The development and construction of the waste treatment and payload fabrication/preparation facilities
(2) The development and construction of the launch site facilities
(3) The development of standards, criteria, and regulations for the space disposal option
(4) The major policy decisions required to allow the space option to proceed.

The interaction of these major areas is shown in Figure 18. The next three paragraphs discuss the three major areas identified in the figure.

The waste treatment and payload fabrication facilities include the system for recovery of the wastes from storage, processing the waste, preparing an acceptable waste form, and loading the waste in a specified container. Since the defense HLW is stored at DOE sites, it is expected that the waste treatment and payload fabrication facilities would be built at the site where the waste is located. Currently, these facilities do not require NRC operating licenses or construction permits. The disposal of commercial HLW will require all the processing facilities to have NRC licenses. Since the waste treatment and payload fabrication facilities are much like a fuel reprocessing plant, such facilities could be licensed under regulations written in 10CFR 50.* These facilities would go through the standard licensing process, with a construction permit first being obtained, and finally an operating license. Both preliminary and final safety analysis reports would be required and the appropriate reviews would be carried out by the NRC.

The launch site facilities include the Nuclear Payload Preparation Facility (NPPF), a ground transport system, and launch vehicle system including the mission operations and recovery system. These facilities will be the same for defense or commercial HLW. The launch facilities are viewed as a site with a radioactive materials license and the launch system as a transport vehicle carrying a licensed transportation payload. The licensing of a facility for possession handling of radioactive material and the licensing of a container for shipping materials are the methods currently used in the regulations. Operations at the NPPF are expected to be simpler than those carried out in many hot cells. The Interagency Review Group(23) has recommended that the NRC license all facilities for the long-term storage of radioactive waste. The launch vehicle is viewed as a transport vehicle, such as a plane or truck. The current procedure, as applied, would be to license the payload for shipment in the Shuttle. Obviously, a new set of design criteria would have to be set so that the payload and its contents would perform as intended under accident conditions. If a specific disposal site, such as the lunar surface, were selected as a space disposal site then the site would likely be licensed as any terrestrial site. However, it is expected that a solar orbit would not be licensed but specific criteria would be specified which the solar orbit would have to meet.

Several major policy decision points will occur during the development of the space option. The first of these is a decision to proceed with the research and development required for the space option. If this decision is positive, the research required to develop the waste treatment processes, waste forms, and payload fabrication should proceed. Also, the standards, criteria, and regulations should be drafted. In conjunction with this, a draft environmental impact statement for the program must be prepared. A final program EIS on space isolation would be prepared and international

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*Existing United States Nuclear Regulatory Commission (NRC) regulations are quoted frequently in this section. 10CFR 50 refers to Part 50, Title 10, Code of Federal Regulations - Energy. See Reference 22 for full title.

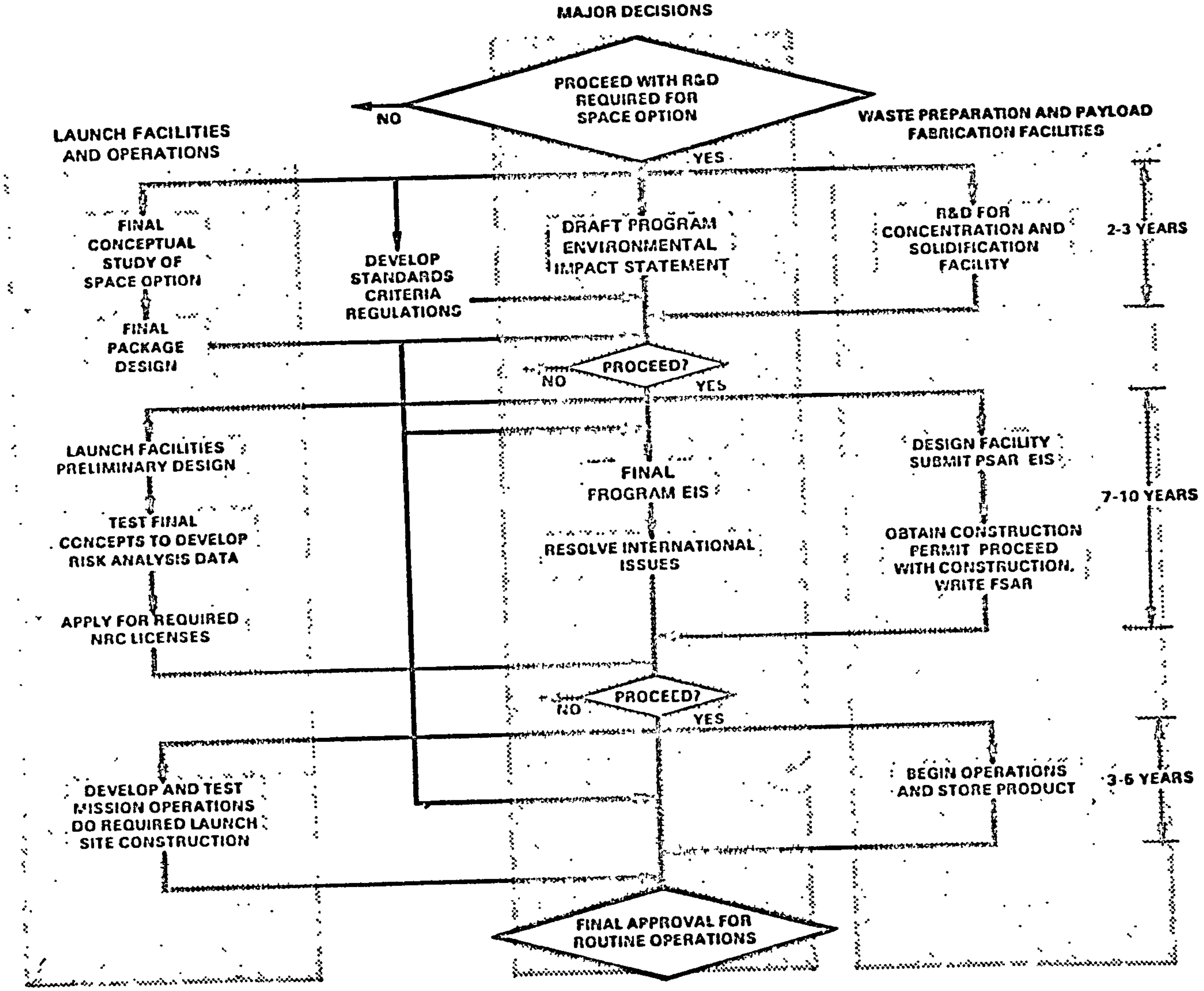

FIGURE 18. INTERACTION OF LICENSING WITH OTHER MAJOR DECISION AREAS

issues identified and resolved. Testing of systems such as reentry and rescue systems must be carried out. These tests would allow a quantification of risk and consequences. The next decision would be to develop and test the complete mission operation. Required launch site facility construction would begin and final testing be completed. These would lead to the final approval of routine space disposal operations.

5.6.2 Safety Test Requirements

The unique nature of the space option for disposing of nuclear waste and the possible high concern over possible releases of nuclear waste material in the event of accidents (especially launch accidents) is expected to lead to an extensive requirement for testing. Only testing related to critical safety problems is presented here. Safety testing that is expected to be accomplished, prior to carrying out actual disposal missions, includes: (1) materials characterization tests; (2) scale model response tests; (3) full-scale ground-based subsystem response tests; (4) flight tests of specific hardware items; and (5) qualification flight tests of the entire space disposal mission, both small and large scale. This section summarizes a preliminary two-phase plan for safety testing for the space option.

5.6.2.1 Safety Tests Anticipated During 4-Year Space Option Study

The safety related testing anticipated during the proposed 4-year Concept Definition and Evaluation Program is expected to involve only critical components of the conceptual space disposal system. Only those safety tests required to reduce the uncertainty in risk are appropriate during the 4-year study program. The Draft Concept Definition and Evaluation Program Plan for Space Disposal of Nuclear Waste(5), identifies areas of safety testing fo- the space disposal concept. During the fourth year, safety testing of "critical payload features" would be performed for the baseline concept.

Risk associated with launch accidents, regardless of the type of nuclear waste that is disposed of in space, will be of utmost importance in determining feasibility. Certainty in payload survival is essential to the concept. Therefore, safety tests of protection system concepts, where material components are exposed to the expected sequential environments of the on- or near-pad booster failure are likely to be performed. Protection systems, in general, include: thermal protection; insulation; impact shield, radiation shield; primary container; and the waste form itself. Scale-model testing of these system components appears to be appropriate. The physical and chemical characteristics of materials proposed for use in protection systems may also have to be determined to greater confidence levels.

Risk associated with inadvertent reentry of nuclear waste payloads, depending upon the baseline concept, is also expected to remain an important part of the space option risk. Aerodynamic heating, ablation and thermal shock tests, associated with worst-case reentry environments, may be necessary for scale-model system concepts. In addition to the consideration of testing of payload protection systems, the response of the "baseline" surrogate waste form to reentry environments may also be required. The consequences of a reentry accident depends not only upon how much of the waste form might be released in the upper atmosphere, but also upon the particle size distribution. Because of the manner in which a waste form may be released (melting), an actual test involving a surrogate waste form may be the only way to obtain confidence in the health risk prediction. Tests to measure scale-model payload response include the use of hypersonic and supersonic wind tunnels, and the use of liquid rocket engine plume facilities (mostly for thermal shock).

5.6.2.2 Safety Testing for Development Program

Three categories of tests are anticipated during the development program for the space option: ground-based tests, flight tests of specific items, and qualification flight tests. A number of specific tests for each category are identified below. Additional test items are expected to be identified as the program evolves.

Most accident conditions can be simulated in ground tests. Sequential testing is likely to be a requirement. The exact conditions under which tests would be conducted would likely be defined as a part of the licensing criteria process. The actual tests would be conducted during the period prior to the application for license from the NRC, and the test results would be included in the supporting data accompanying the license application. Preliminary ground testing of subscale payload models for various portions of the reentry environment can be conducted. Tests involving the waste form are expected to be conducted to demonstrate that the final waste form has the desired characteristics. These tests will probably be conducted in a low-density, high-stagnation-temperature hypersonic or supersonic wind tunnel facility. Ground tests concerning the transportation and handling of the nuclear waste prior to launch will be required to demonstrate payload intact survival under various accident conditions (e.g., ground transport delay combined with loss of primary cooling, dropping of the payload in the NPPF).

A number of specific subsystems will need to be flight tested separately prior to an overall flight demonstration of the entire waste disposal system. Three subsystems are likely to receive specific attention: payload protection, payload cooling system operation, and remote rendezvous/docking. Reentry tests would be designed to demonstrate container survival and/or to detect any container breach and associated surrogate waste form dispersion. Internal waste form melting could occur for high-level waste payloads with cooling system loss, while in the reentry vehicle. Operational safety procedures and operational subsystem reliability could be verified and carried out piggy back on other Space Shuttle missions. Special flight tests would be of the remote rendezvous and docking capabilities with an uncooperative mockup payload. The required rescue mission simulacion would take place in low Earth orbit. Rendezvous and docking would likely use a man-in-the-loop system with continuous control. A simulated deep space rendezvous and docking would be carried out by employing an on-board autonomous system. Both capabilities could be demonstrated in one flight test.

Prior to final operating license approval, it is expected that several qualification flight tests of the entire space disposal system will be required. The tests would be designed to demonstrate the nominal disposal mission profile. Early tests could involve reduced waste form masses; later, after confidence is gained, "fully loaded" payloads could be used. It is likely that the disposal system will also have to demonstrate its ability to correct unexpected subsystem failures. In qualification flight tests, this would likely take the form of several planned simulated subsystem failures or anomalies. These failures would be known to the program test managers, but not to the flight control personnel responsible for conducting the test flight. Successful demonstration of the mission profile while overcoming the unexpected anomalies would be a major step in satisfying NRC and other regulatory requirements and in increasing public confidence in space disposal.

5.7 Conclusions

This section summarizes a few of the general conclusions that have been reached as a result of this Phase III study. The conclusions listed below have been organized by task activity:

Payload Characterization (Task 1)

- The ORNL iron/nickel/copper-based cermet waste form has been judged, at this point in time, to be the most suitable waste form for the space disposal of high-level nuclear waste.
- ^{90}Sr and ^{137}Cs contribute significantly to the internal heating problems associated with the space disposal mission.
- Proposed thermal limits for the waste form restrict the size of the cermet form to 8 to 9 MT per payload when considering the PW-4b waste mix.
- For commerical high-level waste, the neutron dose becomes significant for large payloads (> 5 MT).
- For an unshielded 5.5 MT commerical high-level waste payload, an operating distance of greater than 1 km is required to maintain a dose level to the crew of less than 2 rem/hour; the similiar operating distance for an unprotected defense waste payload is less than 20 meters.
- Radiation shielding provided to the crew by Space Shuttle Orbiter structure is considered to be negligible.

Safety Assessment (Task 2)

- The on-pad catastrophic failure of an Uprated Space Shuttle (liquid rocket boosters replacing the solid rocket boosters) is likely to have significantly less severe thermal accident environments than the standard Space Shuttle.
- Because of its very short duration (less than 15 seconds), the fireball resulting from the on-pad catastrophic failure of almost any liquid propellant booster is considered to be virtually unimportant when compared to the possible long-term residual fires.
- Because of the large uncertainty in the fragment (shrapnel) environment data base, caution must be taken in using the data.
- The simulated reentry of the reentry vehicle (RV) showed that the RV should survive with adequate margins; the terminal velocity for the reference vehicle is 110 m/s.
- Under certain reentry conditions it is likely that the unprotected stainless steel container wall will melt away and allow the release of the cermet waste form material to the atmosphere.
- If the thermally unprotected waste container is cool enough prior to reentry and is made to spin or rotate during reentry, no release of waste is expected.
- For the case of an inadvertent reentry of the unprotected waste container (5 MT waste form) the predicted terminal velocity is excessive (365 m/s).
- Calculations show that the thermal protection provided by the reentry vehicle in the event of a catastrophic Uprated Space Shuttle vehicle failure is adequate, even if the thermal protection system and insulation were lost in the initial explosion.
- For the same degree of payload protection, the total risk of a space disposal program carried out by the HLLV versus the Uprated Space Shuttle is approximately equal.
- The use of a HLLV provides the opportunity to significantly increase protection and decrease the event and total program risk for a similar launch cost.

Health Effects Assessment (Task 3)

- The simplified ORIGEN dilution hazard index is <u>not</u> adequate to determine which radionuclides should be disposed of in space.

- The results from the pathway model assessment indicate that Tc and the actinides are appropriate for space disposal.

- Resuspension of fallout particles does not contribute significantly to the dose commitment resulting from an upper atmosphere release of small particles.

- The health effects resulting from a credible release scenario for a thermally unprotected container are significant. The consequences would be worldwide; changes in the reference concept are necessary.

Long-Term Risk Assessment (Task 4)

- For the reference container and cermet waste form, the probability of total fragmentation into small particles as a result of meteoroid impact is 6×10^{-11} per year.

- If small (less than 1000 microns) radioactive particles are released in the 0.85 A.U. circular solar orbit as a result of a total payload fragmentation event (e.g., meteorid impact), the amount of waste form mass expected to return to the Earth over a 3 million year period is a maximum of 6 kg.

- If rescue capability is necessary in nuclear waste disposal, then the design of both rescue vehicle and payload vehicle systems must accommodate noncooperative rendezvous and docking operations in addition to the nominal cooperative mode.

- Although automated noncooperative rescue is not presently at a stage of technology readiness, preliminary work in this area gives reasonable confidence that this capability can be developed in the near future.

Program Planning Support Analysis (Task 5)

- An approach to the licensing of space disposal has been developed. It would likely involve NRC licensing of the waste processing and payload fabrication facilities, the Nuclear Payload Preparation Facility at KSC, nuclear waste payload, and possibly the space destination (if lunar surface).

- Five SR&T development activities to support nuclear waste disposal in space are expected to be required. These are: defense waste concentration, commercial waste partitioning, waste form thermal and physical response, remote automated rendezvous and docking, and deep ocean recovery. (See Section 7.0 for discussion.)

- A preliminary safety test plan for the space option was developed. It considers materials characterization tests, scale model response tests, full scale ground tests, flight tests and qualification flight tests. Only tests required to reduce uncertainty in risk are appropriate for the early testing phase. Details of the development testing are expected at the end of the proposed 4-year study.

6.0 STUDY LIMITATIONS

A total system study for the space disposal option has yet to be conducted. This study evaluated cases involving the reference concept and a few variations. The study ground rules (see principal assumptions -Section 4.0) define most of the limitations for this study. In this preliminary phase of the space disposal program, many of the interfacing systems and data bases are constantly changing. Results based upon such data are necessarily limited by the point at which these data were fixed, i.e., the reference concept. Also, results are limited by the many assumptions that need to be made, such that the problem is manageable. More sophisticated studies and analysis are expected in future efforts.

For the characterization of <u>defense</u> high-level waste payloads, the results are especially limited by the definition of the waste to be carried and disposed of in space. A considerable amount of work remains to establish a more complete and justified data base for the defense nuclear waste. Also, since the "optimum mix" for space disposal has yet to be determined by DOE, the use here of the Hanford defense waste and PW-4b commercial waste allowed the bounding of the shielding and thermal problems for space disposal. Other waste mix payloads, Idaho and Savannah River defense waste, as well as commercial actinide and technetium payloads are not covered in this work; more definition for these payloads is required in follow-on studies. Data on the reference cermet waste form are preliminary, and should be refined as ORNL continues to characterize this waste form.

The accident environment definition for fragments (shrapnel) was limited significantly by the lack of good experimental data. An in depth experimental study is required before confidence is gained in this area.

The health risk factors used to estimate health effects from accidents, are quite uncertain. They are adequate at present for the preliminary assessments presented to aid in design improvement.

Any analysis is limited by the assumptions made. The reader is urged to read the detailed text of the report (Volume II) to ensure knowledge of all the assumptions that have been made during this study.

7.0 IMPLICATIONS FOR RESEARCH AND TECHNOLOGY

This section summarizes the required technology developments that will have to be undertaken as a part of the supporting research and technology (SR&T) program for space disposal of nuclear waste (see Section 7.4 of Volume II for details).

A distinction needs to be made between technology developments and design problems. Many elements of the space disposal system (OTV, SOIS, reentry vehicle, container, ejection system, etc.) do not currently exist, and would need to be designed, developed, and tested. However, none of these developments would necessarily require the creation of any new technology. As an example, the OTV would use hydrogen/oxygen liquid propellants. The technology for these propellants is well developed and systems using them have been built and flown operationally (e.g., Centaur, Saturn-IVB). This discussion concentrates on those areas where such technology is not presently available and needs to be developed as part of the overall program.

It has been stated that space disposal of nuclear waste is primarily an engineering problem, based largely on existing technology. Only five primary areas of technology development have been identified. The five areas are:

- Waste concentration processes (defense waste)
- Waste partitioning processes (commercial waste)
- Waste form thermal and physical response
- Remote automated rendezvous and docking
- Deep ocean recovery.

Section 7.4 of Volume II of this report contains a detailed discussion of the status, justification, technical plan, resource requirements and target schedules for each SR&T area. Table 15 summarizes the estimated resource requirements for these SR&T areas, based upon a four-year technology development schedule.

TABLE 15. SUMMARY OF SR&T RESOURCE REQUIREMENTS FOR THE SPACE OPTION

SR&T Area	1st Year	2nd Year	3rd Year	4th Year	Total
Waste Concentration Processes (Defense Waste)	100	200	400	300	1000
Waste Partitioning Processes	500	500	1000	1000	3000
Waste Form Thermal and Physical Response	100	250	250	200	800
Remote Automated Rendezvous and Docking	350	500	600	450	1900
Deep Ocean Recovery	150	175	75	50	450
Total	1200	1625	2325	2000	7150

7.1 Waste Concentration Processes (Defense Waste)

Defense nuclear waste exists in large quantities of dilute materials in storage at three different sites in the United States. Preliminary treatment processes have been defined for the Hanford wastes which would be suitable for terrestrial disposal, but which would not give adequate concentration for space disposal. Processes for further concentration have been defined, but are based on laboratory scale experiments and have not been verified as applicable in the scale envisioned. Further definition and demonstration of these proposed processes is required.

7.2 Waste Partitioning Processes (Commercial Waste)

Partitioning of nuclear wastes to separate critical radionuclides for special disposal, such as transmutation or space disposal, has been under study for some time. Methods of separation have been examined for elements such as iodine, strontium, cesium, technetium, and the actinides and lanthinides. Laboratory and pilot plant tests of these processes have been carried out to different degrees of demonstration. None of these processes can be considered fully developed.

7.3 Waste Form Thermal and Physical Response

A preliminary evaluation of potential nuclear waste forms has been accomplished and the reference form selected (cermet-- see Section 5.1). Some of the evaluated waste forms are well-developed, while others have received less attention. Further definition of the characteristics of certain attractive waste forms is required, particularly regarding thermal and physical characteristics, such as dispersion and the formulation of inhalable particles under high temperature reentry environments, and land or ocean impact.

7.4 Remote Automated Rendezvous and Docking

Various portions of the contingency plans for space disposal of nuclear waste would require a remote rendezvous and docking capability (e.g., rescue of a payload from an unplanned orbit). NASA has never conducted an automated rendezvous and docking. However, the Soviets have conducted numerous automated dockings in near-Earth orbits, and some proposed NASA planetary missions (e.g., Mars surface sample return) could require distant automated rendezvous and docking. Although some of the hardware elements required for this operation may already exist (e.g., transponders, aircraft-type search radars) a complete demonstrated technology base does not exist.

7.5 Deep Ocean Recovery

The ability to reach the deepest portions of the ocean floor has been demonstrated in undersea research programs. The ability to remove or recover objects from the ocean floor has been demonstrated as a part of undersea resource utilization and Naval undersea rescue programs. Therefore, the recovery of waste payloads from a known location in the ocean, following an aborted launch can be considered as an existing technology. However, development of special subsmersible systems for this specific application might be required. The key technology requirement is to be able to locate the aborted payload relatively accurately and promptly. If such location is prompt and accurate, survival of the payload in the ocean environment is reduced to a design problem of insuring adequate container strength to survive the pressures encountered during impact and at maximum depths. Corrosion of the container should not be a problem if the recovery is prompt.

8.0 SUGGESTED ADDITIONAL EFFORT

Prior to any development or implementation decision on space disposal of nuclear waste, important issues and problems will have to be addressed by DOE and NASA. Some specific programmatic and design recommendations resulting from the current Phase III study are summarized below:

Programmatic Recommendations

- The Concept Definition and Evaluation Program Plan, that was developed as a part of this study effort, should be implemented (DOE).*
- Supporting research and technology (SR&T) efforts in the areas of defense waste concentration (DOE), commercial waste partitioning (DOE), waste form thermal and physical response (DOE), remote automated rendezvous and docking (NASA), and deep ocean recovery (NASA) should be implemented.
- Pathway hazard model work should be performed, to determine within the reasonable bounds, the radionuclides which, if removed from the mined repository and shipped to space, provide the best long-term risk benefit. Preliminary indications are that technetium and the actinides should be considered for space disposal (DOE).
- The containment requirements and safety specifications developed during this study for the space disposal option should be updated and revised as new information becomes available (DOE).
- A safety index similar to that used for radioactive space power sources should be developed for the space option of nuclear waste disposal (DOE).
- An experimental program for fragmentation of propellant tanks is required to reduce uncertainty in all space nuclear payload safety assessments (NASA).
- ORNL should continue to perform research on the cermet waste form (DOE).
- The techniques of separation of strontium and cesium from the PW-4b reference waste mix should be evaluated (DOE).
- A study evaluating consequences of an inadvertent loss of payload cooling for extended periods, either on the ground or in space, should be conducted (NASA).

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*Note: Parenthetic notation after each recommendation indicates prime agency responsibility.

- There does not appear to be any strong reason for program planners to be concerned about the risk associated with small particle release in solar orbit (NASA).

Design Recommendations

- Any future concepts for space disposal should consider the application of carbon/carbon thermal reentry protection for the container and waste form (NASA).
- The stainless steel wall container material should be replaced with a material (e.g., Ti, Nb etc.) having high structural integrity and a higher melting point (NASA).
- Provisions should be made to insure spinning of the unprotected waste container as a result of an inadvertent reentry (NASA).
- The reference waste mix for space disposal should include the removal ($\geq$ 90%) of cesium and strontium from PW-4b (DOE).
- During mission operations, significant heat producing nuclear waste payloads should be kept as cool as possible; this will likely reduce the consequences from a catastrophic system failure (NASA).
- The concept of integrating defense and commercial waste into a single payload to minimize cooling and shielding requirements should be evaluated (NASA).
- A detailed analysis needs to be performed for actinide payload concepts (DOE).
- The fabrication of large waste forms, by employing various technologies, should be investigated futher (DOE).
- Continued study of employing adequate thermal, radiation, and impact protection systems for HLLV payloads, such that they are carried all the way to the final destination are warranted (NASA).
- The design implications of keeping protection systems all the way to a particular space destination requires further study (NASA).

APPENDIX A

ACRONYMS AND ABBREVIATIONS

APPENDIX A
ACRONYMS AND ABBREVIATIONS

AEGIS	Assessment of Effectiveness of Geologic Isolation Systems
ANPPF	Advanced Nuclear Payload Preparation Facility
A.U.	astronomical unit
BCL	Battelle's Columbus Laboratories, Columbus, Ohio
BNWL	Battelle-Northwest Laboratories, Richland, Washington
C	degrees centigrade
CANDU	Canadian deuterium uranium reactor
CBGS	confined by ground surface tests
CBM	confined by missile
cc	cubic centimeters (cm^3)
CDD	Concept Definition Document
CFR	Code of Federal Regulations
c.g.	center of gravity
Ci	Curies
cm	centimeters
COE	center of explosion
COR	contracting officer representative
DOE	U.S. Department of Energy
DOT	U.S. Department of Transportation
EIS	environmental impact statement
ET	Space Shuttle's External Tank
FSAR	Final Safety Analysis Report
FWPF	fineweave pierced fabric
g	grams
GPHS	General Purpose Heat Source
GWe	gigawatts electric
HARC	Human Affairs Research Centers (Battelle)
HLLV	heavy lift launch vehicle
HLW	high-level waste
HTGR	high-temperature gas-cooled reactor
IR	infrared
K	degrees Kelvin
kg	kilogram
kJ	kiloJoule
km	kilometer
KSC	Kennedy Space Center, Florida
kW	kilowatt
LeRC	NASA's Lewis Research Center, Cleveland, Ohio
LH_2	liquid hydrogen
LOX	liquid oxygen
LMFBR	liquid metal fast breeder reactor
LRB	Liquid Rocket Booster (Uprated Shuttle)
LWR	light water reactor
m	meters
m/s	meters per second
MT	metric tons
MTHM	metric tons of heavy metal (uranium charge to the reactor)

MMH	monomethyl hydrazine
MPC	maximum permissible concentration
MSFC	NASA's Marshall Space Flight Center, Huntsville, Alabama
MWD/T	megawatt days per ton
N	Newtons
N/cm^2	Newtons per square centimeter
N_2O_4	nitrogen tetroxide
NTO	nitrogen tetroxide
NASA	National Aeronautics and Space Administration
NEP	nuclear electric propulsion
NPPF	Nuclear Payload Preparation Facility
NRC	Nuclear Regulatory Commission
ONWI	Office of Nuclear Waste Isolation (DOE's)
ORNL	Oak Ridge National Laboratory, Tennessee
OTV	Orbit Transfer Vehicle
PSAR	Preliminary Safety Analysis Report
R&D	research and development
rem	roentgen equivalent, man
RP-1	rocket propellant number 1 (kerosene)
RSS	Rotating Service Structure (Shuttle)
RTG	radioisotope thermal generator
RV	Reentry Vehicle
s	seconds
SAI	Science Applications, Inc., Schaumburg, Illinois
SAR	Safety Analysis Report
SEP	solar electric propulsion
SOIS	Solar Orbit Insertion Stage
SPS	space power station
SR&T	supporting research and technology
SRB	Solid Rocket Booster (Shuttle)
SSP	solar sail propulsion
W	watt
WCF	waste concentration factor
yr	year

APPENDIX B

METRIC/ENGLISH UNIT CONVERSION FACTORS

APPENDIX B
METRIC/ENGLISH UNIT CONVERSION FACTORS

To convert	into	multiply by
atmospheres (atm). . . .	pounds per square inch (psi). .	14.70
atmospheres (atm). . . .	pounds per square ft (psf). . .	2116.8
calories (cal)	British thermal units (Btu) . .	3.9685×10^{-3}
calories per gram (cal/g).	British thermal units per pound (Btu/lb).	1.80
centimeters (cm)	inches (in)	0.3937
centimeters (cm)	feet (ft)	3.281×10^{-2}
centimeters (cm)	yards (yd).	1.094×10^{-2}
cubic centimeters (cm^3).	cubic inches (in^3).	0.0610
cubic meters (m^3). . . .	cubic feet (ft^3).	35.32
cubic meters (m^3). . . .	gallons (gal)	264.2
degrees Centigrade (C) .	degrees Fahrenheit (F).	1.8 C + 32*
degrees Kelvin (K) . . .	degrees Rankine (R)	1.8
grams (g).	pounds (lb)	2.205×10^{-3}
kilograms (kg)	pounds (lb)	2.205
kilometers (km).	statute miles (mi).	0.6214
kilometers (km).	nautical miles (n.mi.).	0.540
kilometers (km).	feet (ft)	3281
kilowatts (kW)	Btu per hour (Btu/hr)	3413
meters (m)	inches (in.).	39.37
meters (m)	feet (ft)	3.281
meters (m)	yards (yd).	1.094

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*NOTE: Multiply by 1.8 and then add 32.

To convert	into	multiply by
meters per second (m/s).	feet per second (ft/s).	3.281
metric tons (MT)	pounds (lb)	2205
metric tons (MT)	tons (T).	1.102
micrometers (μm)	meters (m).	1.0×10^{-6}
Newtons (N).	pounds force (lb_f).	0.2248
Newtons per cm^2 (N/cm^2).	pounds per square inch (psi). .	1.4504

APPENDIX C

REFERENCES

APPENDIX C
REFERENCES

1. Priest, C. C., et. al., "Nuclear Waste Disposal in Space--MSFC 1979-1980 Conceptual Design Study," PD01-80-1, NASA Marshall Space Flight Center, Huntsville, Alabama (March 1980).

2. Lynch, J. "Draft Executive Summary of NASA CR-153054," Battelle's Human Affairs Research Centers, Seattle, Washington (September 1979).

3. "Alternative Waste Disposal Concepts; An Interim Technical Assessment, ONWI-65, Bechtel National, Inc., San Francisco, California (December 1979).

4. "Concept Definition Document for Nuclear Waste Disposal in Space," NASA/Marshall Space Flight Center, Huntsville, Alabama (January 1980).

5. "Concept Definition and Evaluation Program Plan, 1980-1983," an ONWI working document, The DOE Office of Nuclear Waste Isolation, Columbus, Ohio (January 28, 1980).

6. Pardue, W. M. et. al., "Preliminary Evaluation of the Space Disposal of Nuclear Waste," 8-32391(100), Battelle Memorial Institute, Columbus, Ohio (August 1977).

7. Edgecombe, D. S., Rice, E. E., Miller, N. E., Conlon, R. J., and Yates, K. R., "Evaluation of the Space Disposal of Defense Nuclear Waste--Phase II," Battelle's Columbus Laboratories, Columbus, Ohio (January 1979).

8. Aaron, W. S., et. al., "Progress on the Cermet Approach to Nuclear Waste Management," Transactions of American Nuclear Society, Volume 33, p. 413 (November 1979).

9. Mendel, J. E., et al., "Annual Report on the Characteristics of High-Level Waste Glass," BNWL-2252, Battelle Northwest Laboratories, Richland, Washington (June 1977).

10. Yates, K. R., and Park, U. Y., "Projections of Commercial Nuclear Capacity and Spent-Fuel Accumulation in the United States", Transaction American Nuclear Society, pp. 350-352 (June 1979).

11. Bell, M. J., "ORIGEN--The ORNL Isotope Generation and Depletion Code," ORNL-4628, Oak Ridge National Laboratory, Oak Ridge, Tenn. (May 1973).

12. Soltesz, R. G., "Revised WANL ANISN Program User's Manual," WANL-TMI-1967, Westinghouse Astronuclear Laboratory, Pittsburgh, Pa. (April 1969).

13. "Shuttle Liquid Rocket Booster Study," NASA/Marshall Space Flight Center, Huntsville, Alabama (April 1979).

14. Hanley, G. M., et. al., "Satellite Power Systems (SPS) Concept Definition Study--Final Report (Exhibit C), Transportation Analysis," SSD79-0010-4, Volume IV, Rockwell International, Downey, California (March 1979).

15. Bader, B. E., Donaldson, A. B., and Hardee, H. C., "Liquid-Propellant Rocket Abort Fire Model," AIAA Journal of Spacecraft, Vol. 8, No. 12 (December 1971).

16. Gayle, J. B., and Bransford, J. W., "Size and Duration of Fireballs from Propellant Explosions," NASA-TMX-53314, NASA Marshall Space Flight Center, Huntsville, Alabama (August 1965).

17. Riehl, W. A., Presentation Charts on Shuttle Accident Environments, NASA/Marshall Space Flight Center, Huntsville, Alabama (December 1978).

18. Baker, W. E., et. al., "Workbook for Predicting Pressure Wave and Fragment Effects of Exploding Propellant Tanks and Gas Storage Vessels," NASA CR-134906, prepared by Southwest Research Institute, San Antonio, Texas for NASA/Lewis Research Center, Cleveland, Ohio (November 1975).

19. Logan, S. E., and Berbane, M. C., "Development and Application of a Risk Assessment Method for Radioactive Waste Management," EPA 520/6-78-005, The University of New Mexico, Albuquerque, N. M. (July 1978).

20. Anspaugh, L. R., "Resuspension Element Status Report, X. Use of NTIS Data to Predict Air Concentration of Plutonium," in P. B. Dunaway and M. G. White, eds., "The Dynamics of Plutonium in Desert Environments," Report NVO-142, U. S. Atomic Energy Commission (1974).

21. Anspaugh, L. R., Shinn, J. H., Phelps, P. L., and Kennedy, N. C., "Resuspension and Redistribution of Plutonium in Soils," Health Physics 29:571-582 (1975).

22. United States Nuclear Regulatory Commission, Rules and Regulations, Title 10, Part 50, Code of Federal Regulations - Energy.

23. Deutch, J. M., et. al., "Report to the President by the Interagency Review Group on Nuclear Waste Management," TID-29442, Washington, D.C. (March 1979).

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