72SD4201-4-1

SPACE DIVISION
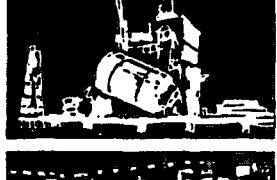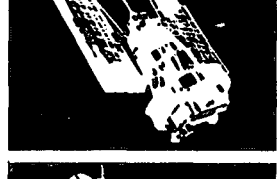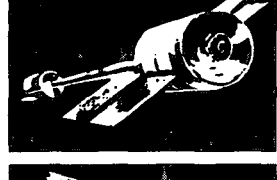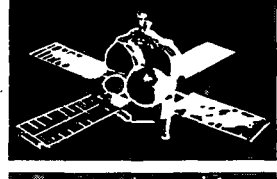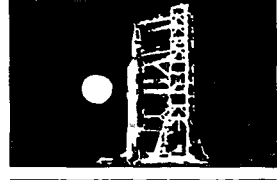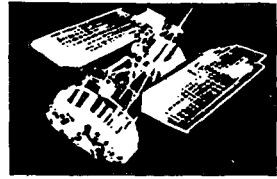
manned space flight nuclear system safety

Volume IV

SPACE SHUTTLE

NUCLEAR SYSTEM TRANSPORTATION

Part 1

SPACE SHUTTLE NUCLEAR SAFETY

GENERAL ⊕ ELECTRIC

ABSTRACT

This document reports the results of an analysis of the nuclear safety aspects (design and operational considerations) in the transport of nuclear payloads to and from earth orbit by the Space Shuttle. Three representative nuclear payloads used in the study were (1) the Z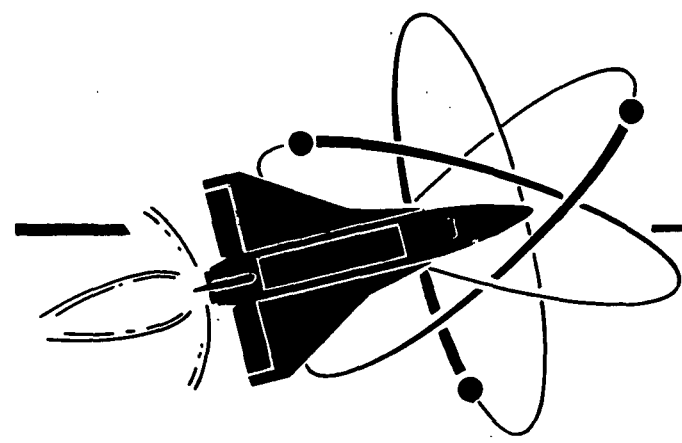irconium Hydride Reactor Brayton Power Module, (2) the Large Isotope Brayton Power System and (3) Small Isotopic Heat Sources which can be a part of an upper stage or part of a logistics module. Reference data on the Space Shuttle and Nuclear Payloads are presented in an appendix. Safety oriented design and operational requirements were identified to integrate the nuclear payloads in the Shuttle mission. Contingency situations were discussed and operations and design features were recommended to minimize the nuclear hazards. The study indicates the safety, design and operational advantages in the use of a "nuclear payload transfer module". The transfer module can provide many of the safety related support functions (blast and fragmentation protection, environmental control, payload ejection, etc.) minimizing the direct impact on the Shuttle.
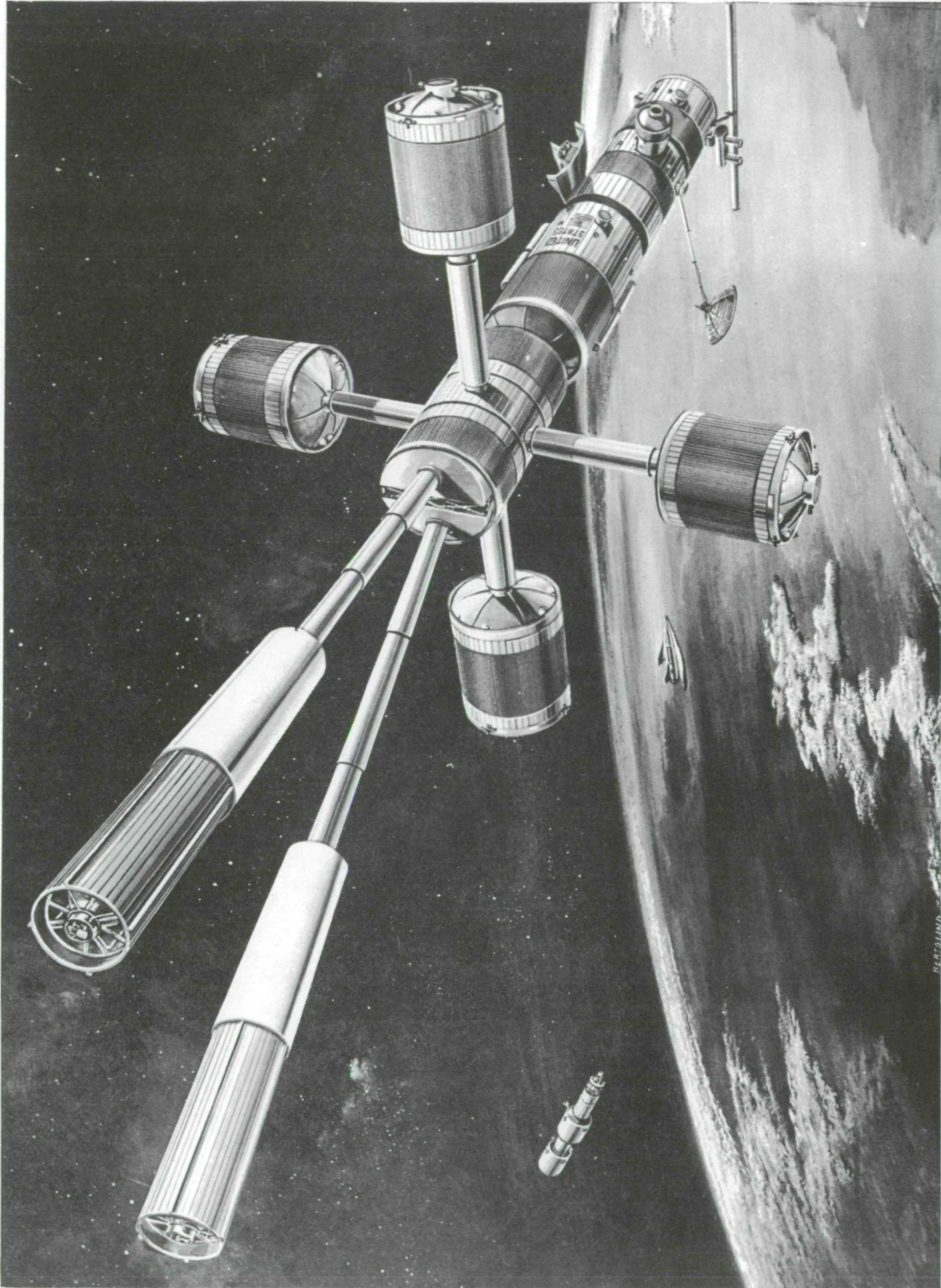
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FOREWORD

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

1. A flexible tool for scientific research.

2. A permanent base for earth oriented applications.

3. A foundation for the future exploration of our universe.

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

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

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

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

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

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

Table A. Manned Space Flight Nuclear System Safety Documentation

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

*Limited distribution

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

Table B. Study Area Cross Reference

Legend:
- *☐4 PRIMARY DISCUSSION
- ○ SUMMARY OR SUPPLEMENTAL DISCUSSION

*Section number is included where appropriate

STUDY AREAS	VOL I		VOL II		VOL III				VOL IV		VOL V		VOL VI	VOL VII	
	72SD4201-1 Part 1 Space Base – Executive Summary	Part 2 Space Shuttle – Executive Summary	72SD4201-2 Part 1 PSAR–Space Base	Part 2 Appendix (CRD)	72SD4201-3 Part 1 RDD–Reactor System, Space Base	Part 2 AMD–Reactor System	Part 2A AMD Appendix	Part 3 NSAD–Reactor System	72SD4201-4 Part 1 Space Shuttle Nuclear Safety	Part 2 Terrestrial Nuclear Safety Analysis	72SD4201-5 Part 1 Guidelines – Space Base	Part 2 Guidelines – Space Shuttle	72SD4201-6 System Safety Plan	72SD4201-7 Part 1 Literature Search and Evaluation	Part 2 ASRDI Forms
SPACE BASE PROGRAM															
Reference Vehicle Data	○		☐3												
Radiation Limits	○		☐4,A					○	○						
Radiation Environment/Hazards	○		☐6		☐3-5							○5			
Radiation Effects	○		☐6,A										○6		
Mission Support Nuclear Safety	○		☐5						○3-5						
Orbital Operations Nuclear Safety	○		☐6,7					○	○3-5						
Design & Operational Considerations	○		☐5,7					○				○5			
Guidelines & Requirements	○		○								☐○				
Reactor System Studies	○		☐7☐												
Terrestrial Safety Analysis															
Reference Design					☐	☐			○ABC						
Accident Models & Source Terms						☐	☐		○2,3						
Risk Analysis							☐		○2,3						
System Safety Plans												☐			
Technology Development Required	○		☐8		○							☐7,8			
SPACE SHUTTLE PROGRAM															
Reference Vehicle Data	○							☐ABC							
Nuclear Payload Integration	○							☐3-5							
Design & Operational Considerations	○		○					☐3-6							
Guidelines and Requirements	○		○					○3-5		○☐					
Terrestrial Safety Analysis	○				○ ○	○		○6 ☐							
LITERATURE REVIEW DATA															
Approach and Cross Index														☐	
ASRDI Forms															☐

ABBREVIATIONS

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

TABLE OF CONTENTS

TABLE OF CONTENTS (Cont'd)

LIST OF ILLUSTRATIONS

SECTION 1
INTRODUCTION

The Space Shuttle with boost, maneuvering, payload handling, retrieval and reentry capability is potentially a versatile and reliable transporter of nuclear hardware.

This study, performed under the same contract as the Space Base Nuclear System Safety Study (Contract NAS 8-26283) investigated the nuclear safety and integration aspects of transporting nuclear systems to and from a Space Base by the Space Shuttle.

The prime objectives of the study were to:

- Determine the safety related impact of nuclear payloads on the design and operation of the Shuttle.

- Identify safety related constraints imposed by the Shuttle upon the design and integration of nuclear payloads.

- Assess nuclear hazards to the earth's populace that result from transportation of nuclear payloads.

- Establish nuclear safety and integration guidelines and procedural recommendations for use in the transportation of nuclear payloads with the Shuttle.

Key study ground rules and scope are listed in Table 1-1.

Both the North American Rockwell (NAR) and the McDonnell Douglas (MDAC) Shuttle concepts were investigated. The nuclear systems identified as reference payloads were the isotope-Brayton, Zirconium Hydride (ZrH) reactor-Brayton and Radioisotope Thermoelectric Generator (RTG) power systems, and other small isotope heat sources.

The Shuttle can be used to transport these nuclear systems from the launch pad to a Space Base in low earth orbit (typically 500 km, 55° inclination), and dispose of the nuclear systems at their end of life by return to the earth's surface or injection into high earth orbit.

Table 1-1. Study Ground Rules and Scope

Ground Rules

- The reference mission is the Space Base mission supported by the Space Shuttle as defined by McDonnell Douglas and North American Rockwell for NASA, MSFC, and MSC respectively.

- The Space Shuttle will be used as the transporter in the initial launch and subsequent replacement and disposal/recovery of the nuclear sources.

- The nuclear payloads to be considered will consist of complete or modularized isotope-Brayton and ZrH reactor-Brayton powerplants in addition to small isotope sources. The payload configurations and operational capability are those studied by NAR and MDAC for NASA.

- The Space Shuttle baseline is assumed to be capable of handling a payload of at least 11.3 t (25 klb) to a 500 km (270 nm), 55° inclined orbit with payload dimensions of up to 4.6 m (15 ft) diameter and 18.3 m (60 ft) in length.

- Dose rate to the Shuttle crew should be minimized. Maximum dose rate to the crew from nuclear payloads is to be limited to 150 mrem/day (5 cm depth dose).

Study Scope

The study includes the following:

- The total Space Shuttle system/Space Base program nuclear safety aspects including crew/personnel safety, mission success, and the impact on supporting facilities.

- Parametric evaluations appropriate for effective application to future missions.

- The nuclear system safety aspects of the nuclear payload transport missions for the following operations:

  a. Preparation and transportation at Launch Site.
  b. Launch and ascent to the Space Base.
  c. Rendezvous and docking at the Space Base.
  d. In-orbit transfer (loading-unloading).
  e. End of Mission return to earth including reentry and landing.
  f. End of Mission disposal into high orbit.
  g. Emergency disposal.
  h. Abort/contingency modes.

- Means for effecting normal and emergency in-flight maintenance and repair of nuclear systems with assistance by the Space Shuttle.

For purposes of this study, it was assumed that the Shuttle could also be used to transport nuclear sources or spacecraft into low earth orbit, where the payload can be checked out and subsequently deployed from the cargo bay, and then placed in a high earth orbit or planetary trajectory.

The safety related analysis of the integration and operational aspects of the transport of the nuclear payloads by the Space Shuttle are contained in this document (Volume IV, Part 1). The terrestrial nuclear safety aspects of these missions are contained in Volume IV, Part 2. The related guidelines and requirements are detailed under separate document Volume V, Part 2.

SECTION 2
SUMMARY

2.1 GENERAL

This study has investigated the nuclear safety integration and operational aspects of transporting nuclear payloads to and from earth orbit by the Space Shuttle. The representative payloads considered were (1) the Zirconium Hydride (ZrH) reactor-Brayton power module, (2) the isotope-Brayton power module, and (3) small isotope power systems or heat sources.

2.2 REFERENCE DESIGN SUMMARY

This section contains brief descriptive data concerning the Space Shuttle and nuclear payload configurations utilized in the analysis. Reference should be made to the Appendix in this volume for detailed descriptions of the Space Shuttle configuration and mission (Appendix A), Reactor Power Module (Appendix B), and Isotope-Brayton Power Module (Appendix C).

2.2.1 SPACE SHUTTLE

The Space Shuttle launch configuration consists of two separate vehicles, (a) a booster which provides the initial lift-off thrust, and (b) the Shuttle orbiter which carries the payload into earth orbit after separating from the booster subsequent to first stage thrust termination. The reference Space Shuttle systems used in this study are illustrated in Figure 2-1 and are based on the concepts identified in the NASA Space Shuttle Phase B studies completed in March, 1971 (References 2-1 and 2-2). The upper drawing shows the North American Rockwell (NAR) design while the lower drawing depicts that of McDonnell Douglas Corporation (MDAC).

The nuclear payload to be delivered to the Space Base is placed in the Shuttle orbiter's cargo bay. The maximum allowable payload envelope is the same in both the NAR and MDAC designs - 4.6 m (15 ft) in diameter by 18.3 m (60 ft) long.

Since the nuclear payload is carried inside the Shuttle, the Shuttle configuration rather than the booster was of most importance in this study. The NAR and MDAC Phase B Shuttle configurations are shown in Figures 2-2 and 2-3, respectively. In both configurations, the cargo bay is in close proximity to the primary LH_2/LO_2 tankage. This is undesirable from a nuclear safety standpoint in the event of a Shuttle explosion and fire.

NAR

- DELTA WING BOOSTER AND SHUTTLE
- CARGO BAY
  - 4.6 METERS DIAMETER x 18.3 METERS LONG
- LOX/LH$_2$ ROCKET ENGINES
  - 2 SHUTTLE
  - 12 BOOSTER
- GLOW = 2.26 x 10^6 KG
  - PROPELLANTS - 1.84 x 10^6 KG

MDAC

- DELTA WING SHUTTLE
- SWEPT WING BOOSTER
- CARGO BAY
  - 4.6 METERS DIAMETER x 18.3 METERS LONG
- LOX/LH$_2$ ROCKET ENGINES
  - 2 SHUTTLE
  - 12 BOOSTER
- GLOW = 2.1 x 10^6 KG
  - PROPELLANTS - 1.76 x 10^6 KG

DIFFERENCES IN BASIC LAUNCH CONFIGURATIONS DO NOT SIGNIFICANTLY AFFECT NUCLEAR SAFETY

Figure 2-1. Reference Space Shuttle Launch Configurations

SHUTTLE DRY WEIGHT   - 126,100 KG
TOTAL PROPELLANT WEIGHT - 250,100 KG
_____
TOTAL SHUTTLE WEIGHT   - 376,200 KG

14.7 M

63 M

LH₂

LOX

LH₂

LOX

A

A

VIEW A-A

- ARTICULATION (MANIPULATOR ARMS)
  FOR CARGO TRANSFER
- TANKAGE "SURROUNDS" CARGO BAY
- CARGO BAY ~ 16.6 M FROM CREW
  COMPARTMENT
- MANIPULATOR OPERATOR'S STATION
  ~ 2.3 M FROM CARGO BAY

MANIPULATOR ARMS
(LEFT AND RIGHT)
MANIPULATOR OPERATOR'S
STATION
PASSIVE DOCKING RING

2 + 2 CREW
COMPARTMENT
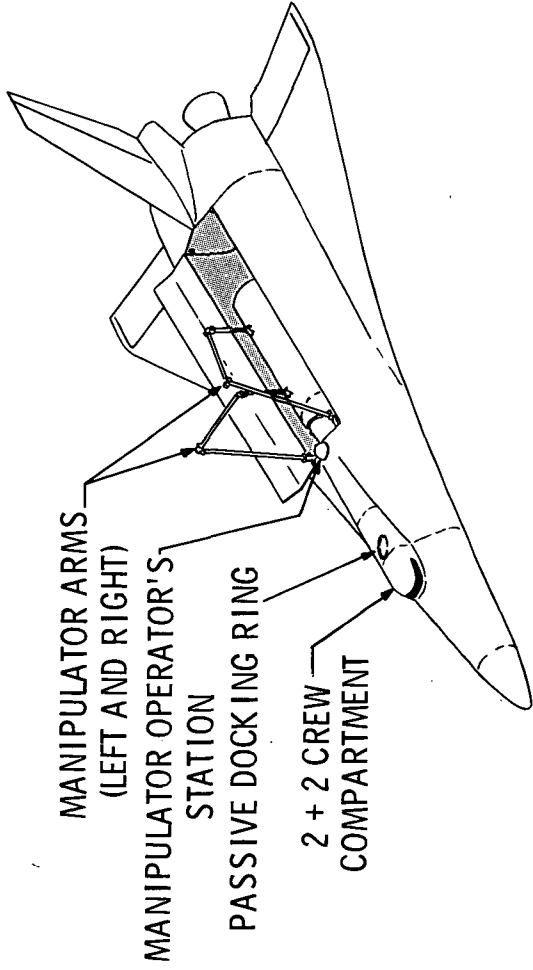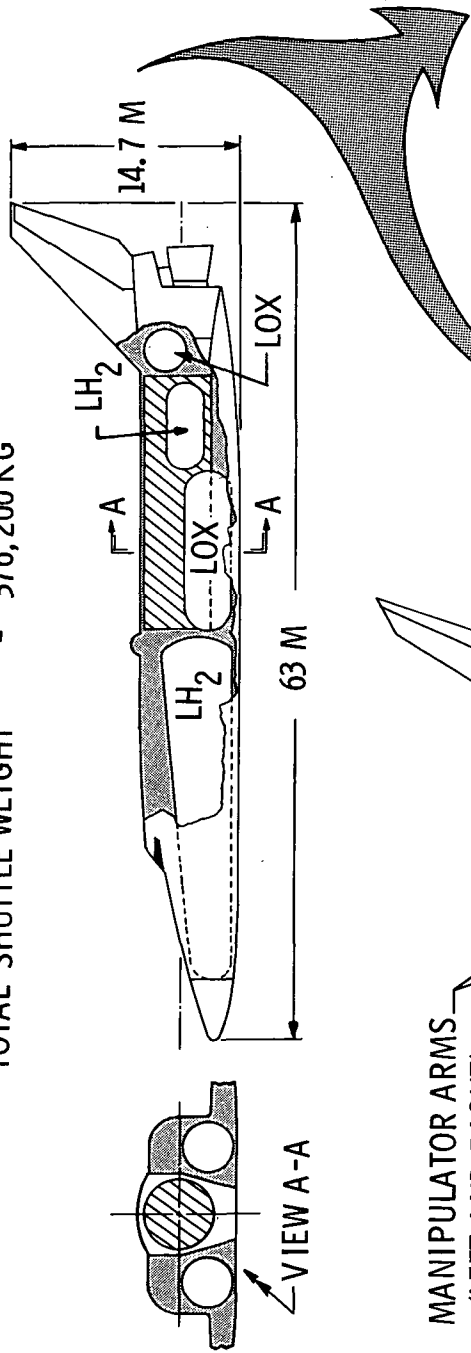
Figure 2-2. NAR Shuttle Orbiter Configuration

SHUTTLE DRY WEIGHT   - 127,400 KG
TOTAL PROPELLANT WEIGHT - 255,200 KG
TOTAL SHUTTLE WEIGHT   - 382,600 KG

18.2 M

53 M

LOX

LH₂

LOX

LH₂

A

A

VIEW A-A

PAYLOAD ADAPTER

FLEX TUNNEL
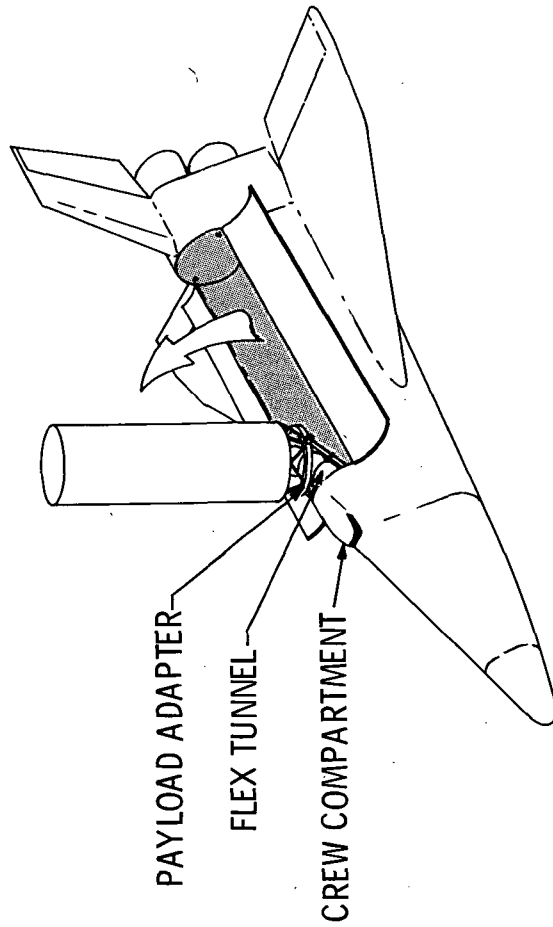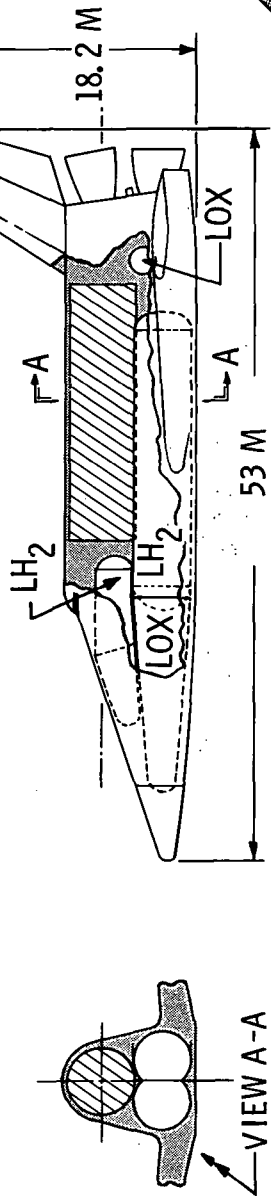
CREW COMPARTMENT

• 90° ROTATION FOR CARGO TRANSFER

• CARGO BAY LOCATED ABOVE MOST TANKAGE

• CARGO BAY ∼ 6.1 METERS FROM CREW COMPARTMENT

Figure 2-3.   MDAC Shuttle Orbiter Configuration

Contrasting cargo transfer schemes are used in the two designs. NAR has selected general purpose manipulator arms to transfer payloads, whereas the MDAC approach is to use a 90 degree rotation scheme to dock the payload to the Space Base.

The NAR Shuttle has two crew locations - the manipulator operator's station and the pilot's cockpit, respectively. The MDAC Shuttle has only one crew location, the pilot's cockpit, located 6.1 m forward of the cargo bay.

2.2.2 NUCLEAR PAYLOADS

This study has considered three representative nuclear payloads that may be transported to and from earth orbit by the Space Shuttle: (1) ZrH reactor-Brayton power module, (2) isotope-Brayton power module, and (3) small isotope heat sources.

2.2.2.1 ZrH Reactor-Brayton Power Module

The reactor power module identified for the reference Space Base Program is 6.6 m in diameter and does not fit within the 4.6 m diameter Shuttle cargo bay. Therefore, the Space Station ZrH reactor power module with a Brayton cycle power conversion system was used in this study because of its compatibility with the Space Shuttle cargo bay dimensional limitations. The basic reactor (Figure 2-4) is the same as that identified for the Space Base Program (Reference 2-3), with the following exceptions:

1. Normal operation is at 125 kWt compared to the 330 kWt of the Space Base Program, resulting in decreased radiator area. (Transport of the Space Base power module by Space Shuttle might involve a deployable radiator or multiple Shuttle launches).

2. The reactor/shield assembly incorporates less radiation shielding resulting in a lower mass but increased dose rates around its perimeter.

The reference reactor power system can be packaged in various configurations to maintain Shuttle compatibility as illustrated in Figure 2-5. One obvious method is to package the reactor and Brayton power conversion equipment in a single reactor module that does not exceed the maximum allowable payload dimensions. However, because of the mass involved with a single reactor-Brayton power module and the low $W/C_D A$ of such a configuration, other packaging designs appear to be desirable. An alternative scheme (dual reactor module approach) is to package the reactor/shield assembly, intermediate NaK loop, and NaK-to-gas

- REFERENCE ZrH REACTOR DESIGN
- THERMAL POWER = 125 KW
- REACTOR OUTLET TEMPERATURE = 922°K
- COOLANT T = 311°K
- SOLID SHIELD
  - WEIGHT = 4960 KG
  - DOSE RATE = 150 MREM/DAY @ 62 METERS
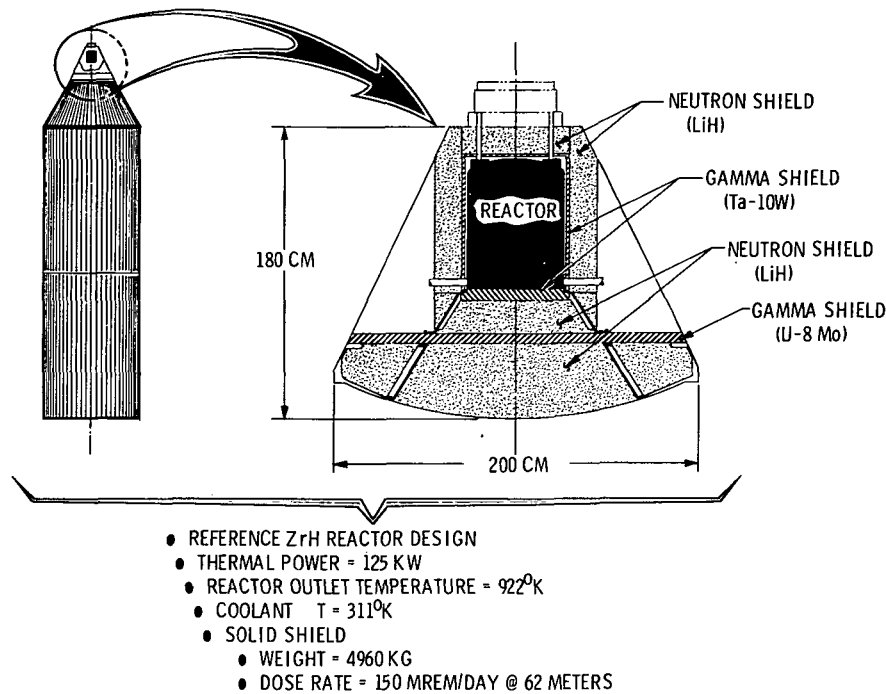
Figure 2-4. Reactor/Shield Assembly

heat exchangers in one module and the Brayton power conversion unit in a second module with gas line disconnects between the two modules. This allows more flexibility in packaging the reactor power system, but requires two Shuttle launches. A third packaging approach involves a separable heat exchanger that can be used in conjunction with either of the first two schemes. This allows the reactor/shield assembly to be separated from the rest of the power system and therefore launched and disposed of separately. This approach facilitates the handling operations and allows for greater flexibility in packaging.

2.2.2.2 Isotope-Brayton Power Module

The isotope-Brayton power system could consist of one or more large isotope heat sources coupled with several power conversion systems to provide the desired total electrical power output. For purposes of this study, two 52 kWt heat sources are operated simultaneously to provide 25 kWe usable power.

Three configurations for the 25 kWe isotope-Brayton power system are depicted in Figure 2-6. The common nuclear component to be found in each of the three systems is the Isotope Reentry Vehicle (IRV). The IRV consists of a planar array of plutonium-238 fuel capsules (heat source)

—CONFIGURATIONS—	— CHARACTERISTICS —
SINGLE REACTOR MODULE 18.3 M 4.6 M	● REQUIRES ONE SHUTTLE LAUNCH ● APPROACHES MAXIMUM ALLOWABLE SHUTTLE PAYLOAD WEIGHT ● LOW W/C_DA – SHORT ORBITAL DECAY TIME ● TYPICAL SINGLE MODULE WEIGHT = 10,300 KG

DUAL REACTOR MODULE
 	
4.3 M
18.0 M
12.2 M
	● ENGINE ROOM FARTHER FROM REACTOR
	● REDUCES PAYLOAD WEIGHT
	● HIGH W/C_DA – LONG ORBITAL DECAY TIME
	● TYPICAL MODULE WEIGHTS
	  – REACTOR MODULE – 6800 KG
	  – BRAYTON MODULE – 3100 KG

● SEPARABLE HEAT EXCHANGER	● REACTOR/SHIELD ASSEMBLY CAN BE SEPARATED FROM POWER SYSTEM ● NO NaK LOOP DISCONNECTS ● MODULAR APPROACH TO TRANSPORTING AND HANDLING OF REACTOR POWER SYSTEMS ● FACILITATES HANDLING AND SHUTTLE TRANSPORT OPERATIONS

Figure 2-5. Typical Reactor Power System Configurations

ENGINE ROOM
10 m DIAMETER
4.6 m LENGTH

POWER BOOM
4.3 m DIAMETER
14 m LENGTH

MODULAR SYSTEM
6.1 m DIAMETER
12.8 m LENGTH

- COMMON NUCLEAR COMPONENT IS THE ISOTOPE REENTRY VEHICLE (IRV)
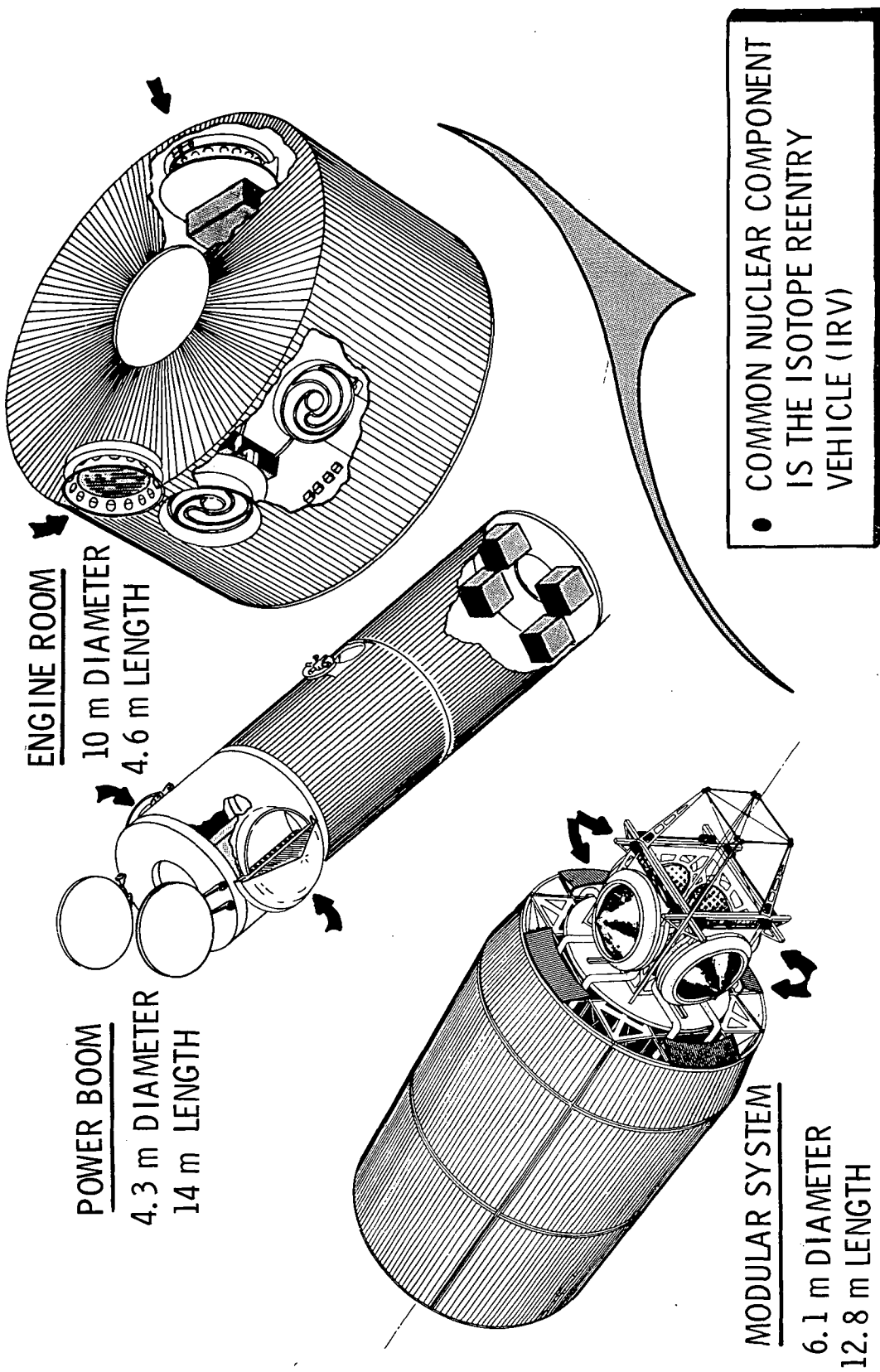
Figure 2-6. Typical Isotope-Brayton Configurations

contained within a reentry body. The "power boom" module (Reference 2-5) is 14 m (46 ft) long, 4.3 m (14 ft) in diameter, employs two IRV's, and contains four power conversion units (two on line, two redundant). In this system, the Xe-He working gas is ducted the length of the module to provide separation distance between the heat sources and the power conversion units, thereby attenuating the radiation level at the units and permitting in-flight maintenance. The Shuttle would transport the IRV's separate from the main radiator assembly to allow for thermal control of the IRV's.

In the "engine room" configuration (Reference 2-6), the system is housed in a 10 m (33 ft) diameter cylinder, 4.6 m (15 ft) long, which is launched and compatible with the 10 m diameter Space Base modules. Three power conversion units are provided: two operating, and one spare. These are rail-mounted so that either operating power conversion unit can be replaced by the spare as required. This system uses two IRV's which can be transported by the Shuttle either jointly or singularly.

The "modular" power system (Reference 2-7) is 6.1 m (20 ft) in diameter and 12.8 m (42 ft) long. Its radiator has been divided into segments so that the power conversion unit and corresponding radiator segment are contained in one structure. The system shown contains four IRV's and four power conversion modules, but it could be configured from 2 to 6 units of each. Each segment is designed to be Shuttle compatible which permits transport of an IRV, radiator segment and power conversion unit in one launch, or the IRV can be transported separately.

2.2.2.3 Small Isotope Sources

Two small isotope sources considered representative in future space operations, that might be transported by the Shuttle are the Multi-Hundred Watt (MHW) Radioisotope Thermoelectric Generator (RTG) and the Radioisotope for Thermal Energy (RITE) fuel capsule. The MHW-RTG is designed to deliver 150 w of electrical power from a heat source loading of 2400 w thermal of Pu-238. It could be used singly or in multiples to power unmanned vehicles such as a Grand Tour spacecraft on deep space missions. Design operating temperature of the MHW capsule is $1533^{\circ}K$ ($2300^{\circ}F$). The RITE fuel capsule is intended to provide heat for

an Environmental Control/Life Support (EC/LS) waste processing system to be used on large manned spacecraft. The capsule used in this unit is loaded with 420w thermal of Pu-238 and operates at a temperature of $1033^{\circ}K$ ($1400^{\circ}F$).

2.3 STUDY SUMMARY AND CONCLUSIONS

A summary of the most significant safety related considerations and associated recommended guidelines resulting from the study are contained in the following paragraphs.

2.3.1 TRANSPORTATION OF A ZrH REACTOR-BRAYTON POWER MODULE

A ZrH reactor power module presents a relatively low nuclear hazard prior to orbital operations if pre-flight criticality tests are limited to low power levels. After operations in orbit, the reactor could have a potentially large core fission product inventory, thus increasing the nuclear hazards during retrieval, disposal or recovery operations which would be performed by the Shuttle.

In addition to a launch into a low earth orbit, the Shuttle has the capability to boost a 13.6 kg reactor power module from a 500 km to an 835 km circular disposal orbit which provides an orbital lifetime of at least 250 years. An alternative to this disposal mode is to return the reactor to the earth's surface.

Several power module ground handling and orbital transfer techniques were defined. Two important safety ground rules which should be followed in these operations are (1) maintain positive handling control at all times including situations where two modules must be handled to enact replacement of a spent or failed module, and (2) minimize the Shuttle crew dose rate (maximum of 150 mrem/day) by maintaining adequate separation distances between the crew and radiation source within the cargo bay, allowing time for reactor radioactive decay, and making maximum use of reactor and Shuttle shadow shielding.

In addition to the nuclear hazards, the NaK in the reactor primary and intermediate coolant loops can result in hazards due to the exothermic reaction that occurs when NaK combines with oxygen sources. Environmental protection must be provided the power module including periods within the Shuttle cargo bay. In-orbit retrieval operations could involve the placement of a thermally hot reactor power module in the cargo bay. Thermal control provisions would then be required. A short waiting period of approximately 2 days after reactor shutdown could eliminate the need for post-operational thermal control.

Some of the safety related considerations for the Shuttle/reactor mission are summarized below.

- Radiation Protection - No additional radiation protection is required for the crew with a pre-operational reactor placed in the cargo bay. A similar conclusion can be made for the post-operational case provided the reactor is placed toward the rear of the Shuttle cargo bay, not prior to ten days after reactor shutdown. Adverse radiation effects on Shuttle subsystems are not expected, however, integrated doses over many nuclear missions would merit further consideration (material selection and location of solid state electronics, film, etc.).

- Blast and Fragmentation Protection - The Shuttle presents a severe blast and fragmentation environment. Little or no additional blast and fragmentation protection is required of an unoperated reactor, however, the positioning of the payload away from the Mobile Launcher tower to provide an unobstructed ejection path, will reduce fragmentation damage. Design for intact impact of the core in the post-operational case could be required due to the potential high fission product inventory.

- Environmental Protection - The cargo bay should be capable of preventing LO_2 and LH_2 vapors from entering. Double containment or an inert cover gas "blanket" around the power module (particularly around its liquid metal components) will reduce liquid metal hazards.

- Thermal Control - Temperature transients within the cargo bay could cause NaK freeze up. Auxiliary heating may be required to resolve this problem. If it were found necessary to place a reactor power module into the cargo bay immediately after reactor shutdown, up to 1 kWt cooling could be required to remove decay heat. A transfer of this nature should be avoided and a waiting period of at least 2 days planned.

- <u>Payload System Status and Controls</u> – The receipt of 80 data points and displays (periodic and continuous monitoring), and sending of 25 control signals are required of Shuttle systems.

- <u>Electrical Power</u> – A maximum of 1 kw electrical power is required for 2 days, if decay heat thermal control is necessary. Other electrical requirements should not exceed 0.5 kw total. Either power from batteries or the Shuttle Electrical Power System could be considered.

- <u>Attachments and Payload Handling</u> – The power module center of gravity may be located toward the reactor/shield and away from the primary attach points. Additional support may be required to prevent longitudinal buckling. The use of a cradle type "transfer module" which supports the reactor and in turn is placed in the cargo bay can significantly reduce Shuttle integration requirements and increase safety during handling operations. A capability of emergency payload ejection into a deep ocean area (during launch or end-of-life recovery operations) could be provided by the "transfer module".

2.3.2 TRANSPORTATION OF AN ISOTOPE-BRAYTON POWER MODULE

Transport of an isotope-Brayton power module presents several different safety considerations than does a reactor. No liquid metal hazard exists with an isotope-Brayton power module as contrasted with a reactor power module. Coolant loops generally contain relatively non-hazardous organic fluids. Important differences occur in the Prelaunch Phase where an isotope heat source presents continuous thermal and radiation hazards. The isotope heat source must be cooled at all times prior to lift-off. In addition, it is a constant source of neutron radiation with increased gamma radiation occurring as the isotope decays-reaching a peak at about 18 years. Shielding must be provided accordingly.

For these reasons and due to the relatively passive nature of the power module prior to operation, the heat source should be installed in the Shuttle orbiter as late as is practicable in the countdown timeline.

Each of the 130 isotope-Brayton fuel capsules contains approximately 12,000 curies of Pu-238 isotope. Rather extensive blast, fragmentation and fireball protection coupled with a well designed fuel capsule and fuel form are required to prevent release of the fuel to the environment should an accident occur.

The principal recovery mode is assumed to be a return to earth by the Space Shuttle. Consideration should be given to an ejection of the heat source out of the cargo bay onto the continental shelf or into deep ocean areas should an abort occur during ascent or be imminent on landing.

The principal safety related Shuttle integration considerations for transport of the isotope heat source are summarized below:

- Radiation Protection - No auxiliary shielding is required for the Shuttle orbiter crew for normal operations provided the base of the conical heat source is parallel to the cargo bay and at least 5.5m from the nearest crew member.

- Blast and Fragmentation Protection - Blast and fragmentation protection must be provided while in the Shuttle. The most severe problem exists at launch due to the large amount of propellant. The payload must be provided an unobstructed ejection path, preferably into an ocean or swamp area, should a launch pad explosion occur.

- Thermal Control - Thermal control of an isotope heat source is required within the shuttle to maintain acceptable capsule temperatures. Where an entirely passive system is not feasible, redundant and/or back-up systems must be provided. The design of the blast and fragmentation shield is intimately involved in thermal control design.

- Payload System Status and Controls - The receipt of a maximum of 62 data points and display functions (periodic and continuous monitoring), and sending of 32 control signals are required of Shuttle systems.

- Electrical Power - A maximum of 300w of electrical power is required, and the total energy requirement will not exceed 23 kw-hr for support of the thermal control system. This power could be supplied by batteries.

- Attachment and Payload Handling - The use of a supporting cradle "transfer module" will greatly reduce Shuttle interface requirements and provide possible ejection capability over the continental shelf or deep ocean areas if diagnostic data during ascent and landing warrant it.

2.3.3 TRANSPORTATION OF SMALL ISOTOPE SOURCES

The impact on the Space Shuttle and the operational procedures involved with transporting small isotope heat sources are generally less severe than the impact of transporting an isotope-Brayton heat source or reactor power module. The radiation hazard when transporting

a small isotope heat source is a function of the fuel composition, inventory and placement with respect to the crew. The transport of certain isotopic fuels may require auxiliary crew radiation shielding. However, the most common material, Pu-238, should not require any additional Shuttle shielding. Thermal output will generally be lower than an isotope-Brayton heat source, but individual packaging restrictions within the cargo bay could necessitate additional cooling. The blast and fragmentation hazard should be minimized by positioning the source away from propellant tanks and permitting unobstructed ejection after a launch pad explosion.

2.3.4 OVERALL CONCLUSIONS

In addition to establishing nuclear safety guidelines and safety-oriented requirements (Volume V, Part 2) to reduce the risk to the general public and Shuttle crew, several key conclusions involving the Shuttle transport of nuclear payloads have been identified.

- Safety and handling can be improved and support requirements imposed on the Shuttle reduced if a transfer module is used to support the nuclear payload within the cargo bay of the Shuttle. The transfer module is simply a carriage-type of assembly in which the nuclear payload is placed prior to being installed in the Shuttle orbiter. The entire nuclear payload/transfer module assembly is placed in the Shuttle cargo bay. By using such an assembly, the integration items required for the transportation of nuclear payloads, such as blast and fragmentation protection, radiation shielding, thermal control, and electrical power, can be incorporated into the transfer module rather than being designed into the nuclear payload or the Space Shuttle.

- The nuclear payloads must be designed to fit within the 4.6 m (15 ft) diameter by 18.3 m (60 ft) long Shuttle cargo bay. An additional Shuttle-imposed constraint limits placement of the payload's center-of-gravity. This constraint is not expected to restrict most power module configurations anticipated.

- Any nuclear payload to be transported by the Space Shuttle is subject to the normal operational Shuttle-induced environments, in addition to various potential accident environments. During normal operation, the environment within the Shuttle orbiter cargo bay is relatively mild and comparable to that of other launch vehicles.

However, a launch pad explosion of the Space Shuttle produces a blast and fragmentation environment that is more severe (approximately one order of magnitude greater) than that of either the Titan III-C, INT-21, or Saturn V. This is primarily due to the proximity of the Shuttle orbiter cargo bay to propellant tankage. Considerable blast and fragmentation protection may be required to protect the nuclear payloads from such an accident environment.

● A launch complex configuration where the nuclear payload is facing away from the Mobile Launcher tower is desirable. Space Shuttle/Launch Complex configurations which position the nuclear payload between the Shuttle propellant tanks and the Mobile Launcher tower present an undesirable fragmentation environment and should be avoided.

● Based on the results of a terrestrial nuclear safety analysis, it was determined that the risk to the general public is low in transporting either a nuclear reactor or isotope-Brayton power module by the Space Shuttle. In both cases, the most significant risks would result in the Disposal/Recovery Phase. Reducing the risk in this phase can lower the overall mission risk significantly (e. g., the provision for no reactor excursion, the capability of emergency ejection of the payload into a deep ocean area during launch or landing operations, and the improving of the impact characteristics of the aged isotope system). Results of the study have shown that the use of a Shuttle for recovery of a reactor power module as contrasted to a boost to high earth orbit, can reduce the overall risk to the general populance during disposal by at least an order of magnitude. The detailed terrestrial safety analysis is contained in Volume IV, Part 2.

2.4 REFERENCES

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        January 1971.

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        August, 1971.

SECTION 3
SAFETY ASPECTS IN THE TRANSPORTATION OF REACTOR POWER MODULES WITH THE SPACE SHUTTLE

3.1 GENERAL

Figure 3-1 outlines a typical mission profile for the Shuttle transport of a reactor power module along with the principal packaging considerations. The mission can be broken down into four major phases:

- Prelaunch

- Shuttle Launch/Ascent

- On-Orbit Operations

- End-of-Mission

The Shuttle transport mission begins with the prelaunch activities at the launch site. This includes the checkout of the entire reactor-Brayton power module upon receipt at the Nuclear Assembly Building (NAB), the installation of the reactor power module in the Shuttle orbiter cargo bay, and the mating of the Shuttle booster and orbiter vehicles. Following the Shuttle launch/ascent and Space Base rendezvous operations, the reactor power module is transferred from the Shuttle orbiter to the Space Base.

The Shuttle orbiter can be used for disposal of a spent reactor, either by placing the power module into a high orbit or by returning it back to earth. The ΔV capability of the Shuttle permits deploying the power module into an 835 Km (450 nm) circular orbit where the orbital decay time is at least 250 years (Reference 3-1).

During all of these mission phases, various integration considerations play an important role in implementing the nuclear safety of the Shuttle mission. This section discusses the nuclear reactor packaging items that are required when transporting a reactor power module by the Space Shuttle and the mission operational procedures that are involved.
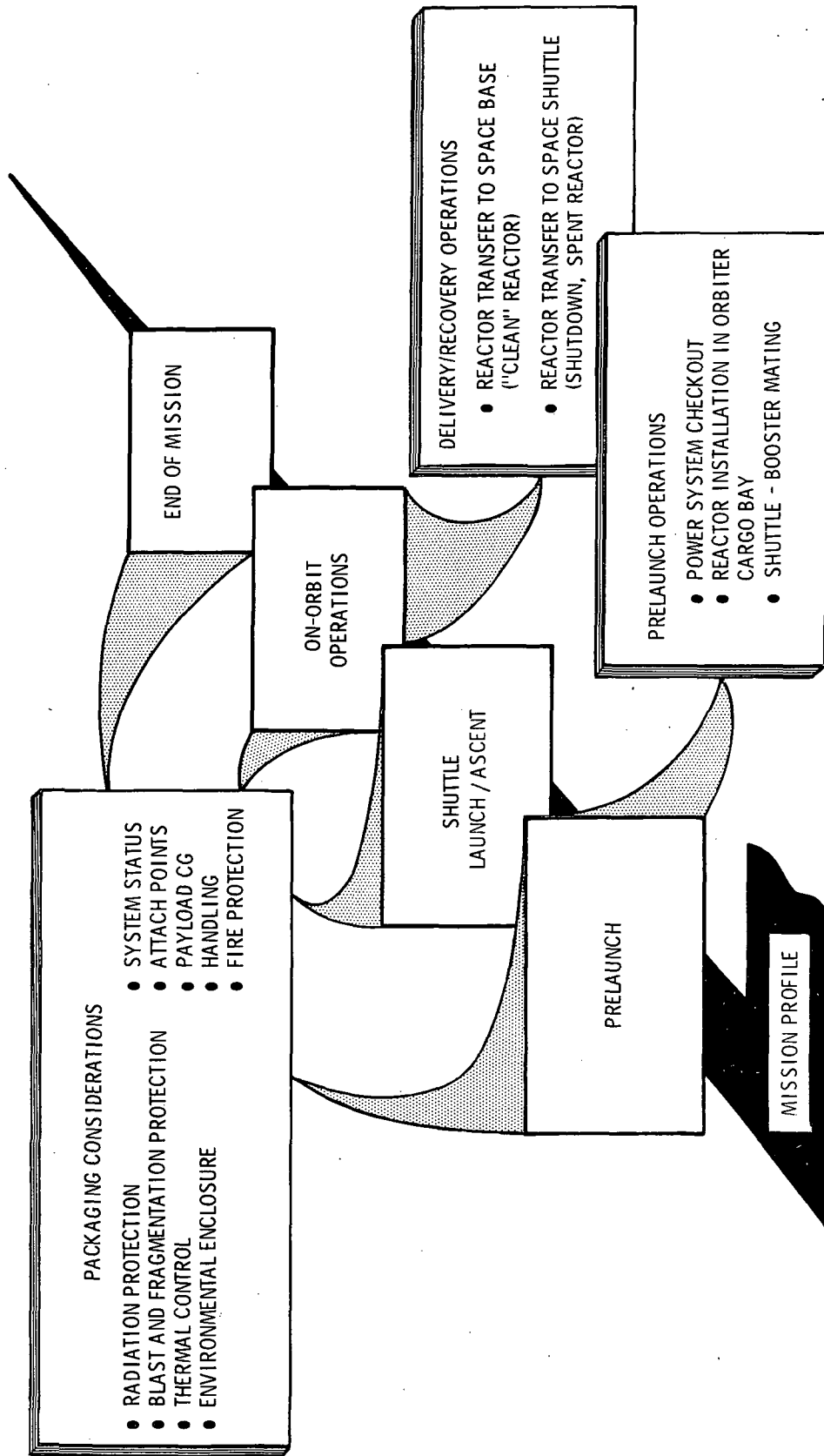
Figure 3-1. Mission Operations and Reactor Packaging Considerations

3.2 SHUTTLE REACTOR POWER MODULE PACKAGING AND INTEGRATION

The Space Shuttle cargo dimensions of 4.6 m (15 ft) in diameter by 18.3 m (60 ft) in length are the primary Shuttle imposed design constraints for the reactor power module. The cargo bay envelope limits the cylindrical length and therefore the radiator surface area. The available radiator area has direct impact on reactor power system growth capability. A further Shuttle imposed constraint limits the envelope of the payload's center of gravity as discussed in Appendix A.1.2 of this volume.

In addition to the above mentioned constraints imposed on the reactor power module by the Space Shuttle, the following safety and integration items that may affect the Shuttle design and packaging of reactor modules (Figure 3-2) include:

- Radiation Protection

- Blast and Fragmentation Protection

- Environmental Protection (Enclosure)

- Thermal Control

- Payload System Status and Controls

- Electrical Power

- Attachments and Payload Handling

Thermal, radiation, mechanical, electrical and Shuttle induced environment interfaces must be accommodated. The following sections discuss the key safety related integration and packaging requirements for transporting a reactor module aboard the Space Shuttle.

3.2.1 RADIATION PROTECTION

The nuclear radiation environment from a reactor being transported by the Space Shuttle is presented in Appendix B. Dose rates to the crew from a pre-operational reactor are substantially less than 150 mrem/day. Based on this data, no crew radiation protection will be required during launch/ascent. However during the reactor Disposal/Recovery Phase, radiation protection may be required because of the large core fission product inventory following 5 years of reactor operation.
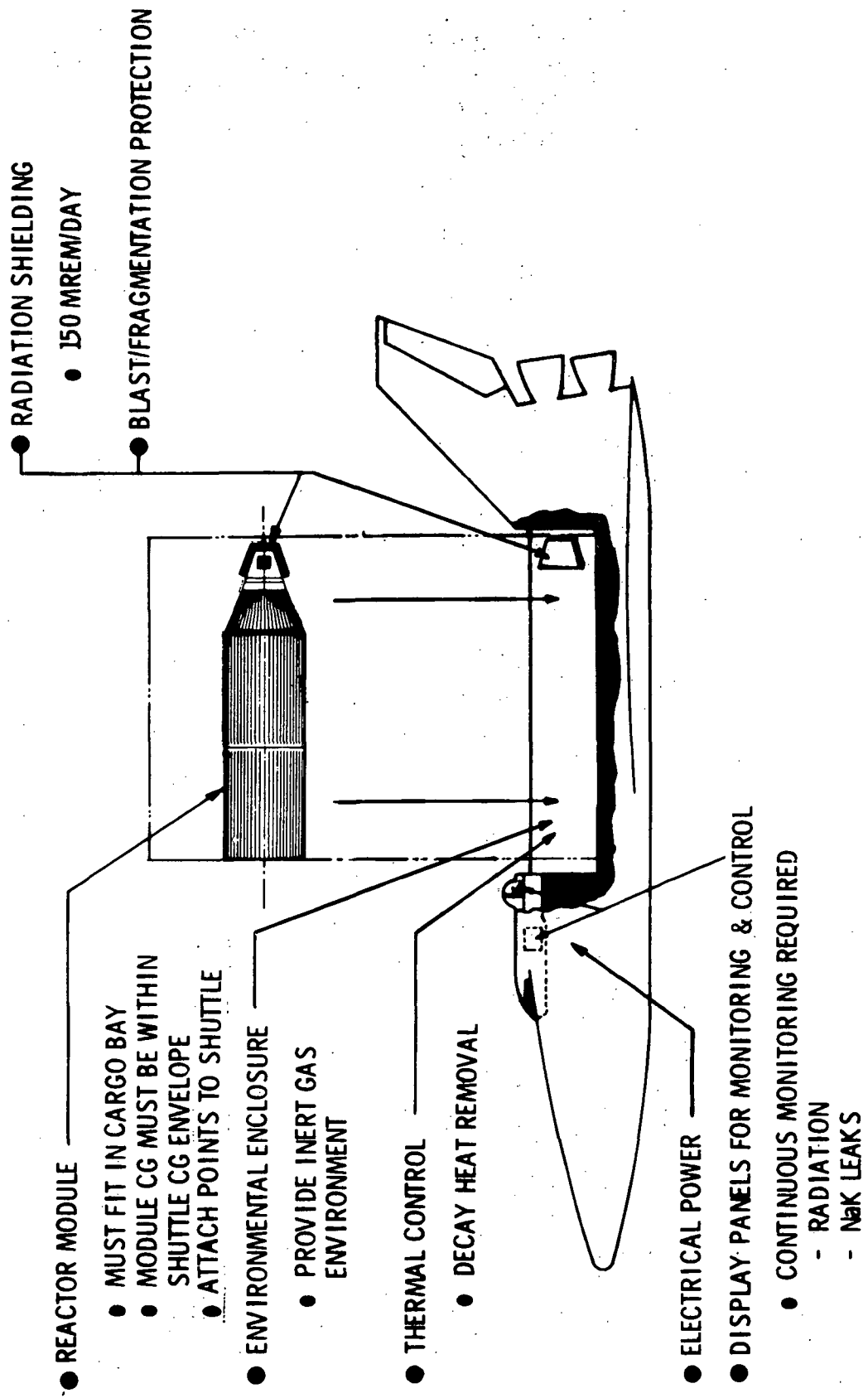
Figure 3-2. Reactor Packaging/Shuttle Integration

Two reactor module orientations in the cargo bay are possible - reactor aft or reactor forward. Figures 3-3 and 3-4 show, for the aft and forward orientation, respectively, the estimated tungsten gamma shielding thicknesses required to reduce the Shuttle crew dose rates to 150 mrem/day as a function of time after reactor shutdown. A significant penalty in radiation shielding weight must be accepted if a forward reactor orientation in the cargo bay is required. However, with the reactor positioned aft in the cargo bay, the thickest part of the reactor shield lies between the reactor and the crew, and the radiation shielding required to limit the dose rate to the Shuttle crew to 150 mrem/day is minimum. No shielding may be required if a spent reactor is not loaded aboard the Shuttle prior to a waiting period of 10 days following reactor shutdown.

Scattered (reflected) radiation from hardware located in the near vicinity of the reactor can be a contributor to the total radiation received by the crew. As shown in Figure 3-3, even though the reactor is located further from the crew compartment in the NAR design than in the MDAC design, the radiation dose to the crew is higher. This can be attributed to the increased scattered radiation resulting from the reactor being closely surrounded by Shuttle structure and propellant tanks on three sides.

If radiation protection is required for the Shuttle crew, the mass of additional shielding would depend on the reactor fission product inventory and the location chosen for shield placement. The radiation shield must be located somewhere along the path the radiation follows. The two most likely positions are at the reactor or at the crew locations as shown in Figure 3-5.

Radiation damage to Shuttle components from the reactor is only of significance in the transport of a spent reactor. Shuttle structural materials will not be affected. Critical components are solid state electronic devices, film, and emulsions. The impact on Shuttle components is related to the integrated dose and hence is mission dependent. Radiation sensitive components should be located away from the nuclear sources. Consideration can be given to localized shielding, and hardening techniques can be applied where required. Reference should be made to Volume II, Part I, Appendix, A for detailed radiation limits on typical space subsystem components.

- REACTOR PLACED AFT IN CARGO BAY

- DOSE RATES

- NAR
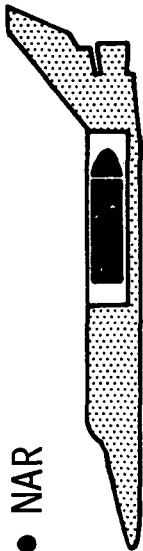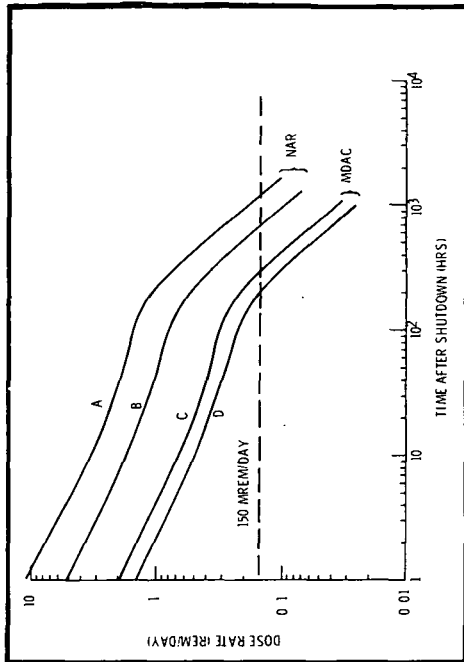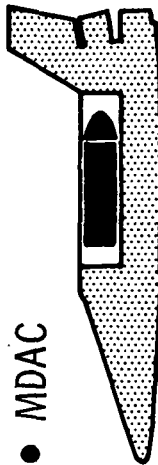
A. MANIP. OPER. STA., EITHER RM
B. PILOT'S COCKPIT, EITHER RM
C. PILOT'S COCKPIT, DUAL RM
D. PILOT'S COCKPIT, SINGLE RM
   RM = REACTOR MODULE

- MDAC

- RADIATION SHIELDING
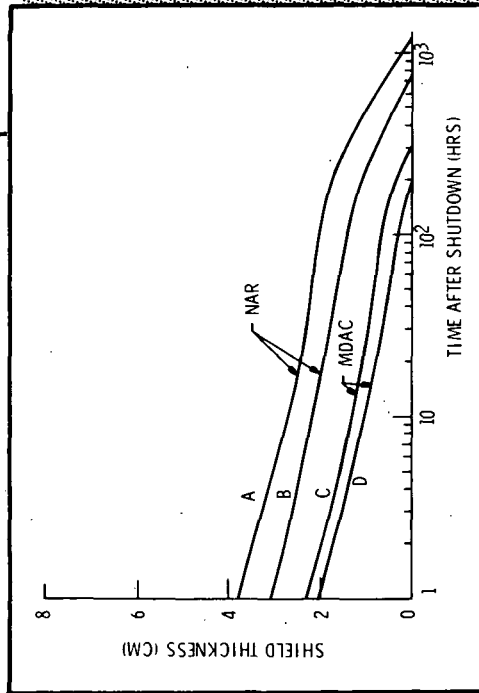
RADIATION SHIELDING FOR CREW NOT REQUIRED WHEN REACTOR LOADING IS DELAYED 10 DAYS AFTER SHUTDOWN

Figure 3-3. Shutdown Reactor Radiation Environment (Reactor Aft in Cargo Bay)
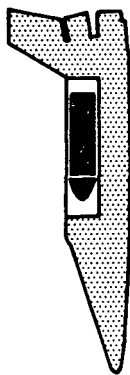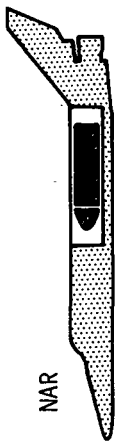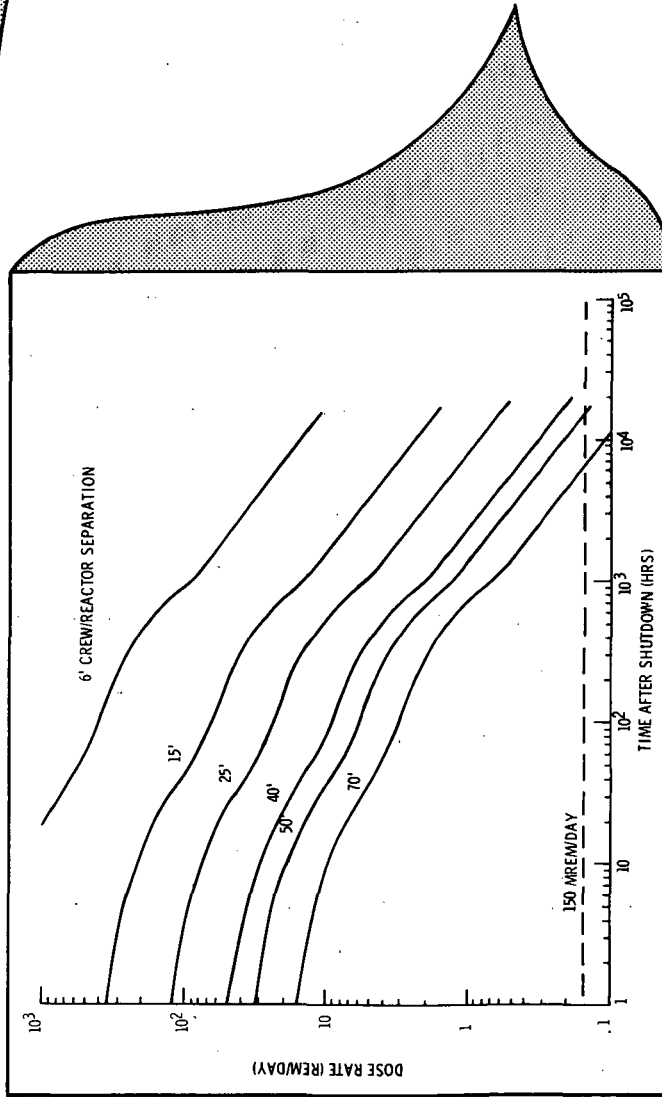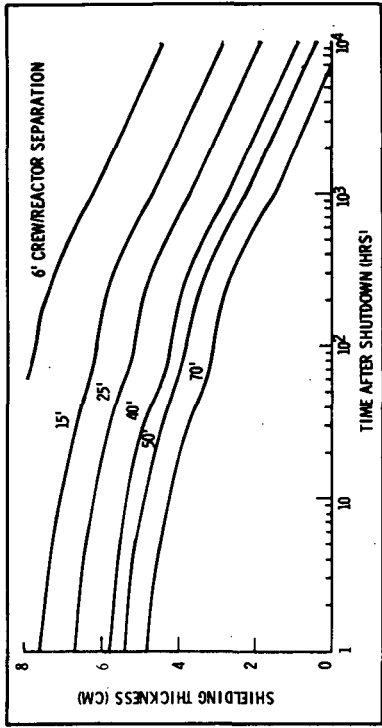
Figure 3-4. Shutdown Reactor Radiation Environment
(Reactor Forward in Cargo Bay)
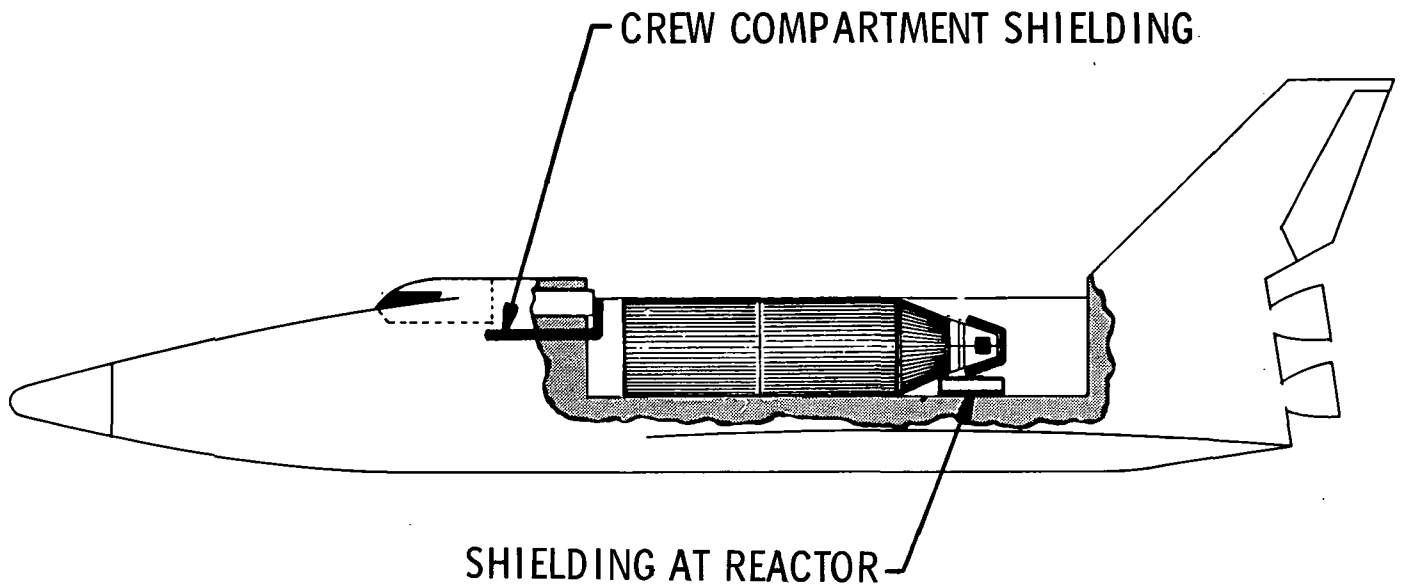
Figure 3-5. Typical Shield Locations in Shuttle

3.2.2 BLAST AND FRAGMENTATION PROTECTION

Prior to initial reactor startup in orbit, little or no blast and fragmentation protection is required due to the small fission product inventory present in the reactor core. However, following reactor operation in space and the resultant buildup of relatively large fission product inventories, blast and fragmentation protection must be provided to reduce the probability of a release of these fission products to the environment (space vacuum or the Earth's atmosphere) following an accidental Shuttle explosion.

The Shuttle blast environment on the launch pad and the assumed "worst case" Shuttle blast environment at 30.5 km (100 kft) upon reentry are defined in detail in Appendix A.3. In reference to Figure 3-6, it is seen that the overpressures resulting from a launch pad explosion and fire are so high that it precludes the use of any material that would withstand the blast loading. In all likelihood, in the event of a Shuttle explosion and fire on the launch pad,

the power module (or for that matter, any type of payload in the orbiter cargo bay) would be thrown or blasted out of the cargo bay by the resultant overpressures. It then becomes a matter of protecting the reactor from the primary and secondary fragmentation following such an explosion. A Shuttle launch configuration concept (Figure 3-7) which positions the orbiter between the booster and the Mobile Launcher (ML) is particularly undesirable due to the possibility of slamming the nuclear payload against the ML tower in the event of a launch pad explosion.
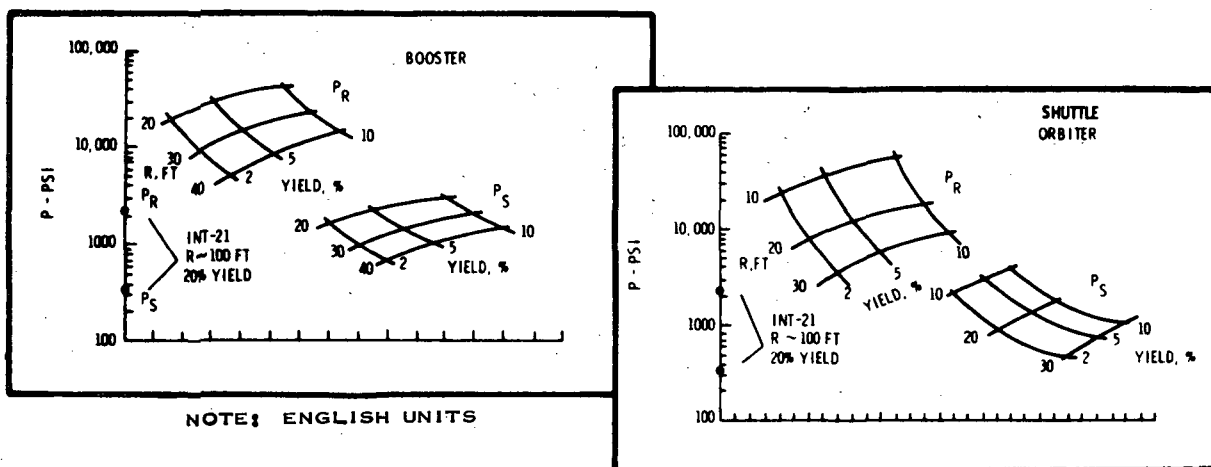
Figure 3-6. Blast Pressures Resulting from a Launch Pad Shuttle Explosion

An accidental explosion of the Shuttle at altitude greatly reduces the blast environment due to (1) the decrease in atmospheric pressure (density), and (2) the reduced Shuttle propellant loading. The possibility of fragmentation of the reactor core is also diminished due to the demonstrated inability of hypergolic propellants to forcibly ignite in a vacuum (Reference 3-2).

From the Space Shuttle blast, fragmentation, and shielding analysis (Volume IV, Part 2, Appendix A), it is seen that a 1.8 cm (0.7 in) thick titanium shield may prevent primary fragmentation of the reactor/shield assembly throughout the mission. The shielding weight involved is highly dependent on the shield design and where it is located in respect to the reactor.
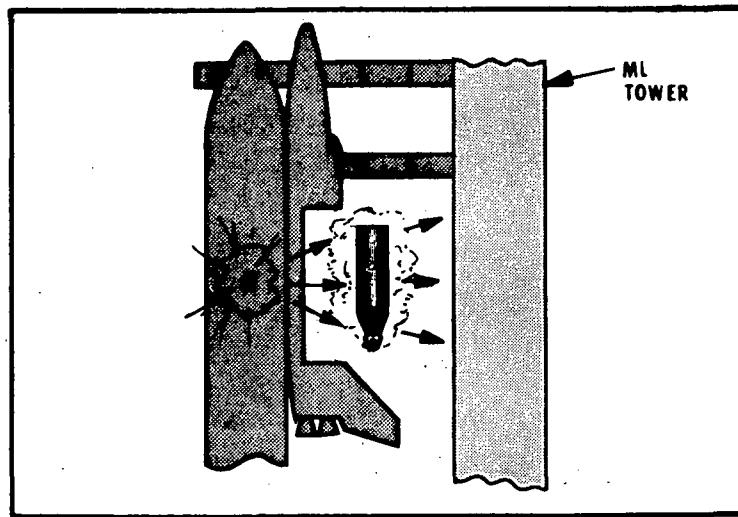
Figure 3-7. Undesirable Shuttle Launch Pad Configuration Due to
Severe Fragmentation Potential

3.2.3 ENVIRONMENTAL PROTECTION (ENCLOSURE)

The reference ZrH reactor power module contains approximately 170 kg (375 lbs) of sodium-potassium liquid metal (NaK-78) in the primary and intermediate NaK loops (Reference 3-3). All NaK loops will be filled before the final acceptance testing at the factory and will remain filled throughout all subsequent operations. This sodium-potassium liquid metal reacts with a number of metals, gases, and liquids, including water and oxygen. For this reason, special precautions must be taken to prevent liquid metal fires and corrosive reactions, while the

reactor power module is within the Shuttle cargo bay. An "inert gas blanket" (e.g. Argon, Helium) coupled with double wall containment should be employed to prevent the presence of moisture and other oxygen sources from coming in contact with the NaK coolant in the event of a coolant leak. An added safety precaution involves the sealing off of the cargo bay from the rest of the Shuttle, especially from the LO_2 and LH_2 vapor boil-off of propellant tanks or fuel cell storage bottles.

The requirements for an inert gas environmental enclosure are significantly increased if a liquid metal NaK coolant is used in the primary heat rejection loop rather than an organic coolant (i.e., Dow Corning 200).

3.2.4 THERMAL CONTROL

As shown is Figure 3-8, the Space Shuttle presents a significant temperature variation within the cargo bay during the mission (Reference 3-4). The orbit temperature regime for unin- sulated cargo makes freezing of primary, intermediate, and heat rejection loops a strong possibility (NaK freezes at approx. $260^\circ K$). The final thermal environment in the cargo bay may change as Shuttle design evolves; however, there are several approaches available if coolant freeze up within the cargo bay is considered undesirable.

1) Provide an insulating blanket around the reactor power module.

2) Add a 200-watt radiant heat source within the radiator cavity.

3) Preheat the NaK (and organic) fluids and the lithium hydride shield, and allow this stored heat to maintain acceptable fluid temperatures.

4) Divert a portion of the Shuttle's waste heat to provide a thermal source.

5) Orient the cargo bay to face the sun with the hatch open during the sun cycle periods.

An additional potential problem area is heat dissipation from the reactor core after long term reactor operation (due to fission product decay). The afterheat generation in a reactor which has been operated at 125 kWt for five years is given in Appendix B. The curve in Figure B-6
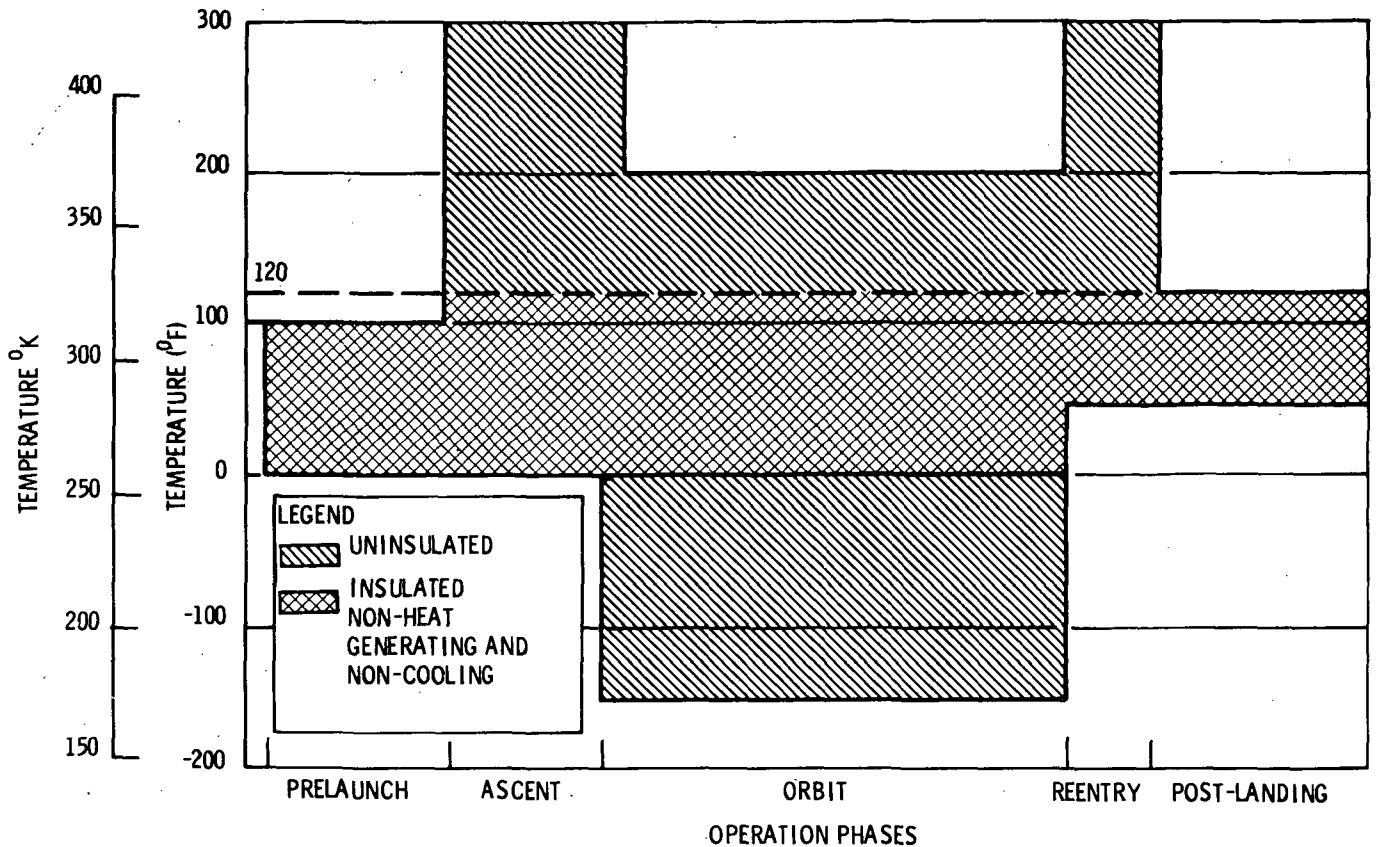
Figure 3-8. Typical Module Temperature Range Within Shuttle Cargo Bay

represents the maximum heat dissipation required in the cargo bay in order to maintain constant reactor temperature conditions. The decay heat generation of over 1 kWt immediately after shutdown decreases to less than 0.5 kWt after two days.

A minimum 2 day waiting period is desirable. Since the afterheat generation is relatively low several days after shutdown, it is possible that no special reactor/shield heat removal apparatus would be needed since the heat capacity and natural heat loss from the Shuttle itself may be sufficient.

3.2.5 SYSTEM STATUS AND CONTROLS

Knowing the condition of the reactor power module within the Shuttle cargo bay permits an assessment by the crew of the "go/no-go" status of the payload (1) prior to launch, (2) prior to final rendezvous and docking, and (3) prior to initiating the reentry, final approach and landing. A detected failure condition, such as a liquid metal or radiator coolant leak, would

3-12

eliminate the need for docking and subsequent removal of a damaged power module. A detected failure condition of the power module which is deemed a hazard upon landing could result in the emergency ejection of the power module into a deep ocean area prior to earth landing. Provisions must be made within the Shuttle crew compartment for the recording and/or display of a maximum of 80 data points (sensors) for maintaining periodic and, in some cases, continuous system status of power module integrity, radiation levels, NaK leaks, power module and cargo bay temperatures, etc. In addition to the monitoring equipment, some 20 separate control signals are required to provide environmental control regulation, handling, attachment and deployment controls from the Shuttle.

Table 3-1 identifies the number of possible control and monitoring functions required.

3.2.6 ELECTRICAL POWER

Provision for up to 1 kw of electrical power may be required by a reactor power module while being transported by a Space Shuttle. The power requirement is dependent on the design characteristics and condition of the power module. Up to 0.2 kw may be required to prevent NaK freeze-up, however the majority of the power required is needed for operation of coolant pumps for the removal of fission product decay heat from a reactor which has just been shut down.

Table 3-1. Reactor Power System Control and Monitoring Requirements

CONTROLS	
Function	*Number Required
Inert gas environment	4
Positioning latches	12
Heaters	2
Separation system	2
Auxiliary power system	4
	Total 24
SENSORS (DATA POINTS)	
Function	*Number Required
Radiation monitors	6
NaK leaks (pressure monitors)	20
Temperature monitors	8
Positioning and Handling	18
Auxiliary power system status	12
Inert gas pressure and composition	8
Valve positions	6
	Total 78
*Redundancy accounted for	

These electrical power requirements can be substantially reduced if (1) the NaK heating requirement is placed on the Space Base rather than on the Space Shuttle (NaK would be heated subsequent to mating of the reactor module to the Space Base and prior to reactor start-up), and (2) a short wait time of two days is observed for thermal cooling prior to placing the shutdown, spent reactor in the cargo bay.

Electrical power required, could be supplied by batteries that are carried into the cargo bay as a part of the payload or by the Space Shuttle Electrical Power System.

3.2.7 ATTACHMENT & HANDLING

As discussed in Appendix A, the payload retention and deployment system is designed to accommodate payloads 4.6 m (15 ft) in diameter by a length that may vary from payload to payload, not exceeding 18.3 m (60 ft). The nuclear reactor module that is to be transported by the Space Shuttle must then be designed with fittings that can mate directly with the various attach points on the Shuttle. If the 90 degree rotation scheme is the selected mode of deployment, the reactor will have to be fitted with a docking ring that is mated to the payload adapter located at the end of the Shuttle's flexible tunnel. (Refer to Appendix Section A.1.3) If the manipulator arm concept is used, the reactor power module must be equipped with cargo bay attach points and also attach points for the manipulator arms.

Alternate cargo replacement/recovery schemes (transfer by space tug, use of integral propulsion modules, etc.) will also require special fittings and attach points.

A typical reactor power module configuration is characterized by the center of gravity near the reactor/shield end of the module. Radiator design may provide adequate axial structure strength, but side loading bending moments must be compensated by the attach points. In the following subsection a special handling and support fixture is recommended, which would provide design integration and safety advantages.

3.2.8 TRANSFER MODULE

One method of minimizing the design impact and increasing the safety of operations involving the power module and the Shuttle is to position the reactor in a "transfer module" which is, in turn, placed in the Shuttle cargo bay (see Figure 3-9). By using such a transfer module, the power module will not have to be designed with standardized attach fittings that mate directly to the Space Shuttle, but the reactor will be mounted on the transfer module in the most convenient way possible. The transfer module is then designed to be compatible with the Shuttle cargo bay, attach points, and deployment scheme.

The transfer module also offers added ease in safely handling the reactor power module. The power module can be mounted on the transfer module at the manufacture's site and not be removed until the module transfer operations are initiated in orbit.

A key advantage in using a transfer module is that it not only reduces the impact on the reactor when being transported by the Space Shuttle, but that it reduces the impact on the Shuttle when transporting a nuclear reactor power-module. In the previous sections safety related Shuttle and power module packaging items and integration requirements have been identified, such as blast and fragmentation protection, crew radiation shielding, an inert gas environmental enclosure, double containment, a thermal control system, various monitoring and control devices, and an electrical power system. When a transfer module is used, much of the necessary ancilliary equipment could be incorporated into the transfer module rather than being mounted to the Shuttle directly. Without a transfer module, payload support would be required from the Shuttle systems. For example, the blast and fragmentation protection and crew radiation shielding could be made part of the transfer module. Tankage for the inert gas environmental enclosure and batteries for the electrical power could also be mounted to the structure of the transfer module.

There are, however, disadvantages associated with this concept. The weight of the transfer module must be included in the total payload weight. This reduces the useful payload weight that can be launched. Also, the overall dimensions of the actual payload envelope would be reduced since the transfer module will occupy some of the allowable cargo space.

RADIATION SHIELDING
• 150 MREM/DAY

BLAST/FRAGMENTATION PROTECTION

TRANSFER MODULE
• MUST BE COMPATIBLE WITH SHUTTLE PAYLOAD ATTACH FITTINGS
• ALLOWS MINIMUM IMPACT ON SHUTTLE

REACTOR MODULE
• MUST FIT IN CARGO BAY
• MODULE CG MUST BE WITHIN SHUTTLE CG ENVELOPE

ENVIRONMENTAL ENCLOSURE
• PROVIDE INERT GAS ENVIRONMENT

THERMAL CONTROL
• DECAY HEAT REMOVAL

ELECTRICAL POWER

DISPLAY PANELS FOR MONITORING & CONTROL
• CONTINUOUS MONITORING REQUIRED
  - RADIATION
  - NaK LEAKS

Figure 3-9.   Reactor Packaging/Shuttle Integration Using Transfer Module

3.2.9 DESIGN AND PACKAGING GUIDELINES

A summary of the key guidelines for the design and packaging of a reactor power module within a Shuttle is contained in Table 3-2.

Table 3-2. Shuttle/Reactor Power Module Design and Packaging Guidelines

- Provide multiple and independent radiation monitoring equipment with instantaneous and recording outputs for all mission phases.

- Provide multiple and independent system monitoring and control equipment with instantaneous and recording outputs for all mission phases.

- Provide inert gas blanket and or double containment during prelaunch period (to preclude NaK-oxygen reaction in event of NaK leak).

- Provide blast overpressure and fragmentation protection adequate to assure containment of all radioactive material in event of an accident (critical requirement for isotopes; may be desirable for reactors).

- Provide fireball protection adequate to assure containment of all radioactive material in event of an accident (critical requirement for isotopes; may be desirable for reactors).

- Consider crushup material in cargo bay to minimize damage upon Shuttle land impact.

- Provide up to 1 kw electrical power (either transfer module or Shuttle).

- Prevent propellant boil-off and other O_2 sources from entering the Shuttle cargo bay with the doors closed.

- Consider use of "transfer module" integration scheme to reduce and simplify Shuttle interfaces and to improve safety in handling nuclear payloads.

- Provide a free, unobstructed and directed ejection path for the reactor power module in the event of a Shuttle booster or orbiter explosion on the launch pad.

- Provide for decay heat removal and radiation shielding if spent reactor is transferred to Shuttle less than 10 days after shutdown.

- Provide certified equipment to handle nuclear payloads.

- Provide certified facilities to:

  - Store reactor power modules
  - Checkout reactor power modules and components
  - Perform radiological monitoring and control functions

3.3 REACTOR TRANSPORT OPERATIONAL PROCEDURES

The typical mission operations that are involved in transporting a reactor power module with the Space Shuttle are discussed in this section.

3.3.1 PRELAUNCH

Upon arrival at KSC, the reactor power module, inside its environmentally controlled trans-porter, will be taken to the Nuclear Assembly Building (NAB) where it will undergo a series of prelaunch checkouts. The initial step is to visually inspect for shipping damage. Follow-ing this, an intensive sequence of electrical continuity and functional tests will be performed. Fluid loop tests will then be performed to confirm pump operation and loop head flow charac-teristics. For the Brayton Power Conversion System (PCS) checkout, cold-gas tests will be performed to confirm rotor lift-off and rotation. For a more detailed description of the pre-launch activities at KSC, refer to Volume II, Section 5 of this study.

Following these tests, the reactor power module is shipped (in its environmentally controlled transporter) to either the Vehicle Assembly Building (VAB) or the launch pad complex for in-stallation in the Shuttle cargo bay. Figure 3-10 shows four alternative schemes for installa-tion of the reactor power module in the Shuttle cargo bay. Schemes A and B depict the power module being installed in the cargo bay while in the VAB, whereas schemes C and D show the installation occurring at the launch pad.

Throughout this phase of the mission, it is important to realize that the reactor is relatively non-radioactive and personnel can have reasonably good access to the power module. Be-cause of the relatively non-hazardous state of the reactor, it makes little difference, from a normal radiation standpoint, whether the reactor is installed in the Shuttle in the VAB or at the launch pad provided liquid metal systems can be adequately protected. Installation at the launch pad may, however, be preferable in that this operation can occur late in the countdown. This approach would reduce the possibility of prelaunch accidents that could involve the reac-tor and eliminates the possibility of potential nuclear accidents within the VAB and the necessity of providing the nuclear support plans and hardware for that facility.

3.3.2 LAUNCH/ASCENT

Depending on how the Space Shuttle is mounted on the Mobile Launcher (ML), two launch modes are possible (Figure 3-11) - one with the cargo bay facing the ML and one with the cargo bay away from the ML. A current Shuttle launch configuration has the Shuttle cargo bay oriented

3-18
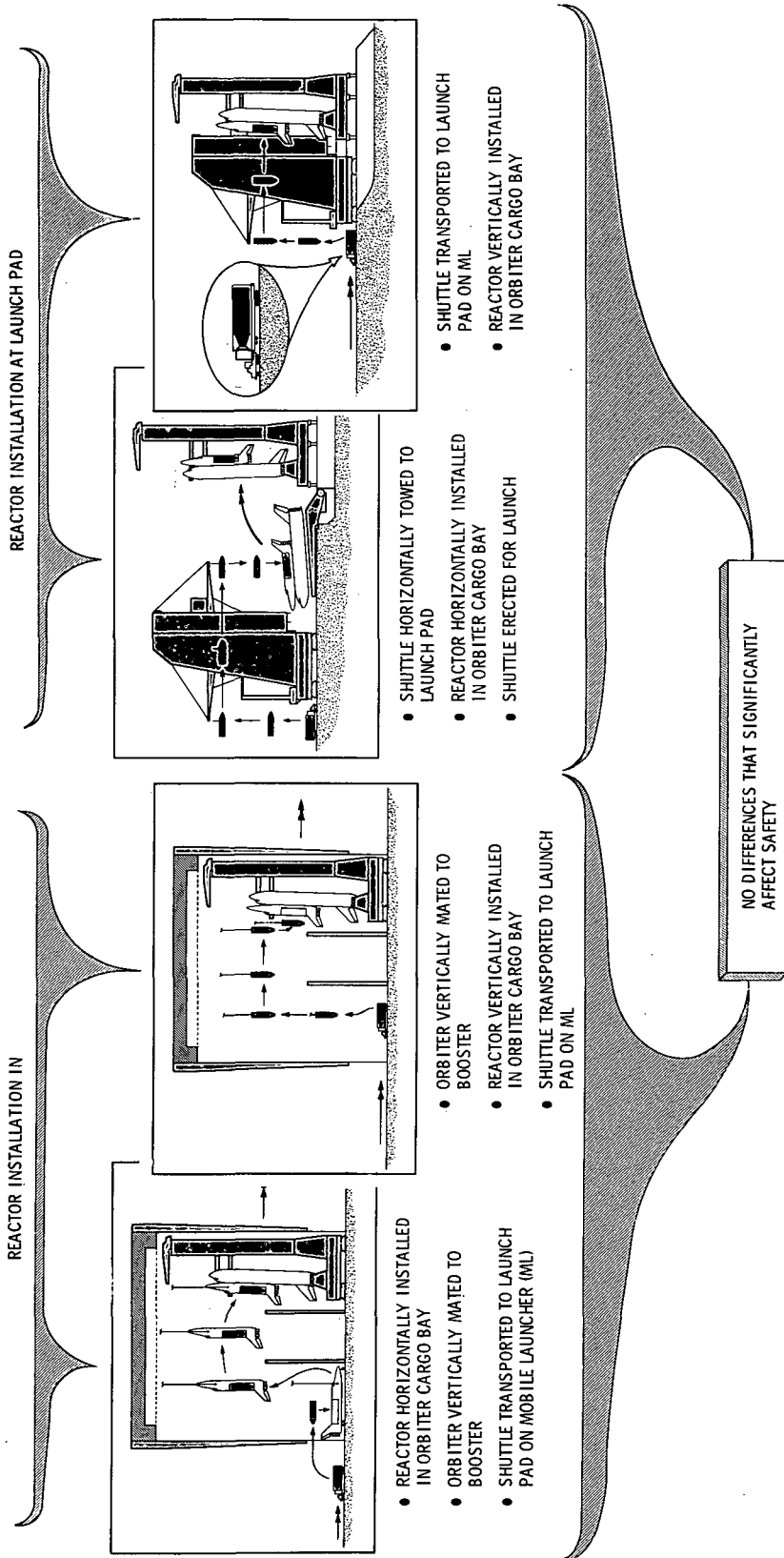
Figure 3-10. Reactor/Shuttle Operations–Prelaunch Installation

REACTOR INSTALLATION IN

- REACTOR HORIZONTALLY INSTALLED IN ORBITER CARGO BAY
- ORBITER VERTICALLY MATED TO BOOSTER
- SHUTTLE TRANSPORTED TO LAUNCH PAD ON MOBILE LAUNCHER (ML)

- ORBITER VERTICALLY MATED TO BOOSTER
- REACTOR VERTICALLY INSTALLED IN ORBITER CARGO BAY
- SHUTTLE TRANSPORTED TO LAUNCH PAD ON ML

REACTOR INSTALLATION AT LAUNCH PAD

- SHUTTLE HORIZONTALLY TOWED TO LAUNCH PAD
- REACTOR HORIZONTALLY INSTALLED IN ORBITER CARGO BAY
- SHUTTLE ERECTED FOR LAUNCH

- SHUTTLE TRANSPORTED TO LAUNCH PAD ON ML
- REACTOR VERTICALLY INSTALLED IN ORBITER CARGO BAY

NO DIFFERENCES THAT SIGNIFICANTLY AFFECT SAFETY

CARGO BAY AWAY FROM MOBILE LAUNCHER
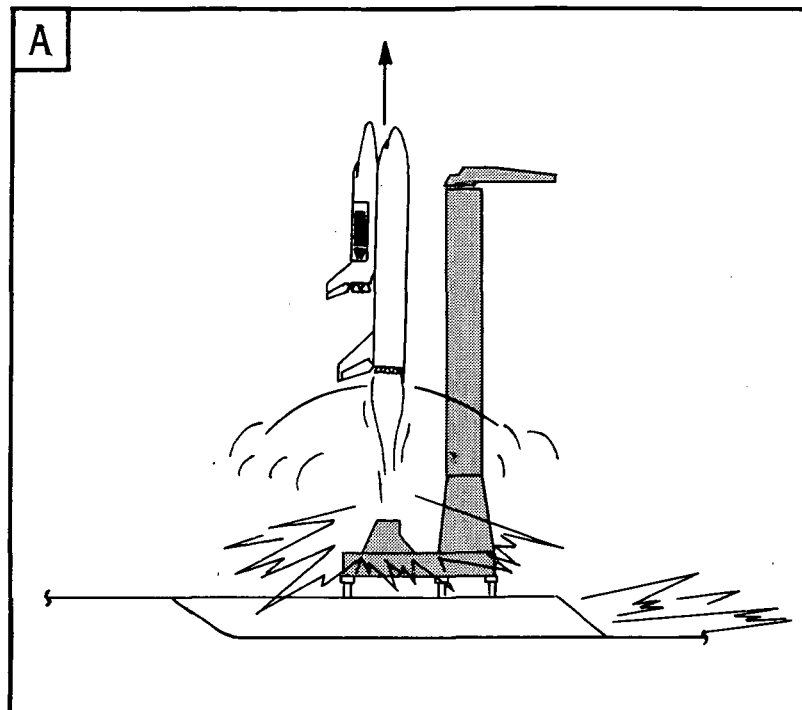
CARGO BAY TOWARD MOBILE LAUNCHER
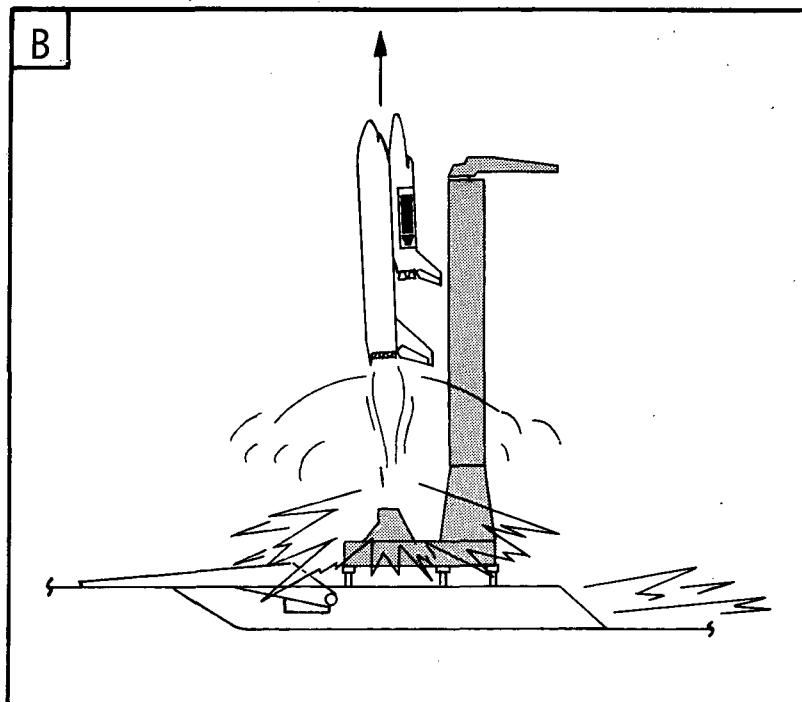
Figure 3-11. Alternative Shuttle Launch Modes

toward the ML. However, in the event of a launch pad abort, it is preferable from a nuclear safety standpoint to have the cargo bay facing away from the ML. This would allow for an unobstructed path for the reactor module to be ejected out of the cargo bay as a result of a launch pad explosion.

3.3.3 ON-ORBIT OPERATION

Once the Shuttle has rendezvoused with the Space Base, the cargo transfer operations are initiated. A desirable objective is to maintain positive control of the power module at all times. For the initial launch of a reactor power module, the operation involves the transfer of a "clean" reactor power module from the Shuttle to the Space Base with no retrieval of a post-operational "spent" power module. Figure 3-12 illustrates five possible modes of power module transfer to the Space Base:

- Articulation - manipulator arms

- 90° rotation - flexible tunnel concept

- Translation - scissors platform

- Space Tug (in conjunction with either articulation, rotation, or translation); the tug may be either manned or unmanned.

- Self-propelled power module (in conjunction with articulation, rotation, or translation).

For the retrieval of a shutdown, spent reactor, the same schemes as shown in Figure 3-12 can be used except with reverse procedures.

Power module replacement and retrieval missions take on an added complexity since two reactor power modules must be handled - the replacement power module that is brought up in the Shuttle and the spent power module that is to be replaced and either taken up to a high Earth orbit for disposal or returned to earth. Figures 3-13 through 3-16 depict various possible schemes for the power module replacement/retrieval operation. The same payload handling schemes, as shown in Figure 3-12, are used in conjunction with either a "rotational docking port" concept or a "temporary docking port" concept.
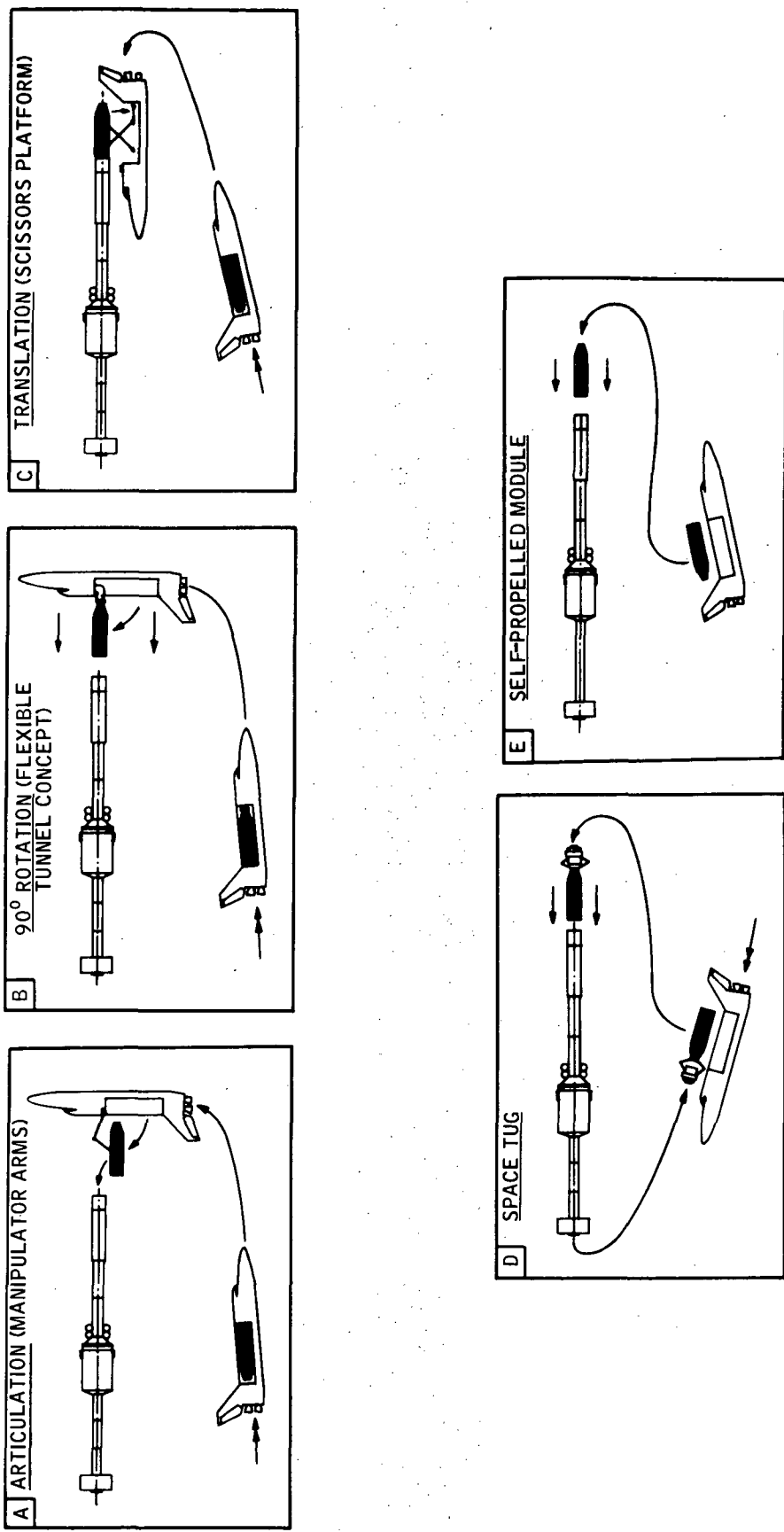
Figure 3-12. Alternate Schemes for Power Module Transfer to Space Base

The rotational docking port concept features a rotational assembly at the end of the power module boom with two usable docking ports. In Scheme A of Figure 3-13, the Shuttle hard-docks with the Space Base (Shuttle docking port located on power module boom). In this position, the shutdown, spent power module is located directly above the Shuttle cargo bay. The spent module is then rotated 90 degrees to the side bringing a second usable docking port into position above the cargo bay to accept the replacement power module. The replacement module is then transferred to the Space Base and docked in place. With this accomplished, the spent power module is then rotated back into position above the cargo bay. Once the spent power module has been transferred to the Shuttle and secured in the cargo bay, the Shuttle un-docks from the Space Base and the replacement power module is rotated back to the "opera-tional" position and the reactor startup operation is initiated.

In Scheme A of Figure 3-14, a similar procedure is followed except there is no direct hard-dock between the Shuttle and the Space Base. The docking is accomplished through the power module itself. The spent power module is first rotated 90 degrees to the side, then the Shuttle slowly moves into position and transfers the replacement module. When the replacement module has successfully been docked, the spent module is rotated into position for retreival.

The rotational docking port is also employed in Scheme A of Figure 3-16 to rotate the re-placement power module to the side prior to the self-propelled module approaching and docking.

The temporary docking port concept is used in Scheme A of Figure 3-15. In this replacement/ retrieval operation, the Space Tug removes the spent power module from the operational dock-ing port and installs it in a temporary docking port on the boom. After the tug has success-fully transferred the replacement power module to the Space Base, the Tug then retrieves the spent module from the temporary docking port and transfers it to the Shuttle.

The remaining replacement/retrieval scheme (Scheme B in Figures 3-13 through 3-16) in-volves the spent power module being released or taken to some defined stand-off distance while the replacement power module is being transferred. Follwing successful transfer of the replacement power module, and spent power module is retrieved by either the Space Tug or the Shuttle itself and secured in the Shuttle orbiter cargo bay.

ROTATIONAL DOCKING PORT　　　SPENT MODULE CONTROLLED RELEASE

OPERATIONAL PROCEDURES

1. ROTATE SPENT POWER MODULE FROM POSITION "A" TO POSITION "B".

2. DOCK REPLACEMENT POWER MODULE TO ROTATIONAL DOCKING PORT AT POSITION "A".

3. ROTATE REPLACEMENT POWER MODULE TO POSITION "C" AND SPENT POWER MODULE BACK.TO POSITION "A".

4. RECOVER SPENT POWER MODULE FROM POSITION "A" AND PLACE IN SHUTTLE CARGO BAY.

5. ROTATE REPLACEMENT POWER MODULE TO OPERATIONAL POSITION (POSITION "A").

1. SPENT POWER MODULE IS RELEASED FROM SPACE BASE (POSITION "A") AND ALLOWED TO ASSUME SOME STAND—OFF DISTANCE AT POSITION "B".

2. SPACE SHUTTLE HARD—DOCKS WITH BASE AND TRANSFERS REPLACEMENT MODULE TO DOCKING PORT (POSITION "A").

3. SPACE SHUTTLE UNDOCKS WITH BASE AND RETRIEVES SPENT POWER MODULE AT SOME STAND—OFF DISTANCE (POSITION "B").

*SPACE STATION SHOWN FOR CONVENIENCE. OPERA—TIONS WOULD BE THE SAME FOR SPACE BASE.

Figure 3-13.　Power Module Replacement/Retrieval Schemes*
(Direct Shuttle Hard-Dock)

ROTATIONAL DOCKING PORT　　　SPENT MODULE CONTROLLED RELEASE
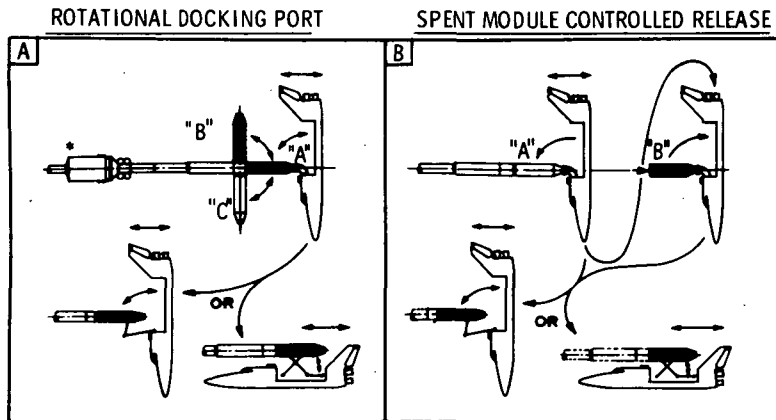
OPERATIONAL PROCEDURES

(SAME AS IN SCHEME A, FIGURE 3-13 EXCEPT NO DIRECT SHUTTLE HARD-DOCK; DOCK AND REDOCK ACCOMPLISHED THROUGH POWER MODULE)

(SAME AS IN SCHEME B, FIGURE 3-13 EXCEPT NO DIRECT SHUTTLE HARD-DOCK; DOCK AND REDOCK ACCOMPLISHED THROUGH POWER MODULE)

*SPACE STATION SHOWN FOR CONVENIENCE. OPERA—TIONS WOULD BE THE SAME FOR SPACE BASE.

Figure 3-14.　Power Module Replacement/Retrieval Schemes*
(Dock Through Power Module)

TEMPORARY DOCKING PORT   SPENT MODULE CONTROLLED RELEASE

OPERATIONAL PROCEDURES

1. TUG REMOVES SPENT POWER MODULE FROM POSITION "A" TO TEMPORARY DOCKING PORT AT POSITION "B".

2. TUG RETRIEVES REPLACEMENT POWER MODULE FROM SHUTTLE (POSITION "C").

3. TUG TRANSFERS REPLACEMENT POWER MODULE FROM SHUTTLE TO OPERATIONAL REACTOR POWER MODULE DOCKING PORT ON SPACE BASE (POSITION "A").

4. TUG REMOVES SPENT POWER MODULE FROM TEMPORARY DOCKING PORT (POSITION "B") AND TRANSFERS IT TO SPACE SHUTTLE.

1. TUG REMOVES SPENT POWER MODULE FROM POSITION "A" TO SOME STAND-OFF DISTANCE AT POSITION "B".

2. TUG RETRIEVES REPLACEMENT POWER MODULE FROM SHUTTLE (POSITION "C").

3. TUG TRANSFERS REPLACEMENT POWER MODULE FROM SHUTTLE TO SPACE BASE (POSITION "A").

4. TUG RETRIEVES SPENT POWER MODULE FROM POSITION "B" AND TRANSFERS IT TO SHUTTLE.

* SPACE STATION SHOWN FOR CONVENIENCE. OPERA- TIONS WOULD BE THE SAME FOR SPACE BASE.

Figure 3-15. Power Module Replacement/Retrieval Schemes* (Space Tug Transfer)

ROTATIONAL DOCKING PORT   SPENT MODULE CONTROLLED RELEASE

OPERATIONAL PROCEDURES

1. SPENT POWER MODULE IS ROTATED FROM POSITION "A" TO POSITION "B".

2. SELF-PROPELLED REPLACEMENT POWER MODULE IS TRANSFERRED FROM SPACE SHUTTLE (POSITION "C") TO OPERATIONAL REACTOR POWER MODULE DOCKING PORT (POSITION "A").

3. SELF-PROPELLED SPENT POWER MODULE IS RELEASED FROM ROTATIONAL DOCKING PORT (POSITION "B") AND IS TRANSFERRED TO THE SHUTTLE.

1. SPENT POWER MODULE IS RELEASED FROM OPERATIONAL DOCKING PORT (POSITION "A") AND IS SELF-PROPELLED TO SOME STAND-OFF DISTANCE AT POSITION "B".

2. SELF-PROPELLED REPLACEMENT POWER MODULE IS TRANSFERRED FROM SPACE SHUTTLE (POSITION "C") TO SPACE BASE (POSITION "A").

3. SELF-PROPELLED SPENT POWER MODULE IS TRANSFERRED FROM POSITION "B" TO SPACE SHUTTLE.

* SPACE STATION SHOWN FOR CONVENIENCE. OPERA- TIONS WOULD BE THE SAME FOR SPACE BASE.

Figure 3-16. Power Module Replacement/Retrieval Schemes* (Self-Propelled Module)

3-25

Independent of which power module replacement/retrieval scheme may be adopted, two general ground rules should be adhered to:

- Maintain positive handling control of the power module at all times.

- Minimize the crew dose rate (maximum of 150 mrem/day)

Recognizing that the spent module controlled release approach does not maintain positive handling control of the spent power module, it may prove to be acceptable, from a risk standpoint if it can be assured that (a) the spent module remains stable when released, (b) tracking of the released module be maintained, and (c) the cargo transfer devices be capable of grappling a "free floating" module.

The radiation dose to the Shuttle crew from a shutdown, spent power module (5 years operation at 125 kWt) in the Shuttle orbiter cargo bay is given in Appendix B. 6. 2. With no gamma shielding for the crew, a minimum wait time (from reactor shutdown to initiation of replacement/retrieval operations) of approximately 10 days is required for the dose rate to go below the maximum allowable 150 mrem/day.

As presently configured, the MDAC approach to transporting and handling cargo using the flexible tunnel 90 degree rotation scheme would be unacceptable (from a nuclear radiation standpoint) for the transport of a spent reactor power module. By using this scheme the power module would be placed in the Shuttle cargo bay with the reactor/shield assembly toward the forward bulkhead, resulting in high (>> 150 mrem/day) dose rates to the Shuttle crew. This scheme, however, could be employed, if a rotational or trunnion mechanism were designed on the transfer module to pivot the reactor power module 180 degrees while it is being rotated either into or out of the Shuttle. The reactor/shield assembly could then be placed toward the rear of the cargo bay thereby reducing the crew dose rates to acceptable levels.

In handling and transfer of a shutdown, spent reactor power module from the Base to the Shuttle cargo bay, the crew locations should be kept within the shadow of the reactor's radiation shield to minimize the dose to the crew and not exceed the dose limit of 150 mrem/day.

In examining the NAR and MDAC Shuttle orbiters and their selected cargo transfer mechanisms (manipulator arms and 90 degree rotation, respectively), it was found (Reference Appendix B.6.2) that the crew locations can be kept within the "shielding cone" for all cases except one - transfer of the dual reactor module to the MDAC Shuttle orbiter. (assuming the configuration is that shown in Figure B.11 of Appendix B). However, allowing for radiation decay, transfer of the dual reactor module to the Shuttle cargo bay can begin five hours after reactor shutdown without exceeding the allowable dose rate to the Shuttle crew. Adequate shielding ($\sim$1.6 cm of tungsten) must then be provided for the crew once the power module is installed in the cargo bay. As stated previously, this additional shielding would not be required if a 10 day wait period was provided. It must be recognized that the reactor type, shielding, and operating power levels and duration affect this data and future missions and configurations should be treated accordingly.

3.3.4 END-OF-MISSION (DISPOSAL OR RECOVERY)

After the reactor has completed its operational lifetime (or in the event of a non-reparable system failure), it is necessary to dispose of the spent reactor power module in a way that will not present a hazard to the earth's populace and ecology. This can be accomplished by either (1) placing the power module in a high earth orbit, thereby increasing the orbital lifetime of the power module, giving the core fission products adequate time to decay to insignificant, non-hazardous radiation levels, or (2) returning the power module to the earth's surface. The Space Shuttle is a candidate for either of these disposal modes.

Figure 3-17 shows that the Shuttle has the capability to boost a 13.6 t (30 klb) power module from a 500 km (273 nm) Space Base orbit to an 835 km (450 nm) disposal orbit. Based on a ballistic coefficient $(W/C_D A)$ of 2390 Newtons/m^2 (50 lb/ft^2) for the power module, the orbital lifetime is estimated to be at least 250 years (Reference 3-1). This represents approximately 9 half-lives of the longest lived fission products (Sr-90 and Cs-137) in the reactor core. Figure 3-18 shows that to place the reactor module in an 835 km circular disposal orbit requires a ΔV of approximately 260 m/sec (850 ft/sec).
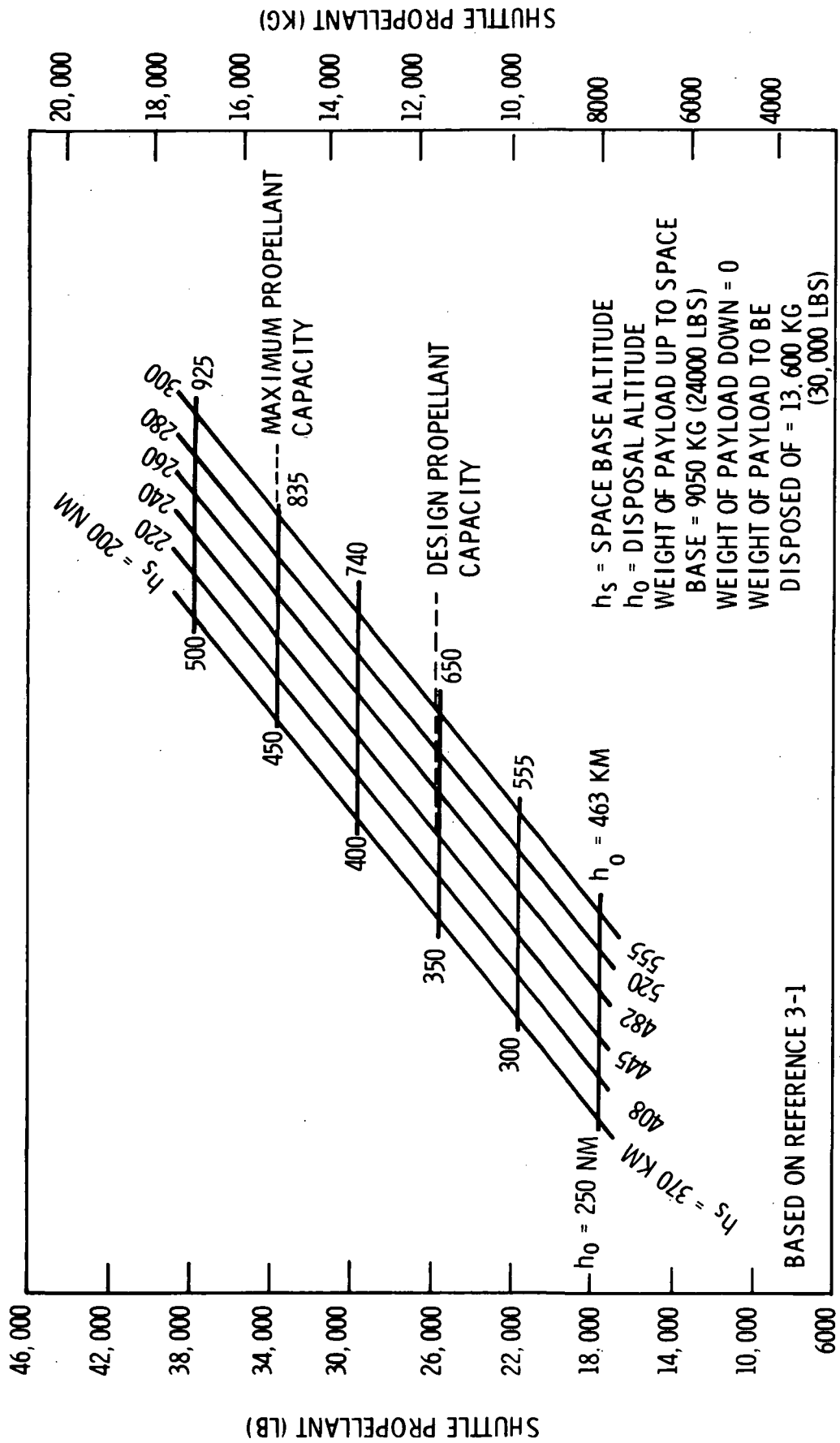
Figure 3-17. Space Shuttle Capability to Boost to High Earth Orbit
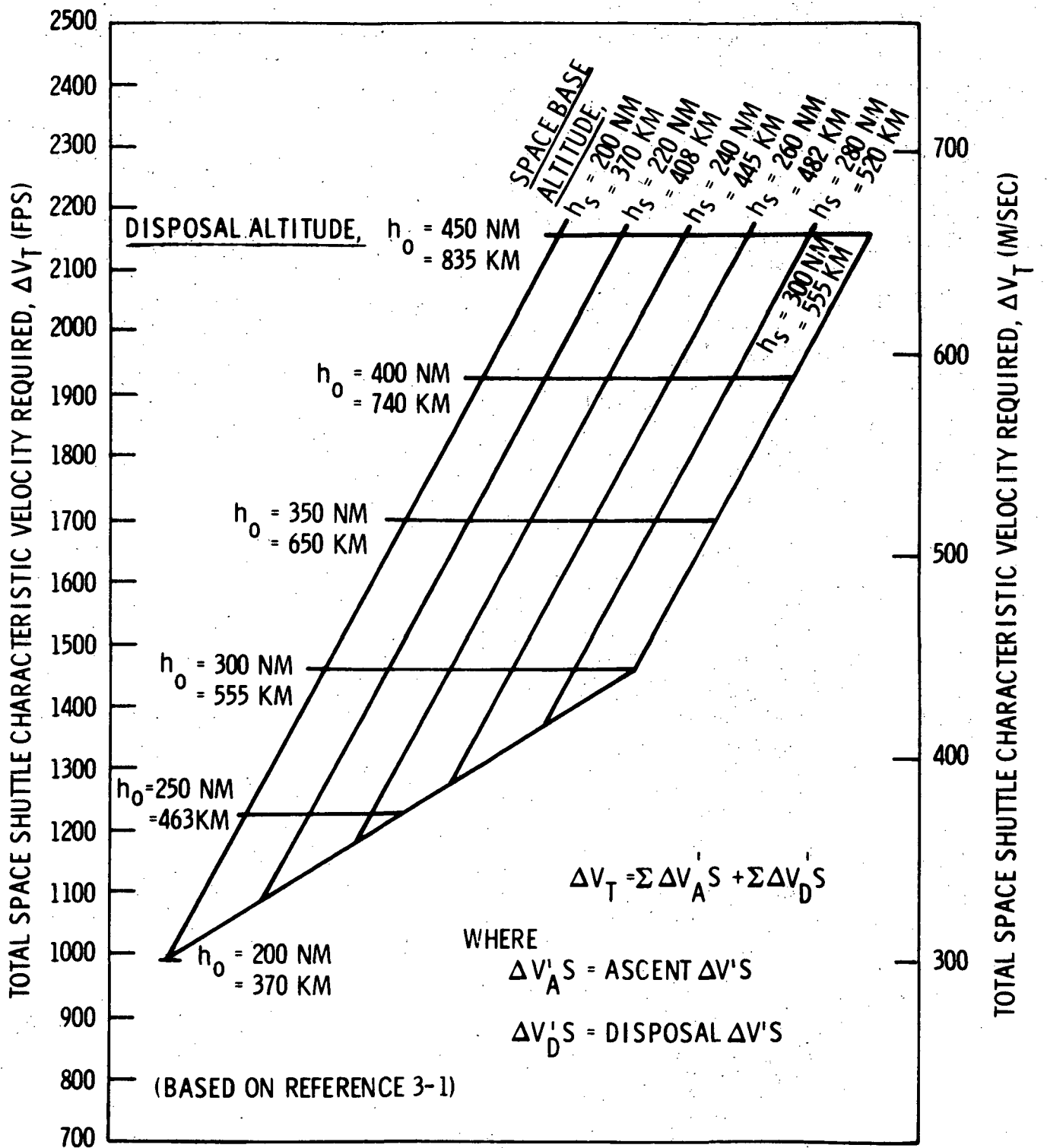
Figure 3-18. Total Space Shuttle Delta V Required to
Boost Nuclear Payload to High Earth Orbit

An alternative to a high earth orbit disposal is to have the Shuttle return the reactor to the earth's surface. This mode should be given much consideration. The results of the risk evaluation conducted in the terrestrial safety analysis (Volume III Part 3 and Volume IV Part 2 of this study) have shown highest risks to occur during disposal*/recovery. The use of the Shuttle to return the reactor to earth reduces this risk by at least an order of magnitude.

A typical ground trace for a Shuttle descent/reentry trajectory is shown in Figure 3-19. As shown, the trajectory carries the Shuttle over large stretches of deep ocean with very little land mass overfly. This type of trajectory is particularly desirable to minimize any potential nuclear hazard that could result from a Shuttle failure.

A normal earth landing should impose no difficulties on the reactor power module. The Shuttle payload attach fittings can be designed to prevent most of the landing forces from being transmitted to the power module, particularly when use is made of a transfer module.

Upon landing and completion of the roll-out, the Shuttle will be taxied to a cargo removal area since it is desirable to place the reactor in a nuclear facility with as little delay as possible. Thorough radiation and liquid metal leak checks will be made immediately. An unloading crane attached to the transfer module or reactor attach points will remove the reactor power module with the Shuttle parked in a normal horizontal position, and will position the module in a transporter for removal to the nuclear facility.

Several safety related considerations are worthy of mention when evaluating the total operations required for the Disposal/Recovery Phase.

1. There is no need for recovery of the radiator and power conversion systems. In fact, a liquid metal radiator adds to the non-nuclear hazards during recovery. Techniques should be developed to recover only the reactor/shield. A separable heat exchanger permits reactor/shield separation from the radiator. The reactor/shield must be

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*Reactor disposal assumes the boost of the power module or reactor/shield into a long life high earth orbit, whereupon it is allowed to undergo orbital decay and eventual reentry into the earth's atmosphere. Although subsequent reboosts by a Shuttle are possible, this mode is beyond the scope of this study.
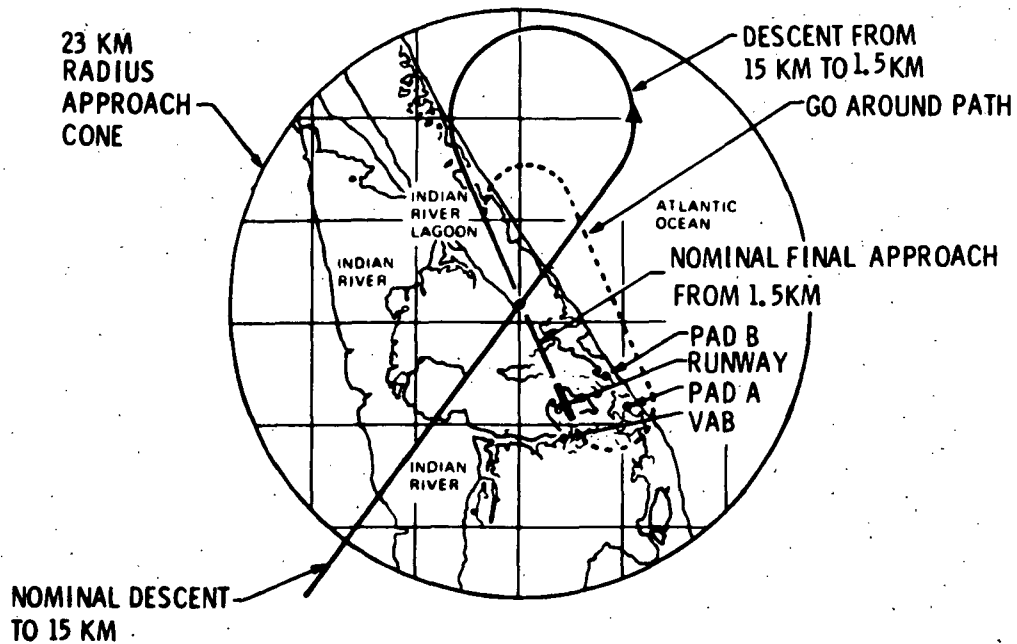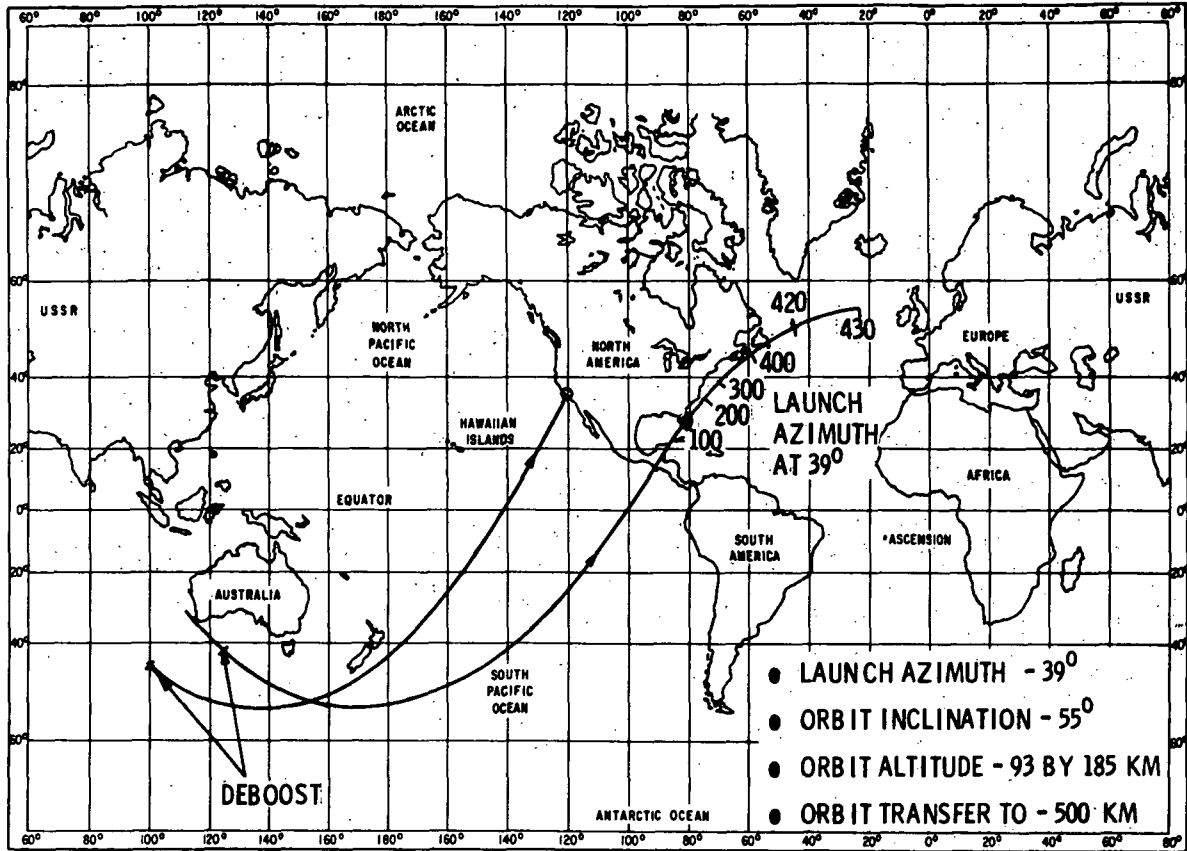
Figure 3-19. Typical Shuttle Descent and Reentry Trajectory

placed further forward in the cargo bay (closer to the crew). Consideration must be given the additional attach points on the reactor/shield required and the possible increased radiation to the crew due to the reactor's close proximity to the crew compartment.

2. <u>Should system status and diagnostic data reveal a malfunction in the Shuttle orbiter or the payload which would present a potential accident situation upon landing, it may be adviseable to eject the reactor over the deep ocean area, thereby eliminating the potential nuclear hazard to the general populace.</u>

3. A spent reactor/shield or entire power module will be radioactive or contain activated liquid metal. Detection of radiation and liquid metal contamination is required. <u>Radiation decontamination of the cargo bay may be required as well as strict environmental precautions taken to avoid liquid metal reactions after landing.</u> A sealed cargo bay coupled with inert gas purging can reduce the potential reactions from residual shuttle propellant or high moisture content air.

A more detailed discussion of these and other contingency situations is presented in Section 6.

3.3.5 OPERATIONS GUIDELINES

A summary of the key safety related guidelines for shuttle operations involving a nuclear reactor power module are contained in Table 3-3.

3.4 REFERENCES

3-1. "Nuclear Reactor-Powered Space Station Definition and Preliminary Design", Volume II, MSC-00741 (SD70-168-2), North American Rockwell, Space Station Program Phase B Definition, under contract NAS9-9953, January 1971.

3-2. J. A. Simmons, R. D. Gift, J. M. Spurlock, and R. F. Fletcher, "Reactions and Expansion of Hypergolic Propellants in a Vacuum", AIAA Journal, May 1968.

3-3. "Reactor Power System Design Document", Volume II, Appendices, MSFC-DRL-160 Line Item 23, MDC G0750, McDonnell Douglas Astronautics Company - West, December 1970.

3-4. "Reactor Power System Design Document", Volume I, MSFC-DRL-160, Line Item 23, MDC G0750, McDonnell Douglas Astronautics Company - West, December, 1970.
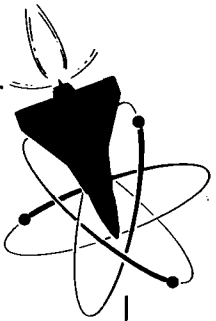
Table 3-3. Shuttle/Reactor Power Module Operations Guidelines

- Provide support personnel and Shuttle crew training with confirmed procedures in the use of multiple and independent radiation monitoring equipment with instantaneous and recorded outputs.

- Provide shuttle crew training with confirmed procedures in use of multiple and independent system monitoring equipment for all mission phases.

- Provide certified operational plans to

  - Receive and store reactor power modules.
  - Checkout reactor power modules and components.
  - Launch and perform orbital transfer.
  - Dispose of or recover reactor power modules.

- Provide fire alarm and protection systems, training and procedures capable of supporting hardware containing nuclear material and liquid metals in:

  - Nuclear facility
  - Transporter
  - Launch pad

- Provide suitable personnel exclusion area at the launch and landing sites (4 km fallback area and approximately 13 km administrative control zone).

- Provide installation, retrieval, and maintenance procedures that do not require breaking or opening of NaK loops.

- Establish emergency procedures and decisions (contingency plans) for emergency situations.

- Provide and maintain inert gas blanket during prelaunch period (to preclude NaK-oxygen reaction in event of NaK leak).

- Consider use of transfer modules to protect and reduce handling and packaging requirements of nuclear payloads.

- Provide redundant equipment and procedures for nuclear cargo handling.

- Prohibit launch during unsatisfactory weather conditions, including moderate to high winds blowing towards populated areas.

- Provide recovery gear for use subsequent to prelaunch accident.

- Provide trained impact/recovery team and procedures for:

  - Recovery
  - Fire protection
  - Radiation Control
  - Decontamination

- Provide tracking and location capability for early land and water recovery.

- Minimize overflight of land and continental shelf.

- Provide nuclear cargo transfer operations that do not involve EVA.

- Provide direct visual or TV coverage of all nuclear cargo transfer operations.

- Provide positive control of nuclear payload during all handling.

- Minimize the crew and support personnel dose rate throughout all operations (maximum of 150 mrem/day).

- Provide rendezvous and docking positions such that the Shuttle crew locations are within the shadow of the reactor shield to minimize the dose to the crew during docking and replacement operations.

- Provide procedures for permanent reactor shutdown prior to separation from Space Base.

- Consider allowing at least 10 days after shutdown before enacting Shuttle operations with a spent reactor. If this procedure is not possible, provide for decay heat removal and radiation shielding if the spent reactor is to be transferred to the Shuttle less than 10 days after shutdown.

- Consider capability of reactor/shield separation from radiator at end of mission disposal or recovery.

- Provide minimum 100 year orbital lifetime for spent reactor in high earth orbit (250 year orbit is preferred to give 9 half life decay).

- Consider means of long term tracking of the power module (for possible recovery at later date).

- Provide emergency capability and procedures for ejection of the payload over deep ocean area or possible ditching of the Shuttle.

- Provide for emergency recovery of nuclear equipment if jettisoned from Space Shuttle.

- Provide touchdown area remote from inhabited facilities.

- Provide certified unloading, decontamination and liquid metal equipment to handle nuclear reactor power module subsequent to landing.

SECTION 4
SAFETY ASPECTS IN THE TRANSPORTATION OF
ISOTOPE REENTRY VEHICLES WITH THE SPACE SHUTTLE

4.1 GENERAL

The packaging considerations, prelaunch, on-orbit and recovery operations associated with a Shuttle-transported Isotope Reentry Vehicle (IRV) containing 52 kWt of Pu-238 isotope fuel are highlighted in Figure 4-1. Although there are many similarities to the reactor mission described in Section 3.0, some vital differences regarding its safety aspects stand out:

- The IRV heat source is a source of radiation throughout the mission; specified crew/heat source separation distances must be maintained or radiation shielding provided.

- The IRV heat source generates thermal energy (constituting a thermal hazard) throughout the mission; this energy must be removed in such a way that temperatures to equipment and material are not exceeded.

- The specific radioactivity of the Pu-238 (in the IRV fuel capsules) far exceeds that of the U-235 in the reactor core prior to reactor full power operation; extensive precautions must be taken to assure the containment of the Pu-238 during all credible accident environments.

- No liquid metal hazards exist in this type of power system.

The facts stated above lead to certain safety requirements in the integration of the isotope-Brayton system with the Space Shuttle.

- The IRV should be installed in the Shuttle payload bay late in the countdown sequence.

- Thermal control must be provided to remove the heat generated by the source; if not passive in nature, redundancy must be provided.

- Blast and fragmentation shielding must be provided.

- The IRV should be located as far as possible from the Shuttle propellants (explosive sources)

DIAMETER — 2.36 M (92 IN)

MASS — 1800 KG (3.90 KLBS)

FUEL — 238 PU O$_2$

INVENTORY — 52 KWT (BOL)

● ISOTOPE REENTRY VEHICLE
— MUST FIT IN CARGO BAY
— CG MUST BE WITHIN SHUTTLE CG ENVELOPE

● THERMAL CONTROL
— COOL IN AIR TO 420°K
— PASSIVE OR ACTIVE CONTROL IN SPACE AND ON REENTRY AND LANDING

● RADIATION SHIELDING
— < 150 MREM / DAY

● BLAST / FRAGMENTATION PROTECTION

● PAYLOAD STATUS AND CONTROL
— DISPLAYS
— CONTINUOUS AND PERIODIC MONITORING
— CONTROL SIGNALS

● ELECTRIC POWER

● TRANSFER MODULE
— COMPATIBLE WITH SHUTTLE ATTACH POINTS
— IRV EJECTION CAPABILITY

Figure 4-1. Isotope Reentry Vehicle Packaging/Shuttle Integration

The design solution that satisfies one of these requirements may complicate solutions that satisfy another, and designs that appear desirable in themselves may lead to undesirable operational procedures; therefore, the approach to Shuttle transport of an isotope-Brayton system must be an integrated approach that takes into consideration all of the design, operational, and safety requirements associated with the Shuttle, the IRV, and the Space Base. The following sections discuss these matters in more detail.

4.2 IRV-ISOTOPE HEAT SOURCE PACKAGING AND INTEGRATION

The packaging and integration of an IRV within the Space Shuttle involves consideration of a number of interfaces, and has a direct impact on safety in the transportation of the IRV to and from earth orbit.

As these requirements and associated design concepts are discussed in subsequent paragraphs of this section, it will become apparent that the design approach followed in meeting a particular requirement will have a significant impact on safety, contingency modes and the design approaches available to meet another requirement. In particular, the approach taken to shielding the heat source from potential accident environments strongly affects the thermal control and handling subsystems, and contingency modes available in the event of failures.

4.2.1 RADIATION PROTECTION

Figure 4-2 presents the radiation environment associated with an unshielded 52 kWt isotope heat source. The maximum allowable radiation dose from a nuclear source to a crewman aboard the Space Base or Space Shuttle is 150 mrem/day per study ground rule. If a crewman is required to be positioned side-on to the heat source, he could remain within about 2 m of its center for 3 hours or at about 5 m (16.5 ft) for nearly an entire day without exceeding the allowable dose. Dose rates along the planes perpendicular to the radiating face of the heat source are somewhat higher, as shown in Figure 4-2. Such an orientation of the heat source with respect to the crew should be avoided, or if necessary, limited to only brief periods during transfer operations.

ISOTOPE REENTRY VEHICLE
RADIATION ENVIRONMENT
(MREM/HR.)
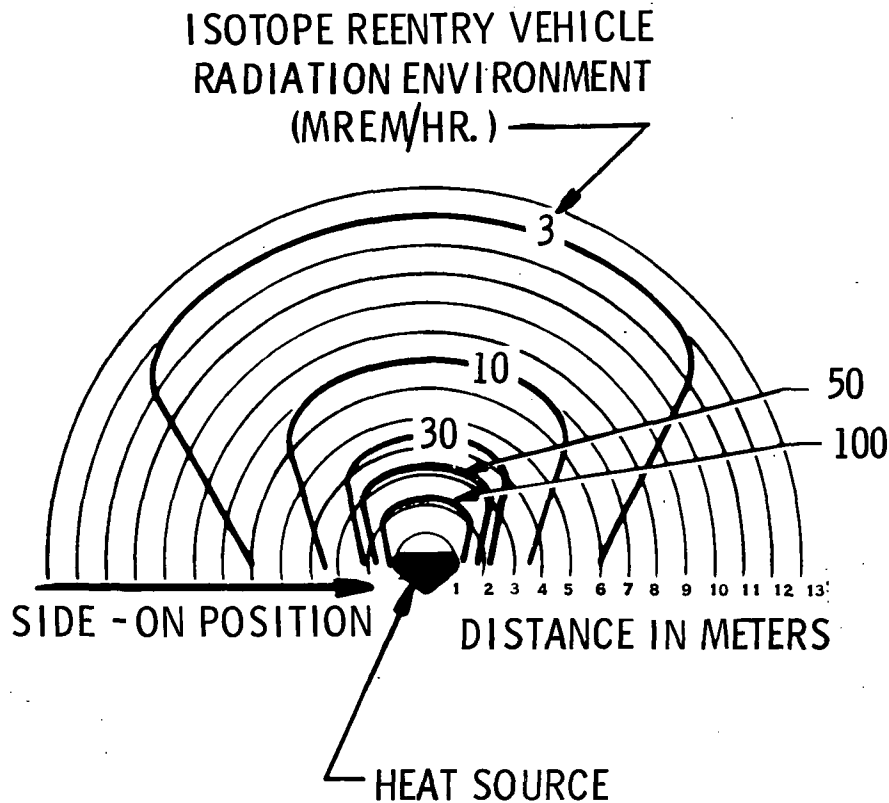
Figure 4-2. Isotope Reentry Vehicle Radiation Environment

Based on the above, no shielding is required for the Shuttle orbiter crew in the course of normal transfer operations, provided that the heat source is located in the Shuttle payload bay at a distance of not less than 5 m from the nearest crew member, and oriented as shown in Figure 4-1. An estimated 5.1 cm (2 in.) of lithium-hydride (LiH) shielding would reduce the minimum allowable separation distance (150 mrem/day is not exceeded) to approximately 4.1 m (13.5 ft); this distance represents the minimum crew/IRV separation distance possible based on the reference Space Shuttle configurations.

4.2.2 BLAST AND FRAGMENTATION PROTECTION

Two of the most critical phases of the mission (from a blast and fragmentation standpoint) are those of prelaunch (after the IRV has been installed in the Shuttle) and launch/ascent. During these operations, the potential exists for a Shuttle explosion and fire with accompanying blast overpressures and fragmentation environment that could, unless preventive measures are taken, result in the breaching of the fuel capsules and subsequent release of fuel.

The potential for such an accidental release of isotope fuel is greatly increased because of the proximity of the Shuttle orbiter fuel tankage to the IRV when it is installed in the cargo bay. Appendix A of Volume IV, Part 2 describes the blast and fragmentation environment in some detail.

Several approaches can be taken to eliminate or minimize the effects of this environment. The most effective action which can be taken is to increase the separation distance between the IRV and the source of the explosion. The blast overpressure and the fragment velocities are rapidly reduced as the separation distance between fuel tankage and the IRV increases. To achieve this, the IRV could be transported in a pod mounted externally on the Shuttle, or it might even be located in the nose of the Shuttle; the added separation distance between fuel tankage and isotope payload that these locations provide will greatly reduce the effects of the blast and fragmentation environment, thus permitting the use of lighter and simpler environmental shielding to achieve a desired degree of safety. The external pod also offers ease of separation, a virtue in certain potential accident situations. The investigation of the feasibility of such schemes for the location of the IRV on the Shuttle, and the respective trade-offs, are beyond the scope of this study.

Although the environmental shielding would be lighter for an externally mounted heat source, such shielding must be provided in any case. Figure 4-3 illustrates three possible approaches to environmental shield design (protection of the heat source capsules from the blast over-pressure, high velocity fragments, and fireball temperatures that might ensue in the event of an explosion of the Shuttle main tankage).

The most straightforward design is the hemispherical environment shield, a design which interposes shielding between the heat source and the shuttle tankage. It permits passive thermal control to be employed (as will be discussed in Section 4.2.3). The hemispherical shielding would prove inadequate (1) if there are explosions on the unprotected side of the heat source, (2) if the heat source could tumble and thus be reoriented prior to the passage of the pressure wave or the fragments and (3) if the unprotected side were slammed against heavy objects such as parts of the Mobile Launcher tower.

• PASSIVE THERMAL CONTROL	• ACTIVE THERMAL CONTROL
HEMISPHERICAL SHIELD AUGMENTED HEMISPHERICAL SHIELD	4π SHIELD
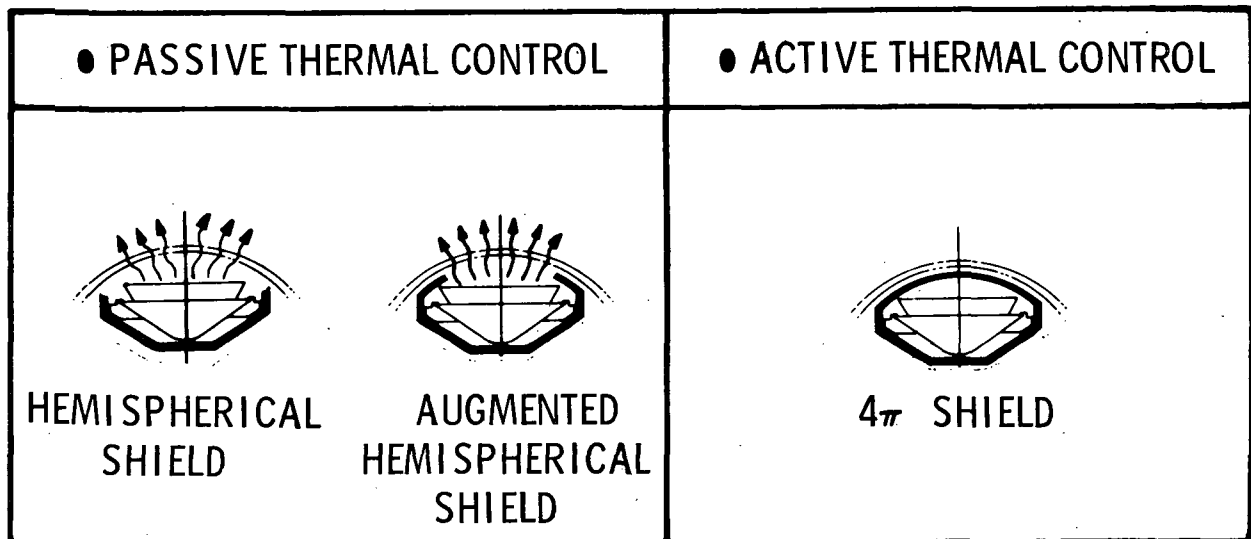
Figure 4-3. Shield Packaging Concepts

As discussed previously in Section 3.2.2, a relative location of the Shuttle on the launch pad which places a Shuttle payload between the source of the explosion and heavy objects, such as the Mobile Launcher tower, presents a severe secondary fragmentation problem. An unobstructed payload ejection path is a requirement for large isotope heat sources such as the IRV. An ocean or swamp impact area should be considered.

A second approach is the 4π environmental shield concept also shown in Figure 4-3. Here, the IRV is completely protected by shielding. While this arrangement offers the maximum protection from blast and fragmentation, it poses a problem in the removal of isotope-generated heat and it is much more difficult to integrate with the Shuttle in a normal mission since an active, or pumped, thermal control loop is required and handling during in-orbit delivery and transfer operations is relatively complicated.

The third approach as illustrated in Figure 4-3 represents a compromise of the first two concepts. It consists of a shield that nearly encompasses the heat source, but has an aperture (away from the probable source of explosion) that permits the radiation of sufficient heat to maintain acceptable heat source temperatures. This arrangement offers nearly complete protection to the heat source while at the same time simplifying the integration with necessary thermal control and handling functions.

4.2.3 THERMAL CONTROL

One of the large potential hazards that arises when transporting an IRV is the constant emission of heat. The heat source contained in the referenced power system generates 52 kilowatts of thermal power at beginning of mission and is reduced through decay of the Pu-238 fuel to 48.5 kWt at end of mission. This heat energy must be removed to prevent high temperature oxidation of the refractory metal alloys in the IRV and to keep the heat source temperature below the ignition point of any propellant fumes which may be in the launch pad area. To achieve this requirement, the heat source is cooled to about 420°K (300°F) with a flow of cold nitrogen prior to launch. The cold nitrogen is supplied by Ground Support Equipment (GSE) located in the Mobile Launcher.

During the orbital and reentry phases of the mission, cooling of the heat source must be accomplished by other means. However, the allowable temperatures are much higher: 1365°K ($2,000^{\circ}$F) for the heat source primary radiating surface during in-orbit operations, and certainly somewhat higher during reentry than the 420°K (300°F) during prelaunch operations since oxidation is no longer a major problem and the fuel loading is substantially reduced. To maintain allowable temperatures during these operational phases, either a passive or an active thermal control system can be employed, depending in large part upon the type of environmental shielding that has been selected. The basic safety requirements are independent of the system used, namely that at any time during the mission there is an emergency back-up for the normal temperature control system which can take over the cooling function in case of a system malfunction.

Figure 4-4 shows the use of a passive thermal control system used in conjunction with a hemispherical environment shield. Throughout prelaunch operations, the heat source would be cooled as previously described. About eight minutes after lift-off, the Shuttle cargo bay doors can be opened to permit the heat source to radiate its heat load directly to space. (See Section 6 for a discussion of contingency operations in the event that the cargo bay doors cannot be opened.) In the meantime, the heat source temperature will have slowly increased, as is shown typically in the curve of Figure 4-5. With the IRV radiating directly to space, the temperature of the radiating surface will not exceed about 865°K (see Appendix B). If the Shuttle doors fail to open, the heat source temperature could go as high as 1700°K (Ref. 4-1) with no emergency cooling capability, however, these elevated temperatures would not be reached until several hours after launch. During reentry operations, cooling of the heat source to an acceptable temperature of perhaps 650° or 700°K can be accomplished by a low temperature nitrogen system similar to that used on prelaunch, but carried aboard the Shuttle. A water boil-off system could also be used to reduce the heat source temperature. Upon landing, the heat source could once again be cooled by Ground Support Equipment.
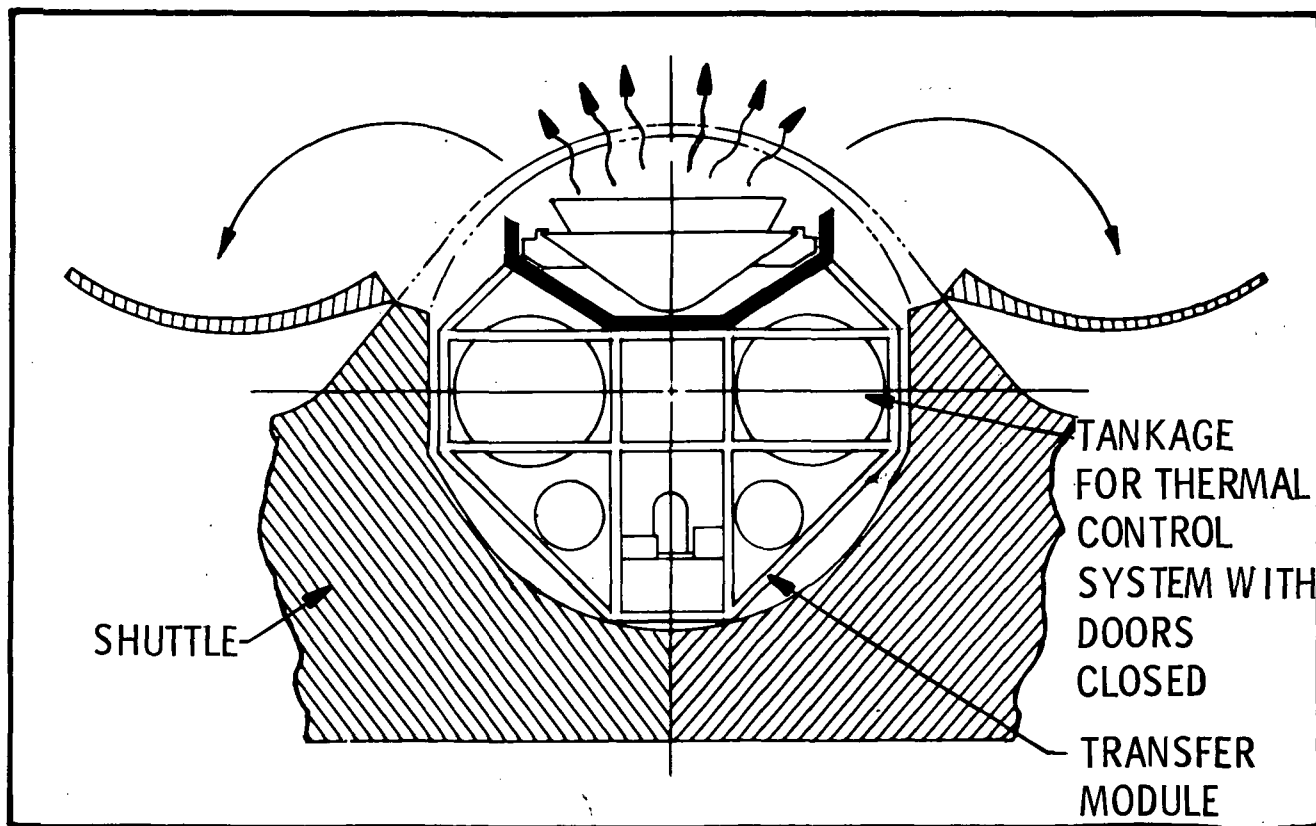
Figure 4-4. Hemispherical Environmental Shield with Passive Cooling
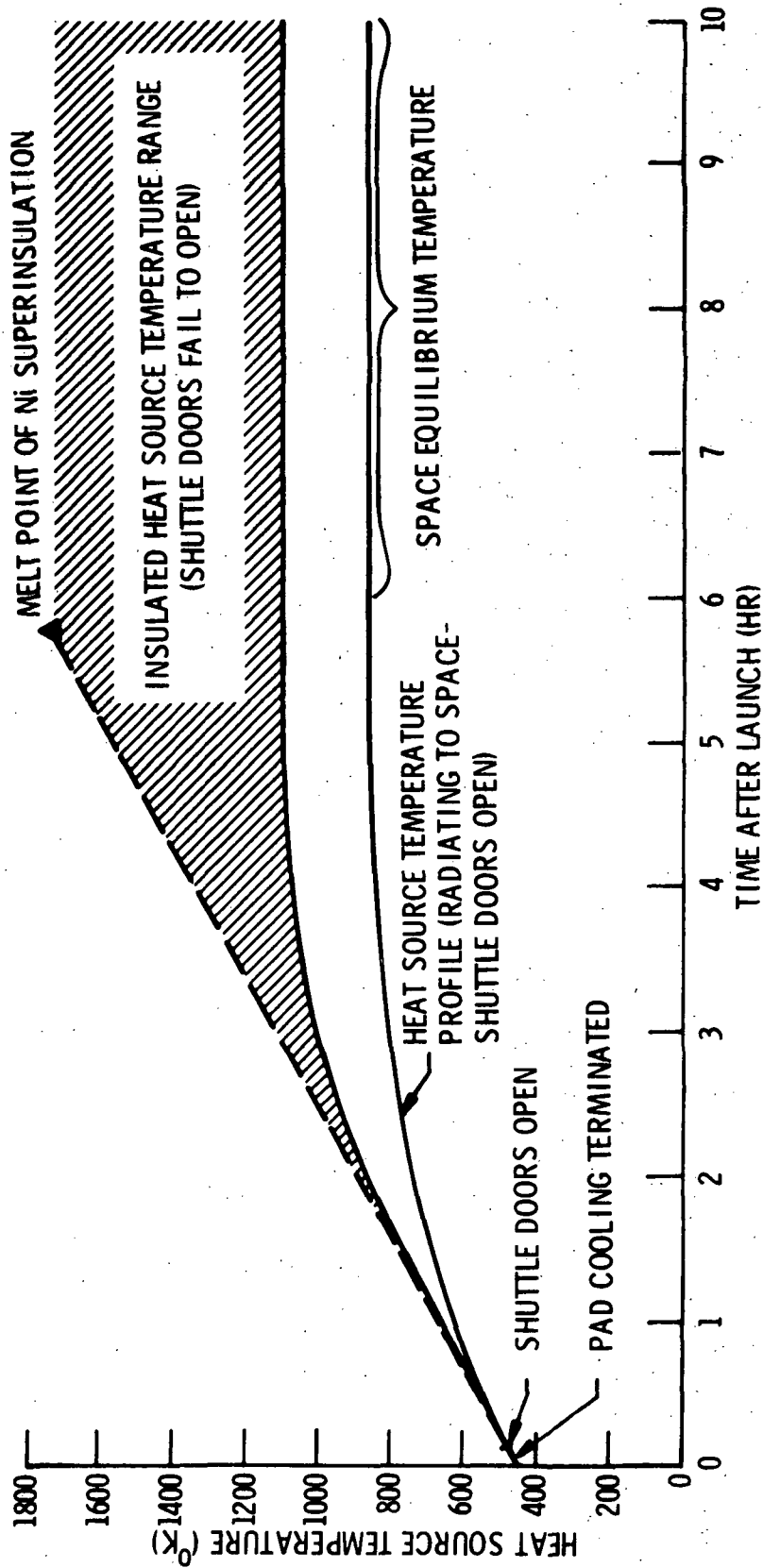
Figure 4-5. Estimated Heat Source Temperature Profile During Launch/Ascent

If a 4π environmental shield is employed, the thermal control system is more complex. Not only the heat source, but all other components within the confines of the shielding (e.g., the IRV recovery gear) must be adequately cooled. This probably will require control to lower temperatures because of the electronic equipment exposure. The cooling can be accomplished by a cold gas system, or by a pumped loop, using perhaps an organic fluid and rejecting the heat to space by means of a radiator mounted externally on the orbiter (Figure 4-6 shows the radiators mounted on the Shuttle cargo bay doors). Once the Shuttle has achieved orbit, the shield can be remotely opened and the IRV exposed to permit the heat source to radiate directly to space (as was the case with the hemispherical shield). For reentry with the 4π shield, the thermal control system must again adequately cool all of the IRV components once the 4π shielding has been closed. The re-radiating pumped loop cannot be used during the critical phases of reentry when high Shuttle skin temperatures exist. During this period either a cold gas system or a water boil-off system must be relied upon. Suitable controls can permit the pumped loop to act as a water boil-off system when desired (see Figure 4-7).

SHUTTLE
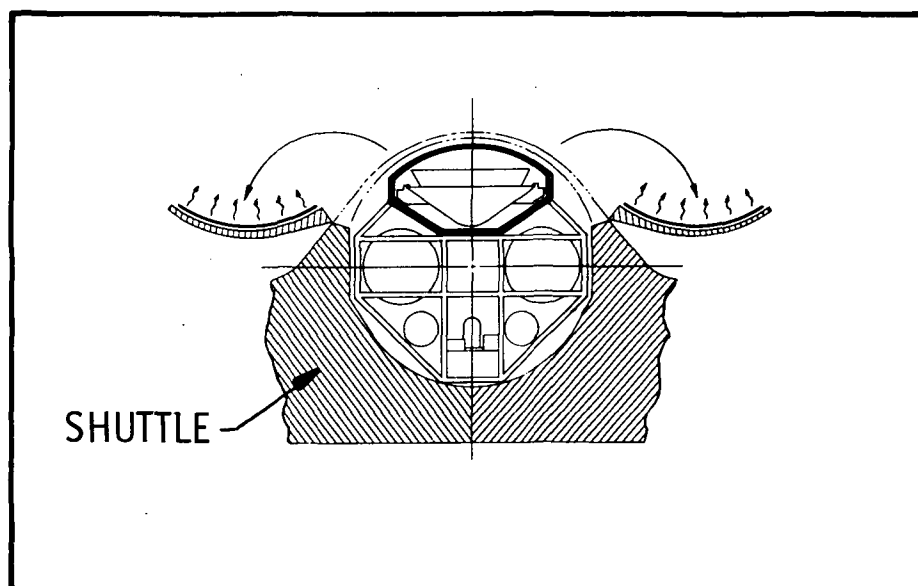
Figure 4-6. 4π Shield with Active Cooling System
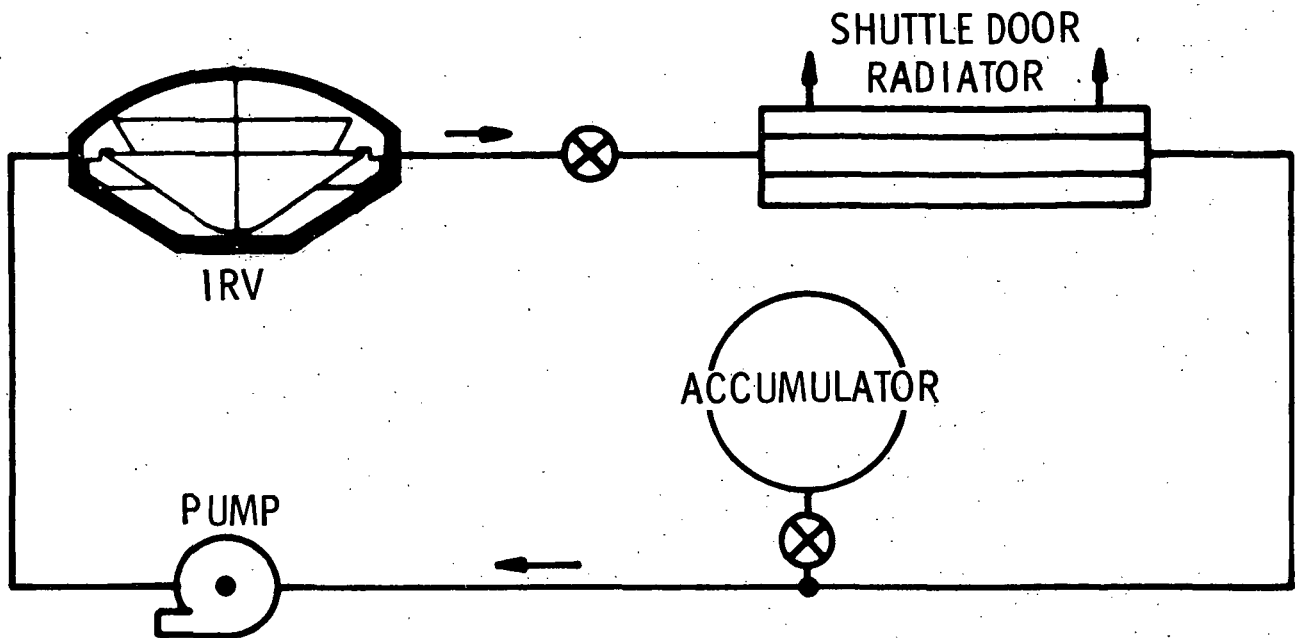
Figure 4-7. Active Thermal Control Loop

4.2.4 SYSTEM STATUS AND CONTROLS

The IRV is a relatively passive item of cargo throughout a normal mission. The thermal control system associated with it is the critical system to be monitored because the heat generated by fuel decay must be dissipated without developing excessive temperatures in the heat source or elsewhere in the Shuttle cargo bay. The number of sensors and controls will be a function of the types of thermal control system that is employed and the thermal control system selection is in turn dependent upon the environmental shielding approach. Table 4-1 has been prepared assuming that 4π environmental shielding and an active pumped loop is used. In this approach, an estimated 62 data points and 32 control devices are required.

4.2.5 ELECTRICAL POWER

The primary requirement for electric power in connection with the IRV is the thermal control system. The power level is dependent upon the type of thermal control system employed.

For a pumped loop, the power demand is estimated to be 300 watts. Normal operating time is estimated to be on the order of two to three hours for a normal reentry and landing so that even with a large power reserve for emergency situations, the energy requirement will not exceed two or three kilowatt-hours. This power could be supplied by batteries or by the Shuttle electrical power and distribution system.

4.2.6 TRANSFER MODULE

From the preceding paragraphs and from the descriptions of the Space Shuttle and the isotope power systems in Appendices A and C, it is apparent that the interface between the Shuttle orbiter and the IRV is extensive. To simplify the interface, and increase the safety of handling and transport operations, a transfer module can be employed; it would be designed to adapt to the Shuttle orbiter cargo bay mounting provisions to provide a self-contained package for the IRV.

Table 4-1. Isotope Brayton Power System Control and Monitoring Requirements

Controls		Sensors (Data Points)	
Function	*Number Required	Function	*Number Required
Thermal Control Loop	6	Radiation Monitors	6
Positioning Latches	10	Heat Source Temperature Monitors	4
Shield Positioner (4π)	4	Cargo Bay Temperature Monitors	4
Water Boil-off Loop	4	Battery and Power System Condition	12
Separation/Ejection System	4	Coolant Pump Operation	8
		Valve Positions	12
Power System	4	Equipment Positions and Status	16
Total	32	Total	62

*Redundancy Accounted for

4-12

The transfer module concept is illustrated in Figure 4-8. Here, the module safely secures the IRV in a hemispherical environmental shield, provides cold gas and/or water boil-off systems for thermal control, stores energy for the operation of an auxiliary electric power system, includes all necessary sensors for system status monitoring and controls for system operation, and is integrated with the handling equipment used during IRV transfer operations. The interface between the transfer module and the Shuttle is reduced to a mechanical (mounting) interface and the accommodation of instrumentation and control leads, displays and panels.

A possible transfer module function quite different from those identified above, but of considerable importance in terrestrial safety of transporting an IRV is the capability of emergency payload ejection over deep ocean areas should diagnostic data indicate a potential accident situation upon landing. Ejection should occur with the Shuttle doors open, however "through-the-door ejection" should be evaluated as an emergency contingency.
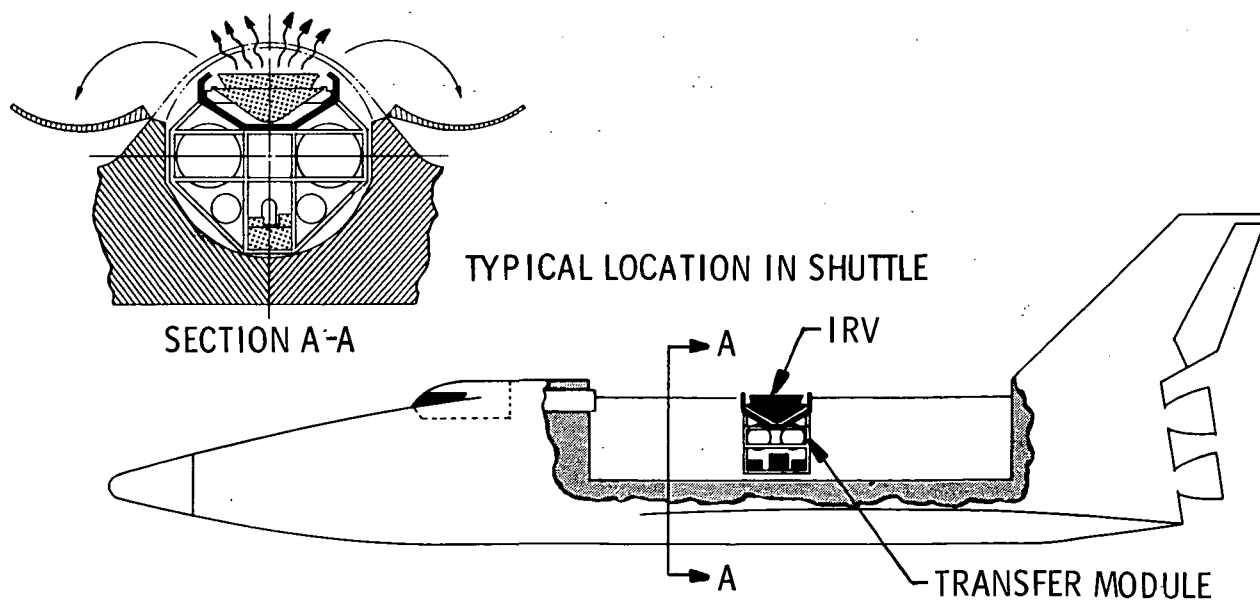
Figure 4-8. IRV Transfer Module Concept

4.2.7 DESIGN AND PACKAGING GUIDELINES

A summary of the key guidelines for the design and packaging of a large isotope heat source module within a Shuttle is contained in Table 4-2.

Table 4-2. Shuttle/Large Isotope Heat Source Design and Packaging Guidelines
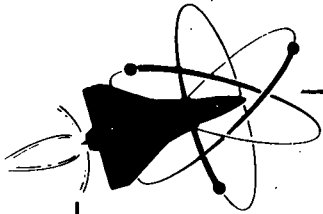
- Provide multiple and independent radiation monitoring equipment with instantaneous and recording outputs for all mission phases.

- Provide multiple and independent system monitoring and control equipment with instantaneous and recording outputs for all mission phases.

- Consider nuclear payload and Shuttle launch pad positioning that produce a directed unobstructed ejection path in event of launch pad explosion.

- Provide isotope heat source cooling to 420°K (300°F) or less during prelaunch.

- Provide passive cooling systems, or redundant active systems throughout all phases of the Shuttle-isotope heat source mission.

- Prevent propellant boil-off and other undesirable gases from entering the cargo bay with the doors closed.

- Provide blast overpressure and fragmentation protection adequate to assure containment of all radioactive material in event of an accident (critical requirement for isotopes).

- Provide fireball protection adequate to assure containment of all radio active material in event of an accident (critical requirement for isotopes).

- Provide approximately 300 w electrical power (either transfer module or Shuttle).

- Consider use of a "transfer module" to reduce and simplify Shuttle interfaces and to improve safety in handling nuclear payloads.

- Assure maximum separation distance between the Shuttle crew - nuclear payload (IRV should be placed with side-on view to crew location).

- Provide intact reentry and impact capability. Consider use of crush-up materials to minimize damage upon Shuttle land impact.

- Provide certified equipment to handle nuclear payloads.

- Provide certified facilities to:

    - Store isotope fuel capsules
    - Load isotope fuel capsules into heat sources
    - Install heat source in IRV
    - Checkout isotope power systems and components
    - Perform radiological monitoring and control functions

4.3 IRV TRANSPORT OPERATIONAL PROCEDURES

The transport operations involving the isotope reentry vehicle (IRV) are similar to those of a reactor power module with notable exceptions described in the following paragraphs.

4.3.1 PRELAUNCH

The initial interaction between the IRV and the Space Shuttle occurs when it is installed in the Shuttle cargo bay. The heat source consists of a planar array of isotope fuel capsules. These capsules are loaded into the heat source structure and the heat source in turn is loaded into the Isotope Reentry Vehicle (IRV) prior to installation in the Shuttle cargo bay (Figure 4-9). The assembly of the IRV/heat source takes place in a nuclear facility located at the launch site at a considerable distance (several kilometers) from the launch pad.

The feature of isotope systems that most distinguishes it from other payloads is the constant production of heat and nuclear radiation. The isotope-Brayton heat source generates 52 kilowatts of thermal power; this heat must be removed and the heat source temperature must be maintained at $420^{\circ}K$ $(300^{\circ}F)$ or below during the prelaunch period (to preclude the ignition of substances such as hydrazine that may exist in the launch pad area). The cooling of the heat source is accomplished with redundant inert gas cooling systems which are a part of the isotope-Brayton power system Ground Support Equipment and could be located in the Mobile Launcher tower. Due to the radiation and thermal environment emitted by the heat source, integration with the Shuttle at the launch pad should occur as late in the countdown time-line as possible.

A radiation monitoring system is an essential element of the complex that is employed to launch isotope power systems; such a system will be installed prior to delivery of the nuclear payload to the pad. It is anticipated that no restrictions to normal prelaunch operations will occur with the IRV except in the immediate vicinity of the IRV where exposure time of technicians will be limited.

Because of its peculiar thermal control and accident protection requirements, it is assumed that the IRV will be placed in an IRV Transfer Module prior to installation in the Shuttle

- PLACE IRV IN SHUTTLE
- INSTALL HEAT SOURCE IN IRV
- LOAD CAPSULES INTO HEAT SOURCE

- ADAPTATION OF CURRENT HANDLING PROCEDURES
- IRV INSTALLED AS LATE AS PRACTICABLE IN LAUNCH COUNTDOWN SEQUENCE
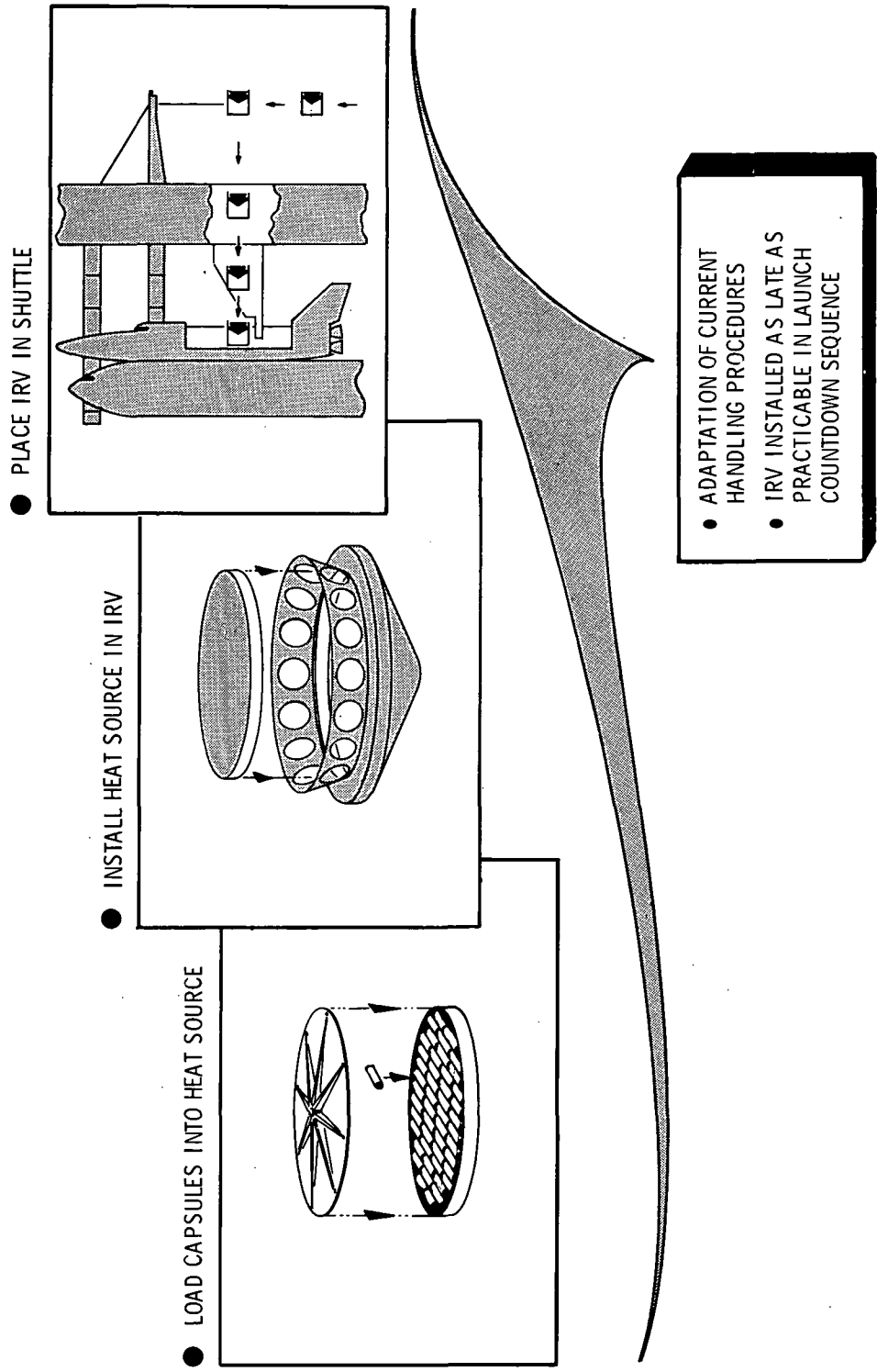
Figure 4-9. Isotope/Shuttle Prelaunch Operations

cargo bay. The transfer module as discussed in Section 4.2.6, simplifies the standard interfaces to the Space Shuttle and increases the safety of the handling and transport operations. In addition, the transfer module can provide blast and fragmentation protection, radiation shielding (if required), and thermal control for the IRV.

The Isotope Brayton Power Conversion Module (PCM) can also be installed in a transfer module before it is placed in the Shuttle cargo bay. The PCM Transfer Module serves simply as a device to protect the PCM during handling operations. Depending on the design configuration of the isotope-Brayton power system, the PCM will be transported with the IRV or in a separate Shuttle launch. It may also be possible for the Shuttle to carry multiples of either or both units. Handling of the IRV Transfer Module and the PCM Transfer Module can be accomplished with conventional handling gear at the launch site. Instrumentation of prime importance required for transporting an IRV in the Shuttle are sensors for measuring the temperature at selected critical points of the heat source and/or fuel capsules and sensors for the prelaunch checkout of the IRV recovery systems. The PCM requires no instrumentation.

4.3.2 LAUNCH/ASCENT

During a normal launch ascent, the heat generated by the isotope fuel is largely taken up by the heat source structure. The temperature of the device increases only slightly from the 420°K to which it is cooled prior to launch during the approximately eight minutes required to penetrate the earth's atmosphere. After this time, the Shuttle cargo bay doors can be opened. The heat source will slowly rise in temperature to its equilibrium temperature of 865°K (1100°F) as was shown in Figure 4-5.

Throughout the launch ascent phase of the mission, system status and radiation monitoring equipment shall be operating to inform the crew of the payload's condition and their radiation exposure.

4.3.3 ON-ORBIT OPERATIONS

The IRV will be delivered to the Space Base from the Shuttle following successful rendezvous operations. Several approaches to delivery, transfer, and recovery are possible; these are discussed in the paragraphs that follow.

Figure 4-10 depicts four different methods of isotope cargo delivery. The first of these involves a direct Shuttle dock to the Space Base and subsequent use of a remote handling system to transfer the IRV from one vehicle to the other. The second approach involves docking the Shuttle to the Base by rotating the cargo module through 90 degrees and then employing the docking mechanism at the outer end of the cargo module to secure the vehicles. Transfer could then take place using a special purpose device for removing the IRV from the cargo bay of the Space Shuttle and installing it on the power system of the Space Base. A third approach makes use of a Space Tug to deliver the IRV from the Space Shuttle to the Space Base. Upon the Tug's arrival at the Base, procedures and equipment similar to those already described would be put to use. A fourth possibility centers around utilization of a self-propelled cargo module, an adaptation of the crew-cargo module concept that has already been developed in Space Station/Space Shuttle studies. The self-propelled cargo module is carried within the Shuttle cargo bay, and upon completion of rendezvous operations, it separates from the Shuttle to transport the IRV to the Space Base. The self-propelled cargo module could be either a manned or unmanned vehicle, and could use equipment and procedures previously described.

Three transfer schemes associated with the delivery of an IRV to the Space Base are detailed in Figure 4-11. All three involve the use of manipulators, either general purpose or specially designed, and in each case, the operations are performed without Extra Vehicular Activity (EVA) on the part of either the Shuttle or Base crew.

Transfer concept (1) employs a general purpose manipulator(s) to transfer the IRV from the Shuttle to the Base. The manipulator(s) may be mounted on the Space Shuttle (Figure 4-11) or they may be mounted on the Space Base. It is also possible to include manipulators mounted on both vehicles. The IRV Transfer Module should be equipped with fittings to

① DIRECT DOCK

④ SELF-PROPELLED MODULE

② DOCK THROUGH CARGO

③ SPACE TUG
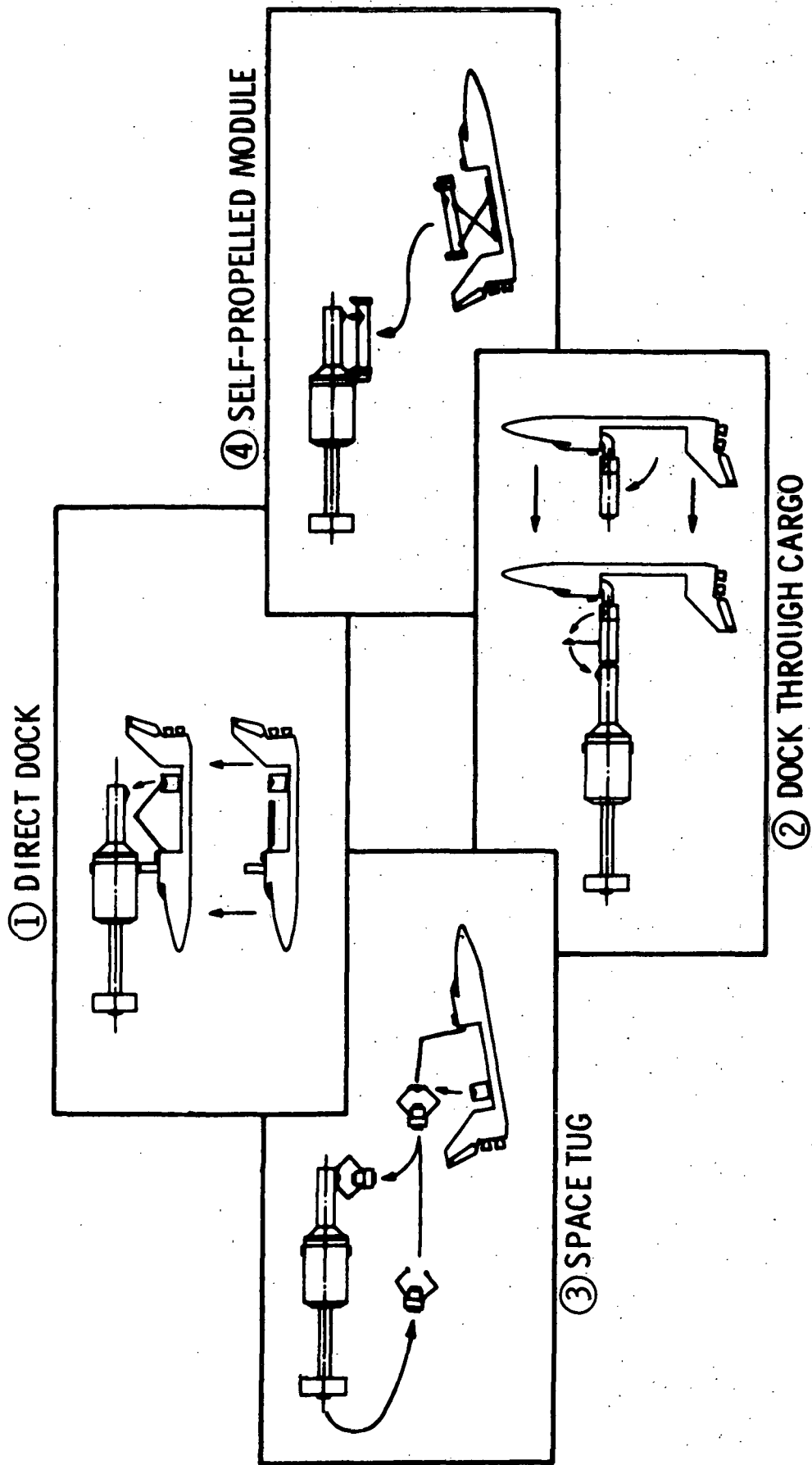
Figure 4-10.   Isotope Cargo Delivery Schemes

② FIXED ARM
ROTATION

① GENERAL PURPOSE
MANIPULATOR

③ GUIDE RAIL
SYSTEM
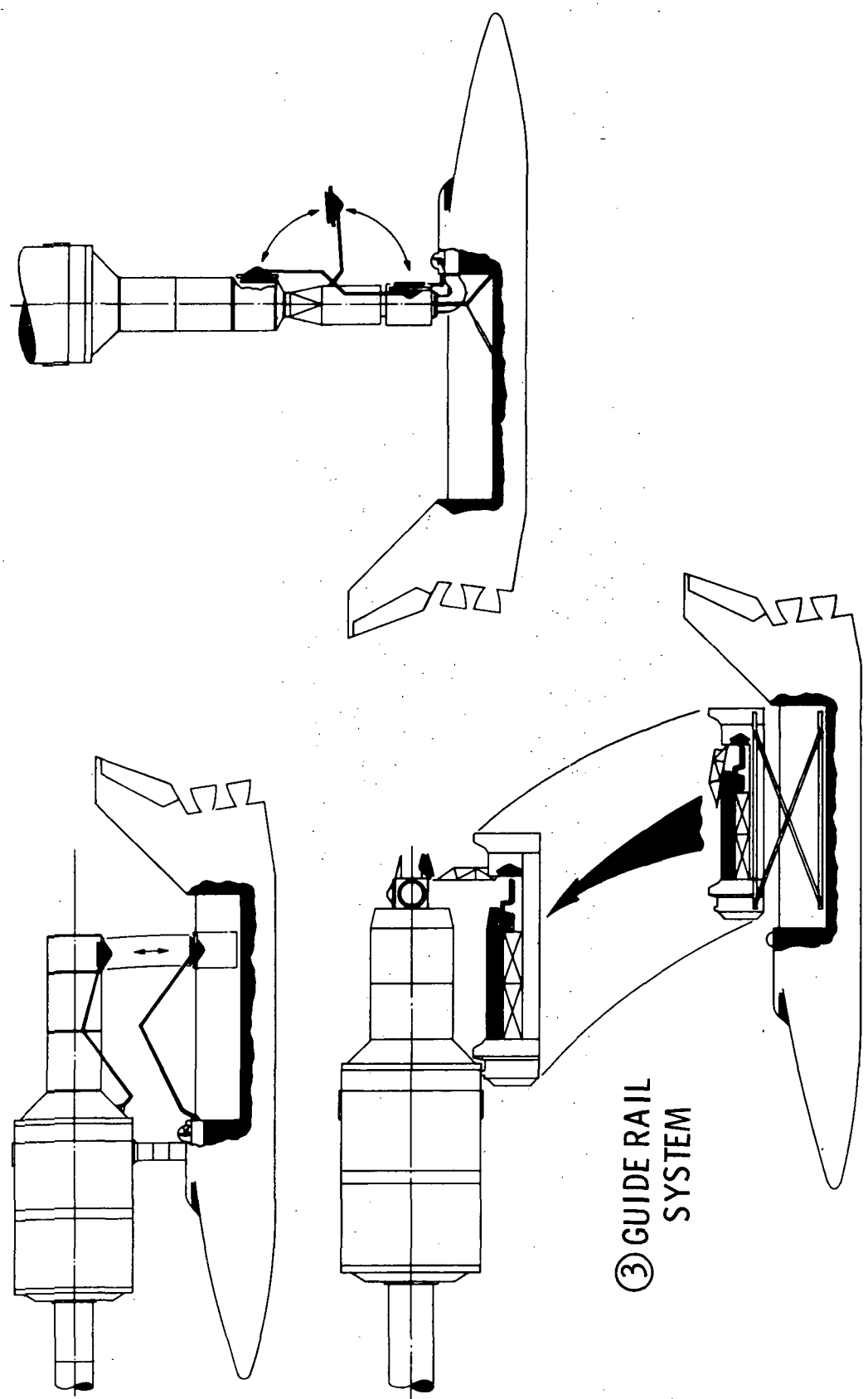
Figure 4-11. IRV Transfer

facilitate opening and closing of the module with the manipulators. The IRV itself should also be equipped with remote handling fittings to permit its removal from the IRV Transfer Module and installation in the power system. It is desirable to limit the travel of these manipulators so that an IRV containing a heat source at equilibrium temperature in space ($\sim 865^{\circ}$K) cannot be placed adjacent to either Shuttle or Base surfaces or equipment that are subject to damage from the relatively high temperature heat source. The manipulators shall be operated by Shuttle and/or Space Base personnel who are in direct visual contact with the equipment being transferred. The general purpose manipulator(s) can also be used to transfer the PCM as well as the IRV.

Concept (2) uses a "special purpose" manipulator or transfer device to remove the IRV from the IRV Transfer Module and position it in the power system on the Space Base. This operation is performed after the IRV Transfer Module has been rotated into a position 90 degrees removed from its normal location in the Shuttle cargo bay, subsequent to docking of the Shuttle to the Space Base. Functions other than the actual rotation of the IRV must be performed by mechanisms other than the special purpose manipulators. For example, the opening or closing of doors or hatches on the IRV Transfer Module could be accomplished by additional manipulators, or by mechanisms integral to the module. The PCM would be handled in a similar fashion. Primary control would come from the Shuttle.

The IRV Transfer Module, when used with the special purpose manipulator, could be designed to index through 180 degrees. With this arrangement, a spent IRV could be stored in the IRV Transfer Module while a replacement IRV would be transferred from the module to its operating position on the Space Base power system.

In Concept (3), an isotope-Brayton Modular Power System (containing radiator, PCM, and IRV) is transferred from the Shuttle to the Space Base by means of a "guide rail system" employing specialized mechanisms that are an integral part of the power system design. Remote manipulators aid only to the extent of disconnecting electrical cables. Typical transfer sequences involving the replacement of an IRV and a PCM are shown in Figure 4-12.

STEP 1

- ROTATE SPENT PCM
  TO DEPLOYED POSITION

- DOCK TRANSFER MODULE

STEP 2

- ROTATE & SECURE
  REPLACEMENT PCM
  TO SUPPORT STRUCTURE

- RELEASE REPLACEMENT
  PCM FROM TRANSFER
  MODULE STRUCTURE

STEP 3

- ROTATE & SECURE SPENT
  PCM TO TRANSFER MODULE

- RELEASE SPENT PCM
  FROM SUPPORT STRUCTURE

- ROTATE REPLACEMENT PCM
  TO DEPLOYED POSITION

STEP 4

- ROTATE SPENT PCM
  INTO TRANSFER
  MODULE & SECURE

STEP 5

- SEPARATE TRANSFER
  MODULE

- ROTATE REPLACEMENT PCM
  INTO SUPPORT STRUCTURE
  & SECURE

Figure 4-12. Typical Transfer Sequence

All three of the approaches shown in Figure 4-11 and discussed here have certain features in common:

- No EVA is required in normal operations.

- All power system assemblies/components are secured at all times. No objects are permitted to "float" free in space, nor is a simple tether an acceptable restraint.

- Transfer operations are performed by crew members of the Space Shuttle and/or Space Base who are able to observe the transfer directly.

All three approaches appear to be acceptable from a nuclear safety standpoint; however, further system definition is required before safety related advantages or disadvantages can be evaluated.

4.3.4 END-OF-MISSION

At the completion of a specified mission or in the event of a heat source malfunction that cannot be repaired, it will be necessary to dispose of the IRV. The Space Shuttle can be employed to dispose of the IRV in one of two ways: boost into high earth orbit, or return to the earth's surface.

4.3.4.1 Boost to High Earth Orbit

In the boost to high earth approach, the Space Shuttle would transport the IRV and deploy it into an orbit sufficiently high so that the fuel inventory would decay to an insignificant quantity before reentry into the earth's atmosphere occurred.

The orbital lifetime of an object is a function of its ballistic coefficient, W/C_DA, which for the reference IRV minus its shielding is 1420 Newtons/m^2 (29.7 lb/ft^2). Table 4-3 lists various circular orbit disposal altitudes, the respective IRV orbital lifetimes as determined from Figure 4-13, and the associated Pu-238 fuel inventories at the time of reentry into the earth's atmosphere. The minimum allowable elapsed time prior to reentry is assumed to be ten half-lives of the fuel. For Pu-238, this is approximately

Table 4-3. Curie Inventory with Respect to Orbital Decay Time

Disposal Orbit Altitude (km)	Orbital Lifetime* (yrs)	Pu-238 Inventory**	
		Ci/Fuel Capsule	Total Curies
500	2.8	11,625	1,511,250
600	10	10,990	1,429,700
700	30	9,410	1,223,300
800	90	5,900	767,000
900	255	1,640	213,200
1000	660	70	9,100
1020	900	11	1,430

*$W/C_DA = 1420$ Newtons/m^2 (29.7 lb/ft^2)

**11,880 Ci/Fuel Capsule after 10 yrs operation on Space Base; 130 fuel capsules/IRV
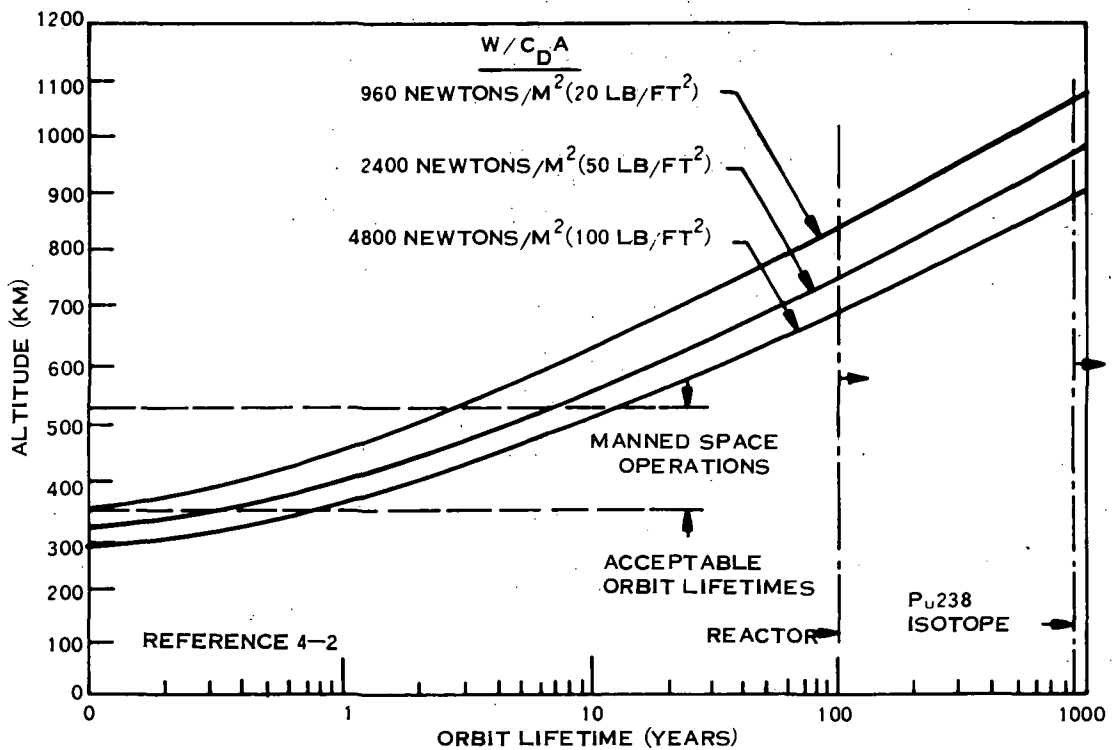
Figure 4-13. Orbit and W/C$_D$A Relationships

900 years, even if some of the long half-life decay products are not taken into account. From the curves of Figure 4-13, it is apparent that the altitude corresponding to a 900-yr orbit lifetime and a 1420 Newtons/m^2 (29.7 lb/ft^2) ballistic coefficient is approximately 1020 km (550 nm). In Figure 3-7, shown previously, curves are plotted to indicate that Shuttle capability is limited to about 650 km (350 nm) at design propellant capacity, and to 835 km (450 nm) at maximum propellant capacity. This results in IRV orbital lifetimes of approximately 17 years and 135 years, respectively. Although these curves are based on a payload mass of 3.6 t (30 klb), the performance improvement due to the reduced mass of the reference IRV is slight, the shuttle and propellant mass being the dominant factor. Therefore, it is concluded that the Space Shuttle cannot deliver the IRV to a suitable high disposal altitude without shuttle refueling. The selected means of disposal is to return the IRV to the earth's surface.

4.3.4.2 IRV Return to Earth's Surface

The Descent/Reentry Phase of Shuttle flight impose no unusual requirements on Shuttle/IRV integration other than the need to maintain thermal control of the isotope heat source during the critical phase of reentry, when the skin temperature of the Shuttle is so high that auxiliary cooling is required. From Figure 4-14, it can be seen that the maximum skin temperature at the dorsal area of the delta-winged Shuttle orbiter (Reference 4-3) is predicted to be 590°K (600°F). From this reference it is estimated that the time at elevated temperature will be on the order of 33 minutes. The IRV transfer module could contain redundant water boil-off systems to accomplish this cooling.

A normal landing presents no difficulties in Space Shuttle/IRV integration. Upon landing and completion of the roll-out, the orbiter will be taxied to the cargo removal area since it is desirable to place the isotope heat source in a nuclear facility with as little delay as is practicable. A radiation and Pu-238 contamination check should be performed prior to the initiation of any operations involving the Shuttle and/or IRV. The water boil-off system should be capable of providing cooling during this period. Shuttle propellant gases should be prevented from entering the cargo bay. To remove the IRV Transfer Module from the cargo bay, a cargo unloading crane is used. Prior to actual removal of the module from
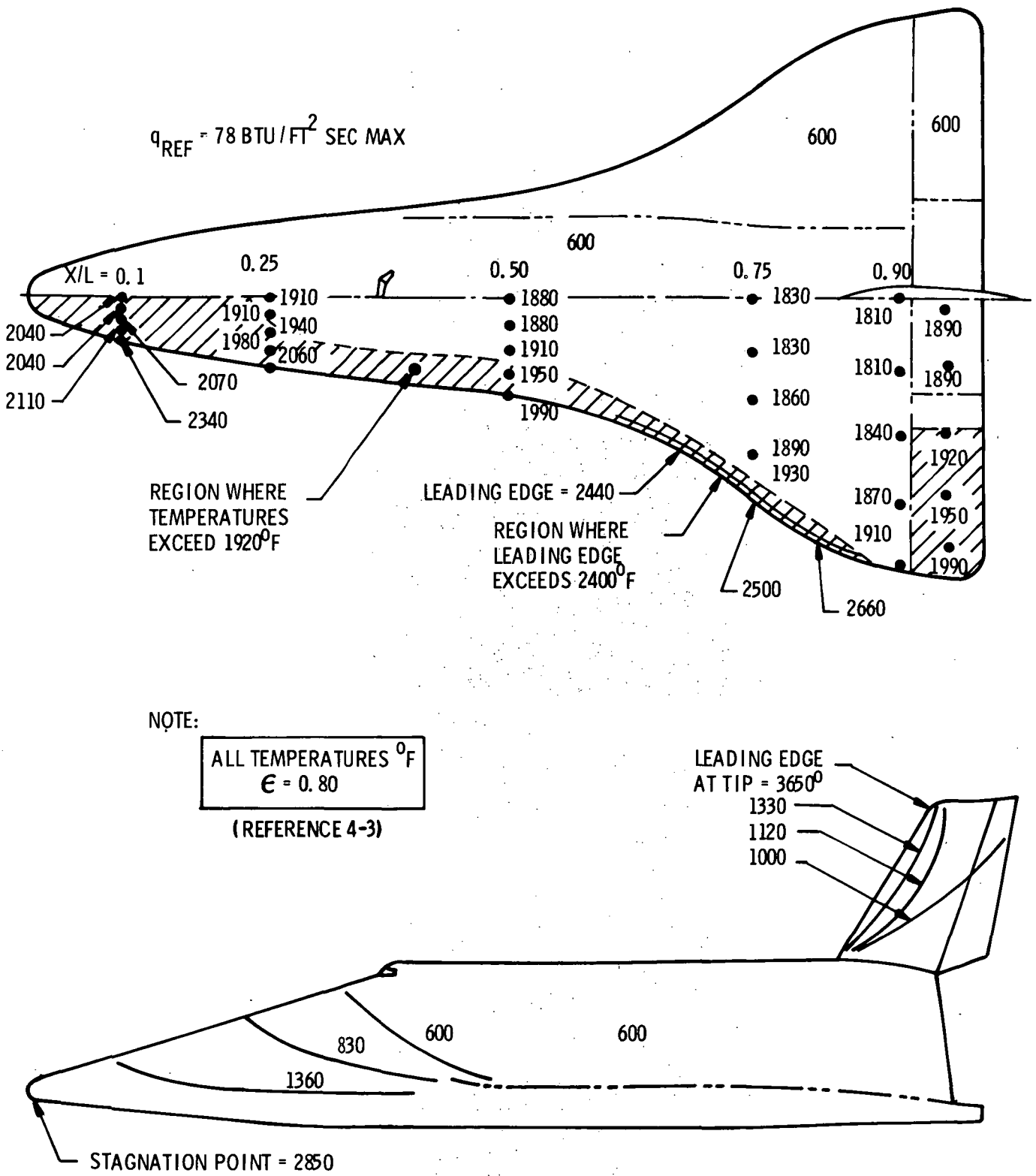
Figure 4-14. Delta Winged Orbiter Design Temperatures

the Shuttle, inert gas cooling will be introduced to cool the heat source, using the same inert gas cooling systems that cooled the heat source prior to liftoff. Maintaining a 420°K $(300^{\circ}$F) heat source temperature will inhibit oxidation of the heat source refractory metal structure and capsule cladding, facilitate handling operations, and reduce ignition potential.

Removal of the nuclear cargo would be accomplished with the Shuttle parked in a normal horizontal position. The IRV within the IRV Transfer Module would be placed within a transporter for transport to a disassembly bay in the nuclear facility at the launch/landing site.

Abnormal descent and landing situations (where crash potential is high) may necessitate the emergency ejection of the IRV onto the continental shelf for recovery or into deep ocean areas to prevent possible radiological hazards to the general populace. Although fragmentation protection is provided, the ejection mode with the cargo bay doors open, or in contingencies, through the doors, should be a primary safety consideration. (See Section 6).

4.3.5 OPERATIONS GUIDELINES

A summary of key guidelines for Shuttle operations involving a large isotope heat source is contained in Table 4-4.

4.4 REFERENCES

4-1   "Preliminary Accident Model Document," Volume III, Isotope, MSFC-DRL-160, Line Item 24, MDC GO744, McDonnell Douglas Astronautics Company-West, January 1971.

4-2   "Nuclear Reactor-Powered Space Station Definition and Preliminary Design," Volume II, Operations, MSC-00741 (SD 70-168-2), North American Rockwell, January 1971.

4-3   "Draft Space Shuttle - Phase B Systems Study Final Report - Technical Summary," MDC E0308, Part II-1, McDonnell Douglas Corporation, under Contract NAS8-26106, March 1971.
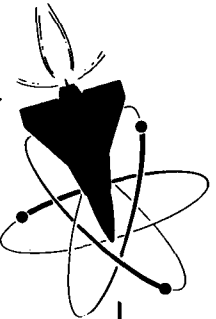
Table 4-4. Shuttle/Isotope Heat Source/IRV Operations Guidelines

- Provide support personnel and shuttle crew training with confirmed procedures in the use of multiple and independent radiation monitoring equipment with instantaneous and recorded outputs.

- Provide shuttle crew training with confirmed procedures in the use of multiple and independent system monitoring equipment with instantaneous and recorded outputs for all mission phases.

- Provide certified operational plans to:

  - Receive and store isotope fuel capsules
  - Load isotope fuel capsules into heat sources
  - Install heat source in IRV
  - Checkout isotope power systems and components
  - Launch and perform orbital transfer operations
  - Retrieve and recover

- Provide fire alarm and protection systems, training and procedures capable of supporting isotope hardware at:

  - Nuclear facility
  - Transporter
  - Launch pad

- Provide suitable personnel exclusion area at the launch and landing sites (4 km fall back area and 13 km administrative control zones are adequate).

- Establish emergency procedures and decisions (contingency plans) for emergency situations.

- Provide and confirm procedures for the cooling of isotope payloads for all phases of the Shuttle mission (no identifiable failure modes or provide redundant cooling systems).

- Provide transfer modules to protect and reduce the handling and packaging of the large isotope heat source (IRV).

- Provide procedures to assure isotope heat source subcooling to 420°K (300°F) or less during prelaunch.

- Install heat source in Shuttle at last practicable point in launch countdown sequence.

- Consider quick retrieval equipment to remove payload during emergency.

- Prohibit launch during unsatisfactory weather conditions, including moderate to high winds to populated areas.

- Provide recovery gear and procedures for use subsequent to prelaunch accident.

- Provide trained impact/recovery team and procedures for:

  - Recovery
  - Fire Protection
  - Radiation Control
  - Decontamination

- Minimize overflight of land and Continental Shelf

- Avoid or limit operations of the crew which place them in the near vicinity of the heat source and in particular those positions perpendicular to the radiating surface.

- Minimize the crew dose rate throughout all operations (maximum of 150 mrem/day).

- Provide for positive control during all isotope handling operations in space as well as on the ground.

- Provide nuclear cargo transfer operations that do not involve EVA.

- Provide direct visual or TV coverage of all nuclear cargo transfer operations.

- Provide redundant or backup equipment and procedures for nuclear cargo handling.

- Consider a shuttle back-up for retrieval operations.

- Provide tracking and location aids for early land or water recovery of large isotopes.

- Provide procedures for the contingency ejection of the IRV over continental shelf or ocean area prior to landing.

- Provide for emergency recovery of nuclear equipment if jettisoned from Space Shuttle into feasible recovery areas (e.g., continental shelf).

- Consider touchdown area remote from inhabited facilities.

- Provide certified removal equipment and procedures to handle large isotopes subsequent to Shuttle landing.

SECTION 5
SMALL ISOTOPE SOURCES

5.1 GENERAL

The Space Shuttle may be employed to transport small radioisotope devices to and from earth orbit. Small radioisotope devices are defined here as RTG's or other isotope units with heat sources rated at 2500 w thermal or less. Typical of such units are the Multi-Hundred Watt Radioisotope Thermoelectric Generator (MHW-RTG), and the Radioisotope for Thermal Energy (RITE) heat source for the Integrated Waste Management System. These two units are presented pictorially in Figure 5-1. The MHW's application in conjunction with the Space Shuttle would typically be to power an unmanned deep space probe that is carried into earth orbit (along with an upper stage such as a Centaur) in the cargo bay of the Shuttle; the RITE heat source, on the other hand, might be delivered by the Shuttle to the Space Base for installation and operation as a part of that vehicle's Environmental Control and Life Support (EC/LS) system.

5.2 MULTI-HUNDRED WATT RADIOISOTOPE THERMOELECTRIC GENERATOR (MHW-RTG)

The MHW-RTG (Reference 5-1) is an advanced radioisotope power system now under development. It will have a higher power density than the SNAP-19 or SNAP-27 RTG's, will use SiGe thermoelements, and will produce higher temperatures both at the fuel capsule and at the generator's external heat rejection surfaces. The MHW-RTG is designed to produce 150 watts of electrical power from a heat input of 2400 watts. Its salient design features are presented in Figure 5-2. The MHW-RTG is designed for modular use; two units can be combined for an output of 300 watts, and so on.

A typical MHW-RTG application is shown in Figure 5-3 where four MHW-RTG's are part of a Grand Tour Spacecraft. This spacecraft, attached to a Centaur upper stage, is installed in the Shuttle cargo bay for transportation to low earth orbit. The in-orbit operations for such a Shuttle transport mission are relatively simple. Following orbital checkout of the spacecraft, upper stage, and separation system, the assembly is deployed from the Shuttle. Its attitude is established, and the upper stage is fired (by command from either the Shuttle or Ground Control) to place the spacecraft into a planetary trajectory.

● RITE

● MHW

● RADIATION LEVELS

	FUEL LOADING WATTS (BOL)	CAPSULE OPERATING TEMP(°K)
MHW	2400	1530
RITE	410	1030
IRV	52000	1370
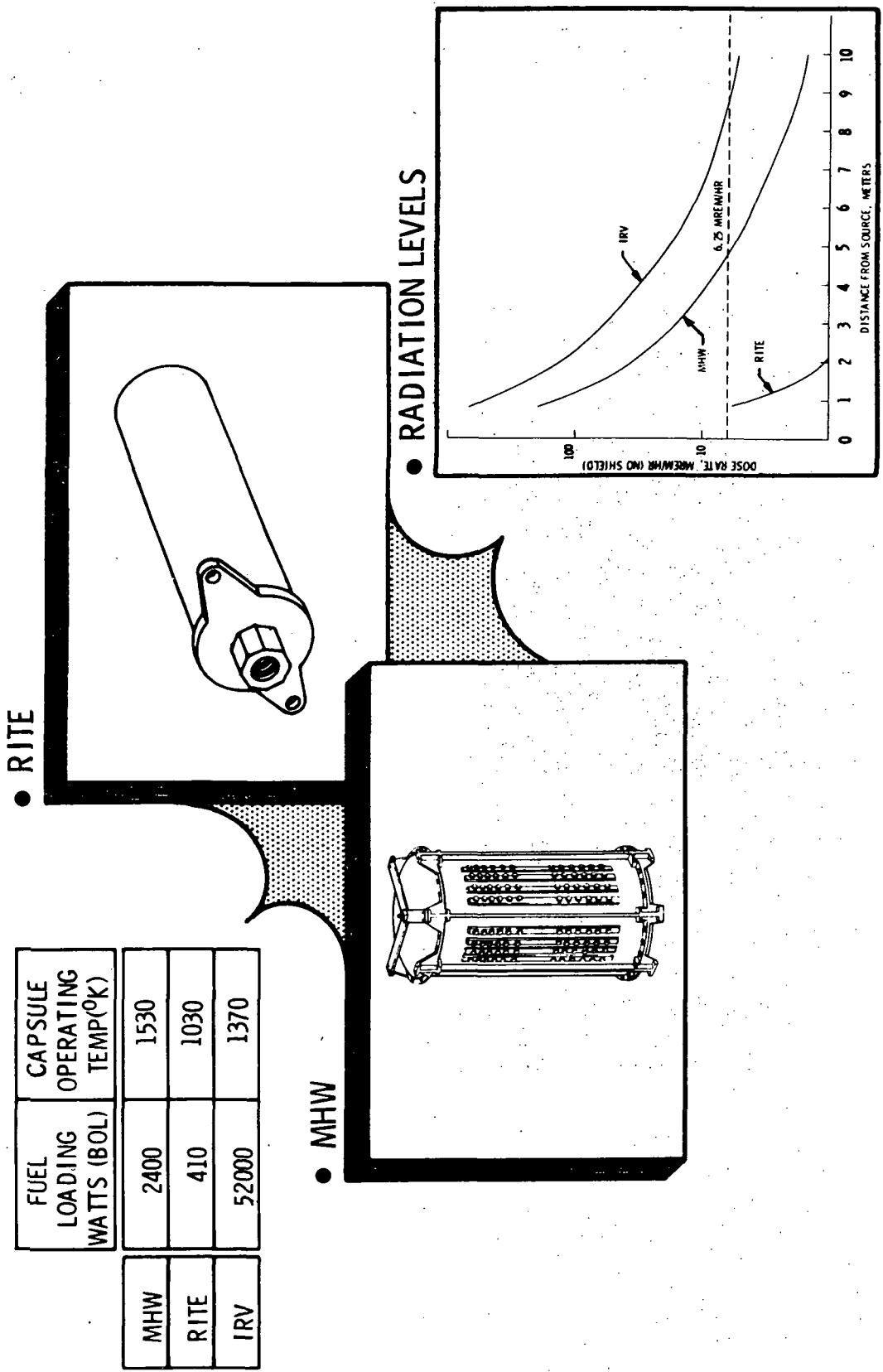
Figure 5-1. Typical Configurations and Characteristics of Small Isotope Systems

THERMOELECTRIC MATERIAL	HOT PRESSED 80 %Si Ge
ISOTOPE FUEL	PLUTONIUM 238
THERMAL INSULATION	MULTIFOIL
RADIATOR EXTERIOR CASING	BERYLLIUM

POWER, BEGINNING OF MISSION (BOM)	137 WATTS
WEIGHT	31.8 KG (70 LBS)
SPECIFIC POWER	6.9 W KG (2 W LB)
HOT JUNCTION TEMPERATURE (BOM)	1272°K (1830°F)
COLD JUNCTION TEMPERATURE (BOM)	590°K (605°F)
CONVERSION EFFICIENCY	6-1/4 %
DIAMETER	0.36 M (14 IN)
LENGTH	0.54 M (21 IN)
OPERATING LIFE	12 YEARS
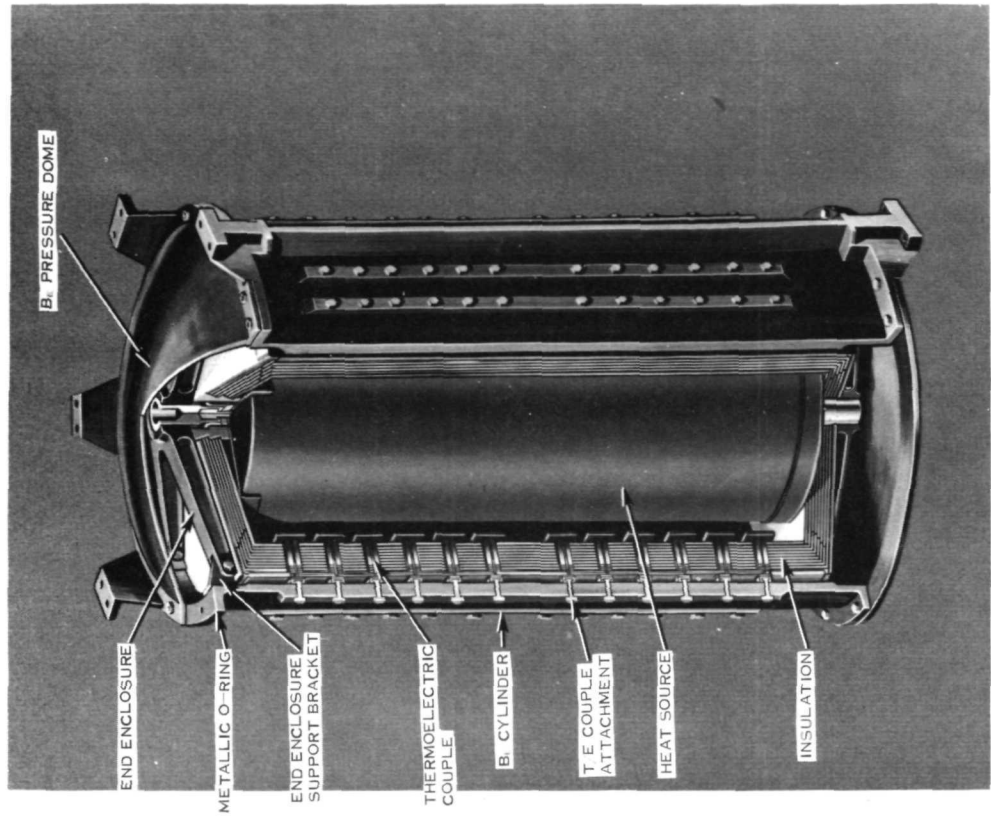
Figure 5-2. MHW-RTG Design Features

5-3

The interfaces to be considered for such an MHW-RTG application are essentially the same as those for the IRV, but because the generator(s) is mounted on the outer structure of the spacecraft instead of on the transfer module, the approach to satisfying all of the interface requirements will be rather different. Blast, fragmentation, and fireball protection should be provided for the generator fuel capsule. Shielding around the MHW heat source on the Spacecraft would result in a significant performance penalty. The required shielding could be located in the Shuttle cargo bay or, in keeping with the transfer module concept, could be mounted on a transfer module that contains the spacecraft, the upper stage, and such auxiliaries as environmental shielding. Since the MHW-RTG itself probably will have adequate cooling within the Shuttle cargo bay, the primary emphasis on thermal control will be to maintain the temperatures of the unmanned spacecraft's components within allowable limits. Thermal control problems would largely be limited to the Prelaunch Phase of the mission since the Launch/Ascent Phase takes the Shuttle and its payload into a space environment in approximately eight minutes, at which time the Shuttle doors can be opened. If cooling of the MHW-RTG's is required, in the event of a contingency situation, an active cooling system such as that described for the IRV (Section 4.2.3) should be employed. The implementation of such a system would require more study and evaluation.
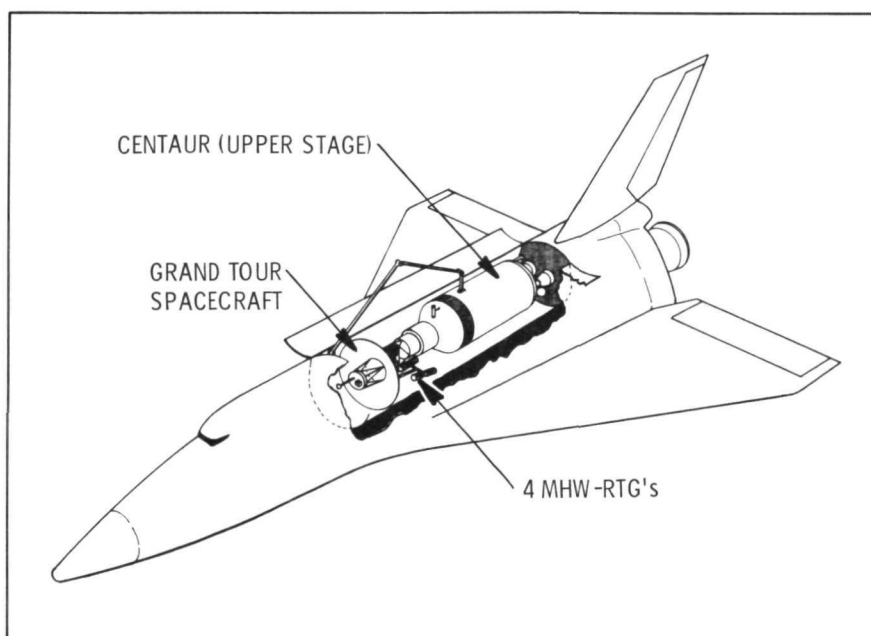
Figure 5-3. Grand Tour Spacecraft Installed in Shuttle

5.3   RITE HEAT SOURCE

Another small radioisotope device that may be transported by the Space Shuttle is the Radio-
isotope for Thermal Energy (RITE) Heat Source which is a part of the Integrated Waste Manage-
ment System (Reference 5-2).   This system, shown in Figure 5-4, is designed to recover
potable water from urine, wash water, and environmental control system condensate, as well
as from solid wastes.

The RITE heat source operates at $1035^{\circ}K$ and generates 420 watts of thermal power.   Although
reentry protection is required, the design for such protection has not yet been identified be-
cause present development is for a ground test engineering unit.   For the purposes of this
discussion, it is assumed that the RITE heat source is equipped with integral reentry heat
protection that will meet all reentry and impact survival requirements.

As other radioisotope fuel capsules, the RITE heat source must be protected from potential
fragmentation and fireball environments that can follow an on-pad explosion of the Shuttle
fuel tankage.   Because of the small size of the RITE fuel capsule, the size and weight of the
blast and fragmentation shielding will be minor compared to that required for the IRV.   A
transportation cask which facilitates handling (both on the ground and in-orbit) and combines
the functions of providing blast and fragmentation protection, thermal control, and reentry
protection can be designed for use with the RITE heat source.   Figure 5-5 shows the RITE
heat source in its transportation cask being transferred from the Shuttle to the Space Base for
subsequent installation in the Base EC/LS system.

The Shuttle provides the prime mode of retrieval of small isotopes.   It is expected that during
a Space Base mission and at the end of mission "close out", isotope heat sources would be
transferred along with other non-expendable cargo to the Shuttle and returned to earth.
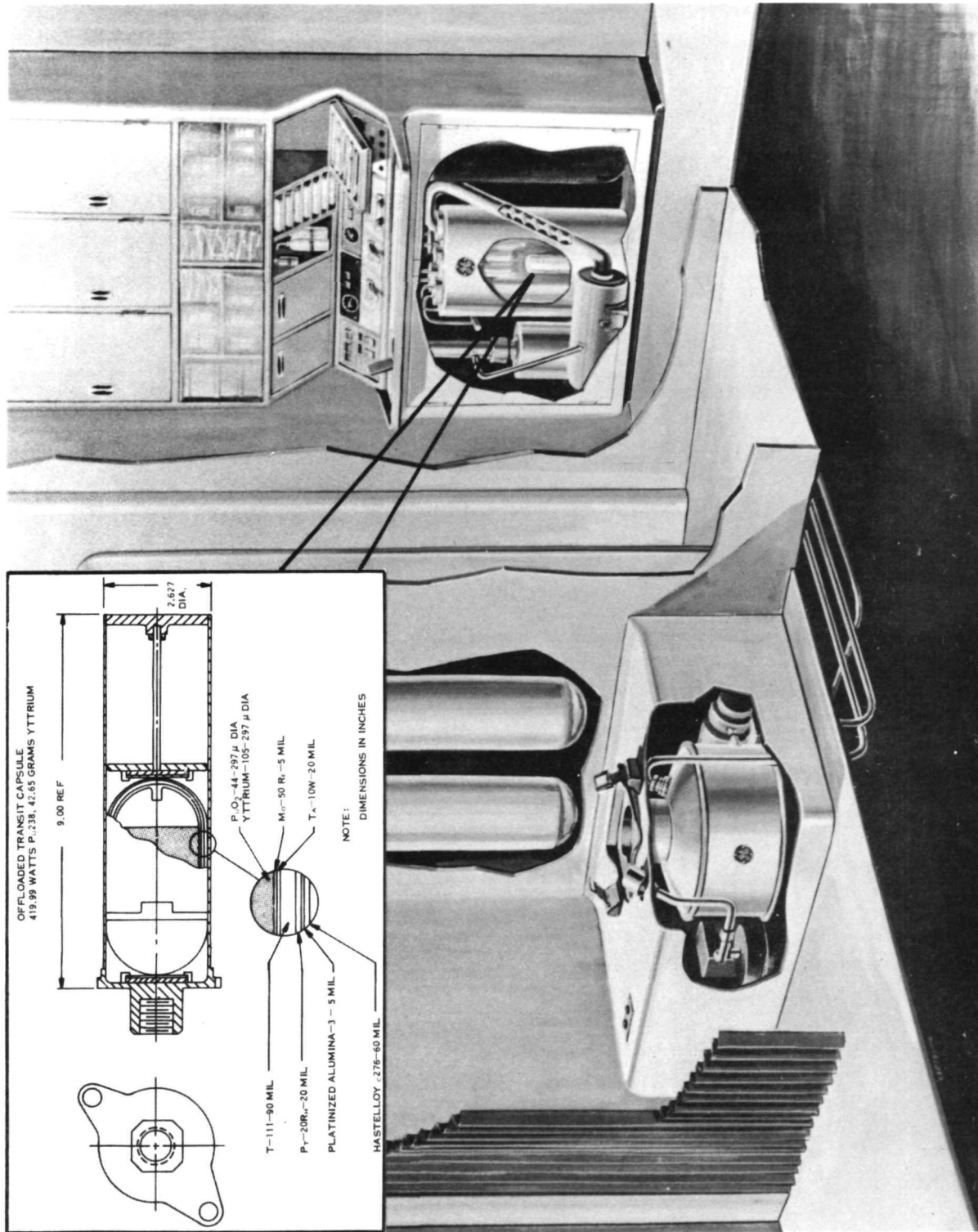
Figure 5-4. Artist's Concept, Integrated Waste Management–Water System Using Radioisotopes
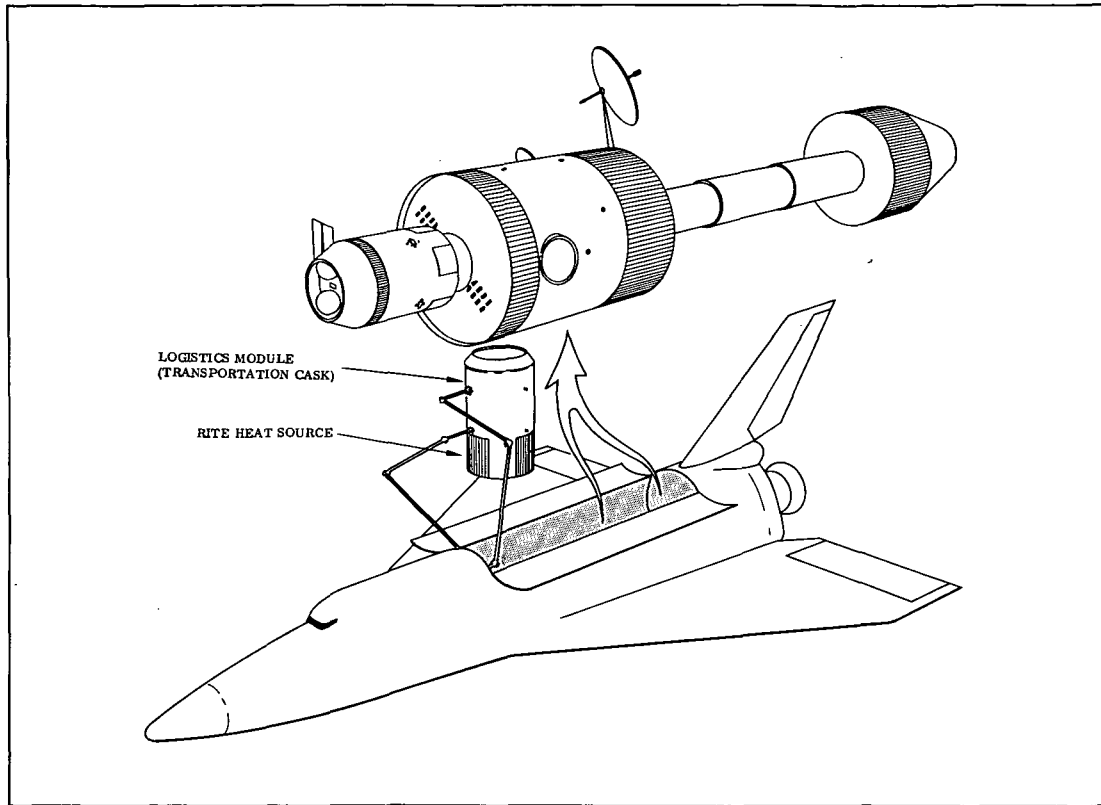
Figure 5-5. RITE Heat Source in Transportation Cask
Being Transferred to Space Base

5.4 GUIDELINES

The basic guidelines specified for the large isotope heat source apply for smaller isotope quantities. The blast, fragmentation and fire protection may be an integral part of the capsule design. Cooling requirements during prelaunch of less than $420^\circ K$ still exist, but the thermal output may be low enough to negate the need for auxiliary cooling.

5.5 REFERENCES

5-1. "Multi-Hundred Watt Heat Source Safety Assessment Report", GESP-7052, General Electric Company, June, 1970.

5-2. "Integrated Waste Management - Water System Using Radioisotopes for Thermal Energy", Summary Report, Contract No. AT(30-1)-4140, General Electric Company, September 8, 1970.

SECTION 6

CONTINGENCY ANALYSIS

6.1 GENERAL

Abnormal and/or emergency situations involving nuclear payloads could result during the mission. If remedial steps are not taken in these situations, the mission could be curtailed and potential hazards to the crew, equipment, the general public, and the ecology could result. The implementation of contingency modes and emergency operating procedures could eliminate or substantially reduce the adverse effects on the mission and the risks to personnel.

The result of a qualitative contingency analysis of Shuttle/nuclear payload transport missions indicates that the implementation of emergency procedures is effective for three situations: (1) where remedial actions contain and control the emergency situation and normal operations can be resumed, (2) where a diminished operating mode can be established until the normal operational conditions are reestablished and (3) where crew and/or equipment abort procedures can be enacted to effect recovery of the crew and/or safe disposal or recovery of the nuclear source. Each situation is a deviation from the normal mode of operations and could require unanticipated implementation.

Effective contingency implementation requires careful planning, procedural preparation and training, which must be performed in parallel with hardware design, development and mission planning.

Several of the key contingency situations are discussed in the following subsections.

6.2 REACTOR POWER MODULE - SHUTTLE MISSION CONTINGENCIES

6.2.1 LIQUID METAL LEAK DETECTED WITHIN CARGO BAY ON LAUNCH PAD

If a liquid metal leak is detected within the power module while on the launch pad, immediate safing procedures are required. A careful diagnosis of the nature and magnitude of the leak is important. Under conditions where liquid metal may have been deposited in the cargo bay, opening of the cargo bay doors could result in a reaction with moisture laden air and a potential fire. To prevent this situation, the cargo bay doors should not be opened until O_2

sources have been removed. The booster should be defueled (several hours). During this time liquid metal fire equipment and fire fighting personnel must be on alert and the cargo bay compartment purged with a dry N_2 or inert gas. In any case, the power module would not be launched with a known liquid metal leak so repairs and/or replacement are required. Although a possibility exists of enacting a repair within the cargo bay, it is generally presumed that the power module would be removed from the cargo bay and transported to a liquid metal servicing facility.

Should a fire result after the above safety precautions have been implemented, rapid smoothering of the liquid metal sources is important. If there are sections in the cargo bay which may be inaccessible to available liquid metal fire equipment, such sections must be protected so that no liquid metal could flow into them or provisions must be made for double containment. Another protective device based on the principle of double containment involves the use of a positive pressure liner which would be placed around the reactor/shield or the entire power module prior to or during installation in the cargo bay. This liner could be designed to contain the leak and also maintain a positive inert gas pressure until the module is within the controlled environment of the liquid metal servicing facility.

6.2.2 DETECTED FAILURE OF POWER MODULE DURING LAUNCH ASCENT OR RENDEZVOUS

System status monitoring and liquid metal leak detectors will provide a means of detecting some failures in a power module prior to docking to the Space Base. Failures during ascent would normally require a termination of the Shuttle ascent boost and a subsequent reentry and/or landing, preferably at the original point of departure. Early in the ascent phase, it may be necessary to consider dumping of Shuttle fuel to meet landing weight limits and to avoid landing with a large potentially explosive fuel load. A normal landing could be permitted under a majority of the detectable failure conditions. Special unloading precautions must be taken, however, if a liquid metal leak has occurred prior to or during landing. Cargo bay doors should not be opened to the ambient environment until radiation and liquid metal leak checks and safing procedures are implemented. The containment of liquid metal within an environmentally controlled liner would permit removal of the power module from the Shuttle in the ambient environment and minimize potential damage of the Shuttle caused

by liquid metal reactions. The radiation environment would be low since the reactor has not undergone full power operation.

6.2.3 SHUTTLE FAILURE DURING ASCENT

A Shuttle failure during the ascent phase, but prior to achieving orbit, could result in (1) an explosion at altitude, (2) a loss of thrust, which could necessitate a ditching at sea or a landing at an unplanned landing site or (3) a loss of control which may also require ditching or an uncontrolled crash.

If shuttle failures occur in orbit, the short orbital lifetime (≈ 1 year) could allow for a backup Shuttle to (1) enact rescue of the crew, (2) provide retrieval of the payload, or (3) provide assistance in the repair of the failed Shuttle whereupon the mission could be continued. These contingency actions increase the probability that the crew and the payload could be rescued.

When an emergency shuttle landing is to be attempted, consideration should be given to the possibility of the ejection of the reactor power module into a deep ocean area prior to landing. Preoperational nuclear hazards of a reactor primarily involve that of an excursion. If assurance can be given that such an event will not happen, a soft landing should be attempted and thereby save the payload. A hard landing could rupture liquid metal components and if environmental containment is not maintained, a liquid metal reaction could result. Readily accessible quantities of liquid metal fire suppression material should be provided in the Shuttle, as this material would probably not be available at an unplanned landing site. Radiation monitors should also be available.

6.2.4 FAILURE OF SHUTTLE DOORS TO OPEN PRIOR TO PAYLOAD EMERGENCY EJECTION

The payload emergency ejection mode during launch or landing may involve the opening of the Shuttle cargo bay doors. If the doors fail to open, consideration should be given to ejection through the doors where such an impact on the doors would cause severence of door hinges or other attachments so that damage can remain isolated from the Shuttle proper. The design and aerodynamic implications of these situations must be addressed.

6.2.5 FAILURE TO REMOVE REACTOR FROM CARGO BAY OR TO DOCK TO SPACE BASE

The primary contingency plan should include consideration for repair, if it is found impossible to remove the reactor from the cargo bay due to failures in the transfer mechanisms or docking of the power module cannot be completed due to interface problems. If repair is possible, a backup Shuttle should be available within approximately 12 days (time allowed for hardware preparation and launch preparation) to provide the necessary logistic and maintenance support. These operations would necessarily require a Shuttle orbital stay time of up to 20 days. The Shuttle with its nuclear payload could be docked to the Base, and powered down in the interim and the Shuttle crew billeted in the Space Base. Radiation limits for the Shuttle crew would not be exceeded for operations involving a "clean" reactor. However, operations involving a spent reactor must be carefully controlled to minimize the radiation doses to the crew.

When in-orbit repairs cannot be affected, the Shuttle should return to its landing site.

6.2.6 RETRIEVAL - DISPOSAL - RECOVERY OF A DAMAGED POWER MODULE

The Shuttle may be required to dispose of or recover a previously damaged power module. The action taken is dependent on the extent of damage. It is therefore important that the damage be known prior to the commitment of the Shuttle so that the proper action can be taken. If damage is of such an extent that considerable hazards would be presented to the Shuttle and crew or placement within the cargo bay would be impossible it would be advise-able to enact a separate (apart from Shuttle) disposal to high earth orbit. If a disposal system were not a part of the power module or the existing disposal system were inoperable, the Shuttle could be called on to bring up a replaceable or strap-on disposal package. Time spent in these operations should be minimized as the damaged power module would possibly remain attached to the Space Base, necessitating a reduction in Space Base power.

In the situations where the Shuttle must be the means of disposal or recovery, the Shuttle cargo bay could be subjected to liquid metal and possible radiation contamination. The extent of potential radiation contamination (activated NaK debris, etc.) should be assessed prior to commitment of the mission, so as not to exceed the allowable crew dose rate of 150 mrem/day during disposal operations (dose rate is based on yearly average - higher dose rates could be permitted during shorter orbital stay times).

A positive pressure liner could possibly be wrapped around the damaged power module prior to installation in the cargo bay. This procedure could protect the Shuttle cargo bay and provide safety advantages in the unloading and Shuttle refurbishment operations at the landing site. In any case, the cargo bay should be designed to facilitate decontamination and minimize Shuttle turnaround time. Clean unobstructed surfaces should be a design objective.

A power module equipped with a separable heat exchanger provides the possibility of retrieval and recovery or disposal of only the reactor/shield assembly. The radiator and internal components would be jettisoned and allowed to reenter by orbital decay where burnup is expected.

6.2.7 DISPOSAL FAILURE RESULTING IN SHORT LIFE ORBIT

Short life orbits of a power module (nominally 1 to 100 years) resulting from a disposal failure, occur due to a failure of the Shuttle during disposal or due to a failure in a power module disposal system. In the former case, the Shuttle can elect to release the power module in whatever orbit was attained and perform an empty cargo bay landing. The possibility also exists of bringing the power module back to earth in the Shuttle, with the landing options available as discussed previously.

If the power module should be in a low earth (short life) orbit, possible retrieval action with a back-up Shuttle could be taken by a reboost to high earth orbit or an earth return. In such situations, the power module would possibly be tumbling and uncooperative satellite retrieval/grappling techniques would be required. Tracking devices (transponders, beacons, etc.), on the power module, would aid in location and rendezvous.

6.2.8 SHUTTLE OR POWER MODULE FAILURE CONDITIONS DETECTED DURING DESCENT FROM ORBIT

Detected failure conditions of the Shuttle which lower safe landing probabilities, or detected hazardous conditions of the power module within the cargo bay present several contingency options during the descent trajectory. An evaluation of the radiological risks involved should be performed. If risks are deemed high enough such that a landing with the payload should not

be attempted – two contingency modes exist (1) a ditching at sea with a crew recovery or (2) the ejection of the payload over a deep ocean area followed by a landing of the Shuttle and crew. The first mode would possibly result in severe damage or loss of the Shuttle. Landing of the Shuttle in the second mode could result in a Shuttle crash, particularly if Shuttle failures existed. In either case, during a safe landing or in a crash, some radioactive and/or liquid metal contamination could be present. Decontamination should be pursued where appropriate, realizing that these procedures may be required at alternate and unplanned landing sites. In mode (1) or (2) where the payload impacts in the deep ocean, amounts of radiation released should have negligible effects on the general populace.

6.3 ISOTOPE HEAT SOURCE – SHUTTLE MISSION CONTINGENCIES

The contingency modes available in a Shuttle mission transporting an isotope heat source(s) are similar to those described for a reactor power module. However, no liquid metal hazards exist due to the absence of a liquid metal inventory. Other notable differences are due to (1) the thermal hazard presented by the heat source necessitating special cooling provisions and (2) the potential value and reusable characteristics of the isotope placing added emphasis on recovery operations. These latter two differences relative to a reactor power module are emphasized in the subsequent discussion.

6.3.1 LOSS OF HEAT SOURCE COOLING ON THE LAUNCH PAD

Normal cooling of the heat source to at least $420^{O}K$ is required to eliminate the isotope heat source as a potential Shuttle propellant vapor ignition source. Loss of on-pad cooling of a large isotope heat source contained within a Shuttle cargo bay will result in an immediate rise in heat source temperature. If the Shuttle doors remain closed during the failed condition, propellant vapor should not enter. The potential for oxidation of the heat source refractory metals increases as the temperature rises. A maximum design temperature of approximately $700^{O}K$ in ambient conditions is suggested. A heat source cooling system failure with Shuttle doors closed, would result in a heat source temperature rise to $550^{O}K$ within a half hour and $700^{O}K$ in approximately one hour. Repair of the prime cooling system on the Mobile Launcher or start-up of an auxiliary/back-up cooling system should be accomplished in this time frame. Failure to do so would require opening of the cargo bay doors to permit use of external cooling systems and prevent damage to the Shuttle.

Draining of propellant tanks may be advisable in this event. Purging of the cargo bay area with dry N_2 would also reduce ignition potential.

6.3.2 LAUNCH PAD EXPLOSION AND FIRE

As contrasted with a pre-operational reactor, a large isotope heat source constitutes a potentially large radiation hazard should significant amounts of isotopic fuel be released in a launch pad fire ball. Calculations show (Reference Vol. IV, Part 2) that when recently developed fuel forms and encapsulation techniques are used for certain missions, fuel release source terms can be kept to a minimum. However, for the Shuttle missions, new design may have to be developed because of the blast and fragmentation damage potential which exists. Fuel release preventive measures, such as the addition of protective shielding and use of a Shuttle launch configuration which permits an unobstructed blast ejection path to carry the heat source or orbiter and payload out of the fireball perimeter, should be design objectives.

6.3.3 FAILURE OF CARGO BAY DOORS TO OPEN ON ASCENT

Candidate operating procedures involved with a "passively cooled" heat source call for the opening of the Shuttle cargo bay doors some 8 minutes after launch to allow the heat source to radiate directly to space. (This feature may not be available if the heat source were entirely surrounded by a blast and fragmentation shield as discussed in Section 4.2.2.)

If Shuttle doors fail to open when a heat source with an exposed radiative surface is in the cargo bay, heat source temperatures would increase similarly to that described for the Launch Pad situation, Section 6.2.1. The requirement for a redundant active cooling system internal to the Shuttle, is identified for the Shuttle return (descent) of the heat source to earth. During this operation, the Shuttle cargo bay doors are closed ($\sim$ 3 hrs prior to reentry) to permit reentry through the atmosphere. This same internal cooling system can be used for back-up cooling on ascent. Ultimate failure to open the doors would necessitate a return to earth, landing and removal of the heat source. Back-up cooling provisions should be capable of operating up to 24 hours. If all cooling fails, temperatures would continue to rise and eventually exceed normal heat source operating temperatures of about 1360°K, causing ultimate damage to the Shuttle. Ejection of the heat source into an ocean

area should be considered if other alternatives lead to reentry burnup or ultimate land impact and/or crash landing.

6.3.4 RETRIEVAL AND RECOVERY OF A DAMAGED HEAT SOURCE

A damaged heat source may constitute an additional radiation hazard due to possible fuel capsule fractures with the potential of a release of inhalable isotope fuel particles (fines). A damaged reentry shield would prevent a successful independent reentry, a backup mode of recovery. This back-up recovery mode should be particularly avoided if fuel capsule fractures are present. Retrieval by the Shuttle should be the objective and the prime mode of recovery. With a failure in fuel capsule containment, the resultant radiation due to release of fines should not be a hazard to the crew, but a thorough decontamination of the Shuttle cargo bay upon landing would be required. Clean, smooth cargo bay surfaces, free from protrusions and crevices would enhance decontamination procedures. A sealed crew compartment (separate ECLS) should be a design objective to assure radioactive vapor from fractured capsules does not enter the compartment.

An intact and controlled heat source reentry and landing must always be an objective. This is particularly important when fuel capsule failure has occurred. The addition of crush-up material in the cargo bay would lessen the potential damage due to a hard landing or crash. A rapid removal of the heat source from a fire after landing and rapid fire suppression will reduce the potential hazard.

6.3.5 RECOVERY VS. DISPOSAL OPTIONS

Due to the relatively high monitary value of the isotope inventory in a large heat source, recovery is generally the prime aim during the end of mission mode. Therefore, recovery provisions such as tracking devices, dye markers, pingers and possible floatation gear are important safety design features. If reliable recovery techniques are available, emergency ejection into a Continental Shelf area rather than in the deep ocean can provide quick recovery. However, consideration must be given to the potential hazards which may result from failure to recover the heat source, such as the contamination of fishing areas and the resultant risk to the general public.

6.4 DESIGN AND OPERATIONAL GUIDELINES FOR CONTINGENCY PLANNING

A summary of the key guidelines for implementing contingency plans for the Shuttle transport of nuclear payloads is contained in Table 6-1.

Table 6-1. Shuttle/Nuclear Payload Guidelines for
Contingency Planning

GENERAL

- Provide capability to defuel the Shuttle in nuclear emergencies on the launch pad.

- Provide dry N_2 purging capability of the Shuttle cargo bay volume while on the launch pad.

- Provide capability of detecting and alerting the Shuttle crew of nuclear payload failures which occur during transport.

- Provide unobstructed blast ejection path for nuclear payloads on the launch pad (particularly important for isotope payloads).

- Minimize radiation dose to crews performing contingency operations (maximum of 150 mrem/day from nuclear sources should be maintained).

- Consider use of a back-up Shuttle to support repair of a failed Shuttle or transfer or retrieval of the payload in orbit for the continuance of the mission.

- Where detected Shuttle failures indicate reduced successful landing probabilities, ditching at sea or payload ejection should be considered.

- Provide contingencies for Shuttle orbital stay times of up to 20 days to allow for repairs to be made.

- Where in-orbit repairs of interfacing non nuclear hardware (transfer mechanisms etc.) are unsuccessful, the shuttle and payload should return to earth.

- Consider feasibility of uncooperative "tumbling" power module retrieval with Shuttle.

- Provide tracking and recovery devices on nuclear payloads.

- Consider payload ejection through cargo bay doors if doors cannot be opened.

- Consider dumping of excess Shuttle propellant prior to landing to minimize explosive potential.

- Provide Shuttle radiation and liquid metal decontamination capability at the launch and landing site.

- Provide a clean, smooth surface cargo bay to facilitate decontamination, and minimize the time required.

REACTOR POWER MODULE

- Provide double containment of liquid metal components where feasible.

- Consider use of a inert gas positive pressure liner for encasement of all or portions of a reactor power module - considered particularly important for the in-orbit retrieval and landing site removal of a damaged power module.

- Provide capability of detecting and alerting the Shuttle crew of a liquid metal leak which would render the power module inoperable and provide potential hazards within the Shuttle cargo bay.

- Consider provision of liquid metal fire suppression material within the Shuttle.

- Consider capability to install a replaceable or strap-on reactor disposal system by the Shuttle crew.

- Consider a Shuttle return of only a reactor/shield by a design which permits in-orbit separation of the radiator and other components.

- Consider reactor reboost capability to a new long-life orbit by the Shuttle.

- Provide a controlled environment liquid metal safing capability at launch and landing sites (reduction or elimination of O_2 sources).

- Consider emergency ejection of reactor into deep ocean area during ascent and landing.

ISOTOPE HEAT SOURCES

- Provide a rapid response back-up isotope cooling system at the launch pad which does not require opening of the Shuttle doors.

- Provide capability to reduce ignitable propellant fumes around cargo bay (i.e., drainage of propellant tanks and or purging immediate payload area).

- Provide a redundant active isotope cooling system within the Shuttle cargo bay to be operable on ascent and return/reentry with at least 24 hours emergency operating time.

- Provide for Shuttle retrieval and recovery of a heat source with a damaged shield or fuel capsule fractures.

- Consider emergency ejection of isotope-Brayton heat source onto continental shelf areas during ascent or landing.

- Consider provision of floatation gear for an isotope-Brayton heat source (possibly time limited).

- Provide a crush-up structure within the Shuttle cargo bay for reduction of isotope fuel capsule damage for the case of a crash landing.

- Provide capability for the rapid removal of a heat source from fire emergencies upon landing.

SECTION 7
TERRESTRIAL SAFETY SUMMARY

7.1 GENERAL

The purpose of the terrestrial nuclear safety analysis is to identify and characterize the nuclear hazards to the general populace associated with the Space Shuttle transport of a zirconium hydride reactor power module and an isotope-Brayton power system to and from the Space Base. The primary objective of the analysis is to evaluate the extent and impact of the identified nuclear hazards on the general earth's populace and on supporting facilities. This section contains a summary of the analysis. Detailed analyses and results are presented in Part 2 of this Volume.

The potential accidents that may occur during the Space Shuttle nuclear payload transport to and from the Space Base are shown in Figure 7-1. The analysis has shown that the transportation of nuclear hardware by the Space Shuttle results in a low risk to the general populace. The highest risk accidents for each mission phase are blocked in on the figure.

For the reactor power system, the analysis assumed the Disposal Phase to involve the reactor module being boosted by means of the Shuttle to a high altitude disposal orbit. In the case of the isotope-Brayton system, the Disposal Phase consists of the return of the isotope reentry vehicle (IRV) with the Shuttle to the landing site. These disposal modes were selected to analyze both modes of disposal employing the Shuttle.

The Space Shuttle launch and descent trajectories are shown in Figure 7-2. Most of the launch trajectory prior to orbit insertion is over water, except for a brief land overflight of Nova Scotia and Newfoundland. The descent trajectory for a KSC landing, is also over water except for land overflight of the southernmost part of Mexico and central Florida.

7.2 REACTOR TERRESTRIAL SAFETY ANALYSIS

For the reactor risk evaluation, two approaches are used: (1) Dose Guideline and (2) Linear Response. In the dose guideline approach, all individuals exposed to the dose guideline value or above are considered exposed. This risk approach results in the number of

Figure 7-1. Shuttle Accidents During Nuclear Payload Transport to and from an Orbiting Space Base

Figure 7-2. Shuttle Launch and Descent Trajectory
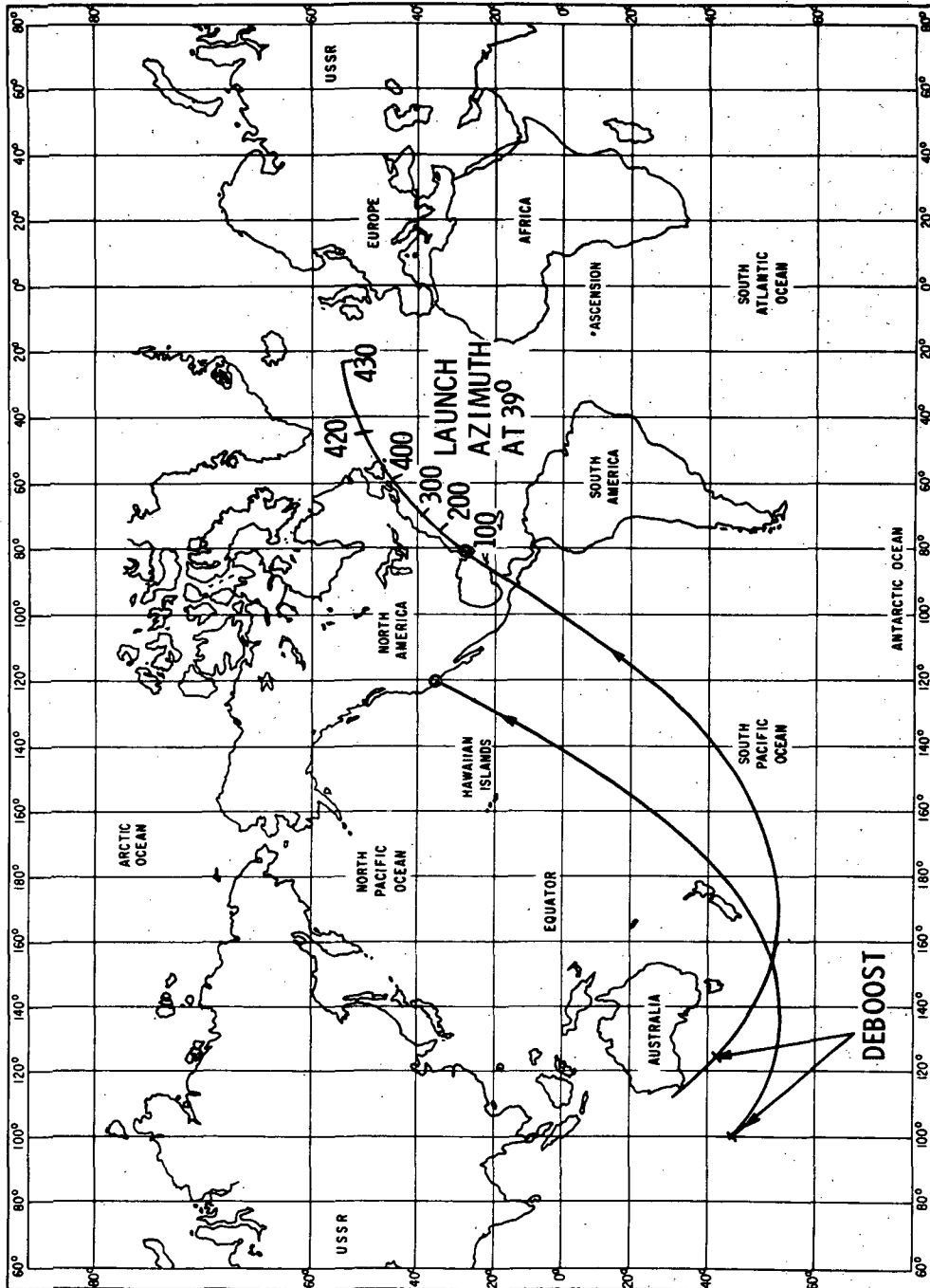
- LAUNCH AZIMUTH – 39°
- ORBIT INCLINATION – 55°
- ORBIT ALTITUDE – 93 BY 185 KM
- ORBIT TRANSFER TO – 500 KM

exposures from an accident, but does not continue on to the biological end point to indicate the number of resulting injuries. The linear response approach is based on the hypothesis of a linear relationship between biological effect and the amount of radiation dose which is supported by the latest existing data on human and mammalian radiation response.

The reactor accident evaluation and relative risk for each of the mission phases is summarized in Figure 7-3. The overall mission risk is low. The dominant risk of the entire mission occurs in the Reactor Disposal Phase and results following a successful boost to the 835 km (450 nm) disposal orbit. After a 250 year orbital decay, land impact may result in destructive excursion (2.7×10^{-3}). Although the core fission product activity is substantially decayed after 250 years, the probability of land impact is high (2.7×10^{-1}). The high land impact probability coupled with the probability of a destructive excursion (1×10^{-2}) is primarily responsible for the resulting exposure index.

The risk analysis summary for the Shuttle/Reactor payload mission (Figure 7-3) indicates the exposure indices for each phase of the mission using the linear response and the dose guideline approach. The two risk analysis approaches result in the same relative phase risk ranking; the Disposal Phase being dominant. The Disposal Phase risk essentially accounts for the total mission risk. Also indicated is the hypothetical mission risk assuming perfectly reliable Shuttle reboosts to long-life orbits. Analysis has shown that a Shuttle orbiter recovery and return to land would reduce the risk significantly (approximately one order of magnitude as indicated in Figure 7-3). Permanent reactor shutdown prior to disposal orbit insertion and prevention of reactor excursions would also contribute to reducing the risk. There would essentially be zero risk associated with the Launch/Ascent Phase if reactor excursions can be prevented.

The linear response method results in an exposure index value in the Prelaunch Phase while the dose guideline method does not. The linear response model considers exposures to zero dose levels and therefore results in an exposure index value based on some probability of injury event at low radiation levels. The linear response method may also be used to indicate

Phase	Highest Risk Accident	Cause	Safeguards
Prelaunch	Launch Pad Explosion and Fire • Destructive Excursion	• Propellant Ignition During Fueling or Countdown	Control Drum Lockout Device
Launch and Ascent	• Orbital Rendezvous Abort • Earth Impact of Shuttle Containing Reactor	• OMS Failure • G&C Failure	Control Drum Lockout Device
Reactor Transfer to Space Base	• Failure to Mate Reactor to Space Base • Reactor not Recovered • Reactor Reentry and Earth Impact	• Reactor Docking Port Failure • Transfer Mechanism Failure	Control Drum Lockout Device
Reactor Transfer to Shuttle	• Shuttle Collision with Space Base • Uncontrolled Orbiter Reentry • Earth Impact of Shuttle Containing Reactor	• G&C Failure	• Maximize Reactor Intact Impact Capability • Provide Tracking Capability
Reactor Disposal	• Successful Boost to 835 KM Disposal Orbit • Eventual Reentry and Earth Impact after 250 Years	• None	• Permanent Reactor Shutdown Prior to Disposal Orbit Insertion • Provide Tracking Capability • Shuttle Recovery and Return to Land

Figure 7-3. Reactor Accident Evaluation and Relative Risk Summary

the degree of injury. By selection of the proper radiation exposure threshold, the number of acute exposures in which clinical symptoms of the radiation exposure are evident, can be determined.

7.3 ISOTOPE TERRESTRIAL SAFETY ANALYSIS

For the isotope-Brayton risk evaluation, only the dose guideline approach is utilized because data on the response from deposited plutonium in the lung as a function of radiation level is not available. Therefore, dose guideline values for the plutonium affected organs (lung, liver, bone and whole body) are used in the evaluation.

The aging effect on the isotope reentry vehicle (IRV), fuel capsules, and the plutonium fuel after ten years of use on the Space Base is considered to have a significant impact on safety. However, recent data appears to indicate that aging effects may not be as pronounced as previously assumed and a reduction of the fuel release source terms may result. The assumed degradation would reduce the IRV and fuel capsule survival capability. This factor accounts for the higher failure probabilities for atmospheric reentry accident environments.

A summary of the isotope-Brayton accident evaluation and relative risk is presented in Figure 7-4. The overall mission risk is low. The dominant risks in the isotope-Brayton accident evaluation occur in the last two phases, i.e., IRV transfer to Shuttle and Shuttle descent and reentry. These phases involve the handling of an IRV which has operated for ten years on the Space Base. The aging effects on the IRV system results in higher failure probabilities and plutonium release source terms. Thus, the exposure indices involving the aged system are higher than those for a new system just launched.

The risk analysis summary (Figure 7-4) for the Space Shuttle/isotope-Brayton nuclear payload mission shows that the IRV Recovery (i.e., descent and reentry) Phase accounts for practically the entire mission risk (assuming aged fuel). Figure 7-4 indicates that up to a three order of magnitude reduction in mission risk may be achieved assuming no adverse aging effects on the isotope system. Particular emphasis on safeguards is therefore

7-6

Figure 7-4. Isotope-Brayton Accident Evaluation and Relative Mission Risk Summary

Chart labels:

RELATIVE RISK →

- RETURN TO EARTH PHASE DOMINANT RISK (ASSUMING AGED FUEL)

$EI = \Sigma P \times N$

*MISSION RISK WITH UNAGED FUEL (I.E., NO IRV, FUEL CAPSULE, AND FUEL DEGRADATION DUE TO AGING EFFECTS)

PRE-LAUNCH	LAUNCH AND ASCENT	TRANSFER TO SPACE BASE	TRANSFER TO SHUTTLE	DESCENT AND REENTRY	TOTAL
KSC	KSC & ATL. COAST	WORLD WIDE $\pm 55^0$ LAT.			

Phase	Highest Risk Accident	Cause	Safeguards
Prelaunch	Launch Pad Explosion and Fire	Ignition of Propellant During Fueling or Countdown	• IRV Ejection Mechanism
Launch and Ascent	• Orbital Rendezvous Abort • Earth Impact of Shuttle Containing IRV	• OMS Failure • G&C Failure	• IRV Ejection Mechanism • Maximize IRV Impact Capability
Transfer to Space Base	• Shuttle Collision with Space Base • Shuttle-Earth Impact with IRV	• G&C Failure	• IRV Ejection Mechanism • Maximize IRV Intact Impact Capability
Transfer to Shuttle	• Shuttle Collision with Space Base • Shuttle-Earth Impact with IRV	• G&C Failure	• IRV Ejection Mechanism
	• Failure to Remove IRV from Docking Port • IRV Ejected from Space Base	• Orbiter Transfer Mechanism • IRV Release Mechanism	• Maximize Intact Impact Capability of Aged System
Descent and Reentry	• Shuttle Crash While Proceding to Landing Site	• Landing Gear Failure • Structural Failure During Reentry	• IRV Ejection Mechanism • Maximize Intact Impact Capability of Aged System

required in the final mission phases to improve mission safety.

7.4   LAUNCH/LANDING SITE ABORT EVALUATION

A Shuttle launch from KSC with a 39 or 45 degree launch azimuth for a Space Base rendezvous mission presents a low risk to the general public. Missions requiring polar or near polar orbits require a launch from the Western Test Range to avoid land overflight.

Landing site location for a Shuttle containing a nuclear payload must consider the potential hazards from the release of radioactive materials should an accident occur. An accident may occur during a de-orbit approach or on landing.

For launch or de-orbit approach, the offsite land traversed and population density in the approach corridor should be minimized. Should a Shuttle abort occur during launch or final approach and landing, ejection of the IRV or Shuttle ditching at sea should be considered.

The landing and launch site should be at the same location because similar equipment, facilities and trained personnel are required to support both operations. Because of weather conditions or possible Shuttle orbiter propulsion or guidance and control problems, alternate landing sites are required. For both low inclination and polar orbit returns, the preferred alternate landing site is WTR since the descent approach is entirely over water.

APPENDIX A
REFERENCE SPACE SHUTTLE

A.1 GENERAL

This section describes the reference Space Shuttle orbiter and booster used in the safety analysis and the reference Space Shuttle mission. The data presented is based on NASA Space Shuttle Phase B studies (References A-1, 2). It is assumed that the nuclear payloads that are considered in this study can be launched aboard the Space Shuttle, whether or not the total nuclear system weight exceeds the current Shuttle payload limitations.

A.2 DESCRIPTION

The launch configuration consists of two separate vehicles – a booster which provides the initial lift-off thrust, and the Space Shuttle orbiter which separates from the booster after first stage thrusting is complete and inserts the payload into earth orbit. As a result of NASA Phase B studies completed in early 1971, two reference launch configurations have been identified and are illustrated in Figure A-1. The upper drawing shows the NAR selected design while the lower drawing depicts that of MDAC.

Both Shuttles have a delta-wing design for high cross-range capability, whereas the reference boosters are of contrasting designs. NAR has selected a delta-wing booster, while the MDAC booster is characterized by an aft-mounted swept wing. The propellant loading in both designs is similar, each employing liquid oxygen and liquid hydrogen as the main propellants.

The nuclear payload to be delivered to the Space Base is placed in the Shuttle's cargo bay. The maximum allowable payload envelope is the same in both the NAR and MDAC designs – 4.6 m (15 ft) in diameter by 18.3 m (60 ft) long.

The following few pages briefly describe the Shuttle and booster vehicles. Major differences between the NAR and MDAC designs that affect nuclear safety will be indicated. In order to perform the study, where possible, the features of both launch configurations have been combined into a single system.

NAR

- DELTA WING BOOSTER AND SHUTTLE
- CARGO BAY
  - 4.6 METERS DIAMETER x 18.3 METERS LONG
- LOX/LH$_2$ ROCKET ENGINES
  - 2 SHUTTLE
  - 12 BOOSTER
- GLOW = 2.26 x 10^6 KG
  - PROPELLANTS – 1.84 x 10^6 KG

MDAC

DIFFERENCES IN BASIC LAUNCH CONFIGURATIONS DO NOT SIGNIFICANTLY AFFECT NUCLEAR SAFETY

- DELTA WING SHUTTLE
- SWEPT WING BOOSTER
- CARGO BAY
  - 4.6 METERS DIAMETER x 18.3 METERS LONG
- LOX/LH$_2$ ROCKET ENGINES
  - 2 SHUTTLE
  - 12 BOOSTER
- GLOW = 2.1 x 10^6 KG
  - PROPELLANTS – 1.76 x 10^6 KG

Figure A-1. Reference Space Shuttle Launch Configurations

A.2.1 SHUTTLE CONFIGURATION

The NAR and MDAC Phase B Shuttle configurations are shown in Figures A-2 and A-3, respectively. It is important to note in both designs, the proximity of the cargo bay and primary propellant tankage. In the NAR design, the cargo bay is located more or less on top of the tankage, whereas MDAC has positioned the cargo bay down amongst the tankage (tankage surrounding the cargo bay on practically three sides). From a nuclear safety standpoint, the proximity of cargo bay and tankage is highly undesirable in the event of a Shuttle explosion and fire (Section A.3). In addition, the positioning of the cargo bay with respect to the propellant tankage can have a significant effect on the crew radiation dose rate from a shutdown, spent reactor module in the cargo bay (Appendix B).

Contrasting cargo transfer schemes are used in the two designs. NAR has selected general purpose manipulator arms to transfer payloads, whereas the MDAC approach is to use a 90 degree rotation scheme to dock the payload to the Space Base.

The NAR Shuttle has two crew locations - the manipulator operator's station and the pilot's cockpit, located approximately 2.3 m (7.5 ft) and 16.6 m (54.5 ft) forward of the cargo bay, respectively. The MDAC Shuttle has only one crew location, the pilot's cockpit, located 6.1 m (20 ft) forward of the cargo bay.

A.2.2 PAYLOAD ACCOMMODATION

The cargo bay is defined as a clear volume for a 4.6 m (15 ft) diameter by 18.3 m (60 ft) long cylindrical payload. The payload retention system in the NAR Shuttle is designed to accommodate payloads 4.6 m in diameter by a length that may vary from payload to payload. The forward attach fittings are designed to take the axial, vertical, and side loads that may be imposed on the Shuttle and payload. The side load is taken on one side only so that unpredicted Shuttle or payload deflections are not introduced into the attach fitting. The aft end of the payload is supported by a single fitting on the Shuttle centerline. The aft fitting accepts vertical loads only and is designed to accommodate thermal or structural deflections in the lateral direction. For payloads less than 4.6 m in diameter, a series of adapters and pallets are available.

SHUTTLE DRY WEIGHT   - 126,100 KG
TOTAL PROPELLANT WEIGHT - 250,100 KG

TOTAL SHUTTLE WEIGHT   - 376,200 KG

14.7 M

63 M

LH₂

LOX

LH₂

LOX

VIEW A-A

- ARTICULATION (MANIPULATOR ARMS) FOR CARGO TRANSFER
- TANKAGE "SURROUNDS" CARGO BAY
- CARGO BAY ~ 16.6 M FROM CREW COMPARTMENT
- MANIPULATOR OPERATOR'S STATION ~ 2.3 M FROM CARGO BAY

MANIPULATOR ARMS (LEFT AND RIGHT)
MANIPULATOR OPERATOR'S STATION
PASSIVE DOCKING RING
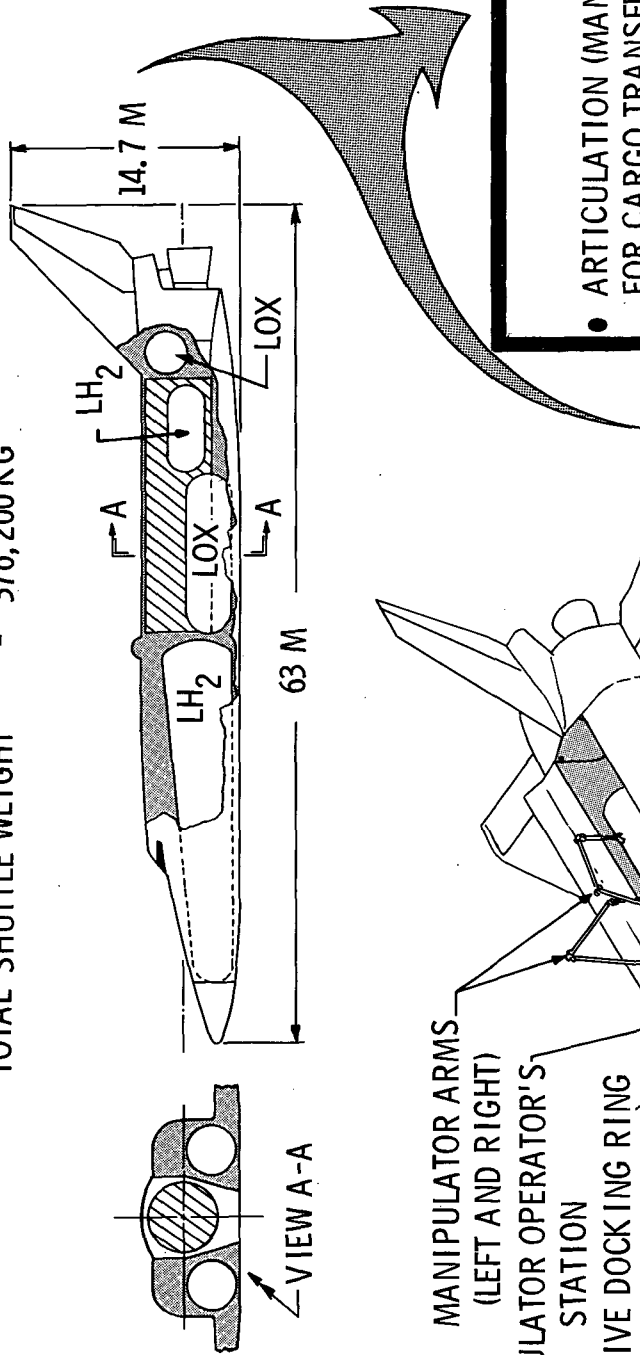
2 + 2 CREW COMPARTMENT
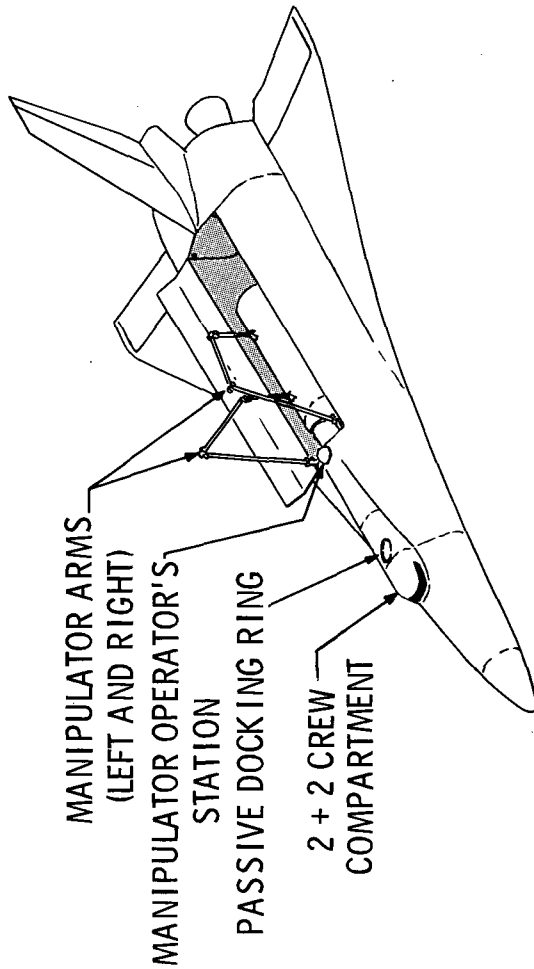
Figure A-2. NAR Shuttle Configuration

SHUTTLE DRY WEIGHT   - 127,400 KG
TOTAL PROPELLANT WEIGHT - 255,200 KG
TOTAL SHUTTLE WEIGHT   - 382,600 KG

18.2 M

LOX

53 M

A

A

LH₂

LH₂

LOX

• 90° ROTATION FOR CARGO TRANSFER

• CARGO BAY LOCATED ABOVE MOST TANKAGE

• CARGO BAY ～ 6.1 METERS FROM CREW COMPARTMENT

VIEW A-A

PAYLOAD ADAPTER

FLEX TUNNEL
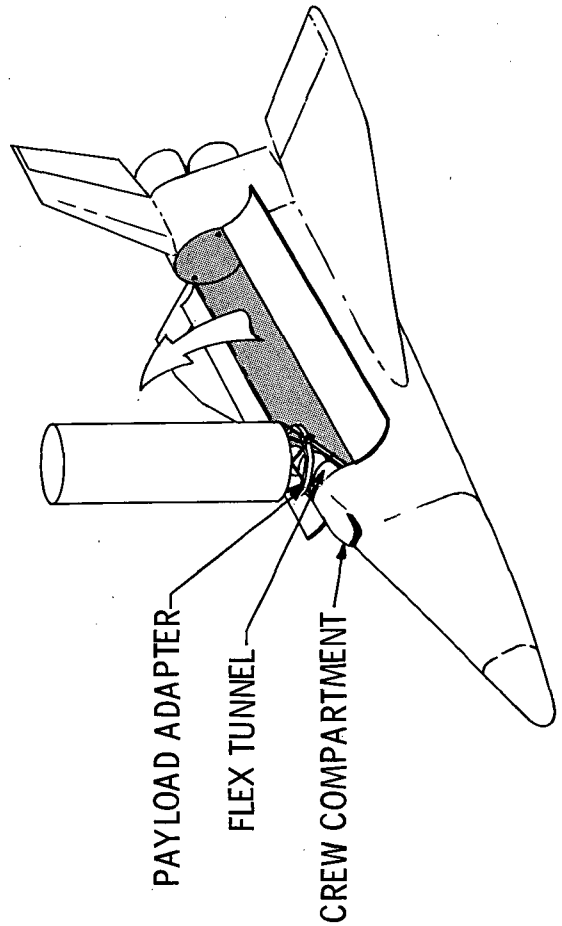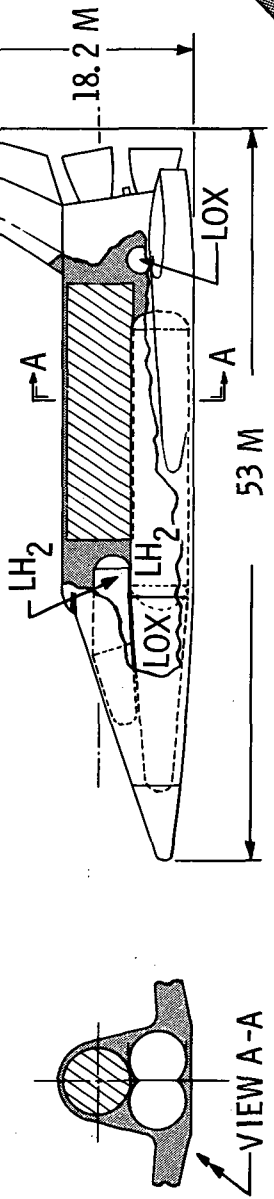
CREW COMPARTMENT

Figure A-3. MDAC Shuttle Configuration

In the MDAC configuration, two trunnion fittings located in the center of the payload bay react loads in all directions except laterally. The shear fitting located at the $\mathcal{C}$ of the bay bottom reacts side laods and yaw moments. The two forward fittings react roll and pitch moments and vertical loads. The latching system is actuated by redundant actuators located in the airlock. Backup to this actuation is by manual operation from inside the airlock.

Any nuclear payload that is to be transported by the Space Shuttle must be designed to fit within the defined payload envelope. An additional Shuttle constraint limits the envelope of the payload's center-of-gravity as shown in Figure A-4. The allowable payload centers of gravity vary with payload mass and are constrained by the aerodynamic centers of pressure. The Figure is applicable for these constraints for a maximum Shuttle payload mass of 11.3 t (25 klbs).

Superimposed on the chart are ranges of typical reactor module and isotope reentry vehicle (IRV) masses. Positioning of a reactor module in the cargo bay is more constraining than positioning an IRV due to the heavier masses involved with reactor modules.

The NAR Shuttle design imposes few, if any, constraints on the positioning of nuclear payloads in the cargo bay. However, positioning of the nuclear payloads is more critical in the MDAC Shuttle since the payload C.G.'s are largely constrained to the forward half of the cargo bay.

A.2.3 PAYLOAD HANDLING AND DOCKING

In the NAR Shuttle, the functions of payload deployment, payload retrieval and docking are accomplished through the use of a pair of manipulator arm assemblies. The manipulator arms are located on either side of the personnel-to-payload access tunnel and are stowed along the payload bay to provide a clear volume for the payload of 4.6 m in diameter by 18.3 m long. Each arm has six degrees of freedom, plus at least one degree of freedom for the tool located at the end of each arm. A cargo specialist station is located in the personnel access tunnel with visibility provisions for line-of-sight viewing of the manipulator operation. The direct vision is augmented by closed circuit TV with cameras mounted on the manipulator arms and in the cargo bay to provide visual check of the payload stowage latching and unlatching.

TYPICAL RANGE OF REACTOR MODULE WEIGHTS

TYPICAL RANGE OF IRV WEIGHTS

NAR

MDAC

PAYLOAD MASS x 10⁻³ ~ KG

$PAYLOAD\ MASS \times 10^{-3} \sim KG$

10

5

0

0   5   10   15   20

PAYLOAD LONGITUDINAL CG LOCATION ~ MEASURED IN METERS FROM FRONT OF CARGO BAY

- PAYLOAD CG'S IN MDAC SHUTTLE CONSTRAINED TO FORWARD HALF OF CARGO BAY
- NAR SHUTTLE ALLOWS GREATER FLEXIBILITY IN PAYLOAD POSITIONING

- ALLOWABLE PAYLOAD CG LOCATIONS VARY WITH PAYLOAD WEIGHT

- AS PAYLOAD WEIGHT INCREASES, PAYLOAD CG LOCATION BECOMES MORE RESTRICTING

Figure A-4. Shuttle Payload Center-of-Gravity Envelope

The total PHDS (Payload Handling and Docking System) comprises two manipulator arms, a docking adaptor, a manipulator operator station, an airlock docking port, a payload retention system, and a closed-circuit TV system to augment direct vision capability and provide visibility for close tolerance operation out of direct view from the cargo specialist.

The manipulator operation is designed basically as a manually operated system with final stowage or initial deployment operations designed as programmed events.

Docking is accomplished through the use of the payload handling and docking system. The manipulator arms of the PHDS are used first to deploy a docking adaptor (if required) and then to attach this adaptor to the other stabilized body. Just prior to physical acquisition, the stabilization systems of the target must be deactivated. The manipulator arms then draw the two bodies together to a hard docked configuration.

Removal of the docking hardware in whole or in part is not required in order to facilitate transfer through the docking port. The docking port is located on the top centerline of the Shuttle aft of the crew and passenger compartment and is externally accessible at all times.

In the MDAC Shuttle, payload deployment, retrieval, and docking are accomplished by a rotation scheme using a flexible tunnel concept as illustrated in Figure A-5. Payloads are deployed 90 degrees out of the cargo bay by redundant actuators located in the airlock. The payload is supported (for docking loads) in the deployed position by simple over center struts – similar to landing gear drag struts. The struts are locked over center in the deployed position by springs. The over center mechanism is unlocked by cables actuated in the airlock. Deployment actuation is backed up by manual actuation from the airlock.

The payload release and docking mechanism consists of a square docking frame supported on eight extenable shock attenuators. The attenuators/actuators are extended and retracted by redundant nitrogen sources. They are capable of retracting payloads (after docking, capture) to engage structural latches for subsequent pressurized crew/cargo transfer and payload stowage in the cargo bay for payload return to earth.

A-8
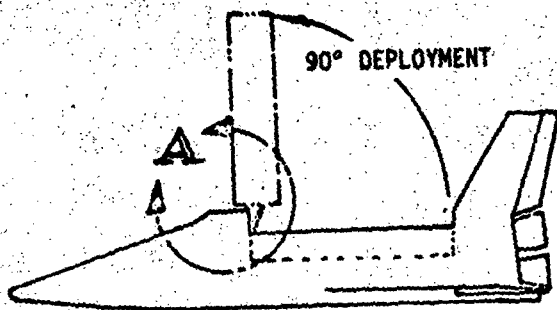
90° DEPLOYMENT

○ 90° DEPLOYMENT FOR PAYLOAD DOCKING
AND RETRIEVAL
○ ACTUATOR LOCATED INSIDE AIRLOCK
(PRESSURIZED)
○ DOCKING MECHANISM - SQUARE FRAME &
LATCH TYPE
○ DOCKING MECHANISM TAKES NO
FLIGHT LOADS

DEPLOYMENT MECHANISM
(Stowed Position)

REFERENCE A-2

AIRLOCK

PAYLOAD (REF.)
ADAPTER

ACTUATION

CREW ACCESS TUNNEL
FLEX TUNNEL
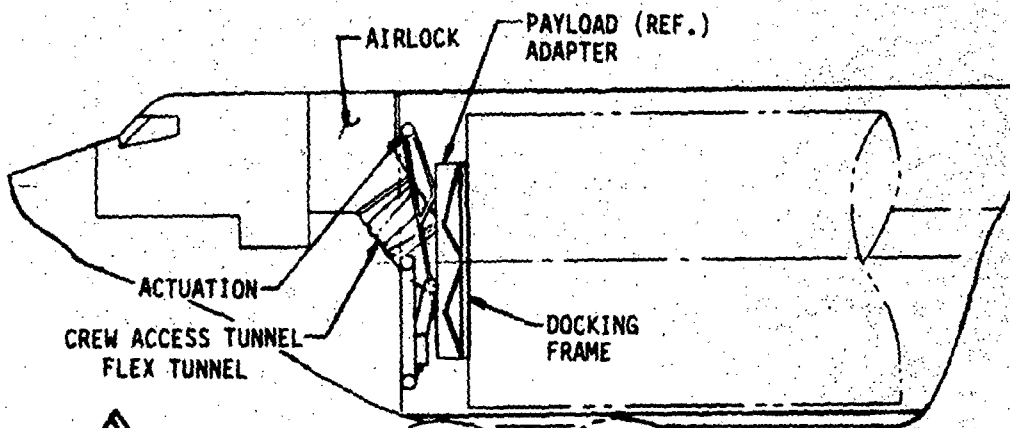
DOCKING
FRAME

DEPLOYMENT MECHANISM
(DEPLOYED & EXTENDED)

DOCKING FRAME
(SHOWN EXTENDED)

FLEX TUNNEL

OVER CENTER
LOCK/UN LOCK
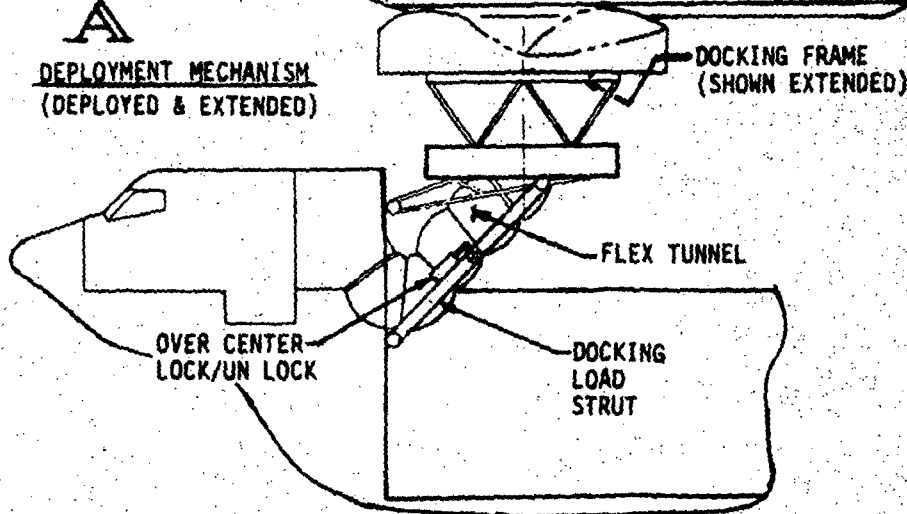
DOCKING
LOAD
STRUT

Figure A-5. Payload Deployment and Docking Mechanism (MDAC Shuttle)

The flexible tunnel allows for transfer of personnel from the Shuttle to the payload in either the stowed or deployed positions without interrupting the tunnel pressure seal.

A.2.4 BOOSTER CONFIGURATION

The NAR and MDAC Phase B Shuttle booster configurations are depicted in Figure A-1. Both boosters consist of 10 m (33 ft) diameter cylindrical tanks to contain the launch propellants and to serve as the structural backbone of the vehicles. The NAR booster is a delta-wing configuration, whereas the MDAC booster is characterized by an aft-mounted swept wing. The propellant loading in both designs is similar, each employing liquid oxygen and liquid hydrogen as the main launch propellants.

For the vertical launch, mated with the Space Shuttle, the booster thrust is provided by 12 main propulsion engines, with a nominal thrust of 2.44×10^6 Newtons (550 klbs) per engine, that are arranged in the aft end of the vehicle.

Control of the vehicle during powered ascent is provided by gimballing the main engines for thrust vector control and by using elevons for addition roll control. Subsonic cruise thrust for flyback after a space mission is provided by air-breathing engines. These engines are normally stowed within the wing and body structure envelope during vertical flight and reentry.

The booster incorporates a mating and separation system on its top surface to support the Shuttle during vertical flight and to perform the separation of the two vehicles.

A.3 REFERENCE MISSION

The overall mission profile of the Space Shuttle is shown in Figure A-6. Lift-off and the first 3-1/2 to 4 minutes of the Shuttle flight are accomplished by utilizing the liquid oxygen/hydrogen rocket engines of the booster. At an altitude of approximately 69 km (225 kft), the Shuttle and booster separate. The booster engines are shutdown and the booster glides back through the atmosphere. Following reentry, jet engines on the booster are deployed and started, and it cruises back to a runway much the same as a conventional jet transport would do.

While this return of the booster has been taking place, the Shuttle engines are ignited for injection into earth orbit. Once it achieves orbital conditions, it is then maneuvered to the correct orbit altitude and inclination for performing its primary mission. After mission completion, auxiliary propulsion rockets on the Shuttle are fired and the Shuttle is decelerated and enters the atmosphere. Following the reentry maneuver, jet engines on the Shuttle are used to power it to the landing site. The Shuttle is configured to permit it to be maneuvered aerodynamically over great distances during the reentry. This capability will permit the use of the original launch or alternate landing sites for the final landing approach
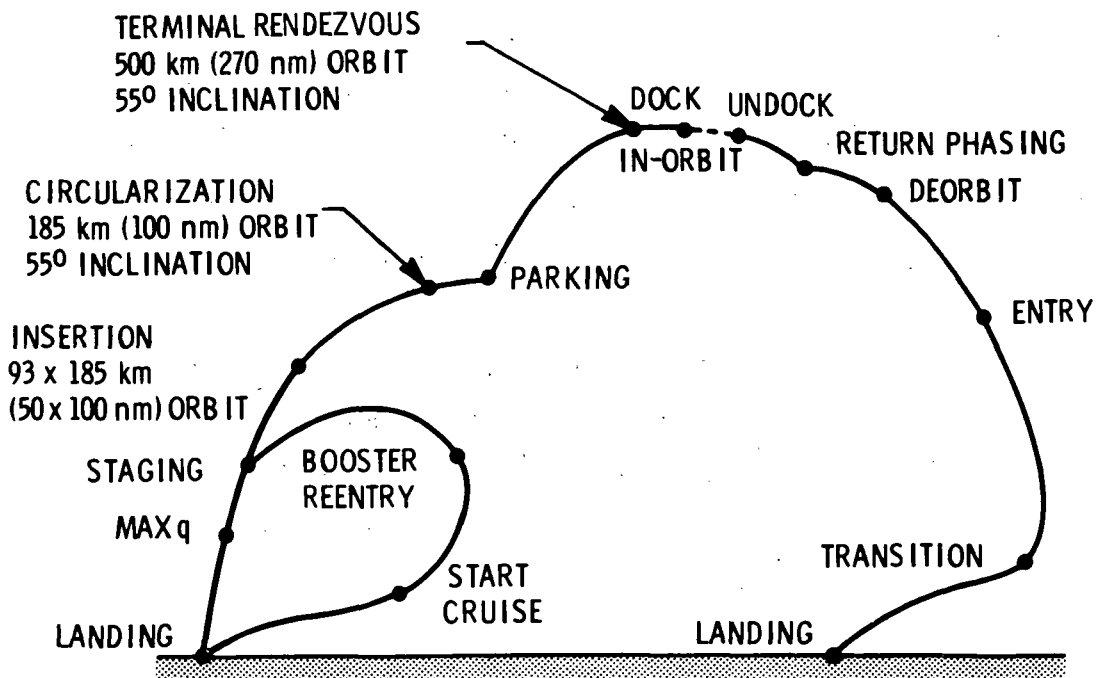
Figure A-6. Space Shuttle Flight Profile

A.3.1 ASCENT OPERATIONS

Ascent operations consist of four phases: launch initiation, mated ascent, staging and solo Shuttle ascent to initial earth orbit, nominally 93 x 185 km (50 x 100 nm). The launch initiation phase starts when the mated booster/Shuttle is ready for launch. When the booster engines are ignited, the thrust builds up to 50 percent in about three seconds. It is held at that level for 1/2 second to assure that all engines are operating within normal limits, and then advances to the level providing $T/W = 1$ when the hold-down mechanism is released

(approximately T + 8 seconds). Failure of the engines to perform normally at any point in this sequence results automatically in initiation of shutdown.

The Shuttle subsystems are all readied, prior to and during the launch sequence, for immediate use in attempting any preplanned abort procedures that may be necessary throughout the launch initiation and mated ascent phases. In particular, the Shuttle is always ready to fire its main propulsion system and separate from the booster when an inflight abort is commanded by the booster or Shuttle crew.

The mated ascent phase starts with lift-off and ends with the initiation of staging. The Shuttle functions during the mated ascent do not impact the performance of the mated ascent. The Shuttle is simply maintained in readiness for an abort and normal staging to follow. The functions of the booster and Shuttle crews are essentially the same: the monitoring of their respective subsystems' operation and the maintenance of readiness to respond to an abort situation.

Staging is initiated by a signal indicating impending propellant depletion (booster propellant depletion occurs approximately 210 seconds after lift-off) and is considered completed when the two vehicles have physically separated. The staging and separation are performed automatically, and thus, the booster and Shuttle crew functions are basically limited to monitoring.

Immediately, upon receipt of the depletion signal, the Shuttle engine start sequence and the booster engine throttling are initiated. The Shuttle engine thrust is built up to a 50 percent level and held there until booster engine cutoff is initiated, and the separation system activated. The Shuttle engine thrust is increased to 100 percent at approximately 3.5 seconds. At 4 seconds, the physical separation occurs.

After staging, the Shuttle performs operations to take it to a 93 by 185 km (50 by 100 nm) injection trajectory. Engine cutoff will be initiated by a signal from the guidance, navigation, and control (GN&C) subsystem when the proper orbit insertion velocity is reached.

In case of one Shuttle engine failure, the remaining engine will operate at an emergency power level and, in conjunction with the orbit maneuvering engines, will provide orbit injection or once-around abort capability. In addition, the attitude control propulsion system (ACPS) provides roll control while the remaining operating engine controls the Shuttle in pitch and yaw.

During Shuttle ascent, the Shuttle crew monitors the status of all subsystems for high, low, and nominal readings to provide a real-time system performance assessment.

A.3.2 RENDEZVOUS OPERATIONS

Rendezvous operations start immediately after insertion of the Shuttle into the initial 93 x 185 km orbit. The Shuttle is in command and control during the rendezvous. Two-way duplex voice communication is provided between the Shuttle and the Space Base. The Shuttle will provide signals for range and range rate measurement, and will be capable of transmitting and receiving data from the Space Base. The Space Base will be capable of transponding the tracking signal generated by the Shuttle. Both Shuttle and Space Base will have external lighting to aid in rendezvous station-keeping and docking.

To rendezvous with the Space Base, a series of phasing and orbit transfer maneuvers are required. Two types of phasing are possible: catch-up phasing, and catch-back phasing.

For the catch-up technique, a shorter orbital period (faster angular rotation) is achieved in an orbit lower than that of the Space Base, causing the Space Base to back up relative to the Space Shuttle.

The catch-back technique requires the expenditure of ΔV to establish a high orbit with its period greater than that of the Space Base. The catch-back technique would be used when the time saved (as compared with catch-up) is worth the cost of ΔV paid in reduction of payload. This is applicable in the rescue mission, for example.

The actual rendezvous maneuver starts with the terminal phase initiation (TPI) burn, which puts the Shuttle into a 482 km x 502 km orbit. The final rendezvous braking maneuver is shown in Figure A-7.

A.3.3 ON-ORBIT OPERATIONS

All maneuvers in the vicinity of the Space Base are performed with the attitude control propulsion system. Typical nuclear payload transfer operations are discussed in Sections 3.3.3 and 4.3.3 of this volume.

When the nuclear payload transfer operations are completed, the Shuttle undocks from the Space Base, separates to a safe distance, and begins its deorbit burn (or boost to high earth orbit). During on-orbit station-keeping, the Shuttle will fly a slow roll for thermal control.

r_3 = 460M (1500 FT)

TARGET ORBIT

r_4 = 150M (500 FT)

r_2 = 910M (3000 FT)

GATE 3

GATE 4

$V_3 \leqq 3$ M/SEC
(10 FT/SEC)

GATE 2

$V_4 \leqq 1.5$ M/SEC
(5 FT/SEC)

$V_2 \leqq 6$ M/SEC
(20 FT/SEC)

GATE 1

r_1 = 1830M (6000 FT)

$V_1 \leqq 9$ M/SEC
(30 FT/SEC)

INTERCEPTOR ORBIT
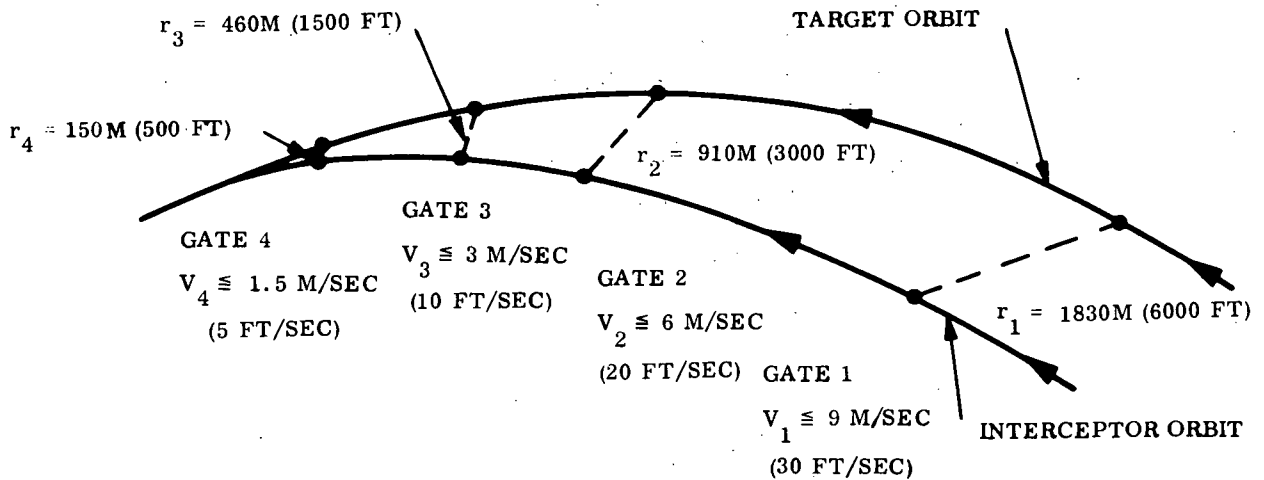
NOTE: BRAKING GATE ΔV'S APPLIED ALONG LINE-OF-SIGHT

Figure A-7. Final Rendezvous Braking Maneuver

A.3.4 DE-ORBIT AND REENTRY OPERATIONS

The high cross-range (HCR) delta-wing Shuttle reduces the requirement for deorbit phasing maneuvers. That is, the vehicle will have the aerodynamic capability to fly to the primary (or selected alternate) landing site without orbital period adjustments. At least two opportunities are available during any 24-hour period to land at the primary (launch) site.

The deorbit and reentry mission phase begins with computation of the deorbit burn initiation time from inputs of Shuttle position, orbital parameters, landing site location, and predicted reentry ranging characteristics. The vehicle is oriented to the proper burn attitude shortly before OMS (Orbit Maneuvering System) engine ignition. Engine burn duration (ΔV) is a function of the orbital altitude and the desired reentry conditions. After engine shutdown, the Shuttle is rotated to a reentry attitude corresponding to the lateral range requirement.

The reentry maneuvers are classified in two categories: reentry phase and terminal phase. During the reentry phase, the objective is to reach trajectory coordinates near the landing field at an altitude of approximately 15 km (50 kft). During this period, maneuvering commands are executed by the control system using aerodynamic surfaces and the attitude control propulsion system for attitude control. At completion of the reentry phase, the Shuttle performs terminal phase maneuvers to reach the final approach targeting coordinates at an approximate 3.7 km (12 kft) altitude.

A.3.5 SHUTTLE APPROACH AND LANDING OPERATIONS

The final approach is initiated at approximately 3.7 km (12 kft) above the runway altitude when the vehicle is 18.5 km (10 nm) from the runway. At the start of final approach, the landing gear will be lowered and the speed brakes set at approximately 30 percent to permit the Shuttle to achieve an approach glide path angle of approximately 12 degrees. The flight crew will verify automatic landing system status.

The Shuttle's landing velocity will be approximately 306 km/hr (165 knots) at runway contact with a sink rate of approximately 1.5 m/sec (5 ft/sec). The Shuttle's ground rollout distance is approximately 1.4 km (4500 ft) for a dry runway and approximately 2.8 km (9000 ft) for a

wet runway. Since this latter figure is not compatible with the requirement to land on a 3-km (10,000 ft) runway, a drag parachute is to be utilized. The drag chute will allow the Shuttle to land on wet runways with rollouts comparable to dry runways without a chute.

When flying with airbreathing engines, in the event that the landing cannot be safely accomplished on the first approach, a powered go-around will be initiated. The go-around will be performed under visual flight rules and conditions, keeping the runway in sight. The vehicle will perform a climbing turn and follow a race-track pattern to intercept the approach glide slope 2.8 km (1.5 nm) from the runway. The go-around distance is approximately 28 km (15 nm). From the point of glide slope intercept, the final approach and landing are identical to that previously described.

A.4   SHUTTLE INDUCED ENVIRONMENTS

While being transported by the Space Shuttle in the cargo bay, the nuclear payloads are subject to various Shuttle induced environments – both normal and accident. Figure A-8 summarizes these Shuttle induced environments within the cargo bay.

Except for the postulated temperature range to which a nuclear payload may be exposed while in the cargo bay, the normal Shuttle environment (Table A-1) is no more severe than that of other typical launch vehicles such as the Titan III-C, INT-21, or Saturn V. Shuttle payloads may be exposed to a broader range of temperatures due to the proximity of tankage containing cryogenic propellants.

In the event of a launch pad Shuttle explosion, payloads are subject to severe blast overpressures. This is due to the proximity of the cargo bay and tankage. Figure A-8 shows the expected reflected pressures (P_R) and side-on overpressures (P_S) as a function of assumed explosive yield and distance from the center of the explosion (R) for a booster explosion and/or Shuttle explosion on the launch pad. It is important to note that the blast overpressures are approximately the same for either a booster explosion or an explosion of the Space Shuttle. Also plotted are the blast overpressures resulting from a launch pad
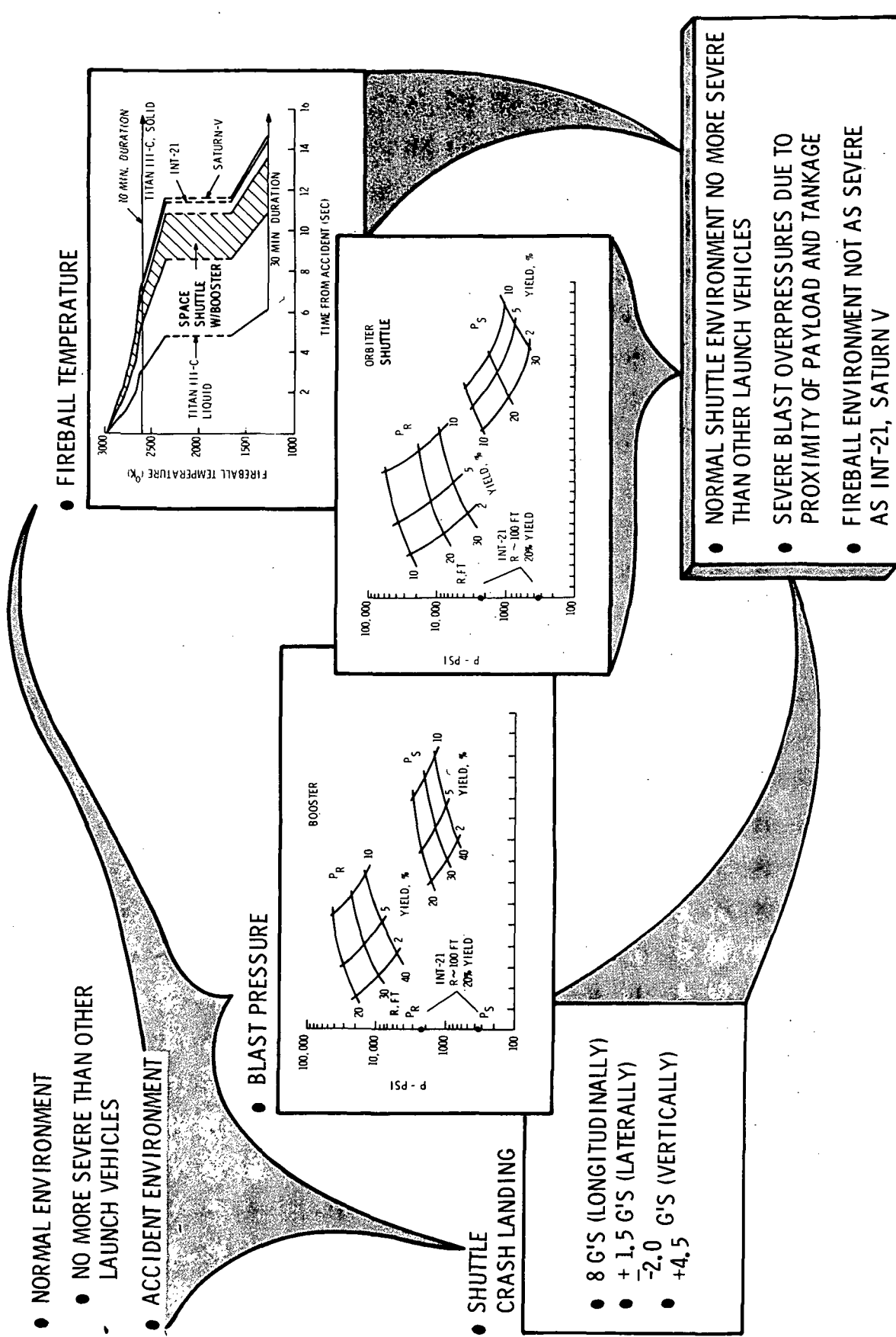
Figure A-8. Shuttle Induced Environments

A-17

Table A-1. Shuttle Induced Environments Within Cargo Bay (Normal Operation)
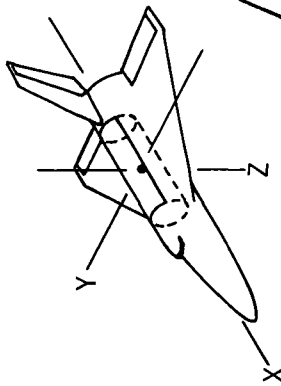
	TEMPERATURE	PRESSURE (NEWTONS/M²)	ACCELERATION	RANDOM VIBRATION*	SINUSOIDAL VIBRATION**	ACOUSTIC SHOCK
PRELAUNCH	256°K TO 311°K	1×10^5	0	0	0	0
LAUNCH/ASCENT	172°K TO 432°K	1×10^5 TO 1×10^{-6}	3.0 G'S (X-AXIS) ±1.0 G'S (Y-AXIS) ±1.0 G'S (Z-AXIS)	16 G (RMS)	8 G'S (X-AXIS) 2 G'S (Y-AXIS)	154 dB
ON-ORBIT	172°K TO 367°K	1×10^{-6}	0	0	0	-
REENTRY	172°K TO 432°K	1×10^{-6} TO 6.5×10^4	-.5 G'S (X-AXIS) ±1.0 G'S (Y-AXIS) -2.0 G'S (Z-AXIS)	-	-	-
LANDING	283°K TO 322°K	6.5×10^4 TO 1×10^5	-1.0 G'S (X-AXIS) ±.5 G'S (Y-AXIS) -2.5 G'S (Z-AXIS)	-	-	-

*APPLICABLE TO EQUIPMENT MOUNTED TO PRIMARY STRUCTURE THAT IS NOT APPRECIABLY MASS LOADED; DOES NOT APPLY TO LARGE MODULES SUCH AS PAYLOAD ITSELF; FOR SUCH LARGE COMPONENTS, DEFINITIONS OF MOUNTING STRUCTURE AND DYNAMIC RESPONSE ANALYSES ARE REQUIRED

**RESULTS FROM LOW FREQUENCY OVERALL BODY BENDING DYNAMICS OF SPACE SHUTTLE

NORMAL ENVIRONMENT WITHIN SHUTTLE CARGO BAY NOT SIGNIFICANTLY DIFFERENT FROM OTHER LAUNCH VEHICLES

explosion of the INT-21 launch vehicle (Reference A-3). As indicated, an explosion of the INT-21 results in much lower blast overpressures (one order of magnitude) due to greater payload-tankage separation distances.

Figure A-9 shows the estimated worst case blast environment during Shuttle reentry (see Vol. IV, Part 2, Appendix A).

Following a launch pad explosion, the nuclear payload may be engulfed in the resultant fireball. Figure A-8 compares the estimated Shuttle fireball environment with that of the Titan III-C, Solid; Titan III-C, Liquid; INT-21; and the Saturn V. As indicated, the expected thermal environment should be somewhat less severe than that of the INT-21 or Saturn V.

Also shown in Figure A-8 are the loads Shuttle payloads should be designed to withstand in the event of a Shuttle crash landing.

A.5 REFERENCES

A-1. "Space Shuttle Phase B Final Report", Vol. II, Technical Summary, MSC-03307 (SD71-114-2), North American Rockwell Corporation, March 26, 1971.

A-2. "Space Shuttle Program Phase B Systems Study Final Report", Part II, MDC E0308, McDonnell Douglas Corporation, March 15, 1971.

A-3. "Preliminary Accident Model Document", Volume III, Isotope, MSFC-DRL-160, Line Item 24, MDC G0744, McDonnell Douglas Astronautics Company-West, January, 1971.
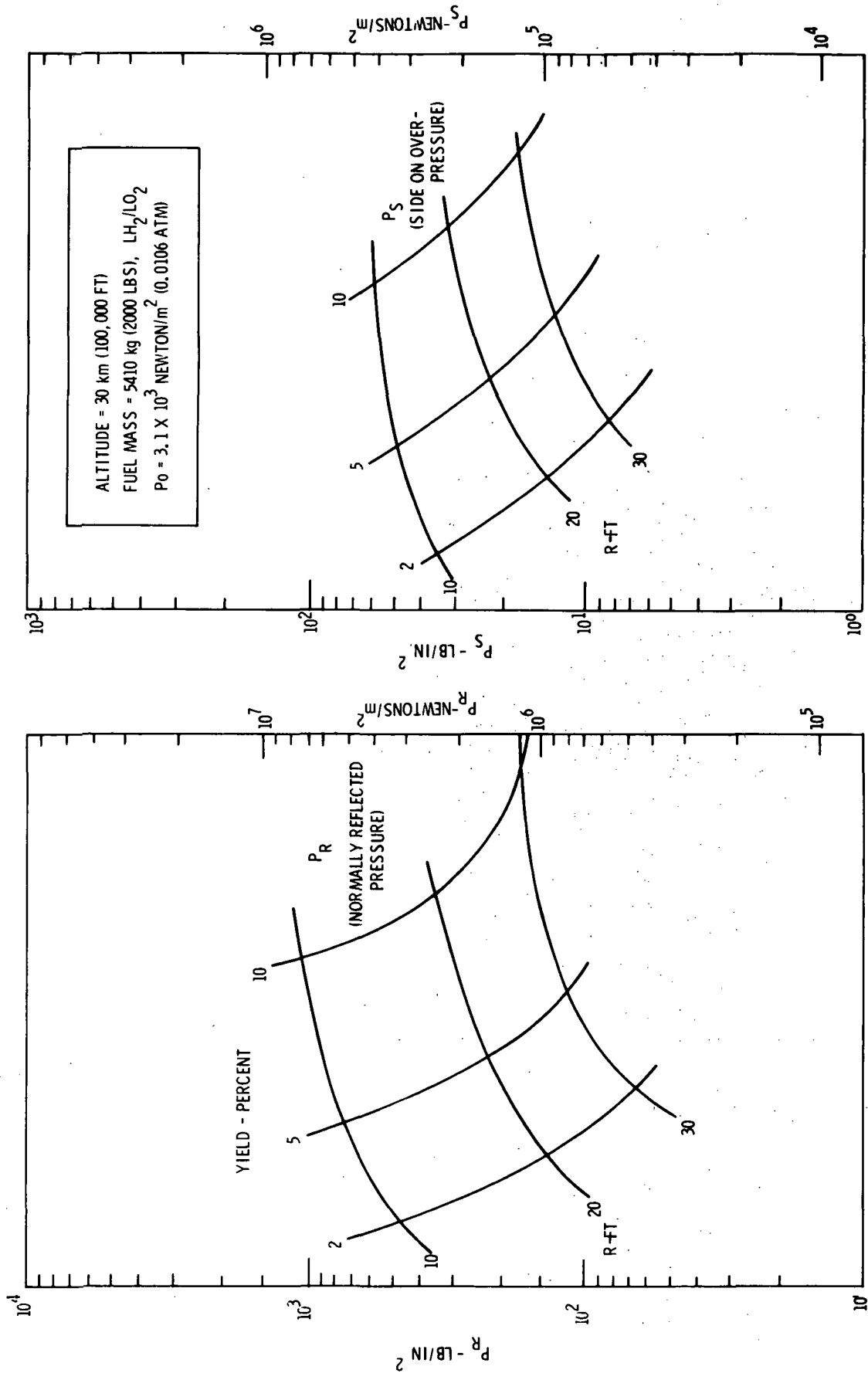
Figure A-9. Shuttle Blast Environment During Reentry (30 km)

APPENDIX B
REFERENCE REACTOR POWER MODULE

B.1 GENERAL

This appendix describes in relative detail the reference zirconium hybride (ZrH) reactor power system and various packaging configurations that enable the powerplant to be transported in the Space Shuttle cargo bay. The major reactor induced environments that can have a significant effect on Shuttle integration and transport are also discussed.

To be transported via the Space Shuttle, the reactor power module must be designed to fit within the 4.6 m (15 ft) diameter by 18.3 m (60 ft) length. The reference Space Base ZrH reactor power module is not "Shuttle compatible". Therefore, the reference ZrH reactor-Brayton power system for the Shuttle nuclear safety study is that identified in previous Space Station Phase B Studies (References B-1, 2 & 3). The major differences between the Space Base and Space Station reactor power system configurations are (1) larger heat rejection surface area in Space Base configuration (would require either a deployable radiator or multiple Shuttle launches), and (2) somewhat less radiation shielding in Space Station configuration.

The basic ZrH reference reactor has been designed to operate at a maximum of 600 kWt. However, for purposes of the Shuttle nuclear safety study, the reactor thermal output is assumed to be 125 kw meeting the Space Station delivered electrical power requirement of approximately 24 kWe.

Typical reactor power module configurations designed to be "Shuttle compatible" are shown in Figure B-1. The top configuration is a single module reactor power system assembly. The ZrH reference reactor, equipment gallery, and shadow shield assembly are located in the conical structure on the left. The module is 4.6 m (15 ft) in diameter and 18.3 m (60 ft) long with the cycle waste heat radiator covering all but a 0.61-m (2 ft) section of the aft cylindrical segment of the module. The maintainable equipment compartment and the Brayton cycle power conversion units are located at the base of the power module.

-CONFIGURATIONS-	— CHARACTERISTICS —
SINGLE REACTOR MODULE 4.6 M 18.3 M	• REQUIRES ONE SHUTTLE LAUNCH • APPROACHES MAXIMUM ALLOWABLE SHUTTLE PAYLOAD WEIGHT • LOW W/C$_D$A - SHORT ORBITAL DECAY TIME • TYPICAL SINGLE MODULE WEIGHT = 10,300 KG

DUAL REACTOR MODULE
 	
4.3 M
18.0 M
12.2 M
	• ENGINE ROOM FARTHER FROM REACTOR
	• REDUCES PAYLOAD WEIGHT
	• HIGH W/C$_D$A - LONG ORBITAL DECAY TIME
	• TYPICAL MODULE WEIGHTS
	  - REACTOR MODULE - 6800 KG
	  - BRAYTON MODULE - 3100 KG

• SEPARABLE HEAT EXCHANGER 	• REACTOR/SHIELD ASSEMBLY CAN BE SEPARATED FROM POWER SYSTEM • NO NaK LOOP DISCONNECTS • MODULAR APPROACH TO TRANSPORTING AND HANDLING OF REACTOR POWER SYSTEMS • FACILITATES HANDLING AND SHUTTLE TRANSPORT OPERATIONS

Figure B-1. Typical Reactor Power System Configurations

A second configuration is a dual module reactor power system assembly with separately Shuttle launched reactor and Brayton modules. The reactor module is non-pressurizable, 4.3 m (14 ft) in diameter, and approximately 12.2 m (40 ft) in length. This module houses the nuclear reactor assembly and its shielding. Associated equipment located within this module includes the Brayton heat exchangers, pumps, gas and water piping, intermediate NaK loop piping, augmented shield tank, and a ballast tank* provided for artificial-g operation.

The Brayton module is a cylinder approximately 18.0 m (59 ft) in length and 4.3 m (14 ft) in diameter. It provides part of the separation distance required for radiation safety between the Space Station and the reactor module. This module contains a generator room approximately 3 m (10 ft) in length, designed for limited occupancy in a shirtsleeve environment. This room contains an EVA hatch, Brayton power conversion unit, heat rejection loop components and controls, and provides access to the RCS engine quads. It also provides temporary storage area for personnel provisions when occupied.

A third possible configuration could employ either of the two configurations just discussed in conjunction with a "separable heat exchanger". The separable heat exchanger permits separation of the reactor, with its primary liquid metal coolant loop, from the power conversion module and its secondary liquid metal coolant loop, without breaking any liquid metal coolant lines. The separable heat exchanger concept has several inherent advantages over the integral heat exchanger. It allows for the modular approach to transporting and handling of reactor power systems. If payload launch weight becomes a very limiting Shuttle imposed constraint, the separable heat exchanger concept will allow the reactor power system to be launched separately – one launch for the basic module containing the power conversion equipment, radiators, intermediate NaK loop, and associated support structure, and a second Shuttle launch for the reactor/shield/separable HX assembly. Launching in this fashion will allow the nuclear payload to more easily meet the Shuttle payload C.G. constraint. It should facilitate ground handling procedures, and if launched

*This tank uses water for ballast. It is filled after mating to the Space Station (from water generated by fuel cells) and dumped prior to disposal.

in this fashion, other Space Base-bound cargo may be placed in the Shuttle cargo bay since the reactor/shield/separable HX assembly will occupy only a portion of the allowable payload volume and the low reactor radiation level should not be hazardous to most cargo.

In addition, if the selected means of reactor disposal is boost to a high earth orbit, the higher ballistic coefficient (W/C_DA) of the reactor/shield configuration as compared to that of the entire reactor power module means considerably longer orbital lifetimes for a given disposal altitude. This means that the fission products generated during operation aboard the Space Base will be allowed to decay to even lower insignificant levels.

Although the reactor power modules can be configured differently, the basic subsystems are essentially identical. A discussion of the major subsystems follows. Significant differences between the contrasting configurations will be pointed out during the discussion.

B.2 REACTOR AND NAK LOOPS

Figure B-2 shows a cutaway of the reference ZrH reactor that has been under development by Atomics International under the AEC's Zirconium Hydride Reactor Program. The design is similar to that of the SNAP-8 reactor, but has a slightly larger core and an internally cooled reflector siutable for operation within an enclosed shield. Ten cylindrical BeO control drums with neutron-absorbing material on one side are installed in dry wells, the outer surface of which are cooled by the NaK (a eutectic mixture of sodium and potassium) which enters the bottom annular plenum through four inlet nozzles. The NaK flows upward around the dry wells and fixed reflector elements into the upper plenum, downward through the core to the lower plenum, and out through four exit nozzles.

The reactor core consists of a triangular pitch array of 295 fuel elements and has a 29-cm (11.4-in) diameter. The control drums have neutron-reflective material on one side and absorber material on the other. The reactor is controlled by drum rotation, which varies the amount of neutron reflection into the core. Since control drum cooling is provided internally and the neutron-absorber material minimizes the sensitivity of the reactor to backscattering from outside the control drum region, the 4π shield can be located directly adjacent to the reactor.

B-4

The fuel element (Figure B-3) consists of an alloy of 10.5 percent (by weight) fully enriched uranium in zirconium, which is massively hydrided to provide neutron moderation. The hydrogen content of the fuel is 6.3×10^{22} atoms per cm^3 which is about the same as in cold water. The fuel rod is contained within a 0.038-cm (0.015-in) thick nickel alloy cladding tube, which protects it from the NaK coolant and contains the fission products and hydrogen moderator. Because of the significant permeation rate of hydrogen through the bare cladding, a thin glass barrier is fused to the inside of the cladding tube. Small clearances are provided between the fuel rod and cladding to allow for radiation-induced growth of the fuel.

The control drum is 11.4 cm (4.5 in) in diameter by 45.7 cm (18 in) and consists of BeO reflector material fastened to a neutron-absorbing metal (Ta-10W) which also serves as the main structural member. The drum is supported by self-aligning ball-and-socket-type bearings. The control-drum shaft and the bearing socket are coated with flame-sprayed alumina to provide a low-friction surface when in contact with the solid graphite ball. Drum rotation is produced by a stepper motor operating through an integral 6:1 gear set. When the drum is in the fully shutdown position, the gear teeth are disengaged by an electrical cam lockout device to prevent drum rotation resulting from launch acceleration.

All parts of the containment vessel and associated structure are of 316 stainless steel. At Brayton cycle design conditions, the NaK enters the lower vessel plenum at 867°K (1100°F) through four 3.8-cm (1.5-in) inlet lines. It flows upward in the area between the control drum dry wells, turns 180 degrees, flows downward through the core, and exists at 922°K (1200°F) from the outlet plenum. A minor amount of heat is transferred between inlet and outlet coolant through the flow-dividing cylinder. Thus, the NaK mixed-mean outlet temperature from the core is a few degrees hotter than the temperature of the NaK from the pressure vessel.

The reactivity control system for this reactor has been tailored to provide 125 kWt at a 922°K coolant outlet temperature for at least ten years. Samarium-149 and europium-151 burnable poisons will be employed to restrict the available excess reactivity to the band limits described in Figure B-4. Such limits assure the necessary excess required for this
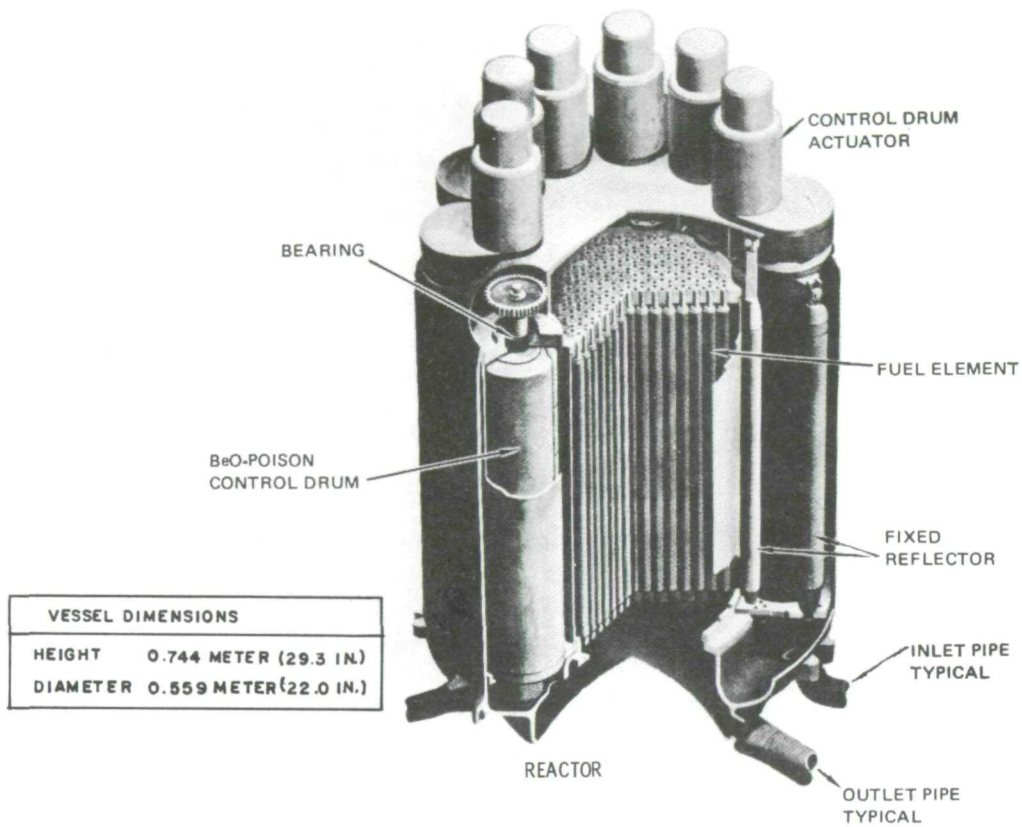
Figure B-2. Zirconium Hydride Reactor Reference Design
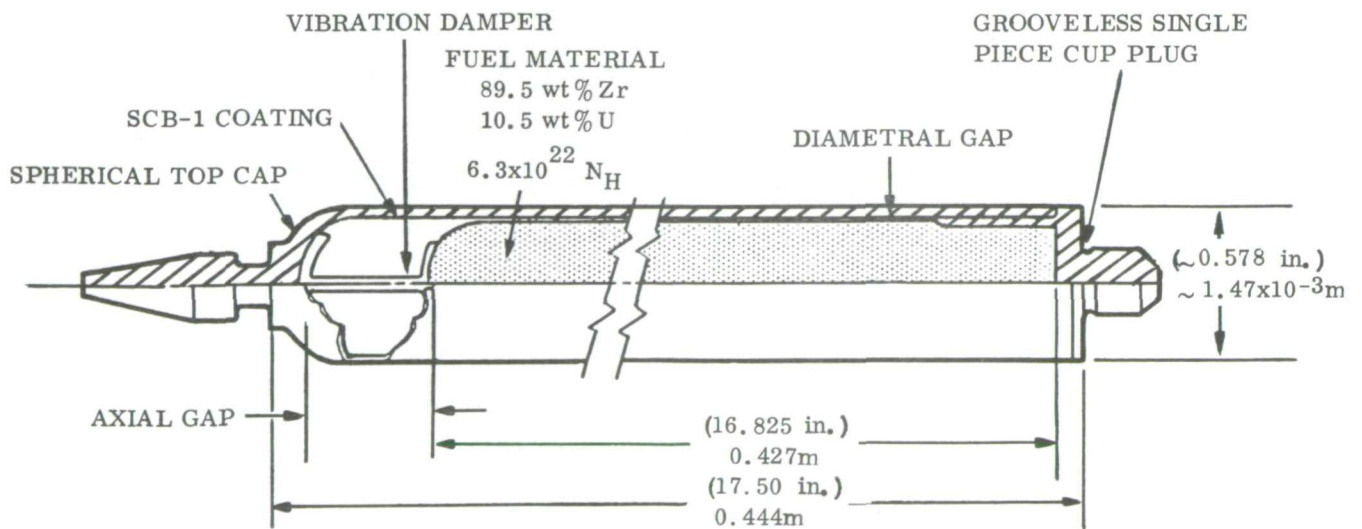
Figure B-3. Reference Fuel Element

extended period of operation and retain the needed control reactivity to assure startup and safe shutdown with one disabled control drum at any time.

The initial excess reactivity drop shown in Figure B-4 represents the normal xenon, hydrogen redistribution, and temperature and power decrements occurring at startup. The increasing excess reactivity trend that follows occurs because the worth of burnable poisons in the core is decreasing at a greater rate than the worth decrement due to uranium depletion, hydrogen losses, and the accumulation of fission product poisons. As the burnable poison loading becomes depleted, the worth of the above core depletion actions predominate and force the excess reactivity to decline and approach zero.

THERMAL POWER = 125 KW
REACTOR OUTLET TEMP = 922°K (1200°F)
COOLANT ΔT = 311°K (100°F)
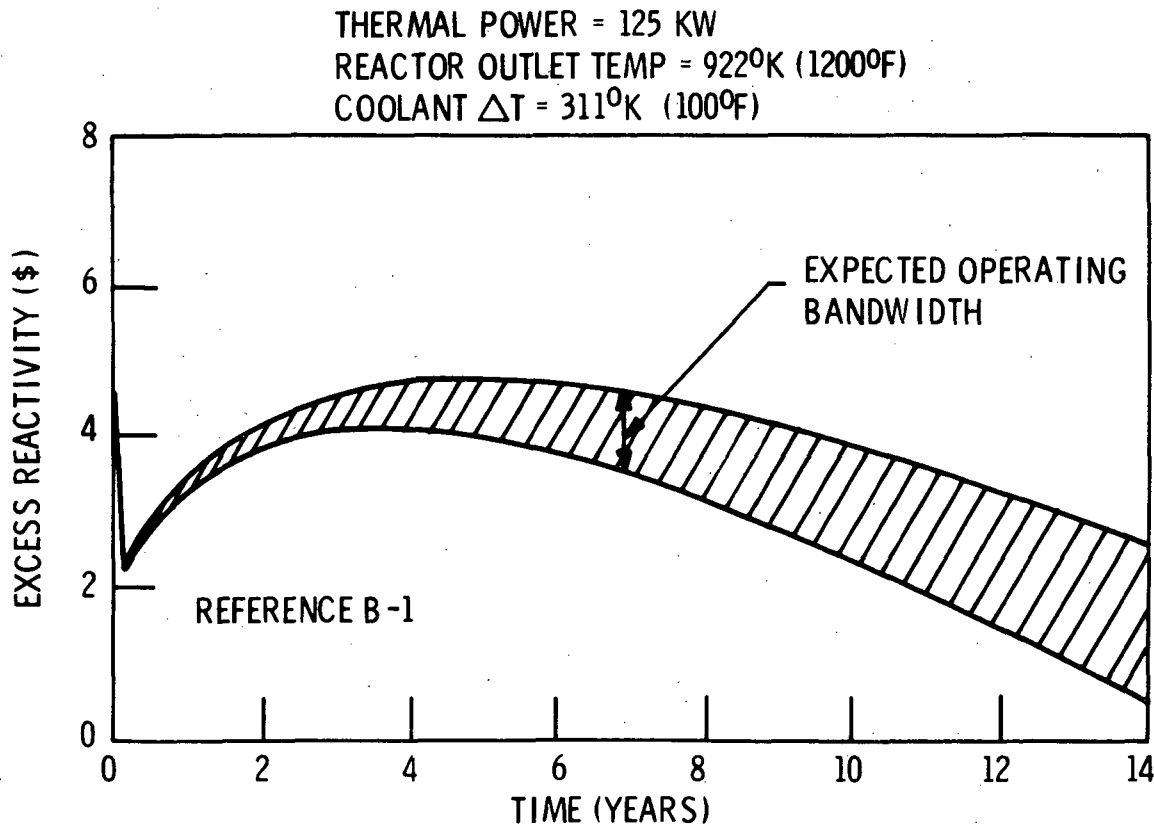
Figure B-4. ZrH Reactor Reactivity - Lifetime Characteristics

Additional reactor design and performance characteristics are presented in Table B-1.

Table B-1. Reference ZrH Reactor Design and Performance Data
(Reference B-1)

Item	Requirement
Reactor thermal output	125 kWt
Reactor coolant outlet temperature	$922^{\circ}K$
Reactor coolant temperature rise	$311^{\circ}K$
Operational lifetime	10 years
Number of fuel elements	295
Fuel element length	42.5 cm
Fuel element outside diameter	1.470 to 1.525 cm
Clearance between fuel elements	Variable
Core diameter	29 cm
Cladding material	Incoloy 800
Hydrogen barrier material	SCB-1
Fuel, hydrogen content	$6.3 \times 10^{22} \dfrac{H \text{ atoms}}{cm^3}$
Fuel, uranium content	10.67%
Fuel-to-clad gap width	Variable
Number of active control drums	10
Control drum materials	BeO/Ta-10W
Reactor vessel outside diameter	55.9 cm
Reactor vessel height	74.5 cm

Thermal energy is transferred from the reactor to the Brayton-cycle power conversion loops by circulating NaK within a primary and intermediate loop. Heat is transferred from the primary to the intermediate loop by means of a NaK-to-NaK heat exchanger. There is approximately 170 kg (375 pounds) of NaK in the reactor power system.

B.3 BRAYTON POWER CONVERSION UNIT (PCU)

The turbine, alternator, and compressor are mounted on a common shaft and comprise the Brayton Rotation Unit (BRU). This shaft is supported by gas bearings during rotation.

The cycle working fluid, a helium-xenon gas mixture, accepts heat from the NaK-to-gas heat exchanger of the intermediate loop. Loop flow rate is modulated by a gas management system.

The turbine converts cycle heat to shaft power, which is used to turn the alternator and compressor. The cycle working fluid flows from the turbine through a recuperator transferring heat to gas flowing from the compressor. Cycle waste heat is rejected to space by an organic liquid radiator. The HeXe mixture flows from the compressor through the recuperator to the NaK-to-gas heat exchanger, completing the cycle.

Three redundant PCU's are required with either one working while the remaining two are on standby, or two working with one standby unit. In either case, the Space Station requirement of net conditioned output of approximately 25 kWe must be met.

In the dual module reactor power system assembly, the Brayton power conversion module is packaged in the Brayton module with the Brayton NaK-to-gas heat exchanger located in the reactor module. The "broken" gas ducts are connected during the docking sequence.

B.4 HEAT REJECTION

Waste heat is rejected from the Brayton power conversion loop to the heat rejection loop (HRL) via a gas-to-organic coolant (Dow Corning 200) heat exchanger. The radiator panels are attached around the circumference on the cylindrical structure. The radiator is located

around the circumference of the Brayton module in the dual assembly. In both candidate reactor power system configurations, the radiating area is 186 m^2 (2000 ft^2).

B.5 RADIATION SHIELD

A major difference in the two candidate reactor power module configurations is in the nuclear radiation shielding designs. The basic solid shield design is the same for both the single and dual module configurations. This represents the minimum amount of nuclear radiation shielding required to limit the direct radiation dose rate to 150 mrem/day in all areas occupied by the crew.

However, in the dual module reactor power system configuration, an augmented water shield is added to reduce this direct radiation dose to inhabitable areas to 20 mrem/day. This was done for two reasons: (1) to achieve greater flexibility in operations and mission planning by increasing the total crew stay-time to 180 days* or greater throughout the entire flight box, and (2) to increase the engine room occupancy time to six hours (increasing the time available for Brayton equipment maintenance).

Figure B-5 shows a cutaway view of the basic reactor/solid shield assembly and identifies the shield materials used in both reactor power module configurations. The solid shield consists of an inner Ta-10W gamma ray shield which completely surrounds the reactor. Surrounding the Ta-10W is a LiH neutron shield. This shielding reduces the side dose for rendezvous to 60 rem/hr at 30 m (100 ft), and reduces the neutron dose sufficiently to prevent activation of the NaK in the intermediate loops. In the Space Station end of the reactor, there is a depleted uranium (8 percent molybdenum by weight) shield followed by a LiH neutron shield. These two shields form a gallery for mounting primary loop components. In addition, they further reduce the radiation level from the reactor and from radioactive NaK in the primary loop to an acceptable level.

---

*A dose rate of 150 mrem/day from the nuclear reactor permits a total crew stay time of only 180 days for orbits within the geomagnetic sphere and at high inclinations outside the South Atlantic anomaly.

- REFERENCE ZrH REACTOR DESIGN
- THERMAL POWER = 125 KW
- REACTOR OUTLET TEMPERATURE = 922^0K
- COOLANT T = 311^0K
- SOLID SHIELD
  - WEIGHT = 4960 KG
  - DOSE RATE = 150 MREM/DAY @ 62 METERS
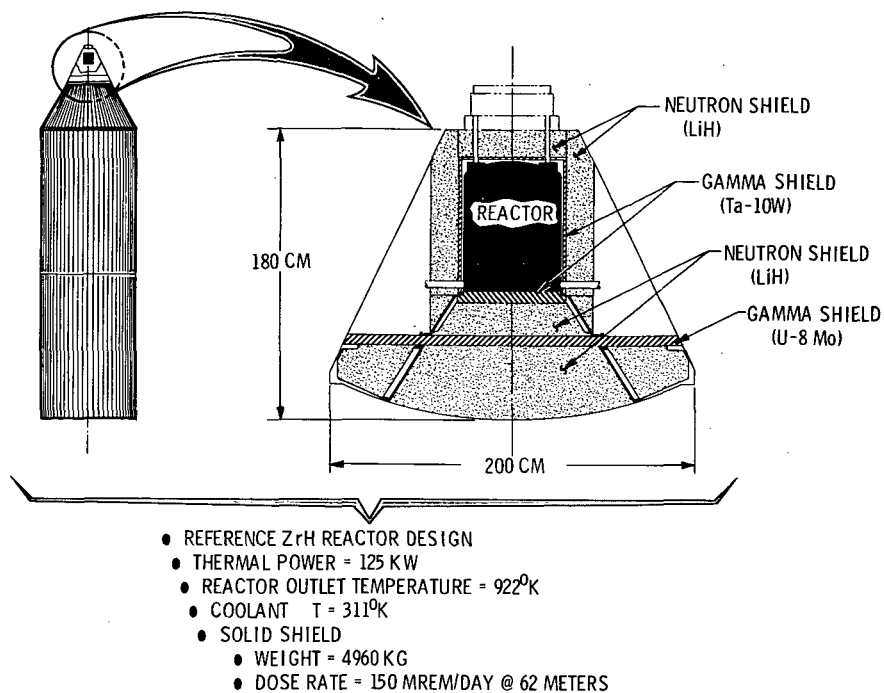
Figure B-5. Reactor/Shield Assembly

B.6 WEIGHT SUMMARY

Detailed weight breakdowns of the candidate reactor power module configurations are pre-
sented in Tables B-2 and B-3. Table B-2 is a summary of component and subsystem weights
for the single reactor module configuration, while Table B-3 presents the weight summary
for the reactor and Brayton modules of the dual module configuration.

B.7 REACTOR INDUCED TRANSPORTATION HANDLING ENVIRONMENTS

Two reactor induced environments are of concern when transporting a reactor power
module via the Space Shuttle - thermal and nuclear radiation.

B.7.1 THERMAL ENVIRONMENT

The afterheat generation in a reactor which has operated at 125 kWt for five years is
given in Figure B-6. This represents the fission product decay heat after reactor shutdown.

Table B-2. Component Mass Summary – Single Reactor Module Configuration
(Reference B-3)

Assembly	Mass (kg)		Distance from Aft End (m)
Reactor		748	17.4
Primary Loop		217	16.8
Ducting	30		
Expansion Compensators (3)	35		
Helical Induction Pumps (2)	147		
Insulation	5		
Intermediate Loops		616	
Ducting	254		9.4
Expansion Compensators (4)	47		15.8
Helical Induction Pumps (4)	295		6.1
Insulation	20		9.4
IHX		59	16.8
BHX (3)		204	2.4
Structure		227	7.0
Docking Adapter		91	0
Radiation Shield		4051	16.8
Radiator		1239	7.0
Fins	277		
Tubes and Fluid	124		
Armor	357		
Structure	454		
Manifolds	29		
HRL Pumps and Valves		44	0.3
Power Conversion Units (3)		2531	2.4
BRU's	612		
Recuperators	313		
Coolers	463		
Ducting	259		
Gas Management Systems	170		
Plumbing and Wiring	102		
Structure and Insulation	612		
Controls and Auxiliaries		431	0.6
Motor Start Equipment (2 units)	68		
Electrical Control Package	75		
Cold Plate	39		
Parasitic Load Resistors	102		
Reactor Control and Wiring	113		
Pump and Control Power Conditioning and Transmission	34		
Total NRM		10,327	10.5
EOL Disposal System		1,474	0.6
Total NRM with EOL Disposal System		11,801	9.3

Table B-3. Component Mass Summary - Dual Module Reactor
Power System (Reference B-1).

Assembly	Mass (kg)
Installed in Reactor Module	
Reactor	748
Reactor support structure & containment	82
Primary Loop	
Ducting	24
Expansion compensators (3)	35
HIP (2)	147
Insulation	3
Intermediate loop	
Ducting	245
Expansion compensators (4)	47
HIP (4)	295
Insulation	24
IHX	29
BHX (2)	48
Control and wiring	113
Radiation shield (solid)*	4964
Total	6805
Installed in Brayton Module	
PCU's (3)	1878
PCU controls & auxiliaries (3 sets)	418
Parasitic load resistors (2)	45
Radiator fin, tube, armor & fluid	683
Radiator manifolds	29
HRL auxiliaries	44
Total	3096
Total electrical generating assembly	9901
*Shields dose plane (62 m) to 150 mrem/day	

NOTE: REACTOR HISTORY - 5 YEARS OPERATION AT 125 kWt

TIME AFTER SHUTDOWN, HOURS

TOTAL FISSION PRODUCT POWER, kWt
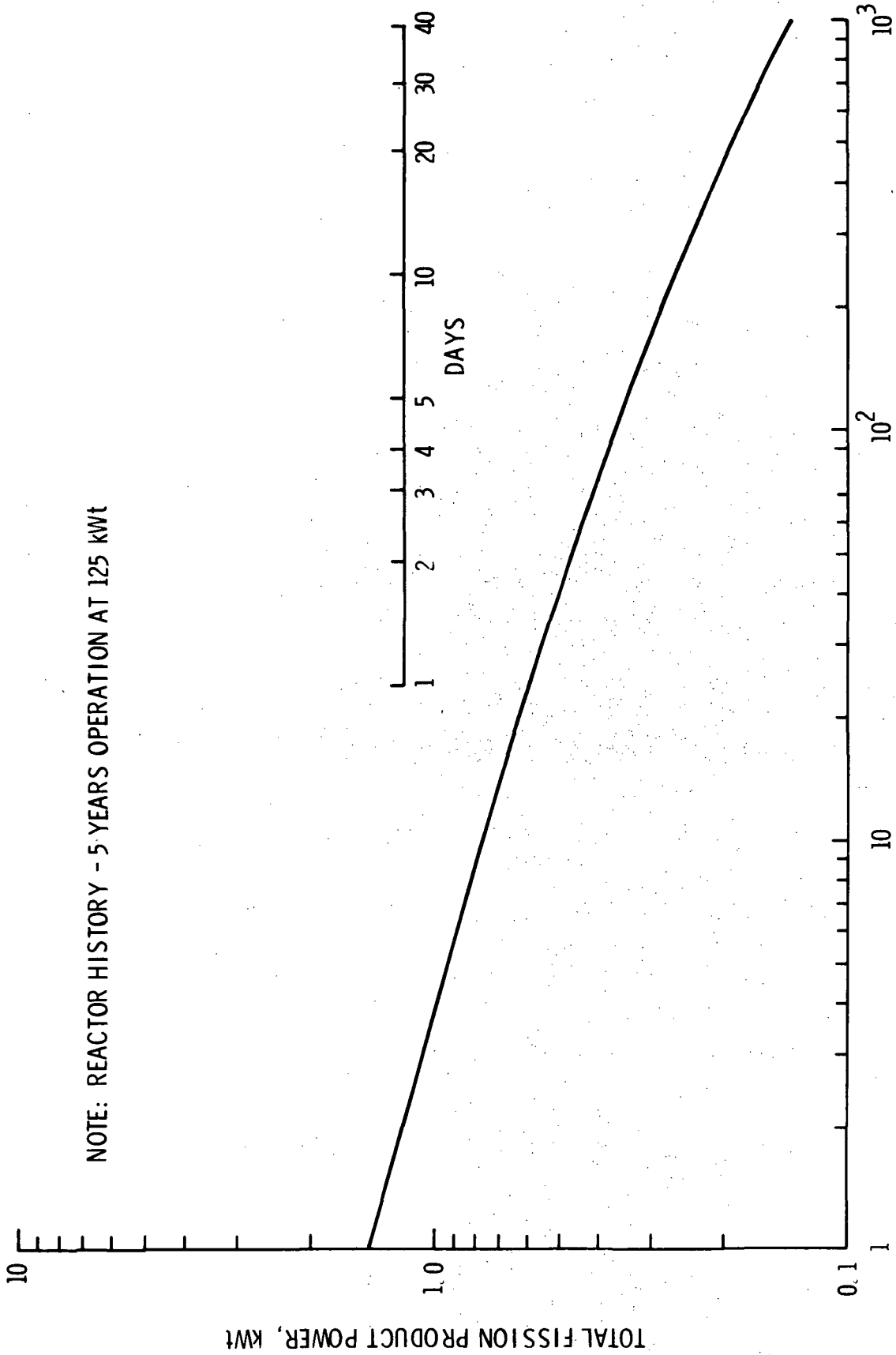
DAYS

Figure B-6. Afterheat Generation in Shutdown Reactor

B.7.2 NUCLEAR RADIATION ENVIRONMENT

Two Space Shuttle configurations are identified in Appendix A, each having an allowable cargo bay payload envelope that is 4.6 m (15 ft) in diameter and 18.3 m (60 ft) long. Figure B-7 shows the crew locations and the allowable payload center of gravity locations. As shown in the figure, the NAR Shuttle version has two crew locations: the pilot's cockpit which is approximately 16.6 m (54.5 ft) forward of the cargo envelope and the manipulator operator's station which is approximately 2.3 m (7.5 ft) forward of the cargo envelope. The C.G. of the 6.8 t (15 klb) dual reactor module must be at least 0.61 m (2 ft) aft of the cargo bay forward bulkhead reference while the C.G. of the 11.8 t (26 klb) single reactor module must be between 3.4 m (11 ft) and 14.3 m (47 ft) aft of the cargo bay forward bulkhead reference.

The MDAC Shuttle configuration has only one crew location which is essentially the pilot's cockpit located approximately 6.1 m (20 ft) forward of the cargo envelope. The C.G. of the dual reactor module must be located in the forward 10.1 m (33 ft) of the cargo envelope while the C.G. of the single reactor module must be located in the front half of the allowable cargo envelope.

The preferred orientation of the reactor modules in the Shuttle, from the viewpoint of minimum dose to the Shuttle crew, is with the reactor end of the module placed aft in the cargo bay. With this orientation, the thickest section of the reactor shield lies between the reactor and the crew. Figure B-8 shows the preferred locations for the reactor modules in the NAR Shuttle, and Figure B-9 shows the preferred locations in the MDAC Shuttle. In the NAR concept, the reactor modules can be placed in the very rear of the cargo envelope, thus providing maximum distance between the crew and reactor (i.e., 19.7 m (64.5 ft) to the manipulator operator and 34 m (111.5 ft) to the crew cockpit). The same is true for the reactor modules in the MDAC Shuttle. Although C.G. considerations preclude placing the dual reactor module in the aft end of the MDAC Shuttle (the C.G. of the dual reactor module is approximately 10.4 m (34 ft) from the front end of the cargo envelope even though Figure B-7 shows that it must be in the front 10.1 m (33 ft) for proper Shuttle balance), the discrepancy of approximately 0.3 m (1 ft) is ignored since there appears to be no reason why the dual reactor module length cannot be decreased by 0.3 m to meet the C.G. constraint.
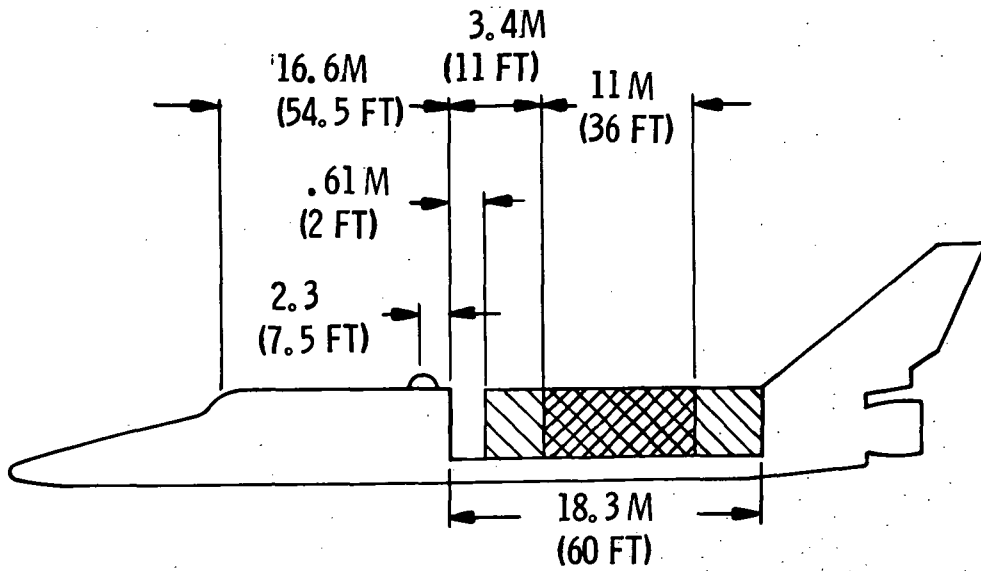
NAR SHUTTLE
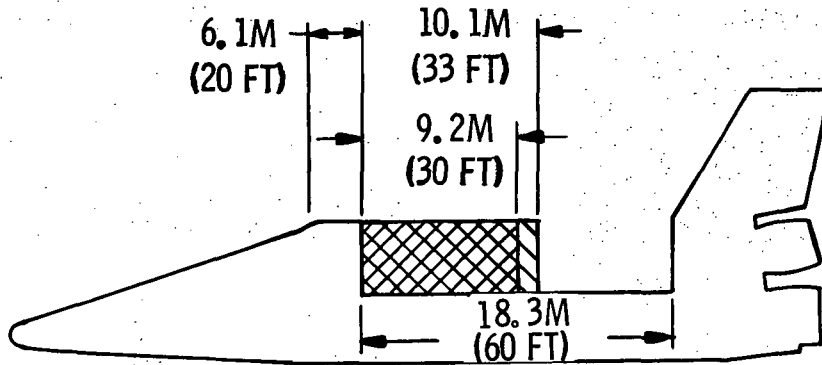
MDAC SHUTTLE

ALLOWABLE CG RANGE

6.8t (15 KLB) DUAL POWER MODULE (POWER MODULE CG ESTIMATED TO BE ~1.8M (6 FT) FROM REACTOR END OF MODULE

11.8t (26 KLB) SINGLE POWER MODULE (POWER MODULE CG ESTIMATED TO BE ~9.4M (31 FT) FROM REACTOR END OF MODULE

Figure B-7. Crew Locations and Allowable Cargo C.G. Locations for Space Shuttle
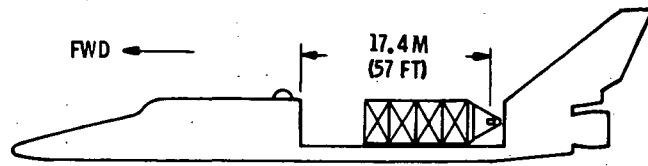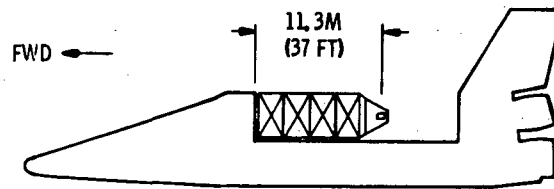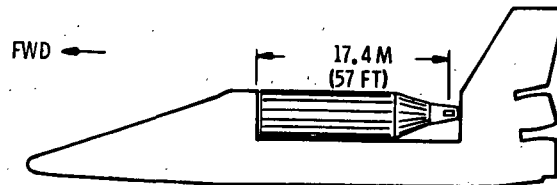
DUAL REACTOR MODULE
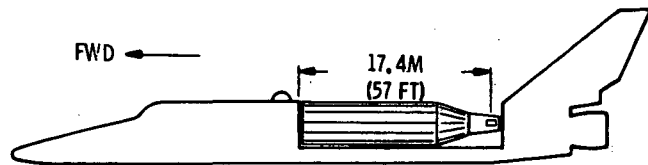
SINGLE REACTOR MODULE

Figure B-8. Reactor Location in NAR Shuttle Cargo
Bay for Preferred Rearward Orientation

DUAL REACTOR MODULE

SINGLE REACTOR MODULE

Figure B-9. Reactor Location in MDAC Shuttle Cargo
Bay for Preferred Rearward Orientation

Figure B-10 presents plots of the dose rates to the Shuttle crew from a spent, shutdown reactor for the various combinations of reactor module and Shuttle configurations shown in Figures B-8 and B-9. The dose rates are given as a function of time after shutdown from a power level of 125 kWt and 5 years of continuous operation. The two top curves, labeled A and B, correspond to the manipulator operator's station and the pilot's cockpit, respectively, in the NAR Shuttle, while curves C and D correspond to the dual reactor module and the single reactor module arrangements, respectively, in the MDAC Shuttle. In the NAR Shuttle, over 99 percent of the crew dose rate is due to radiation which leaves the side of the reactor shield and is scattered to the crew compartments by Shuttle equipment. In the MDAC Shuttle, radiation scattering accounts for approximately 97 percent of the total dose rate.

The dose rates are considerably higher in the NAR Shuttle for two main reasons:

1. The solid angle of leakage radiation intercepted by "solid" Shuttle components is about 3 times larger in the NAR Shuttle. Air breathing engines and other equipment surround 3 sides of the cargo bay in the NAR Shuttle while this type of equipment is placed forward of the cargo bay in the MDAC Shuttle.

2. The average distance from the reactor centerline to the scattering surface is only approximately 3.66 m (12 ft) in the NAR Shuttle compared to approximately 6.1 m (20 ft) in the MDAC Shuttle. The shorter distance and resultant smaller scattering angle in the NAR Shuttle increases the radiation flux at the crew stations.

In handling a shutdown, spent reactor prior to loading in the cargo bay, it is desirable to keep the crew locations within the shadow of the reactor's radiation shield. In examining the NAR and MDAC Shuttles and their selected cargo transfer mechanisms (manipulator arms and 90 degree rotation, respectively), it was found that the crew locations can be kept within the "shielded cone" for all cases except one. As shown in Figure B-11, the pilot's compartment is just outside the shield's shadow of the dual reactor module when it is being loaded into the MDAC Shuttle. The direct dose rate from this configuration is presented in Figure B-12 where it is compared with the dose rate from the same module installed in the cargo bay. The direct dose rate from the deployed module is only 15 percent of the dose rate from the installed module. The elimination of the scattering component

more than offsets the increase in direct dose rate. Transfer of the dual reactor module to the MDAC Shuttle can begin five hours after reactor shutdown without exceeding the allowable dose rate to the Shuttle crew.
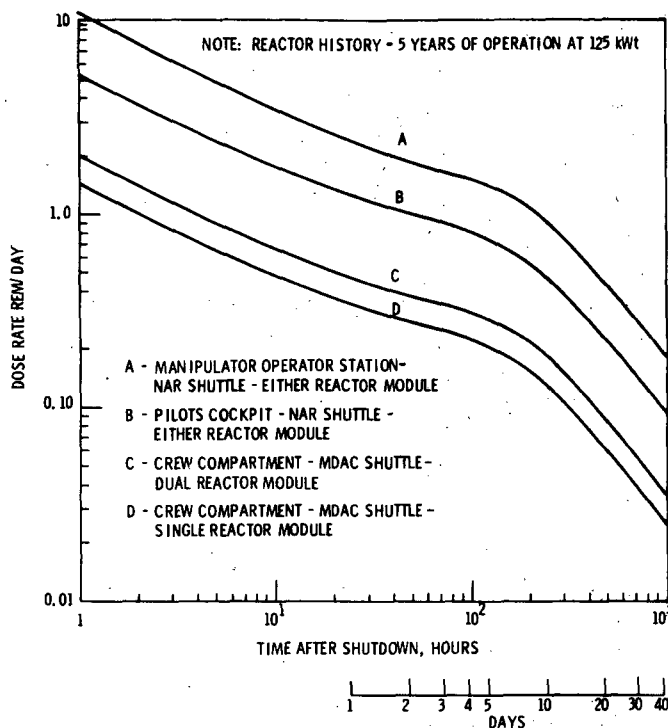
Figure B-10. Crew Dose Rate in Shuttle Carrying and Shutdown
Reactor in the Cargo Bay for Preferred Rearward Orientation

Some of the handling schemes for transferring the reactor power module from the Space Shuttle cargo bay to the Space Base and vice versa, may require the reactor end of the power module to be placed toward the front end of the cargo bay. Figure B-13 illustrates the possible placement of the reactor modules in the NAR Shuttle for the forward reactor orientation. The upper sketch in Figure B-13 shows the location of the dual reactor module for maximum separation of crew and reactor; approximately 9.3 m (30.5 ft) to the manipulator operator's station and 23.6 m (77.5 ft) to the pilot's cockpit. The middle sketch of the same figure shows the most forward location of the dual reactor module which meets C.G. constraints. The crew-reactor separation distances are 3.5 m (11.5 ft) and 17.8 m (58.5 ft) to the manipulator operator's station and cockpit, respectively. The only possible place-
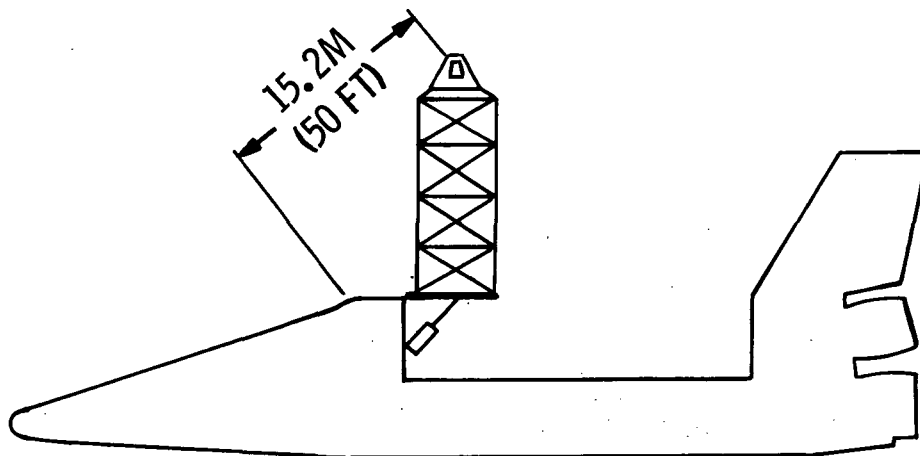
Figure B-11. Dual Reactor Module Deployed from MDAC Shuttle
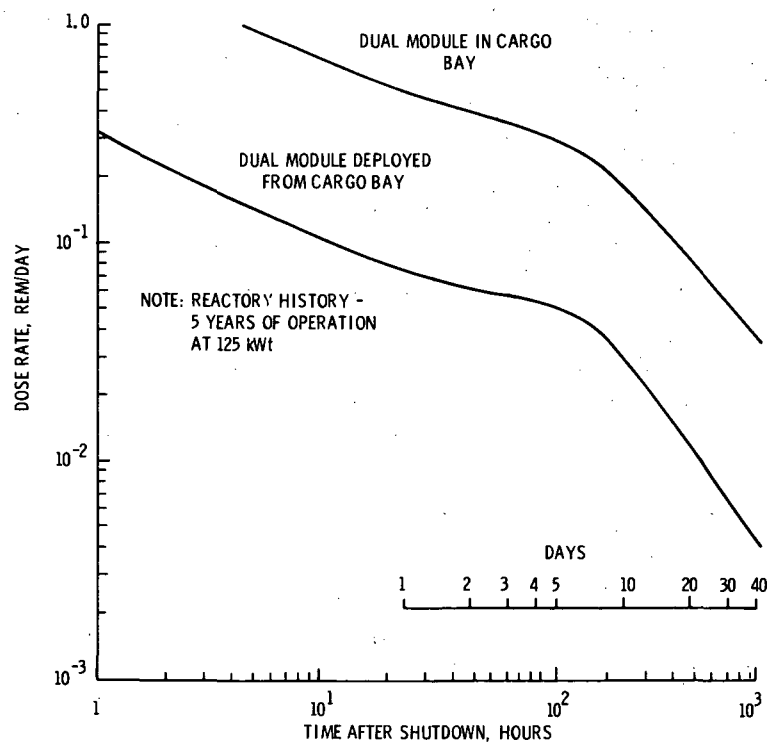
Figure B-12. Dose Rate to Crew of MDAC Shuttle from
Shutdown Dual Reactor Module

ment of the single reactor module in a forward reactor orientation is shown by the lower sketch of Figure B-13. The crew-reactor separation distances are 3.2 m (10.5 ft) and 17.5 m (57.5 ft).

FWD ←—— 7 M (23 FT)

DUAL REACTOR MODULE

FWD ←—— 1.22 M (4 FT)

DUAL REACTOR MODULE

FWD ←—— 0.92 M (3 FT)

SINGLE REACTOR MODULE
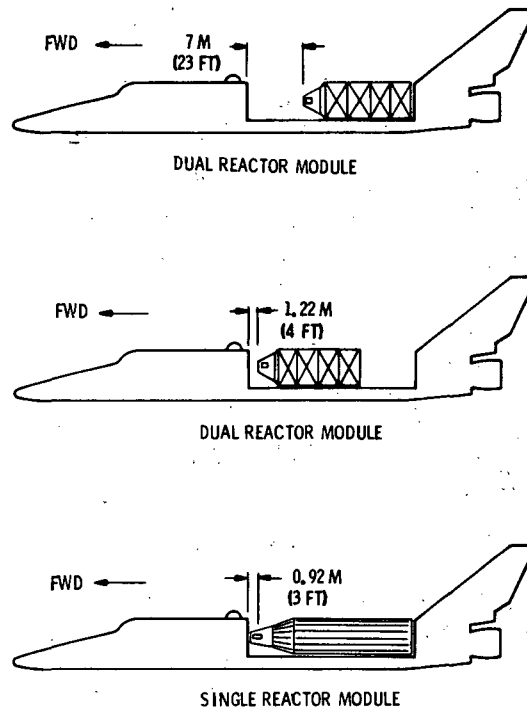
Figure B-13. Reactor Locations in NAR Shuttle Cargo Bay
for Forward Reactor Orientation

Figure B-14 shows the possible installation locations of the reactor modules in the MDAC Shuttle for the forward reactor orientation. The crew-reactor separation distances are 13.1 m (43 ft) and 7 m (23 ft) for the two possible dual reactor module locations shown in the two upper sketches in Figure B-14. The single reactor module installation is shown in the lower sketch even though its C.G. location is approximately 0.3 m (1 ft) aft of the allowable limits of the MDAC Shuttle for the forward reactor orientation. If so desired, there should be no reason why the C.G. location cannot be shifted forward to allow for this type of reactor orientation in the cargo bay.
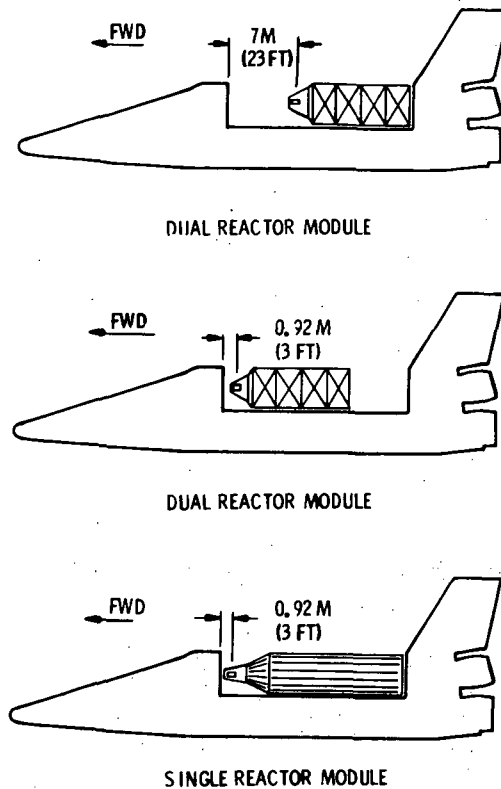
Figure B-14. Reactor Locations in MDAC Shuttle Cargo Bay
for Forward Reactor Orientation

The crew dose rates resulting from forward orientations of the reactor module in the Shuttle cargo bay are presented in Figure B-15 as a function of crew-reactor separation distances. The dose rates are between 10 to 200 times greater than the dose rates for the preferred rearward reactor orientation. Without additional shielding, this configuration would be unacceptable.

During prelaunch and launch/ascent, the dose rates to the Shuttle crew and ground personnel from a "clean" reactor present a much reduced radiation environment from that just discussed. It is assumed for this study that a new reactor module will be criticality tested at 100 watts for approximately 12 days for nuclear checkout purposes. It is also assumed that this checkout will be completed 60 days prior to launch of the reactor. The dose rate to ground personnel working near the reactor module during the prelaunch period and the Shuttle crew during launch can be determined from the curve in Figure B-16. This curve shows the dose rate at a 6.1 m (20 ft) distance from the reactor as a function of time after shutdown from the low power criticality test conditions. The dose rates are in the direction

B-22
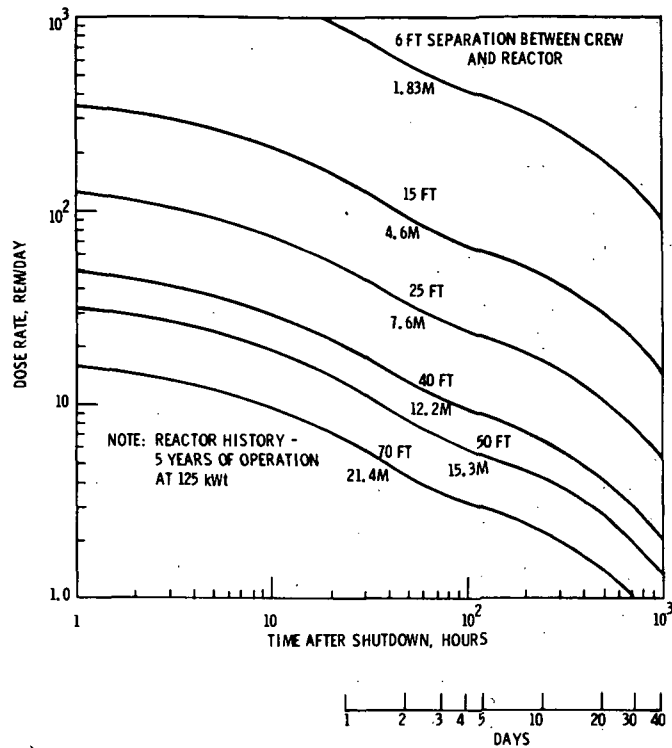
Figure B-15. Crew Dose Rate in Shuttle Carrying a Shutdown
Reactor in the Cargo Bay Forward Orientation
of the Reactor

of the top and sides of the reactor where the shield is the thinnest. Dose rates in the

direction of the thick part of the shield would be less than one percent of the values shown in

Figure B-16. One hour after shutdown, the 6.1 m dose rate is less than the 150 mrem/day

allowed for Space Base occupants. At the time of launch, the reactor module has been shut-

down for 60 days and the 6.1m dose rate is a negligible 0.4 mrem/day. The dose rate at

the shield surface at this time is about equal to the allowable dose rate of 150 mrem/day.

Thus, low power criticality testing of the reactor module will not hamper ground operations

prior to launch.
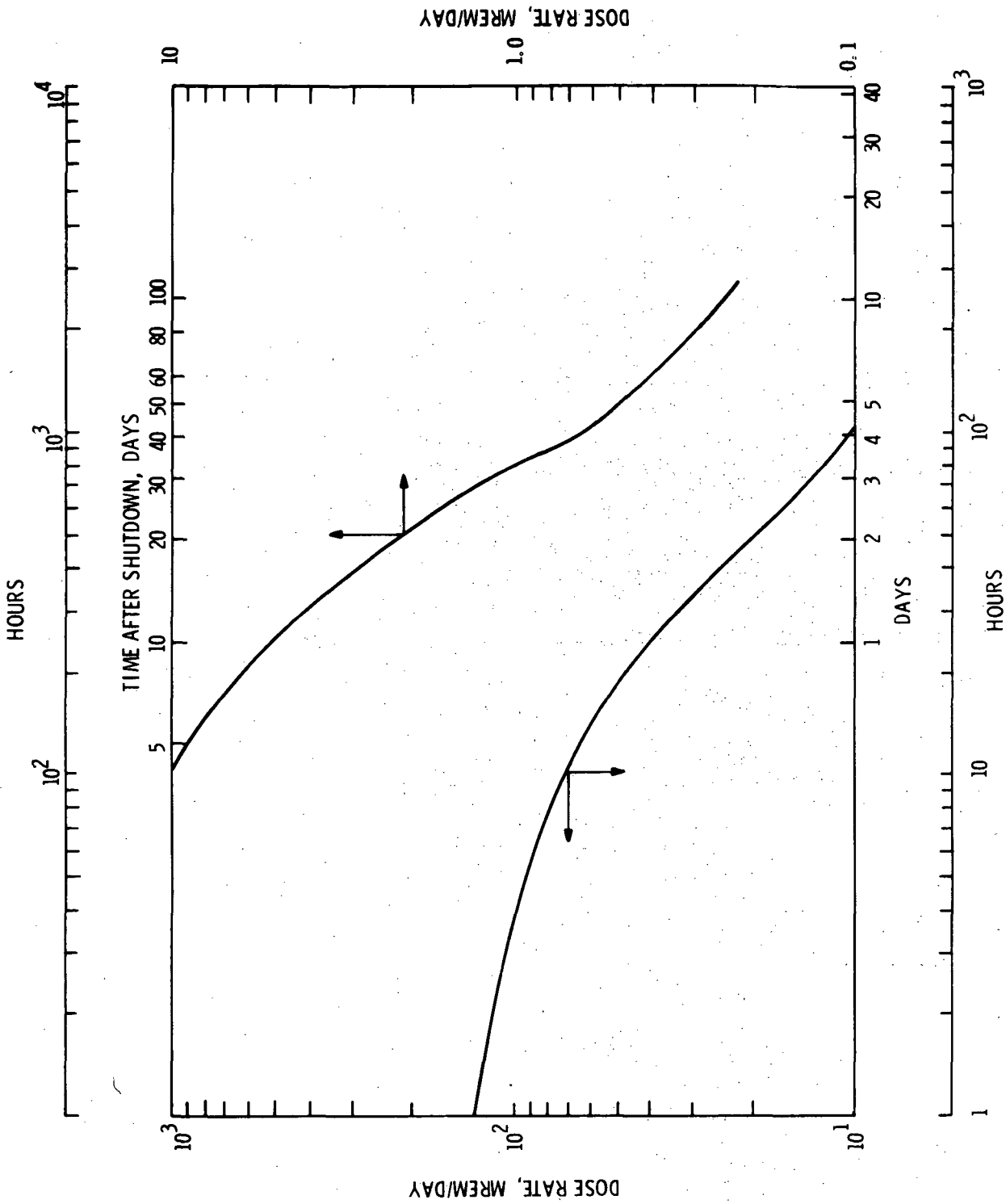
Figure B-16. Dose Rate After Shutdown, 6.1 Meters (20 ft) from Top and Side of Reactor

Figure B-17 compares the dose rate following criticality testing of the reactor, at any time after shutdown and any location, with the dose rate following 5-yr operation at 125 kWt. The data can be used to determine the dose rates to the Shuttle crew from the installation of the "clean" reactor module in the cargo bay by employing the following equation:

$$DC\ (r,\ x) = DO\ (4,\ x-60)\ \cdot\ DR\ (x-60)\ \cdot\ \frac{DC\ (6.1\ x)}{DC\ (6.1\ x\ 60)}$$

where:

DC (r, x)   = dose rate from "clean" reactor at location r (expressed in meters) and time x (expressed in days) after shutdown.

DO (r, x)   = dose rate at location r and time x after shutdown from a "spent" reactor which has been operating 5 years at 125 kWt.

DR(x)   = dose ratio of Figure B-17 at time x after shutdown.

An example will best illustrate the method. A clean dual reactor module is installed in the NAR Shuttle in the forward reactor orientation with the reactor 3.5 m (11.5 ft) from the manipulator operator's station. The Shuttle is launched and reaches the Space Base 65 days after the low power criticality test period of the reactor was ended. What is the dose rate to the manipulator operator during transfer of the clean reactor to the Space Base ? The applicable equation is:

$$DC\ (MOS,\ 65) = DO\ (MOS,\ 5)\ \cdot\ DR\ (5)\ \cdot\ \frac{DC\ (6.1,65)}{DC\ (6.1,5)}$$

and

DO (MOS, 5) = 300 rem/day from Figure B-15

DR (5) = 2.5×10^{-4} from Figure B-17

DC (6.1, 65) = 0.38 mrem/day from Figure B-16

DC (6.1, 5) = 9 mrem/day from Figure B-16
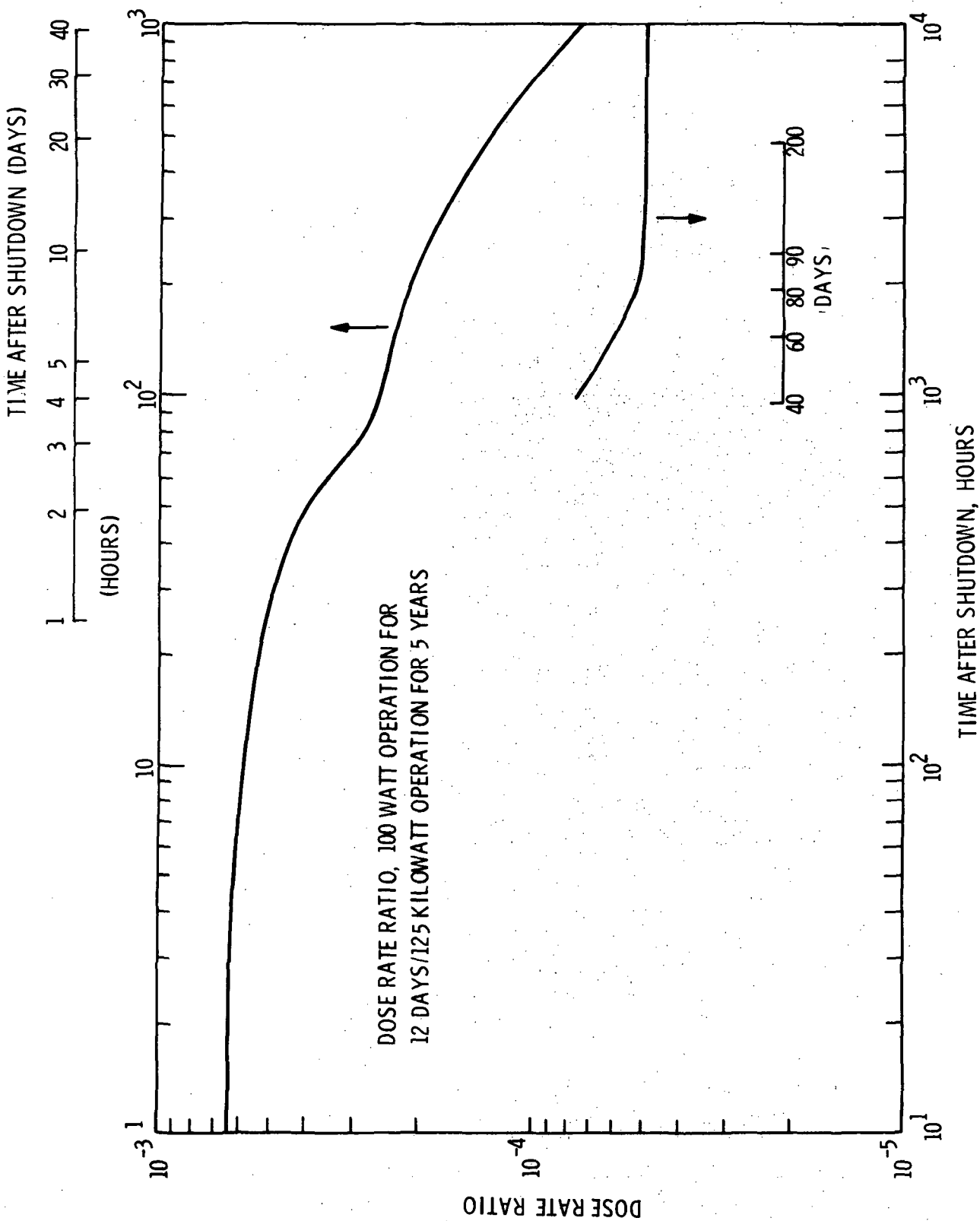
Figure B–17. Dose Rate Ratio vs Time after Shutdown

Performing the required arithmetic, the dose rate to the manipulator operator is found to be only 3.16 mrem/day. This represents approximately two percent of the 150 mrem/day maximum allowable dose rate.

B.8 REFERENCES

B-1   "Nuclear Reactor-Powered Space Station Definition and Preliminary Design," MSC-00741, (SD 70-168), Volumes I, II, and III, North American Rockwell, under contract NAS9-9953, January 1971.

B-2   "Nuclear Reactor-Powered Space Station Preliminary Performance Specification," MSC-02451 (SD 70-527), Volume I, North American Rockwell under contract NAS9-9953, November 1970.

B-3   Reactor Power System Design Document", MDC G0750, Volumes I and II McDonnell Douglas Corporation under contract NAS8-25140, December 1970.

APPENDIX C
REFERENCE ISOTOPE BRAYTON POWER MODULE

C.1 GENERAL

For the purpose of this nuclear safety investigation, an isotope-Brayton power system was used. It is potentially very flexible in application and, therefore, may be found suitable for a number of future missions involving power requirements from 3 kWe to 30 kWe. These missions will in all likelihood involve the Space Shuttle to transport the isotope-Brayton power system to low earth orbit, and may also use the Space Shuttle to return the isotope heat source to the earth's surface. This appendix describes in relative detail the reference isotope-Brayton power system and how it may be configured for Space Station/Space Base applications. The major isotope heat source induced environments that can have a significant effect on the Shuttle integration and transport mission are also discussed.

Three variations of the Shuttle-integrable 25 kWe isotope-Brayton power system concept have been proposed as illustrated in Figure C-1: the engine-room concept (MDAC), the power boom concept (NAR), and the modular concept (GE). In the "engine room" approach, the system is housed in a 10 m (33 ft) diameter cylinder, 4.6 m (15 ft) long. Three power conversion modules are provided: two operating, and one spare. These are rail-mounted so that either operating power conversion module can be replaced by the spare as required. This system uses two isotope heat sources.

The "power boom" configuration is 14 m (46 ft) long, 4.3 m (14 ft) in diameter, employs two heat sources, and contains four power conversion modules (two on line, two redundant). In this system, the gas is ducted the length of the system to provide separation distance between the heat sources and the power conversion modules, thereby attenuating the radiation level at the modules and permitting in-flight maintenance.

The modular power system is 6.1 m (20 ft) in diameter and 12.8 m (42 ft) long. Its radiator has been divided into segments so that the power conversion module and corresponding radiator segment are contained in one structure. The system shown here contains four heat sources and four power conversion modules, but it could be configured of 2 to 6 units of each.

ENGINE ROOM
10 m DIAMETER
4.6 m LENGTH

POWER BOOM
4.3 m DIAMETER
14 m LENGTH

MODULAR SYSTEM
6.1 m DIAMETER
12.8 m LENGTH

- COMMON NUCLEAR COMPONENT IS THE ISOTOPE REENTRY VEHICLE (IRV)
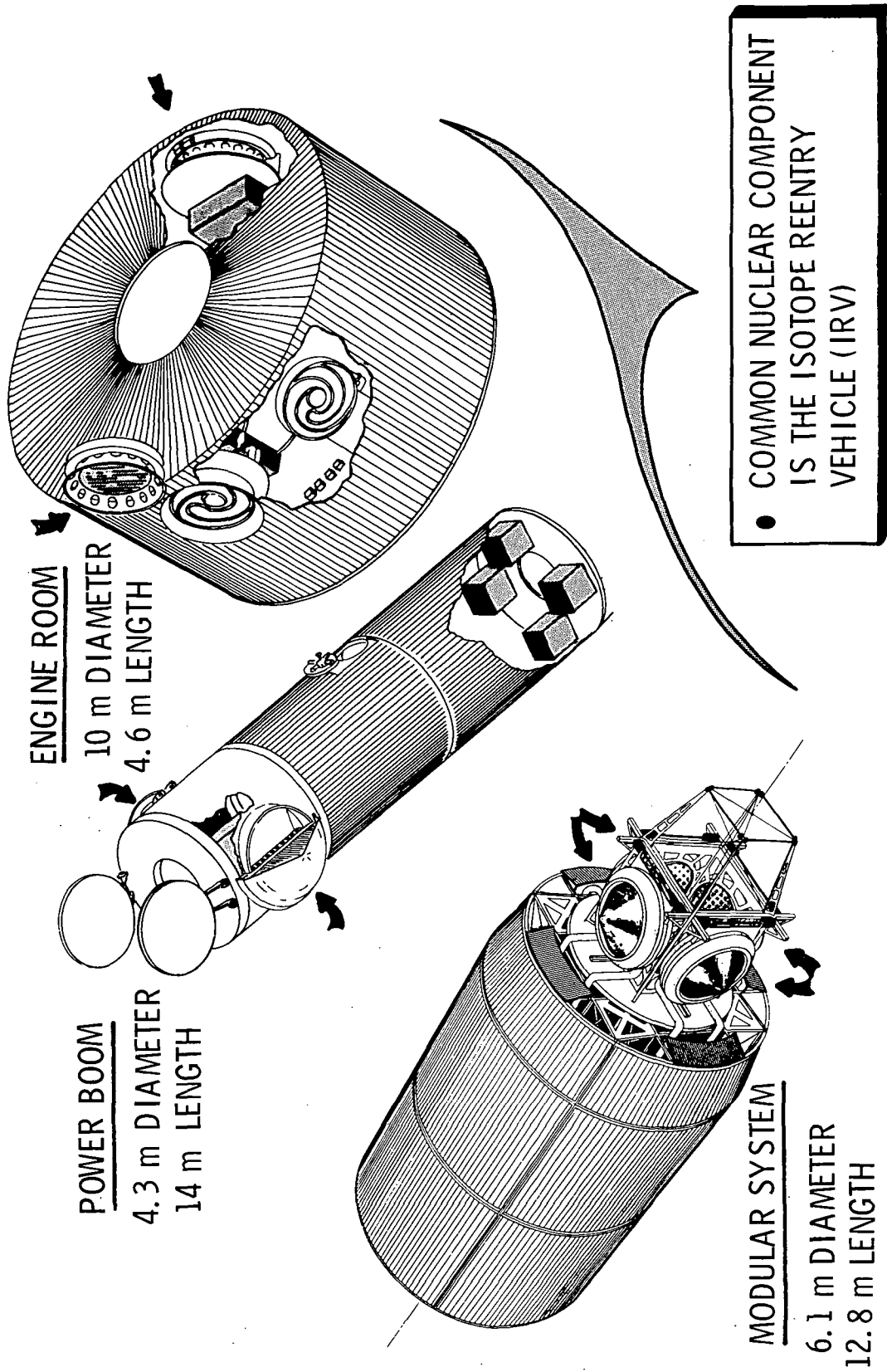
Figure C-1. Typical Isotope-Brayton Configurations

The common nuclear component to be found in each of the three systems is the Isotope Reentry Vehicle (IRV).

The following sections will describe the engine room concept in detail (see Reference C-1) and will indicate the key features of the power boom and modular approaches and how they differ from the engine room.

C.2 SYSTEM DESIGN FEATURES

The function of an Electrical Power System (EPS) is to generate, transmit, condition, control, and distribute electric power to the Space Station/Space Base power-consuming subsystems and experiments (as required) for a mission duration of at least 10 years.

The engine room isotope-Brayton power system configuration consists of two independent units, each of which contains an isotope heat source housed in an isotope reentry vehicle (IRV), a heat source heat exchanger (HSHX) connected to a power conversion system (PCS), primary and secondary radiators, nuclear radiation shielding, and suitable controls, connections, and mounting devices. A single isotope-Brayton unit is shown schematically in Figure C-2. Two of these plus a spare PCS go to make up the reference system. The PCS/heat exchanger modules are mounted on rails so the spare module can be positioned to operate with either heat source.

The system design features radiative transfer from the isotope heat source array to the Brayton cycle HSHX. This arrangement permits PCS module replacement without cutting high-temperature lines. It also makes possible a simple, highly reliable separation system for use in jettisoning the IRV in the event of an on-pad or launch abort and in other emergency situations. The PCS/heat exchanger module has been designed to permit rapid, easy replacement of a failed unit.

The output of the power source assembly group is 29.8 kWe of 1200 Hz, 120/208 vac, three-phase electrical power delivered to separate source buses. In addition to the 29.8 kWe total of electrical power, which corresponds to 25 kWe average available at the AC and DC load

buses, 4.0 kW of thermal power (2.0 kWt from each heat source) is extracted as waste heat at 394°K (250°F) for use by the EC/LS subsystem.
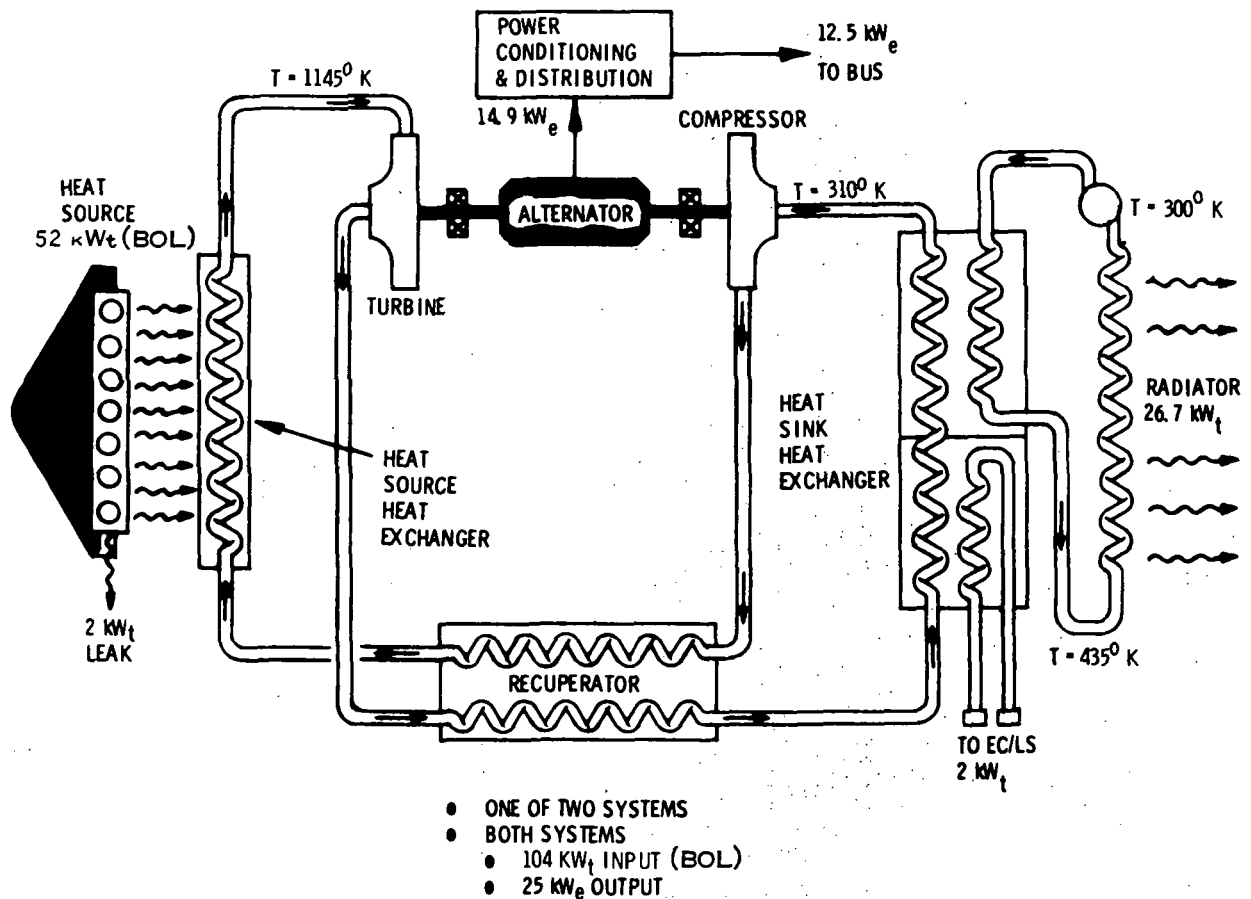
Figure C-2. Typical Isotope-Brayton System

Table C-1 is a summary of the system characteristics for the complete 25 kWe power system. At the operating temperature ratio of 0.262, the power conversion efficiency (ratio of PCS heat input to net unconditioned power) is 32 percent. The upper temperature is limited to 1144°K (1600°F) by the heat source, and the minimum cycle temperature of 311°K (100°F) is established by the sink temperature of 267°K (20°F) and the radiator area.

The mass of the system is estimated to be about 6350 kg (14 klbs) at launch, as shown in the mass schedule of Table C-2.

Table C-1. Isotope/Brayton Cycle PCS Characteristics

Net conditioned power	25 kwe* at 1200 Hz
Conditioning and distribution loss	4.8 kwe
Net raw power	29.8 kwe
PCS module rating	14.9 kwe
Isotope heat source rating (2 at 48.5 kwt)	97 kwt EOL** (104 kwt BOL)
Cycle heat input	(46.5 kwt)
Heat leakage	(2.0 kwt)
Power conversion efficiency (14.9 kwe/46.5 kwt)	32%
Radiator	172 m^2
Design sink temperature	267°K
PCS working gas	Xe-He
PCS turbine inlet temperature	1145°K
PCS compressor inlet temperature	310°K
IRV diameter	2.21 meters
Crew dose rate	25 rem/6 mo

*4.0 kwe bonus for experiments, waste heat provides 4.0 kwt to EC/LS.
**Pu-238 age is 11.0 years.

Table C-2. Pu-238 Brayton Mass Summary

System	Mass (Kg)
Heat source (2 at 776)	1552
IRV (2 at 340)	680
Shielding (2 at 680)	1360
Brayton cycle PCS (3 at 453)	1359
PCS electrical and support (2 at 125)	250
Heat rejection and radiator	788
Structural-mechanical integration	454
Power source subtotal	6443

C. 3 IRV/HEAT SOURCE

The isotope-Brayton power system contains two IRV's, each containing heat sources rated at 52 kWt at beginning of life (BOL). The heat source contains 130 individual capsules each generating 0.4 kWt (BOL). The purpose of the IRV is to achieve thermal integration with the PCS and to assure intact reentry disposal for abort.

The IRV design is an adaptation of the AVCO design. Exploded views of the IRV with the heat source are presented in Figures C-3 and C-4. The AVCO version is shown; the present design is similar with the exception of hexagonal fuel capsules and the absence of a cover plate, since the capsule cladding can withstand the reentry heat loads. Operating characteristics of the IRV heat source baseline design are summarized in Table C-3. Mass of the IRV heat source components are summarized in Table C-4. The heat source mass is 775 kg (1710 lbs), the IRV mass without heat source is 340 kg (750 lbs), and the IRV reentry mass is 1115 kg (2460 lbs), for the reference 221 cm (87 in) IRV design.

The IRV is a 60-degree half-angle, blunt cone configuration 221 cm (87 in) in diameter and 114 cm (45 in) deep. The aft section has a canted and perforated "fence" or flare to prevent backward reentry of the IRV/heat source. Results of aerodynamic testing at Ames indicate a high relaibility associated with performance of the fence. The IRV is protected during reentry by a low-density ablator. Location aids are mounted on the vehicle to assist in tracking and recovery. A ballute located around the periphery of the IRV limits terminal velocity to about 15 m/sec (50 ft/sec) before impact. The IRV terminal velocity is 81 m/sec (265 ft/sec) without ballute deployment.

The heat source consists of a 173 cm (68 in) diameter planar array of the 130 hexagonal fuel capsules mounted on a refractory metal support plate. A refractory truss attaches the heat source to the aluminum honeycomb aeroshell of the IRV. Low-conductivity vacuum multifoil insulation is used to minimize heat loss to the IRV structure.

RETENTION BAR

COVER PLATE

FUEL CAPSULE

HEAT SOURCE
PLATE

BeO

SUPPORT RING

INSULATION
ASSEMBLY

SUPPORT
TRUSS
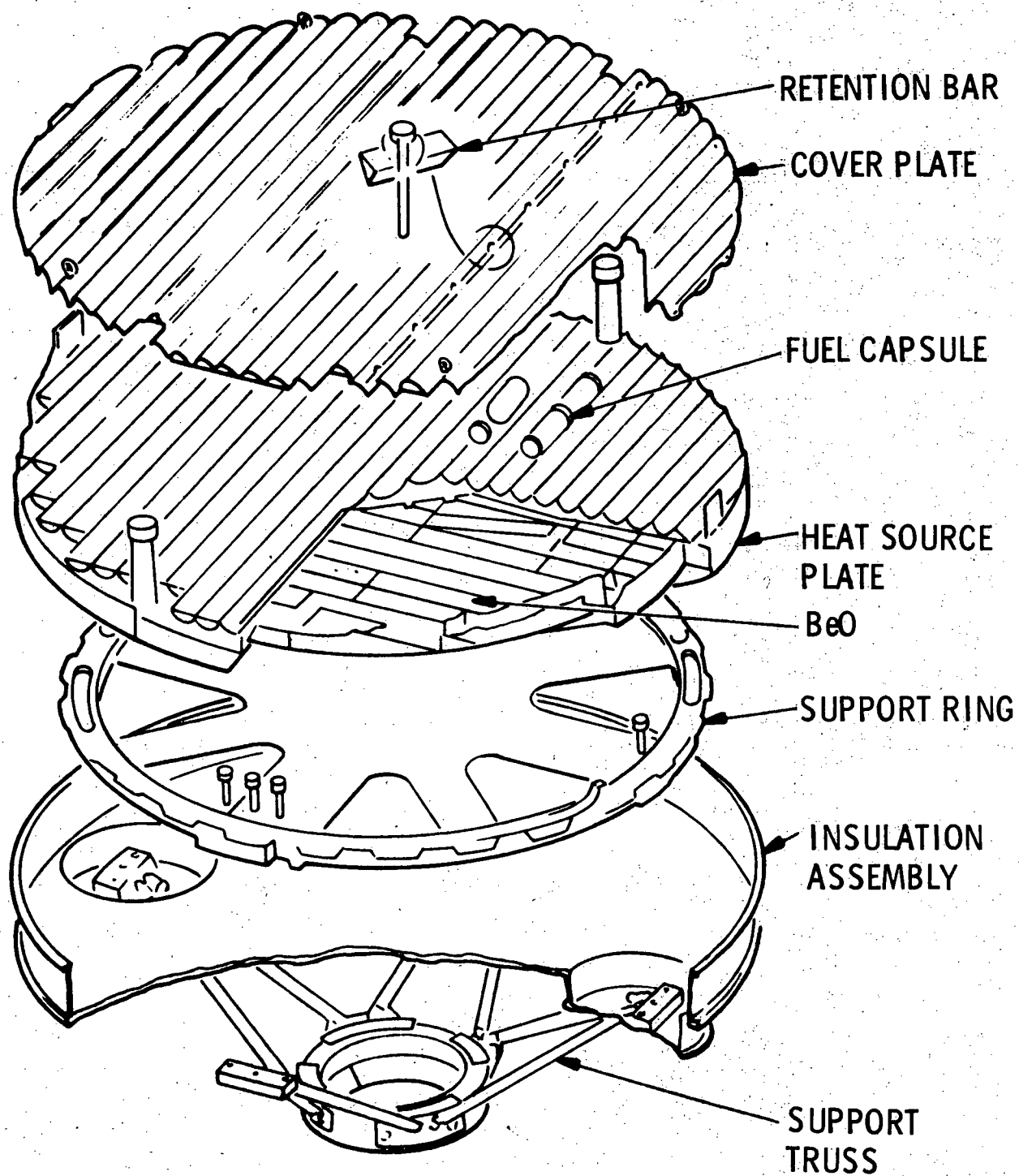
(REFERENCE C-1)

Figure C-3.　Exploded View of Heat Source Plate (AVCO Design)
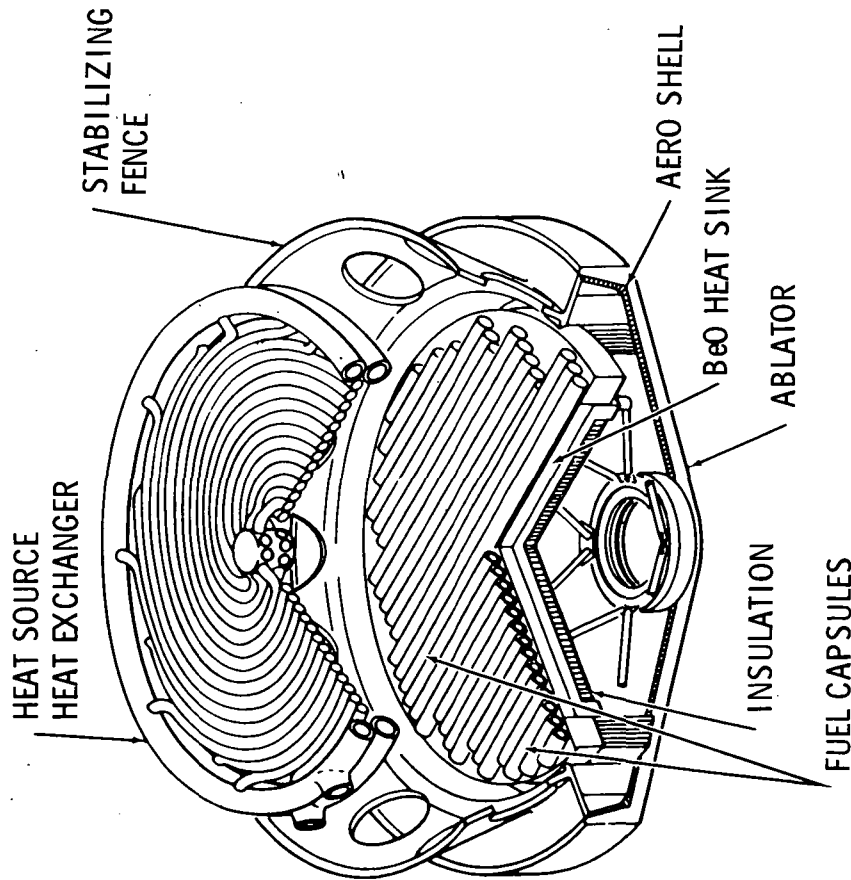
CHARACTERISTICS

IRV DIAMETER	2.21M REF (2.34M ULTIMATE)
HEAT SOURCE DIAMETER	1.73M
POWER LEVEL	48.5 kWt (EOL)
IRV MASS	1116 kg
NO. OF CAPSULES	130
W/C_dA	1530 NEWTONS/M^2 (32 LB/FT^2)
IMPACT VELOCITY	81 M/SEC

(REFERENCE C-1)

STABILIZING FENCE

AERO SHELL

BeO HEAT SINK

ABLATOR

HEAT SOURCE HEAT EXCHANGER

INSULATION

FUEL CAPSULES

Figure C-4. AVCO Isotope Reentry Vehicle

Table C-3. Heat Source and IRV System Characteristics (Reference C-1)

Heat source

Thermal rating	52 kwt (BOL)
Isotope fuel	PuO_2 SSC
Pu-236 impurity	1.0 ppm
Heat source diameter	1.73 m
Heat source radiation area	2.34 m^2
Average fuel operating temperature	1310°K
Thermal storage material	Graphite, BeO
Thermal storage requirement time and temperature rise[a]	60 min for 1310°K to 1645°K

Isotope capsule

Type	PRD vented
Number of capsules	130
Thermal rating	400 w (BOL)
Structural materials	Refractory
Heat shield	Graphite
Length	17.1 cm
Width	8.9 cm (flats)
Mass	4.0 kg
Vent release time, minimum[b]	Unspecified

Reentry vehicle

IRV diameter	2.21 m ref. (2.34 m predicted)
IRV hypersonic (continuum) $W/C_D A$ [c]	1530 Newtons/m^2 (32 lb/ft^2)
IRV impact velocity without ballutes[c]	81 m/sec
Impact attenuation	Intact plate concept

Shield

Neutron yield	5,000 n/sec-gm Pu-238
Shielded dose rate/IRV at 20 ft	7.7 mrem/hr
Materials (neutron/gamma)	LiH/U
Internal diameter	2.26 m ref. (2.39 m predicted)
Integrated crew dose from IRV systems	25 rem/6 mo
U Thickness (3.5 yr/11 yr)	None/0.51 cm
LiH Thickness (3.5 yr/11 yr)	12.7 cm/20.3 cm

(a) Common requirement with previous Avco study
(b) Based on pressure relief prior to 1% maximum creep in T-111 shell
(c) Zero angle of attack

Table C-4. Heat Source and IRV Component Mass** (Reference C-1)

Assembly	Mass		
Heat source			776 kg
Fuel capsules (130 at 4.0 kg)		525	
Fuel (400w, SSC)	(1.36)		
Structural shell	(0.84)		
Liner, oxidation barrier, etc.	(0.34)		
Graphite heat shield	(1.41)		
Total	(3.95)		
Heat source plate		45	
Support structure		20	
Insulation		23	
BeO_2 heat sink		163	
Reentry vehicle			340 kg
Heat shield on cone		160	
Bond		3	
Fence structure		11	
Fence heat shield		64	
Aeroshell structure		51	
Ballute and flotation aids		43	
Recovery Aids		9	
Shielding*			680 kg
U-238 gamma shield		None	
LiH neutron shield (including can and insulation)		680	
Total heat source/IRV mass			1796 kg

*Criteria: 25 rem/6 mo., 2.1 m exclusion distance, 1.0 ppm Pu-236, 3-1/2 yr fuel age

**Mass shown for reference design

Flat sides of adjoining capsules touch each other, and are perpendicular to the heat source plane. This presents two surfaces (canted 150 degrees from each other) for radiation to the conversion system with a planar area of 23,400 cm^2 (3630 in^2). Assuming a collector temperature of 1170°K (1650°F) and a graphite emissivity of 0.85, the emitter surface of the heat source is about 1255°K (1800°F) in normal operation. The average shell temperature is about 1295°K (1950°F) assuming a 0.254 cm (0.10 in) RPG insulation layer. The peak fuel temperature is calculated to be about 1340°K (1900°F) and the average fuel temperature is just under 1310°K (1900°F).

Transfer of the heat from the isotope heat source to the Brayton cycle heat exchanger is accomplished by direct radiation to facilitate both PCS removal and emergency cooling. The HSHX configuration is a tube-fin-spiral involute, two-pass type of heat exchanger. The primary heat exchanger receives radiation on an equal area from the heat source. In case of malfunction of the primary PCS, the IRV is rotated to the heat dump mode while the PCS unit is replaced.

The IRV fuel capsules are SNAP-19 intact-impact heat source capsules rated at 400 watts Beginning-of-Life (BOL). The capsule design is shown in Figure C-5. The fuel is a solid-solution cermet.

C.4 POWER CONVERSION SYSTEM (PCS)

The PCS converts heat source thermal energy to electricity. In the Brayton cycle conversion system, this is accomplished in a closed loop, hermetically sealed, and thermally coupled to the heat source and heat rejection systems by heat exchangers. The Brayton cycle system is a recuperated Brayton cycle using a helium-xenon mixture in the ratio 39 percent He and 61 percent Xenon by weight to yield a fluid molecular weight of 83.8. The fluid is heated in the HSHX by radiant coupling to the IRV heat source. The diameter of the HSHX is about 173 cm (68 in).
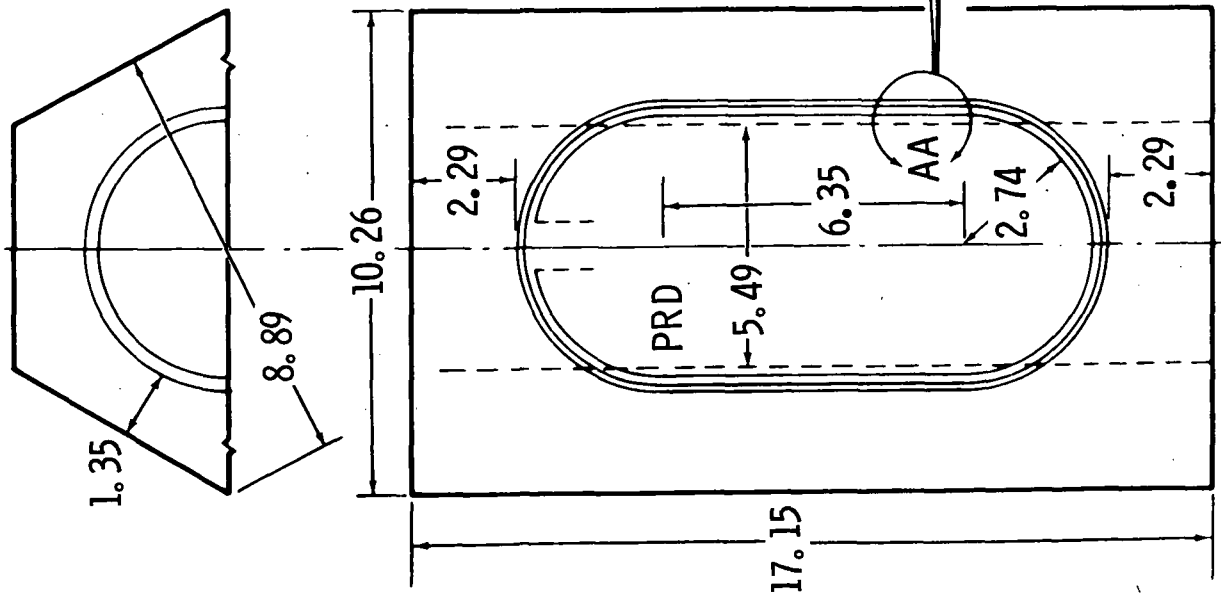
NO. OF CAPSULES   130
THERMAL RATING   400 WATTS
MASS   4.0 kg

POTENTIAL USES – PLUM BROOK
TEST, PIONEER, VIKING

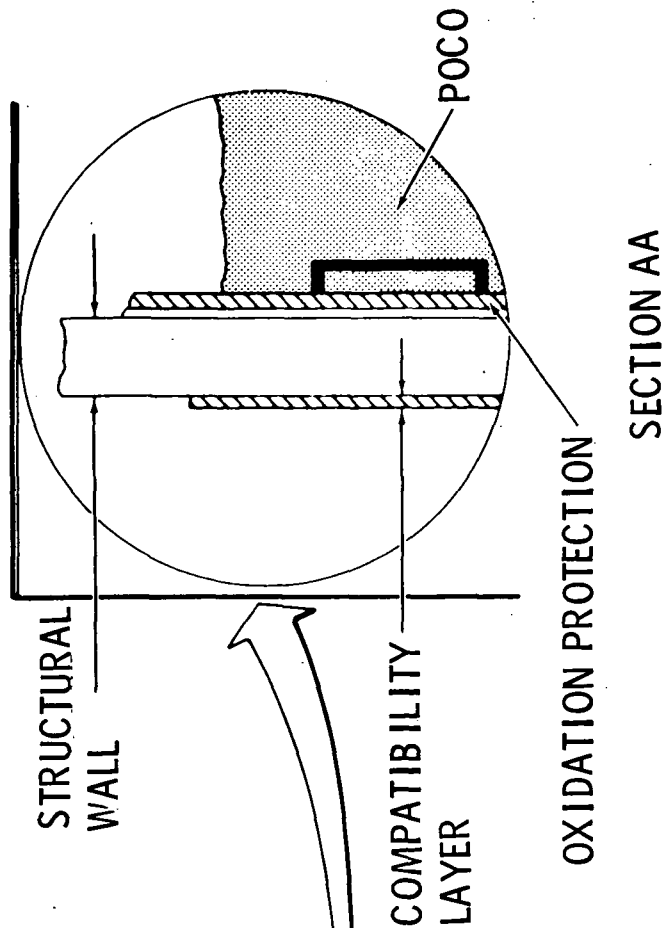NOTE: DIMENSIONS GIVEN IN CM (REFERENCE C-1)

POCO

STRUCTURAL
WALL

COMPATIBILITY
LAYER

OXIDATION PROTECTION

SECTION AA

1.35

8.89

10.26

2.29

PRD

5.49

6.35

AA

2.74

2.29

17.15

Figure C-5. Fuel Capsule

The temperature of the fluid leaving the HSHX is $1145^{\circ}K$ ($1600^{\circ}F$), the maximum cycle and turbine inlet temperatures. The Combined Rotating Unit (CRU) has radial flow turbine and compressor wheels mounted at each end of a Rice alternator. The CRU is supported by hydrodynamic bearings, using the high-pressure (3.7×10^5 Newton/m^2) working fluid bled from the compressor discharge for the bearing. Auxiliary cooling is provided for the alternator housing.

The heat rejection heat exchanger and recupterator heat exchanger are combined in a single integral assembly called the Brayton heat exchanger unit (BHXU). The recuperator section of the BHXU is a gas-to-gas counterflow type heat exchanger. Platefin surfaces or sandwiches are used for both gas flows. The core is formed by alternate stacking of the hot (turbine exit to heat rejection heat exchanger entrance) and cold (compressor exit to heat source heat exchanger entrance) gas flow sandwiches. The waste heat exchanger is a liquid (FC-75) to gas (He-Xe) cross-counterflow arrangement. There are several liquid passes back and forth across a single gas flow path. The core of the waste heat exchanger also uses platefin sandwiches for both the liquid and gas.

The gas management system consists of a helium supply tank, a regulator, and injection valve. The system furnishes makeup helium in the event of leakage and jacking gas for the bearings during startup.

Startup is provided by a motor-generator set energized by the Space Station/Space Base batteries. The motor-generator set provides power to the PCS alternator which acts as a motor to furnish the shaft power to the turbine and compressor during startup. Startup can be effected in less than 5 to 10 seconds with the CRU unloaded. A negligible amount of energy is required to bring the machine to self-sustaining operation.

A PCS mass summary is given in Table C-5. Additional support equipment is required for PCS monitoring control and startup. The mass of this equipment is 250 kg (550 lbs) (Table C-6) not including equipment, such as the monitoring panel, rectifiers, and batteries for startup, which are common with other systems on the Space Base.

Table C-5. Brayton PCS Mass Schedule

Component Description	Total No. of Units	Unit Mass (kg)	System Mass (kg)
CRU	3	57	170
BHXU and EC/LS heat exchanger	3	206	615
Electrical harness	3	71	34
Heat source heat exchanger and duct	3	109	327
Structure and insulation	3	69	208
Total CRU	3	452	1354

(Reference C-1)

Table C-6. PCS Support Equipment Mass Schedule

Component Description	Total No. of Units	Unit Mass (kg)	System Mass (kg)
Inverter	4	7	27
Signal conditioner and speed control	2	9	78
Voltage regulator-exciter	2	34	68
Cold plates	8	5	36
Parasitic load resistors	2	27	54
Gas management and startup	2	23	45
		105	248

(Reference C-1)

C.5 HEAT REJECTION

Primary and secondary radiator sections are used for the Brayton power source system. The primary section rejects 26.75 kWt/module to an apparent sink temperature of 267°K (20°F); the secondary section rejects 2.55 kWt/module to the same sink. The primary radiator rejects the thermodynamic waste heat from the cycle and the secondary radiator cools the alternator and electronic control components. The area of primary and secondary radiator to support each PCS heat rejection is 86 m^2 (925 ft^2). The radiator uses aluminum tubes placed circumferentially around the vehicle with the vehicle skin as the radiator fins. The 2 kWt difference between the waste heat produced by the PCS and that rejected by the radiator is used for EC/LS functions such as desorbtion of silica gel beds and CO_2 molecular sieves.

Mass of the heat rejection system (Table C-7) includes nominal redundancy for reliability and wearout during the 10-year mission life. The radiator is also sized for an α/ϵ degradation to 0.39.

Table C-7. Mass Schedule for Isotope Brayton Cycle
Heat Rejection System

Component Description	No. Required	Mass Unit (kg)	System Mass (kg)
Accumulator	4	5	18
Pump-motor-assembly	4	4	15
Plumbing	2	54	109
Fluid inventory	2	36	73
Primary radiator*	4 Loops (1 Fin)	–	476
Secondary radiator*	4 Loops (1 Fin)	–	98
Total liquid cooling system			789
*Four Loops, two on-line and two standby; all sharing a common fin			

(Reference C-1)

C.6 RADIATION SHIELD

The isotope shields are sized to yield a total integrated crew dose of 25 rem/6 months from two isotope heat sources. The shield performance data and dimensions are listed in Table C-3 and the weight is summarized in Table C-4. All manned compartments of the Base are within the shadow shield of the IRV. It is constructed of lithium hydride encased in a 0.254 cm (0.1 in) thick stainless steel containment can.

At launch, the heat source shield contains 12.7 cm (5 in) of LiH to meet the dose criteria for the first 2-1/2 yrs of operating life. After 2-1/2 yrs, an additional 7.6 cm (3.0 in) of LiH and 0.51 cm (0.2 in) of depleted uranium is delivered by the Space Shuttle to meet the dose criteria for the remainder of the 10-year mission.

The design of the 680 kg (1500 lb) IRV shield for the isotope-Brayton system was influenced by a number of factors, in decrasing order of significance, as follows:

- Allowable crew dose from the isotope system.

- Initial shield design for an intermediate isotope age.

- The large planar source geometry.

- Buildup of impurities in the Pu-238 fuel.

- The expected crew residence time.

- Separation distance.

- Fuel block power.

The effects of the above elements are discussed in Reference C-1.

C.7 ISOTOPE INDUCED TRANSPORTATION AND HANDLING ENVIRONMENTS

C.6.1 RADIATION

Figures C-6 and C-7 show the neutron and photon isodose curves, respectively, for the unshielded 52 kWt (BOL) heat source.

The heat source geometry was based upon the heat source described in Reference C-1.

The heat source was assumed to consist of 52 kWt of $^{238}PuO_2$ in the form of a disc 173 cm (68 in) in diameter.

The radiation source terms are based upon the following data:

Neutron source - 5 x 10^3 n/sec-gm-^{238}Pu

^{236}Pu content   - 1 ppm

Gamma source - assumed 11 year old fuel, source terms taken from Reference C-2.

The radiation calculations are based upon the following assumptions:

- No neutron absorption within the heat source.

- Photons with energies below 0.5 Mev were completely absorbed within the heat source.

- No photon absorption within the heat source for photons with energies above 0.5 Mev.

- The ratio of the dose rate along the disc axis to the dose rate in the radial direction was taken to be 3 in the neutron case and 10 in the photon case.

- A cos (a θ) distribution was assumed for both neutron and photon dose rates where θ is the angle with respect to the Z axis in a cylindrical coordinate system with origin at the heat source center.

  The Z axis is along the disc source axis. (See Figure C-8.)
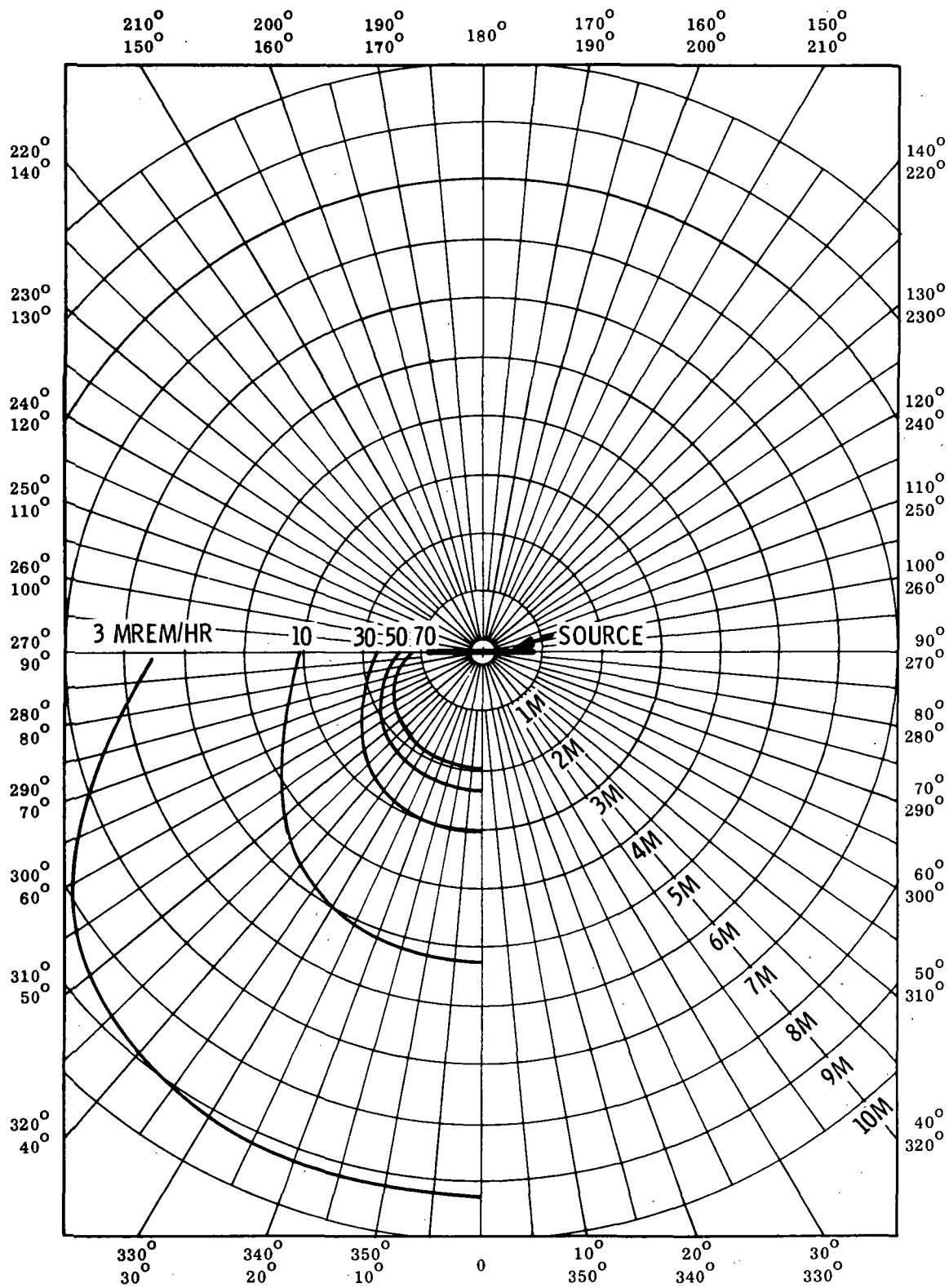
Figure C-6. Neutron Isodose Curves
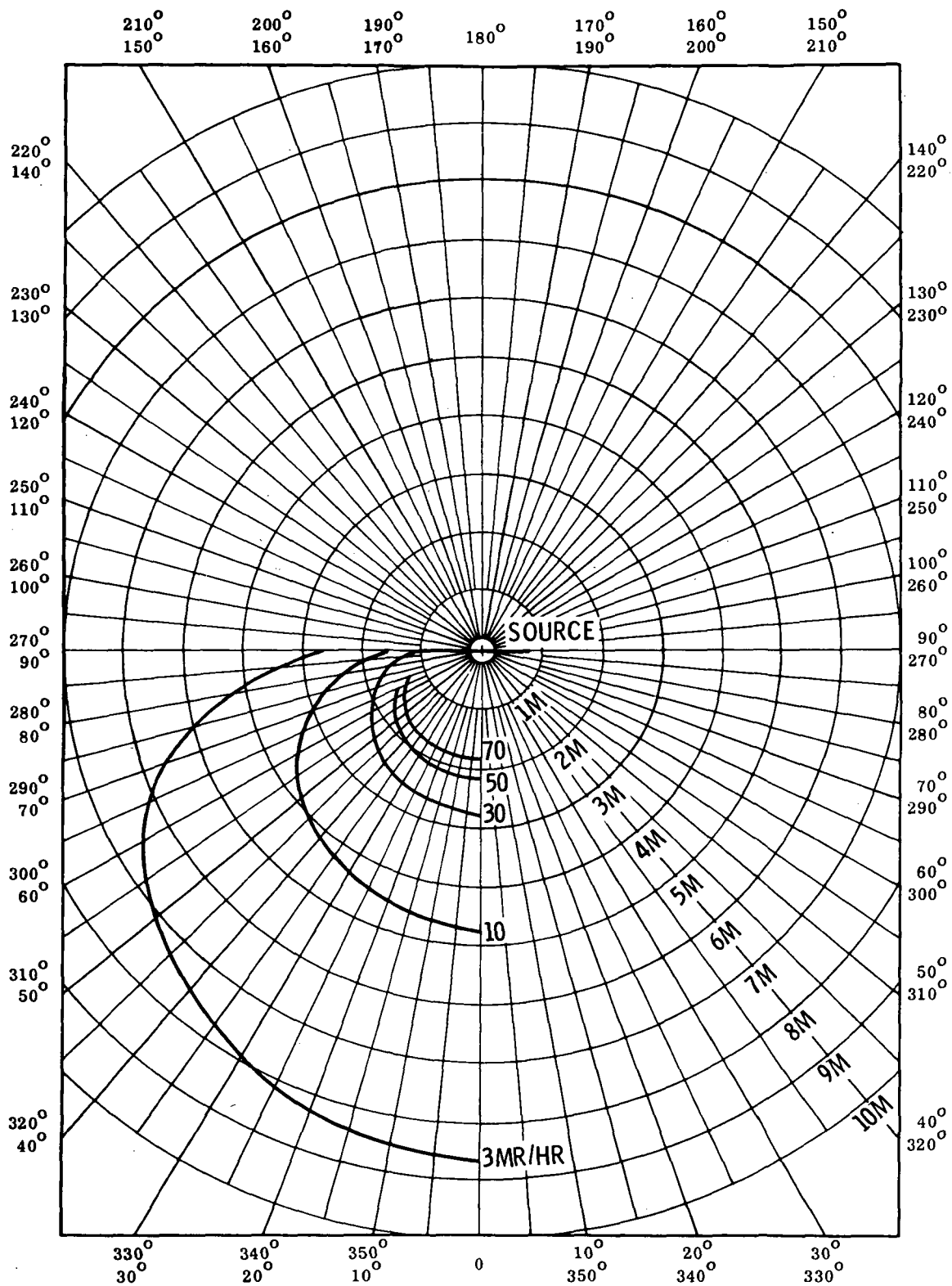
Figure C-7. Photon Isodose Curves

DOSE POINT

DISC SOURCE
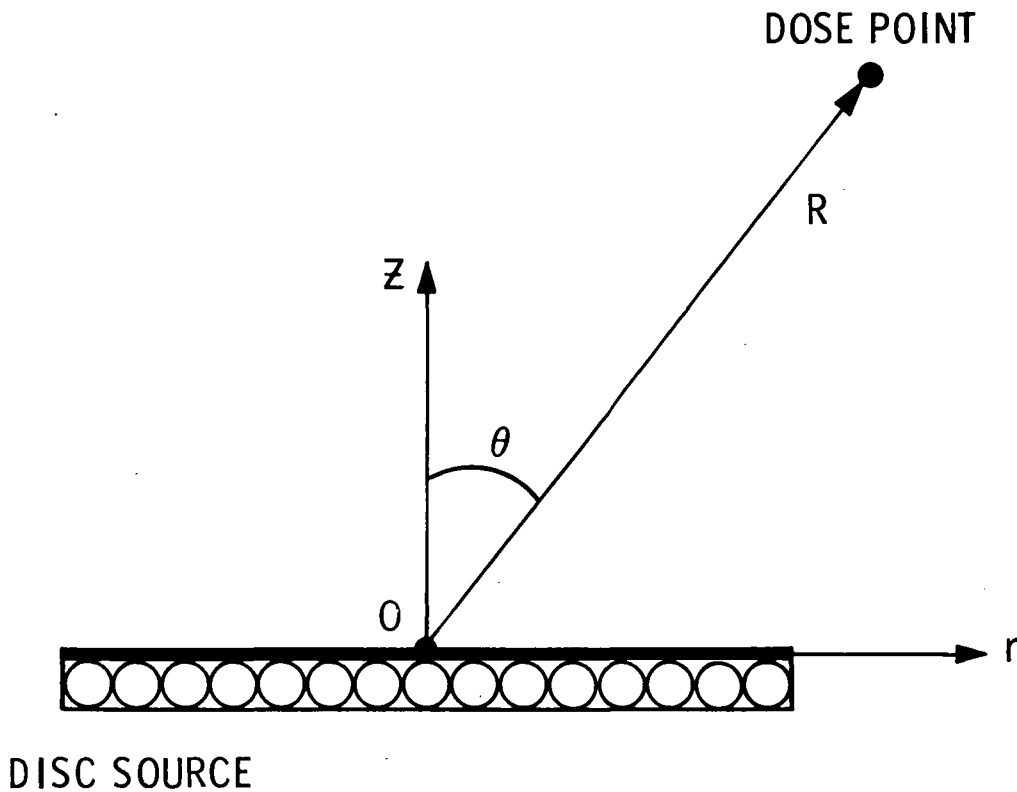
The neutron and photon dose rates were assumed to follow the relationship.

$$D = \frac{D_o \cos(a\theta)}{R^2}$$

The parameter "a" was chosen to satisfy the axial to radial dose rate ratios discussed above. The parameter D_o was evaluated by requiring that the number of particles passing through a closed surface about the source was equal to the source strength.

The resulting equations were:

$$Dn = (2.8 \times 10^6) \cos(0.782\theta)/R^2 \text{ mrem/hr}$$

$$D_\gamma = (2.25 \times 10^6) \cos(0.936\theta)/R^2 \text{ mr/hr}$$

These equations are meant to apply for R > 915 cm (3 ft) to insure that for $\theta = 90°$ the dose point lies outside of the heat source.

C.7.2 THERMAL

An estimate was made of the temperature of the heat rejection surface for the case of pure radiation heat transfer and for radiation plus convection. In each case, 5.3×10^4 watts were to be rejected from one side of a horizontal disc 173 cm (68 in) in diameter. In the pure radiation case, the sink temperature was set at 267°K (20°F) and in the radiation plus convection case it was set at 294°K (70°F). The convection was assumed to take place in 294°K (70°F) air.

The pure radiation case resulted in a surface temperature of 865°K (1100°F) and when convection was added the surface temperature dropped to 810°K (1000°F).

C.8 ALTERNATE CONFIGURATIONS

C.8.1 POWER BOOM

A variation of the engine room isotope-Brayton power system concept is the "Power Boom" concept (Ref. C-3) as shown in Figure C-1. Here, the isotope-Brayton assemblies are installed in a power boom 4.3 m (14 ft) in diameter and 14 m (46 ft) in length. Two 47.2 kWe heat sources are employed, each providing heat to a Brayton power conversion unit. Two power conversion units are connected in parallel to each heat source; normally, the first of these power conversion units is operating and the second is redundant. This approach requires no shielding to meet the 150 mrem/day maximum allowable dose rate to the crew. For equipment maintenance operation in the boom however, water augmentation shielding is provided. The 4.7 t (10.4 klbs) of water is delivered in a supplementary Shuttle launch.

This system is designed to facilitate repair and replacement of equipment in the power source. The power conversion units are located at the base of the boom where they can be worked on in a shirtsleeve environment. At the other end of the boom, compartment covers are provided for heat exchanger replacement; the hinged IRV's are deployed to the heat dump

made up of a Brayton engine module, a heat source heat exchanger, and a radiator which is configured to become a segment of the cylinder that the entire system forms. The outstanding attribute of this concept is its exceptional flexibility, both of design and operation. In addition to this, the modular concept is compact in size, compatible with Space Station/ Space Base operations, and has a potential for highly reliable operation.

An exploded view of the system is shown in Figure C-9; it illustrates how the PCM's and IRV's are supported by the primary support structure. The four-module system illustrated here is approximately 12.8 m (42 ft) long and 6.0 m (20 ft) in diameter; it weighs a total of 9300 kg (20,500 lbs), including 230 kg (500 lbs) of shielding on the primary support structure. The mass breakdown for the system is shown in Table C-9.

Table C-9. Isotope-Brayton Modular Power System Mass

Assembly	Mass
IRV's (4 Required at 1205 kg each)	4820 kg
PCM's (4 Required at 944 kg each)	3775 kg
Primary Support Structure	705 kg
Total 944 kg each)	9300 kg

The system briefly described here delivers 25 kWe to the Space Station/Space Base bus, developed from four heat sources containing a total inventory of 115.6 kWt of Pu-238. The modular system can be designed with any number of modules from two to eight, depending upon the system characteristics the power system designer wishes to emphasize. Figure C-10 indicates how selected power system characteristics vary with a change in the number of modules.

position, and the covers are installed to provide a seal for a shirtsleeve environment during the heat exchanger replacement operations.

The following components of the power source are listed as in-flight replaceable units:

- IRV's (including heat sources)   (1896 kg ea.)

- Heat Source Heat Exchangers   (75 kg ea.)

- Power Conversion Subassembly   (88 kg ea.)
  (BRU, Recuperator, Cooler, and Ducting)

- Gas Management Subassembly   (45 kg ea.)

- Coolant Pump and Accumulator   (15 kg ea.)

A mass summary of this system is presented in Table C-8. This system is composed of components and subassemblies all of which can be accommodated by the Space Shuttle.

Table C-8. Mass Breakdown for Power Boom Concept

Component	Mass (kg)
HSRV	1896
Heat Plenum	113
Power Conversion Unit(s)	1152
Radiator	376
Cooling System Components	59
Emergency Cooling	91
	3687

C.8.2 MODULAR

Another alternate concept is the Isotope-Brayton Modular Power System (Ref. C-4). It consists of four isotope heat sources in IRV's, each coupled to a power conversion module (PCM)
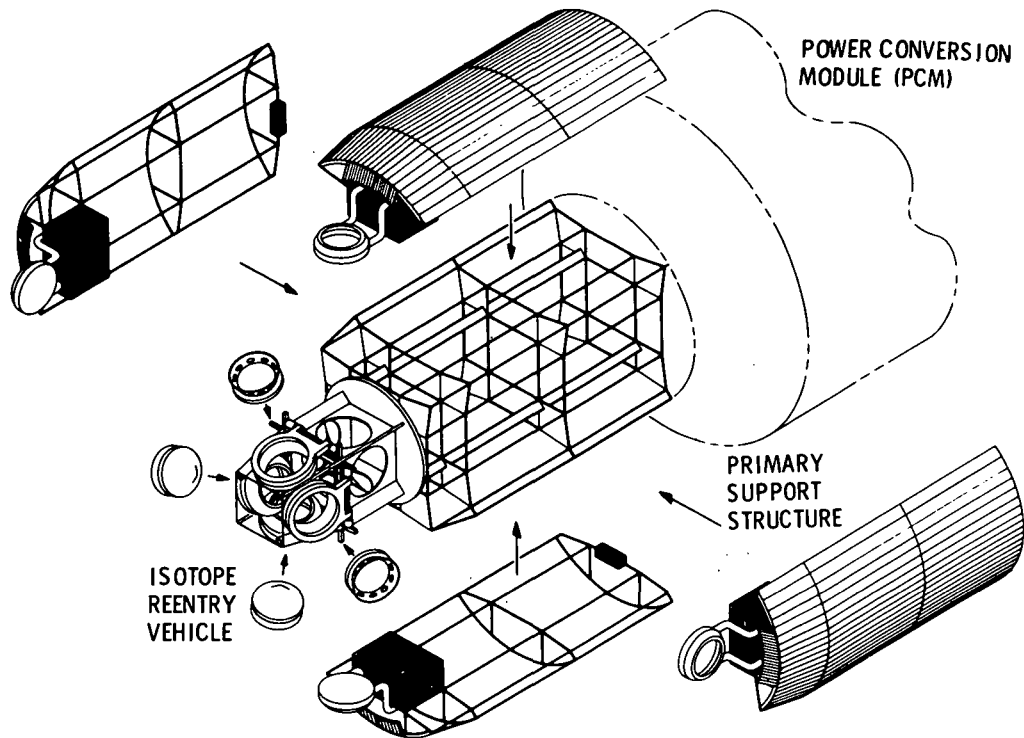
Figure C-9. Building Blocks

NUMBER OF MODULES	SYSTEM MASS (KG)	OVERALL SYSTEM EFFICIENCY (%)	FUEL LOADING (KW$_t$)	RELATIVE SYSTEM COST
2 ①	8010	27.3	98.9	0.92
3 ⊗	8485	25.6	105.9	0.95
4 ⊕	9305	23.4	115.6	1.00
5 ⊗	10,135	21.8	124.0	1.05
6 ⊗	10,885	20.7	130.8	1.11
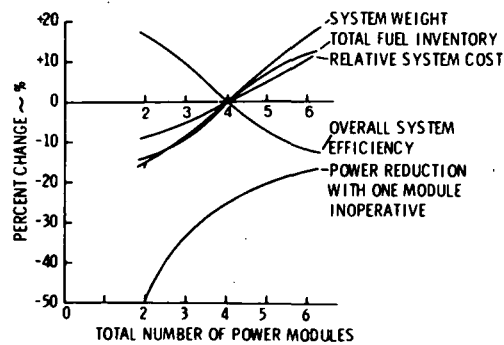
Figure C-10. Module Number Determination

C.9 <u>REFERENCES</u>

C-1 "Space Station Preliminary Design," Vol. 1, Book 1, Electrical Power; MDC G0634, McDonnell Douglas Astronautics Company - West, McDonnell Douglas Corporation, July 1970.

C-2 D. H. Stoddard and E. L. Albenesius, "Radiation Properties of Pu^{238} Produced for Isotopic Power Generators," DP-984, E. I. DuPont De Nemours and Company, Savannah River Laboratory, July 1965.

C-3 "Radioisotope-Powered Space Station Definition," Volume III, Subsystems, MSC-00747 (SD70-502-3), Space Division - North American Rockwell, January, 1971.

C-4 L. H. McCarty, "An Isotope-Brayton Modular Power System for the Space Station," General Electric Company, Space Division, I. E. C. E. C., August, 1971.

CONVERSION FACTORS
INTERNATIONAL TO ENGLISH UNITS

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

I

GLOSSARY OF TERMS

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

II

GLOSSARY OF TERMS (CONT)

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

GLOSSARY OF TERMS (CONT)

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

IV

GLOSSARY OF TERMS (CONT)

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

GENERAL ⊛ ELECTRIC