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NUCLEAR SHUTTLE

SYSTEM DEFINITION STUDY, PHASE III

FINAL REPORT

PREPARED FOR NASA-MSFC
UNDER CONTRACT NAS8-24714
DRL NO. MSFC-DRL-196,
LINE ITEM 3

VOLUME I
Executive Summary

COPY NO. 126

MCDONNELL DOUGLAS ASTRONAUTICS COMPANY

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5301 Bolsa Avenue, Huntington Beach, CA 92647

PREFACE

The material contained in this document represents a portion of the final report documentation for the Phase III Nuclear Shuttle System Definition Study. The study effort was performed as a 12-month extension to the existing Nuclear Flight System Definition Study Contract (NAS8-24714), with the objective of establishing Phase A conceptual definition for two classes of reusable nuclear shuttle concepts. The first concept class is characterized as a 33-ft-diameter configuration that is launched integrally to orbit by a Saturn V INT-21 vehicle. The second concept class is characterized as a modular configuration which is assembled in earth orbit from modules carried to orbit in a space shuttle.

The final report documentation has been organized to provide separable information for the two concepts, where appropriate, and to combine report material common to both concepts in singular documents. The total documentation for the study is listed below, with this document identified in the left margin.

●	Volume I:	Executive Summary
	Volume II:	Concept and Feasibility Analysis
		Part A—Class 1 Hybrid RNS
O		Book 1—System Analysis and Operations
O		Book 2—System Definition
		Part B—Class 3 RNS
O		Book 1—System Analysis and Operations
O		Book 2—System Definition
	Volume III:	Program Support Requirements
O		Part A—Class 1 Hybrid RNS
O		Part B—Class 3 RNS
O		Part C—Test Program Analyses and SRT Requirements
	Volume IV:	Cost Data
O		Part A—Class 1 Hybrid RNS
O		Part B—Class 3 RNS
O	Volume V:	Schedules, Milestones, and Networks
O	Volume VI:	Reliability and Safety Analysis
O	Volume VII:	RNS Project Requirements

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Section 1
INTRODUCTION

The advancement of space technology represented by nuclear rocket propulsion has long been recognized. Early development tests began with the successful KIWI series in 1959. The prospect of developing a successful nuclear rocket stage was enhanced when the NRX-A6 reactor test achieved 1 hour of operation at full power in December 1967.

The leading program in future NASA system development is the space shuttle, which promises significant reductions in transportation cost to earth orbit through the introduction of reusability. The performance capability of the nuclear engine will provide the next major step in the evolution of space transportation systems. The reusable nuclear stage (RNS) extends the economics of reusability to missions beyond earth orbit. The RNS, like the space shuttle, is conceived as a multipurpose transportation system. Initially, it would serve as an interorbital shuttle (primarily lunar and geosynchronous orbits) and provide injection for unmanned probes. In this role and operating in conjunction with the space shuttle, the RNS would reduce transportation costs to lunar orbit by an order of magnitude below Saturn Apollo. The high performance of the RNS would be important for economical performance of ambitious unmanned missions such as a Mars surface sample return probe or delivering large space stations to lunar or geosynchronous orbit. In an evolutionary space program, the RNS would provide unmatched capability for performing manned planetary missions at transportation costs comparable to the Saturn Apollo lunar mission.

This document describes the Phase III Nuclear Shuttle Definition Study which was conducted as a 12-month extension to the Nuclear Flight System Definition Study Contract (NAS8-24714). The initial Phase I study was directed toward defining a nuclear flight propulsion module (NFPM) to be used as a third stage on Saturn V in a expendable mode and the identification of requirements for evolution to an advanced configuration suitable for reusable shuttle and/or manned planetary applications. Both Saturn-derivative and new stage concepts were identified. The Phase II effort was directed toward definition of RNS concepts which would operate in the shuttle mode based in low earth orbit. Following identification of attractive RNS concepts in Phase II, the current study phase completed Phase A definition for two RNS concepts. The first concept is characterized as a 33-ft-diameter configuration that is launched to orbit by a Saturn V INT-21 vehicle. The second concept is characterized as a modular configuration which is assembled in earth orbit from modules carried to orbit in the space shuttle.

Section 2
STUDY OBJECTIVES

The overall objective of this study was to establish Phase A conceptual definition for two classes of reusable nuclear stage (RNS) concepts: a 33-ft-diameter configuration and a modular configuration based on 15-ft-diameter propellant tanks. Specific study objectives which were defined to meet this goal are shown below:

A. Concept definition and evaluation
    1. Update mission performance and timelines
    2. Develop a reliability improvement plan
    3. Perform operations analyses
    4. Define subsystem and system design requirements
    5. Develop system support requirements

B. System trade studies
    1. Perform specific subsystem design analysis
    2. Update flight system definition

C. Program and system definition
    1. Finalize requirements definition
    2. Document baseline system definitions
    3. Complete integrated program plans
    4. Prepare interface recommendations
    5. Define safety and contingency plans
    6. Identify supporting research and technology
    7. Conduct engineering trade studies to support NERVA development

Phase II results served as a strong basis for Phase III study tasks. A major study objective was the identification of operational requirements and their translation into design criteria. A technical definition of both concepts was made which included system specifications, engineering drawings, functional schematics, and system tradeoffs. An integrated program plan was developed including development schedules and costs, manufacturing plans, facility requirements, reliability and quality assurance plans, and an integrated test plan.

Section 3
RELATIONSHIP TO OTHER NASA EFFORTS

The major support system for the RNS is the space shuttle, which provides modular delivery to orbit and propellant resupply as a tanker vehicle (see Figure 3-1). It is the only support system clearly required for reusable operation of a nuclear stage based in orbit. While the nuclear shuttle promises to have a major logistic support requirement function for the space shuttle, cargo bay size limitations may seriously affect the overall economics of the total transportation operation. It was determined in the study that the requirements of orbital support for the RNS are minimal. Such candidate future space systems as orbital propellant depots, orbital maintenance facilities, and remote manipulator units are not required for the RNS. A space tug could be used to support RNS assembly and payload handling, although its functions could be adequately provided by a command and control module from the RNS itself. A chemical lunar lander stage could be used in support of the RNS as a tug and for disposal of NERVA and the propulsion module.

The selected mode of RNS operation is essentially independent of the various space station systems which have been considered. However, some space station elements could become payloads for the RNS. Although the RNS has unique development requirements, it has no basic feasibility questions. The design is soundly based on Saturn stage technology and will benefit directly from the long life system technology developed for the space shuttle.

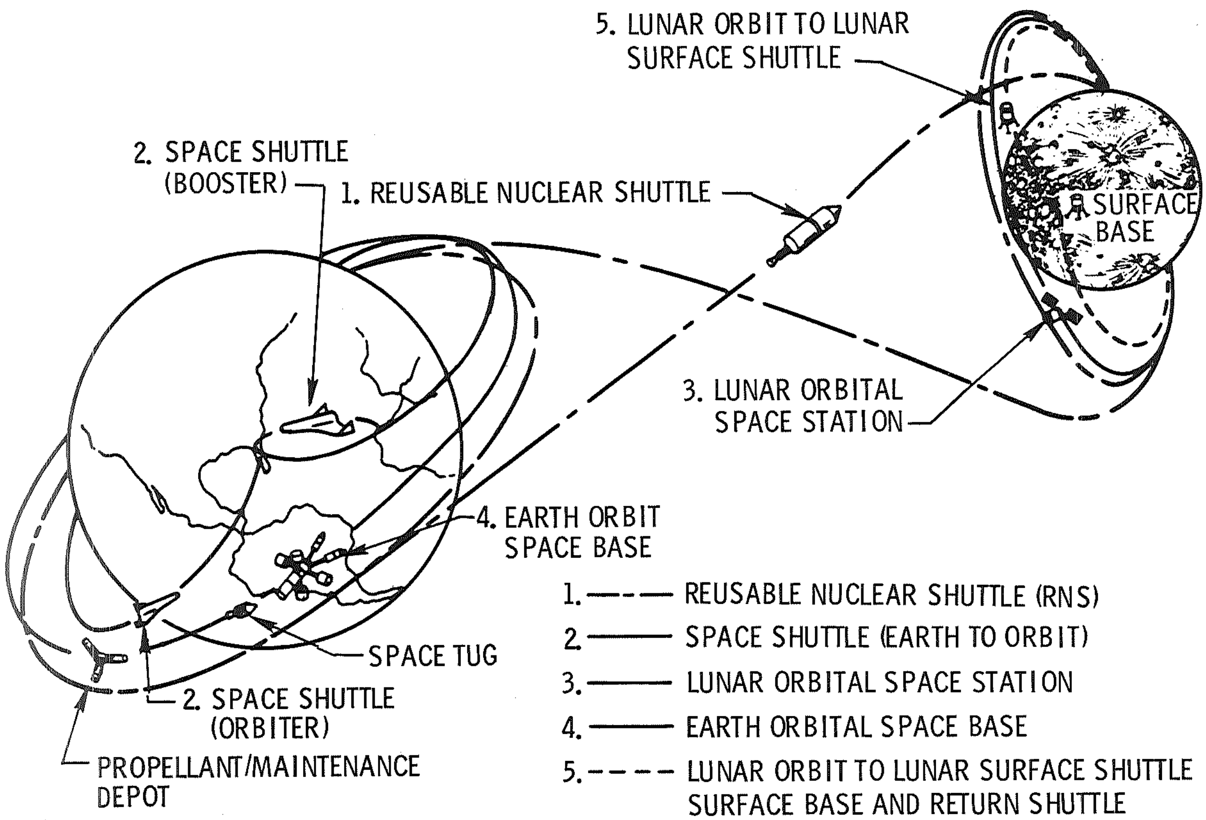


Figure 3-1. Nuclear Shuttle System Operations

Section 4

METHOD OF APPROACH AND PRINCIPAL ASSUMPTIONS

The study plan was formulated upon the results of the preceding Nuclear Flight System Definition Studies. In the preceding studies, a number of potentially attractive concepts were identified for both expendable and reusable launch vehicles. Figure 4-1 illustrates three major classes of the concepts identified in the earlier studies. The first sketch, identified as Class 1, is a single-module configuration suitable for launch into orbit by the Saturn V INT-21 launch vehicle. It would have the highest transportation cost to orbit, but could be expected to have the maximum structural efficiency and minimum redundant functional equipment. Class 2 represents a system placed in orbit by an intermediate sized expendable launch vehicle or high weight lifting capability version of the space shuttle. The third approach, designated Class 3, limited all modules to dimensions that could be transported within the cargo bay of the space shuttle.

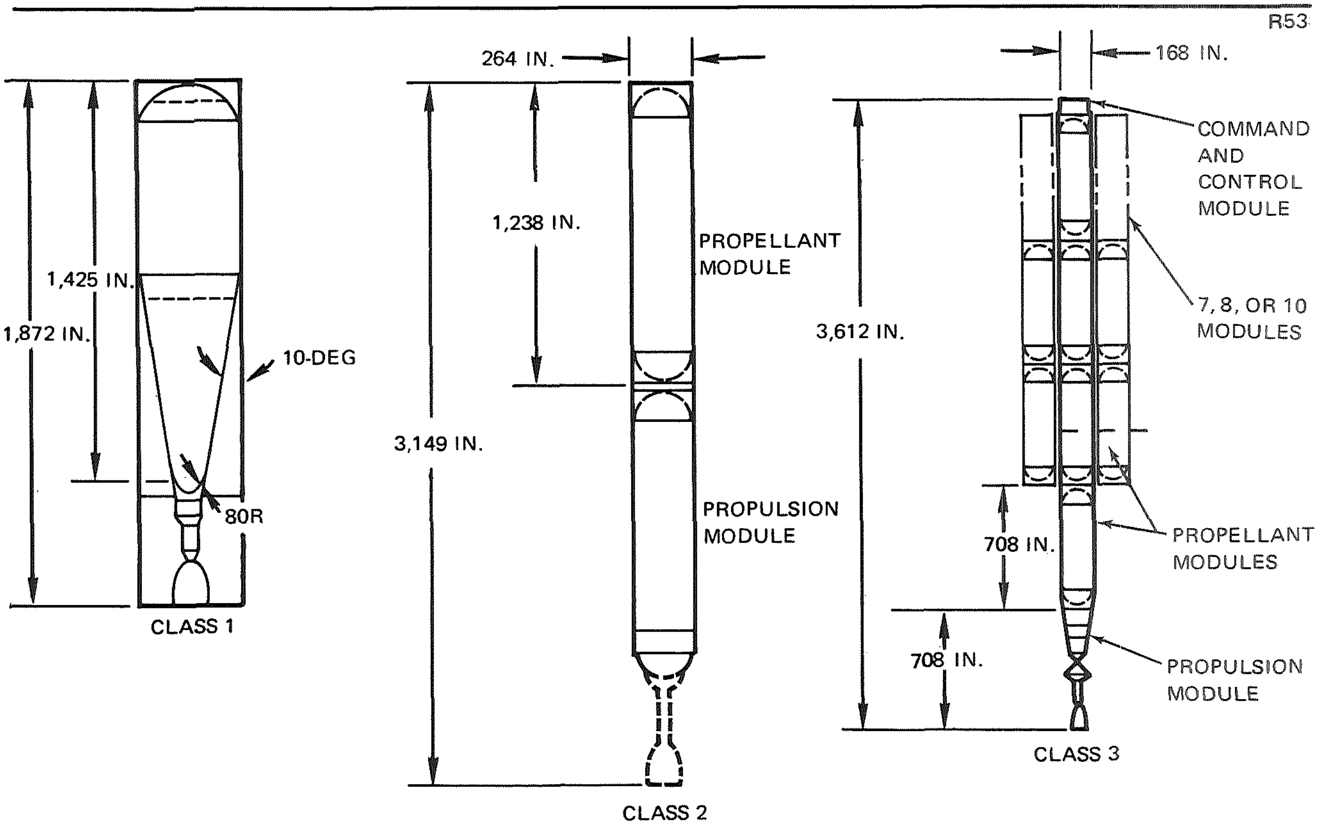


Figure 4-1. Nuclear Shuttle Configurations (Phase II)

During the preceding studies, several key elements were defined which served as a basis for further Phase III activities. Three of these will be discussed here: propulsion module, maintenance level, and Class 3 configuration.

The nuclear engine is about 34 ft long. This allowed a small propellant run tank to be assembled with the engine on the ground as an integral propulsion module which could be launched within the 60 foot cargo bay. The utilization of the propulsion module resulted in the identification of a hybrid configuration for classes 1 and 2 of the RNS. Several attractive operating and design features were identified for this unit and are delineated below:

- o Facilitates NERVA replacement
- o Simplifies orbital docking interface
- o Intermediate shielded location for engine astrionics
- o Advantages accrued for propellant management
- o Reduced design conditions for INT-21 launch
- o Reduced test facility requirements

An additional \$28 million development cost was identified for the hybrid over standard configuration; however, reduction of test facility requirements could more than offset this cost. Additionally, a structural evaluation of the hybrid and standard configurations for all classes of RNS revealed no major structural penalty to the hybrid system.

This result for the Class 1 system is attributable to a lesser launch environment due to the shorter length of the hybrid, and the more favorable geometry of the hybrid which contains more propellant in hemispherical and cylindrical sections than in less efficient conical sections (Figure 4-2).

Maintenance level and approach were investigated in Phase II. Replacement at the component, subsystem, and module level were studied. In order to study a broad range of concepts in detail, a component and subsystem repair and replacement concept was evaluated for Class 1 (Figure 4-3) and a module level for the Class 3. In the former approach, a space tug is docked to the RNS, a subassembly is removed, and a new one is rotated and translated into its place. In the latter concept, the complete front-end unit (command

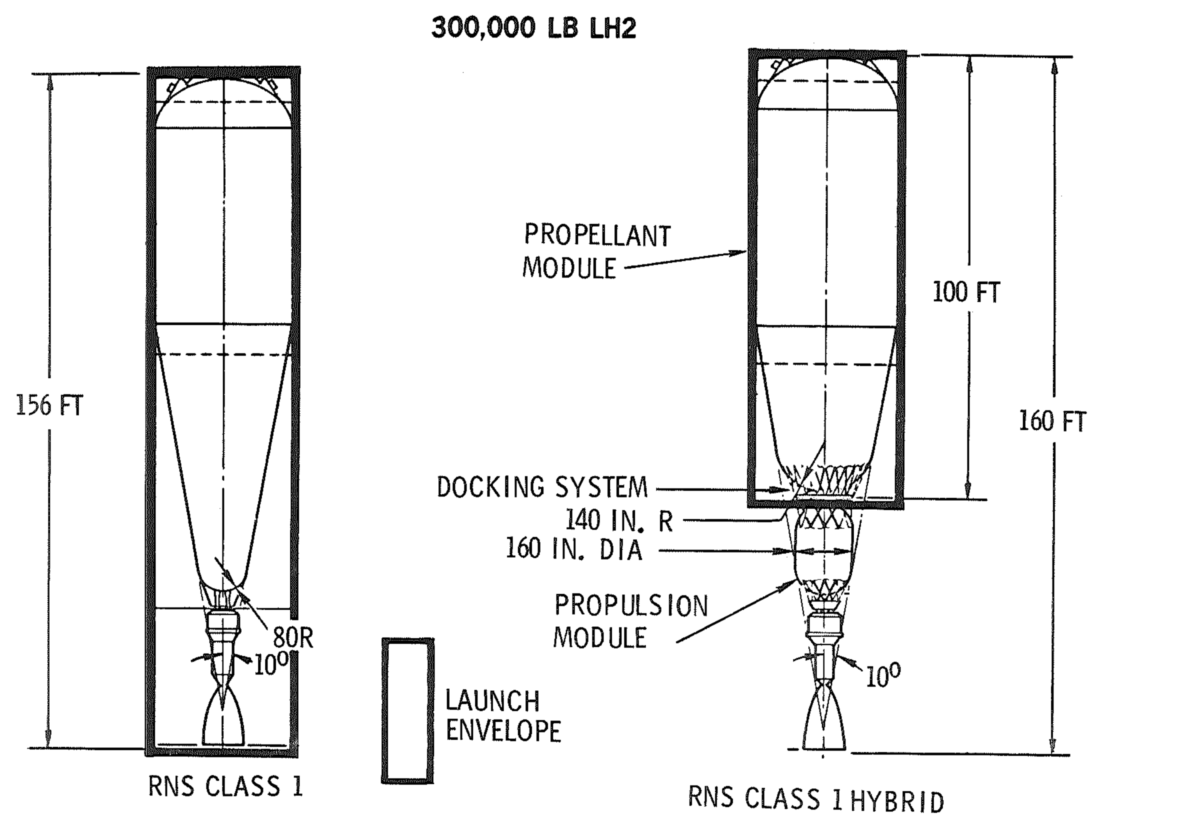


Figure 4-2. RNS Class 1 Configurations

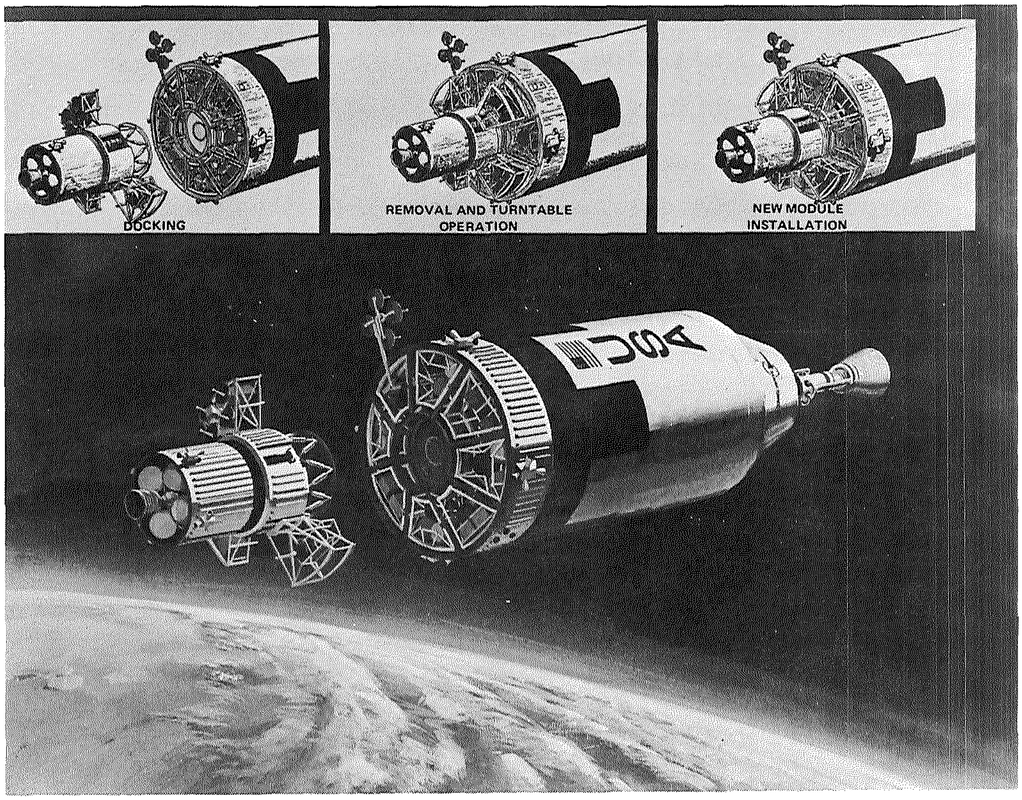


Figure 4-3. Maintenance Concept—Removal and Replacement

and control module) is removed and replaced after each mission. From these studies it was concluded that maintenance on the module level was attractive. It permitted design of a command and control module with 90 percent of the unreliability of the RNS to be maintained on the ground and minimization of the number of unreliable elements on propellant modules. In Phase III other subsystem replacement concepts, including manned operations and use of a command and control module on the Class 1, were to be investigated to arrive at a final maintenance level strategy.

Several requirements dictated the Class 3 configuration. To minimize the shield weight, a tandem set of propellant tanks would be preferable. However, control and stability criteria would dictate a short, squat vehicle. Phase II studies arrived at a four-tier tandem configuration with four outboard tanks supported off the second and third tier tanks in a planar array. In comparing the relative movement between tanks, evaluating required tolerances, and designing requisite structural docking mechanisms, no requirement for a rigid space frame or platform was identified. Further studies were to be performed in Phase III to define the impact of assembly operations on the Class 3 configuration.

This study concentrated on completing a Phase A definition of the selected configurations of both the Class 1 and the Class 3 concepts. Figure 4-4 depicts the Phase III modular concepts to be evaluated on the basis of Phase II results. The Class 2 system remains as a potentially attractive concept. However, NASA determined at the beginning of this study that adequate data for launch vehicles with the required weight lifting capability were not available to permit an adequate definition of the system. Therefore, further study of this concept was postponed.

The present study was organized into nine tasks. The interrelations of these tasks are illustrated in the study logic diagram of Figure 4-5.

The study was started by establishing a reference configuration from each of the two classes of concepts based on previous study results. These concepts were than subjected to detailed operations and systems design analyses with the results being used to make changes to the reference concepts. Extensive reliability and safety analyses in the form of failure mode and effects analysis and fault tree analyses were performed in parallel

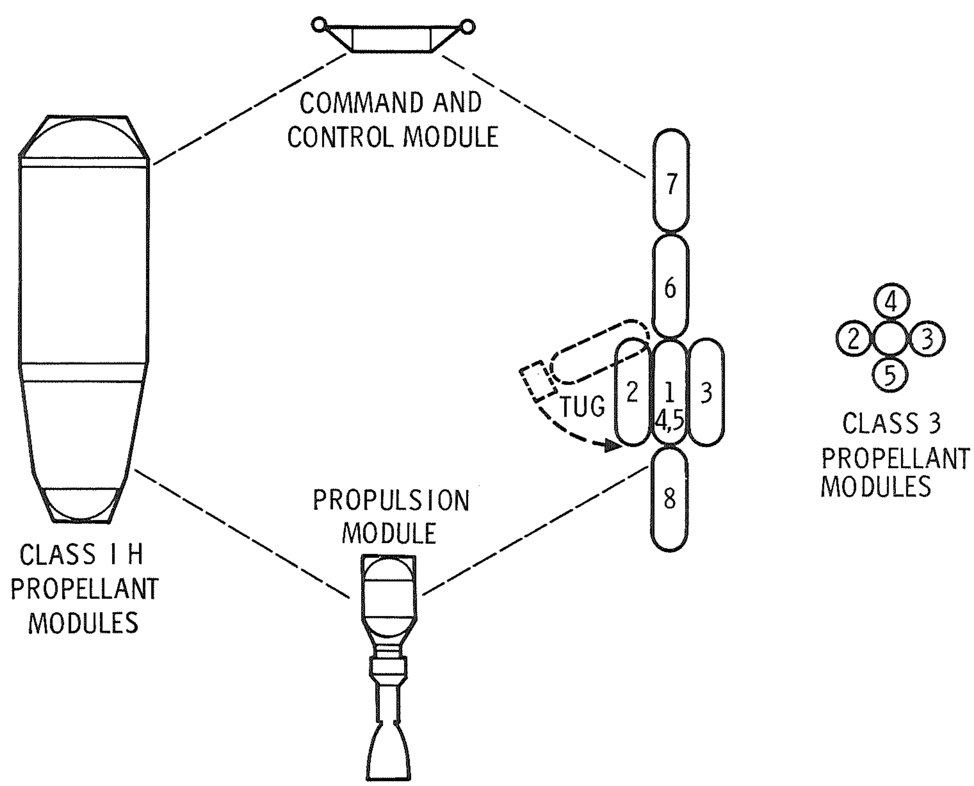


Figure 4-4. Phase III Concepts Evaluated

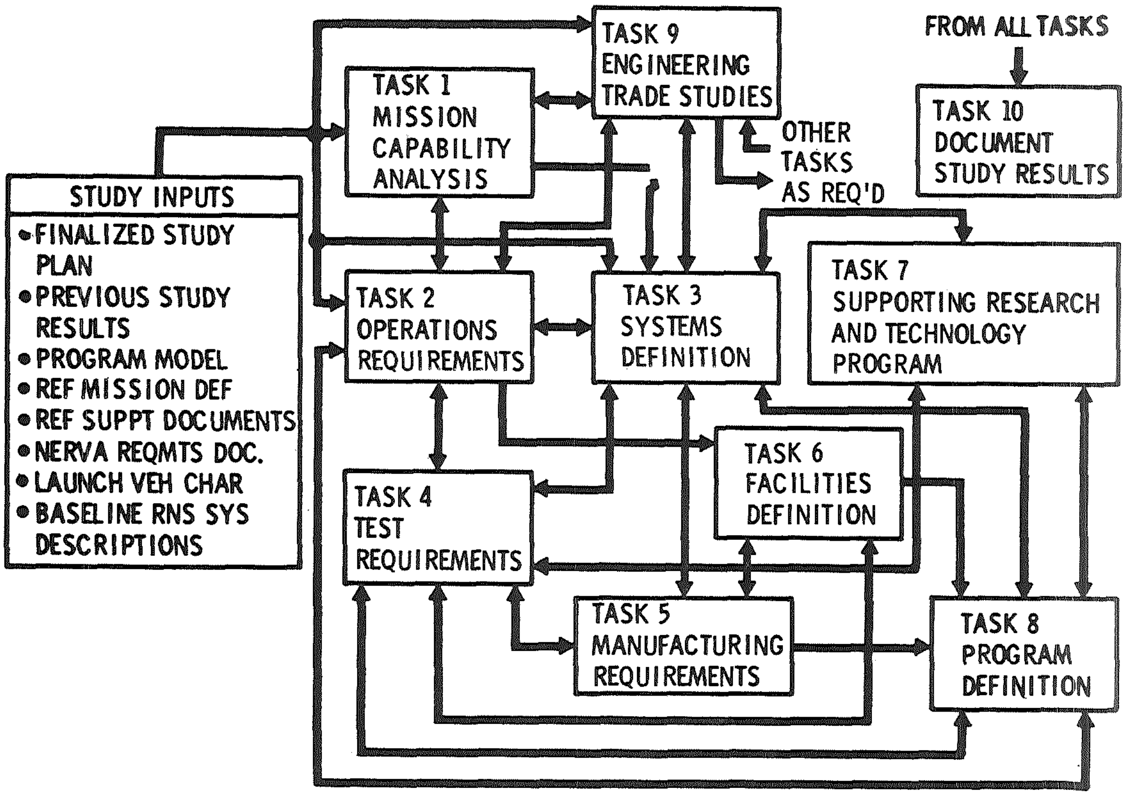


Figure 4-5. Study Logic Diagram

with the design analyses to assure that the selected concepts in addition to having the necessary performance would be safe and reliable.

As the concepts evolved, manufacturing, test, and launch requirements were analyzed with definitive plans established for meeting the requirements. These plans, together with the detailed cost data that were generated, were then used to formulate the integrated program requirements.

Guidelines and Assumptions

The reference lunar missions for operations reporting purposes and worst-condition design analysis are defined in Section 5.1.

The first flight test and initial operating capability (IOC) of the RNS will be in mid CY 1979 and CY 1981. Initial RNS design concepts will reflect a 1974 state of the art.

The space shuttle will provide logistic support to the RNS. Two were considered:

A. 25,000-lb payload capability to 55-degree inclination and 270 nmi yielding 33,000 lb to 260 nmi by 31.5 degree orbit.

B. 40, 000-lb payload capability to 55-degree inclination and 270 nmi yielding 50, 000 lb to 260 nmi by 31. 5 degree orbit.

The cargo bay of the space shuttle will be sized to have a clear volume of 15 ft diameter by 60 ft length.

The program model will consist of lunar shuttle missions only, will consider 2, 4, 6, and 8 RNS flights per year, and will be 10 years. The design life time for the RNS will be up to 3 years in space.

The RNS will be capable of withstanding the applicable natural environment, during all phases of the mission, as specified by NASA TM X-53865 and NASA TM X-53872. The meteoroid shielding will be designed for at least a 0. 995 probability of no tank penetration in one lunar mission (maximum of 45 days). The RNS will be designed to achieve a reliability of 0. 975 for the in-transit phase of each flight.

Pulsed shutdown radioactive decay heat removal on the RNS during a mission will be used to the maximum practical extent for final velocity attainment, midcourse corrections, and/or gross rendezvous maneuvers.

The RNS will be man-rated. All credible single failure modes or credible combinations of failures and errors which result in loss of crew and passengers or unacceptable risk to general population groups will be eliminated by design change and/or mission modification. No single failure or credible combination of failures and errors will prevent or preclude operation of the NERVA engine in the emergency mode.

Total radiation dose from the NERVA engine and plume sources will be limited to 10 REM per passenger and 3 REM per crew member per round trip shuttle mission. Payload attenuation factor will be assumed to be 3.

All costs will be normalized to GFY 1971. An operational cost of $5 million per launch of the space shuttle, and an INT-21 unit cost of $95 million and launch cost of $12 million are assumed. A cost of $13 million is used for the NERVA engine.

Section 5

BASIC DATA GENERATED AND SIGNIFICANT RESULTS

5.1 MISSION APPLICATIONS AND OPERATIONS

5.1.1 Mission Applications

The primary RNS mission applications as a lunar interorbital shuttle. Secondary missions for it consist of a geosynchronous in-orbit shuttle and unmanned planetary probes performed in a reusable shuttle mode. Detailed mission descriptions and performance data are documented in the Mission Planning Handbook.

The lunar shuttle mission provides the basis for RNS design requirements in this study. This mission entails transfer of cargo and men to and from a 260 nmi and 31.5-degree inclination. The design mission consists of eight mainstage burns, which provides for plane rotation at lunar orbit injection and transearth injection (Figure 5-1). Thirty degree plane change maneuvers were specified by NASA and were performed in the throttle mode because of the short engine operation time. A four-burn zero plane change requirement

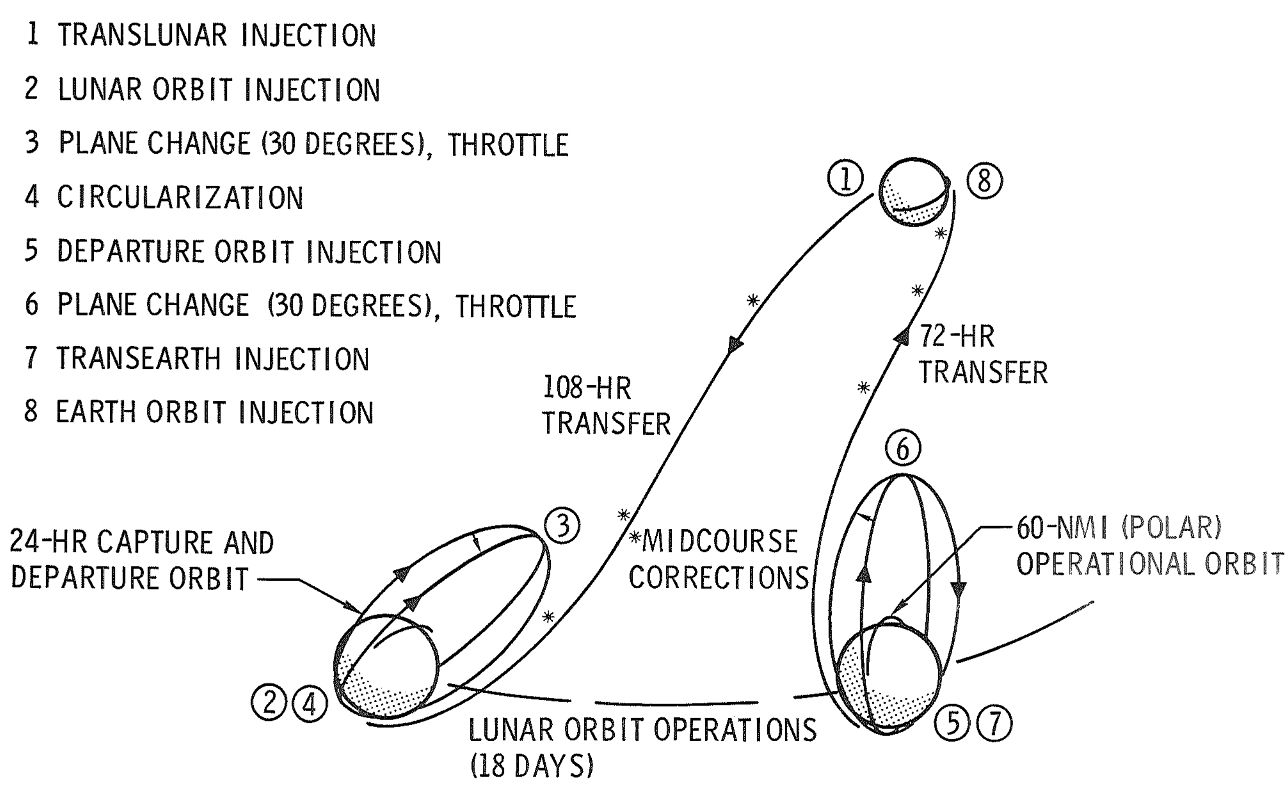


Figure 5-1. Lunar Shuttle Design Mission Profile

mission was defined with a 54.6-day repeating cycle. This later profile was injected directly into a 60-nmi polar lunar orbit and was used as the standard mode of operation. Figure 5-2 shows the performance for the two RNS configurations specified in Sections 5.2 and 5.3. The reference mission considers return of 20,000-lb crew module to earth. For this case the Class 1-H RNS can deliver 100,000-lb payload to lunar orbit for the eight-burn and 127,000 lb for the four-burn missions; and the Class 3, 81,000 lb and 108,000 lb, respectively. For the purposes of this study, an RNS propellant capacity of 300,000 lb was selected. However, RNS payload-to-propellant ratio would benefit from a larger stage capacity resulting from the relatively heavy engine. Figure 5-3 shows the payload delivered to lunar orbit for the case which returns a 20,000-lb crew module to earth orbit as a function of propellant capacity. Geosynchronous orbit payload delivery capability is shown in Figure 5-4. The RNS could be used either by itself in an expendable or retrievable mode, or where it is retrieved and an 80,000-lb propellant capacity space tug is expended for unmanned planetary missions. The relative performance of each of these modes is shown in Figure 5-5. Typical velocity requirements for unmanned missions are depicted.

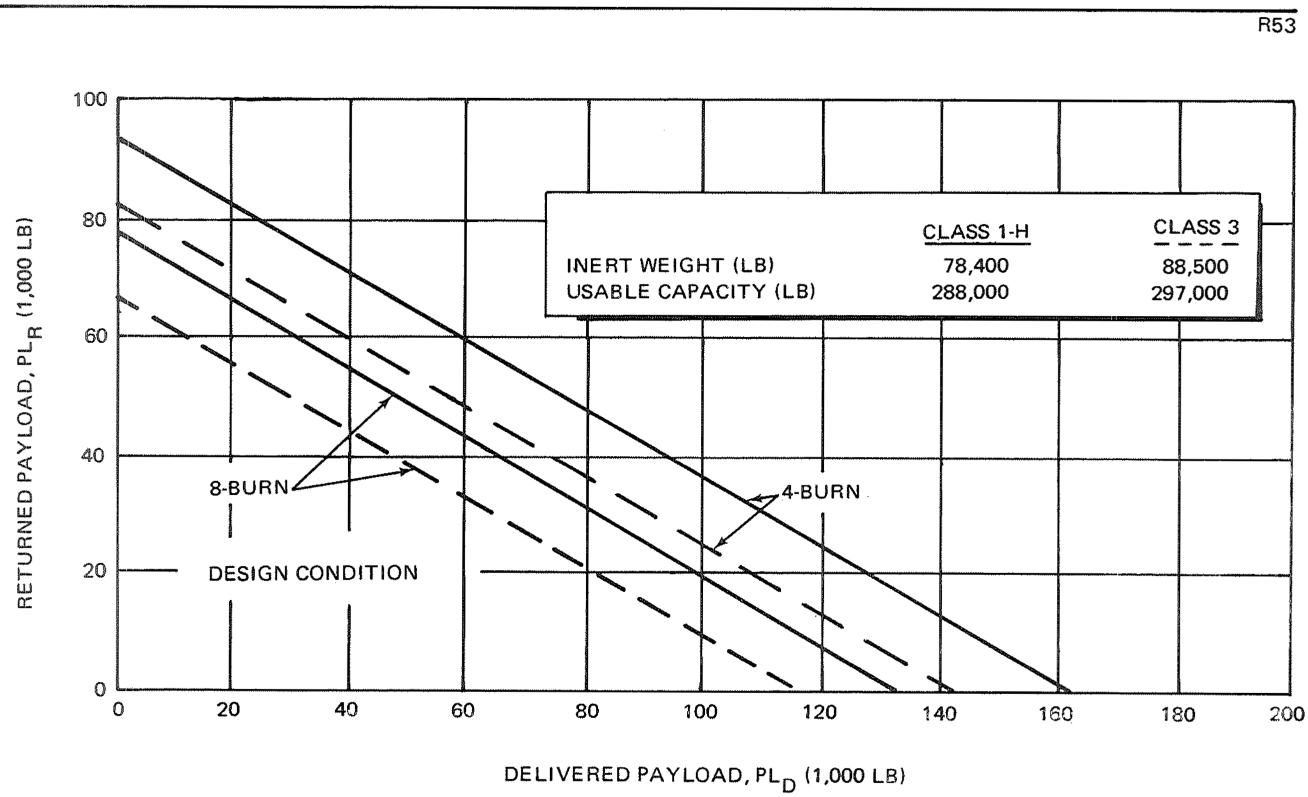


Figure 5-2. Lunar Shuttle Performance

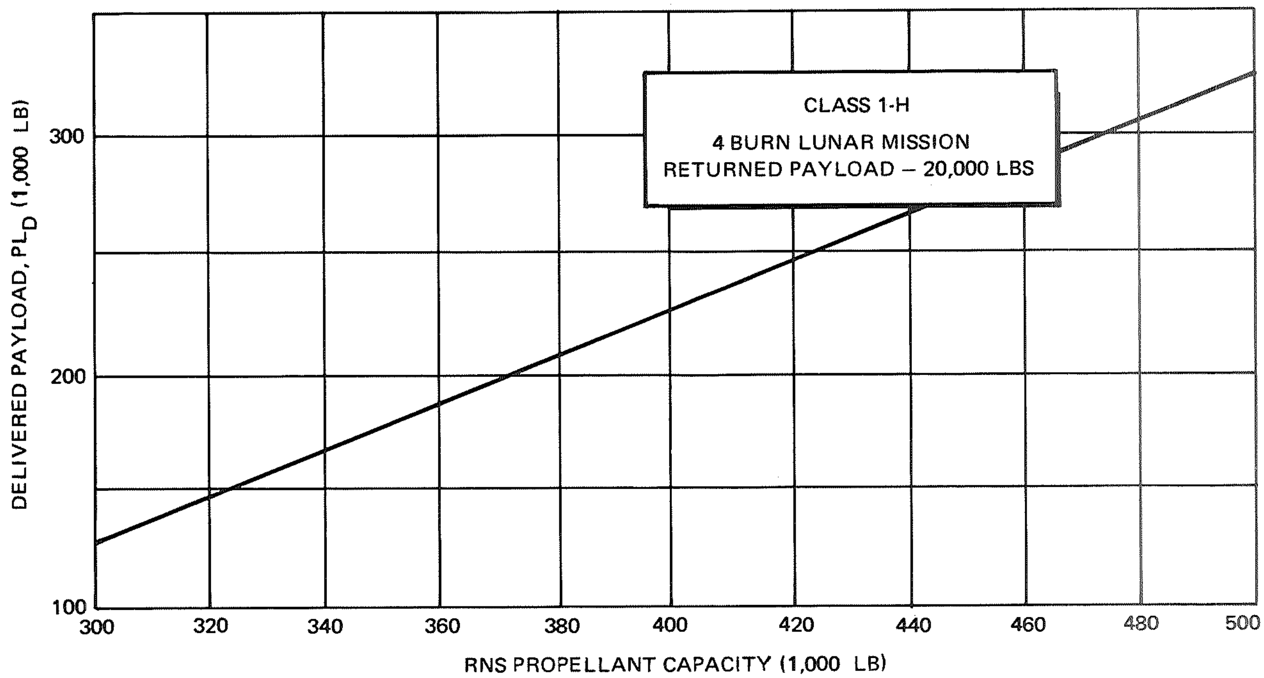


Figure 5-3. RNS Performance Versus Propellant Capacity

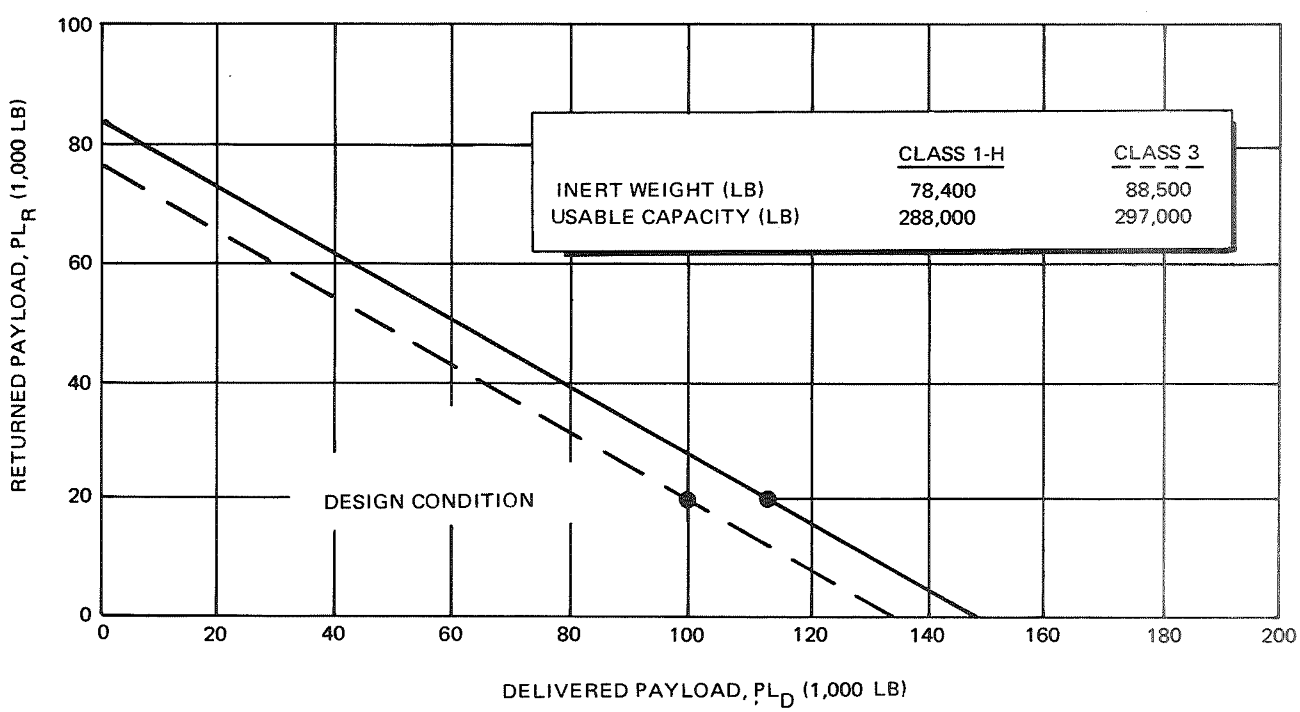


Figure 5-4. Geosynchronous Shuttle Performance

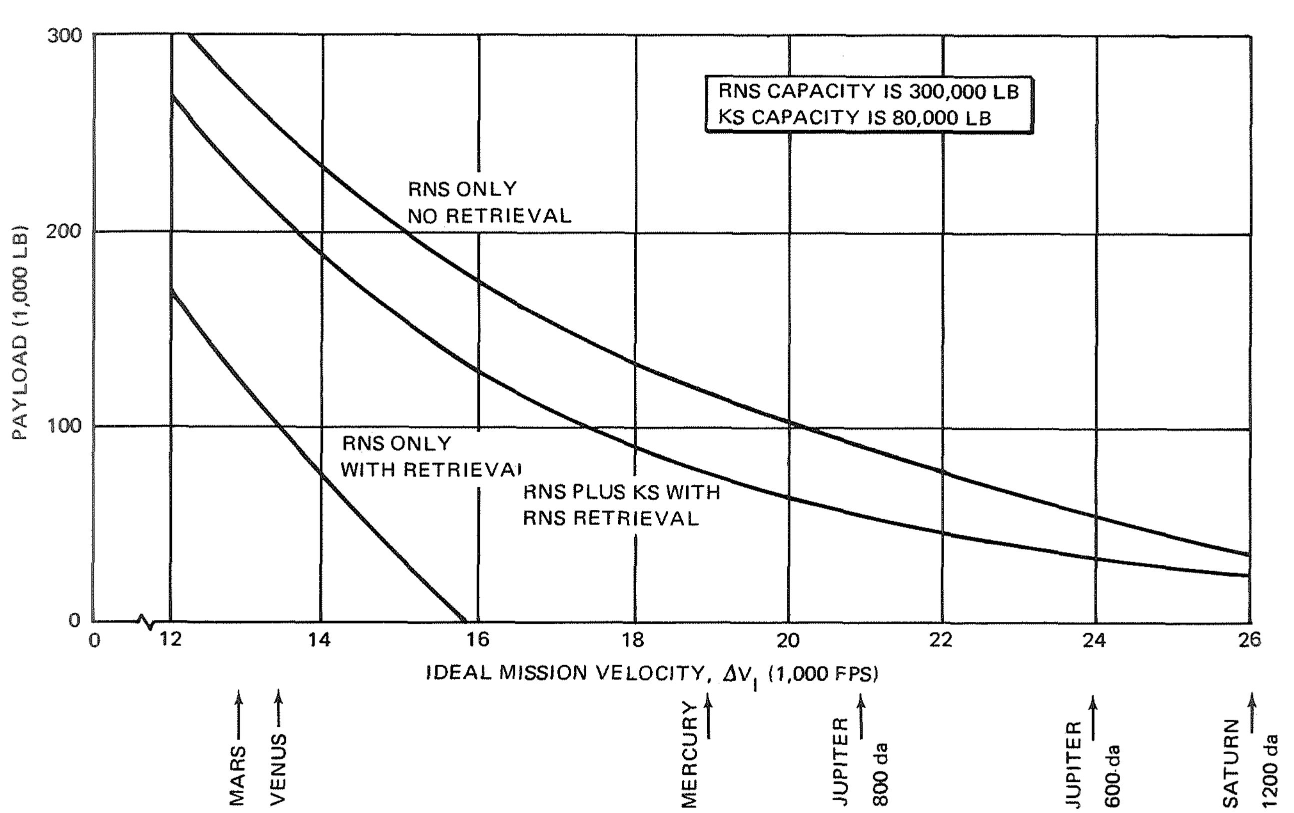


Figure 5-5. RNS Escape Injection Performance—Mode Comparison

5.1.2 RNS Operations

A major portion of the study was devoted to operations analyses to establish a basis for the RNS design. Major categories of operations which were evaluated were: ground and prelaunch operations, launch operations, orbital operations, flight operations, and end of life disposal, and are summarized here along with their impact on design requirements and criteria.

5.1.3 Ground and Prelaunch Operations

The baseline program features are summarized in Section 5.4.

5.1.4 Launch Operations

The launch configuration for the propellant module of the Class 1-H on the INT-21 is 341-ft overall height and presents no facility height problems. The RNS propellant module is designed to comply with the INT-21 ground, launch, and ascent design load envelope, compatible with current design loads for the S-IC and S-II. This imposes a policy of utilizing a wind-biased launch trajectory and accepting a minimum seasonal launch availability of 85 percent for winter winds (Figure 5-6). For the launch of a standard

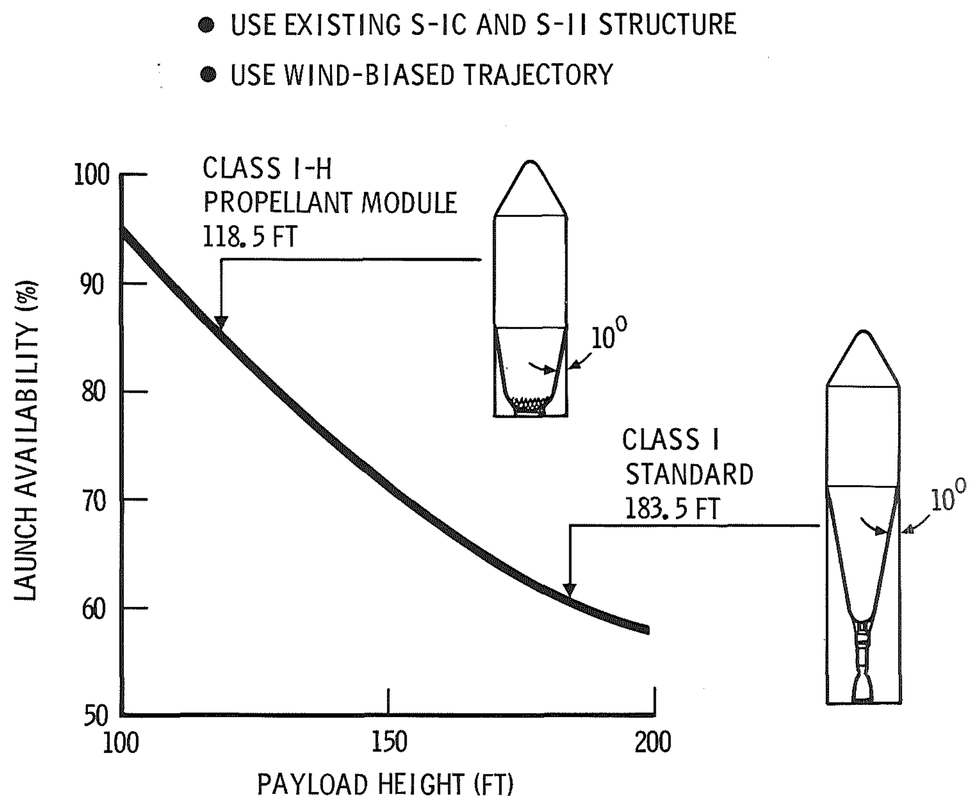


Figure 5-6. INT-21 Launch Implications of RNS Configurations

Class 1, the availability is decreased to 60 percent. The propulsion module for either Class 1 or 3 is launched in an unfueled condition. The NERVA engine contains a neutron-absorbing poison wire safety system during launch to prevent accidental criticality. This safety system is removed after orbit is achieved prior to RNS assembly.

5.1.5 Orbital Operations

The RNS is maintained in a gravity-gradient-stable, local-vertical orientation during all rendezvous and docking maneuvers to minimize RNS attitude control requirements. The impact of assembly and maintenance operations on candidate configurations was assessed.

The Class 1 Hybrid vehicle consists of three discrete modules. Maintenance is performed by replacing these modules analogous to initial orbital assembly. The command and control module (CCM) is recycled to the ground after each mission for maintenance and replenishment of the expendables (APS propellants and fuel cell reactants). The space shuttle is the basic orbital support system and no additional facilities or systems are required.

For initial orbital assembly the CCM is launched first, followed by the propellant module. The CCM rendezvouses with the propellant module and docks to it. Then the propulsion module is launched by the space shuttle (Figure 5-7). It is deployed and separates itself from the space shuttle and maintains a stable attitude using its cold-gas attitude control system. The self-propelled RNS assemblage then docks to the propulsion module. During CCM replacement, the old CCM removes itself, leaving the RNS stabilized by gravity gradient.

The approach for assembly and maintenance in the Class 3 concept is analogous to that for the Class 1 Hybrid with the exception of the additional requirements imposed by the multiple propellant module configuration. The propellant modules are assembled initially in the sequence indicated in Figure 5-8 employing end-to-end docking and rotating the outboard modules into the cruciform cluster. The top of the RNS is completed first, the CCM is attached, and then the bottom is assembled with the propulsion module last. Two space tugs are required for the assembly and clustering operations to both stabilize the vehicle and perform the module rotations. A very small

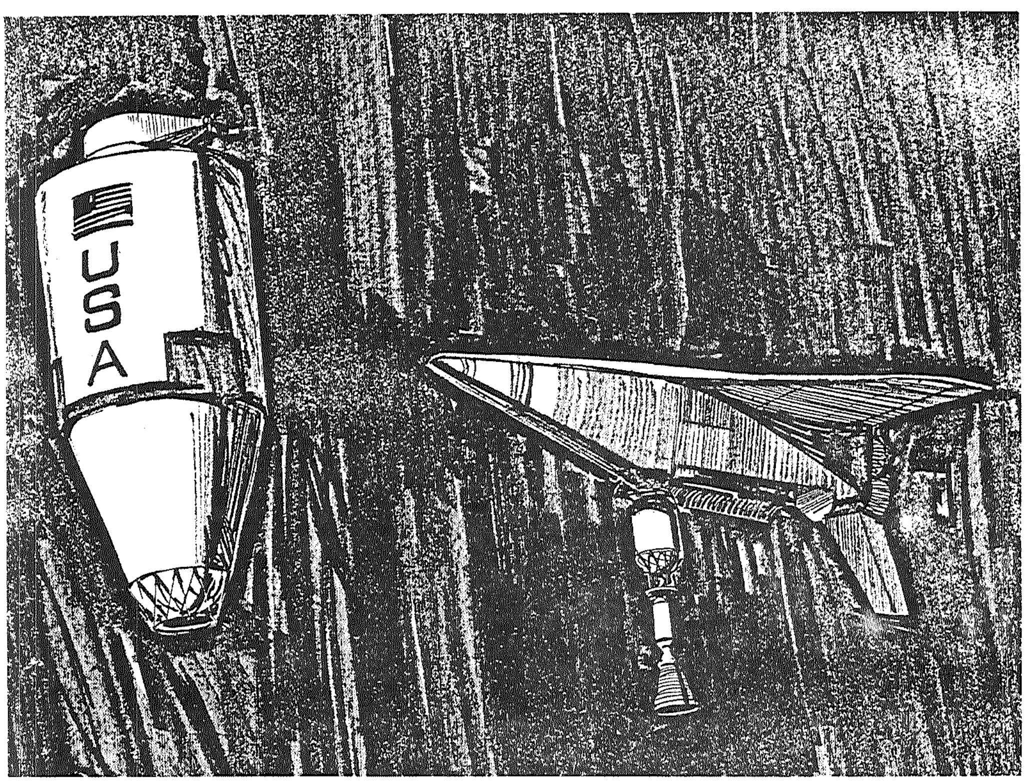
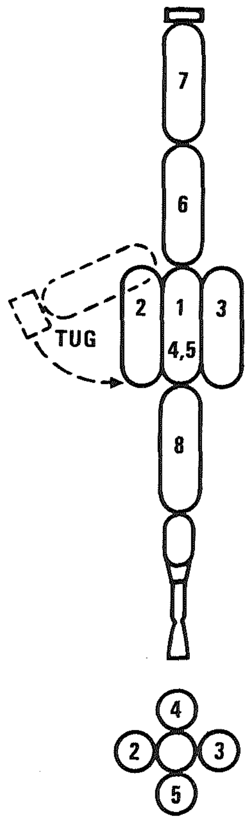


Figure 5-7. Orbital Assembly—Class 1H

APPROACH

- MAINTENANCE AT ASSEMBLY LEVEL
- RECYCLE CCM TO GROUND AFTER EACH MISSION
- 2 SPACE TUGS (OR CCM) FOR ASSEMBLY AND CLUSTERING
- SPACE TUG FOR NERVA DISPOSAL



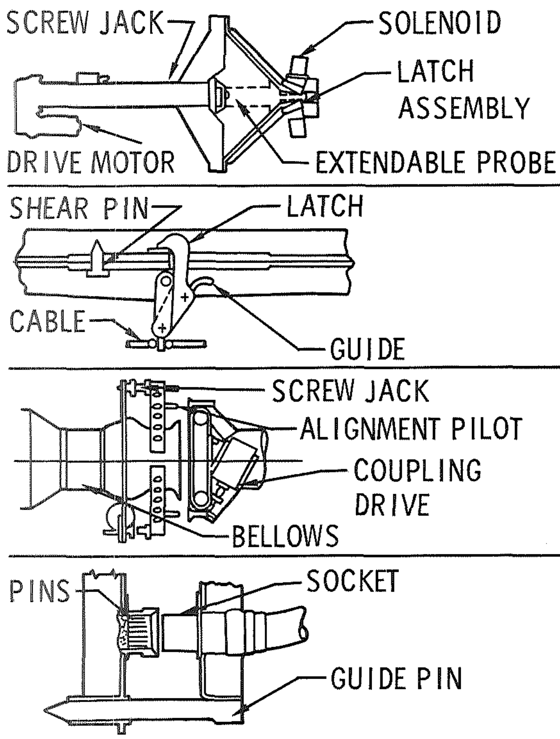
OPERATIONS

- END-TO-END DOCKING
- ROTATE OUTBOARD MODULES INTO CLUSTER
- COMPLETE TOP OF RNS
- PROPULSION MODULE LAST, SELF-STABILIZED

Figure 5-8. Class 3 Assembly and Maintenance Concept

propulsion requirement for these operations would permit use of an RNS CCM to perform the role of a tug. A cruciform Class 3 configuration was selected. Fluid and electrical interfaces are accomplished in orbit using remote assembly mechanisms.

The approach to implementing the module docking and functional assembly operations is depicted in Figure 5-9. First, docking is accomplished with a probe and drogue mechanism. A deployable soft probe is used so that docking forces are not required to actuate the system. This mechanism is used to draw the modules together over the final 3 in. so that a set of cable-actuated latches can be engaged to lock the modules together. After structural latching is completed, fluid line coupling is initiated with a remote-coupling mechanism as shown. A screw jack mechanism deploys the line across the interface and a coupling mechanism closes over the flange to complete the mating. A dual-seal flange is provided for leak check of the interface. After fluid line coupling is completed, the electrical automatic panel assembly is accomplished utilizing a ball screw jack drive to engage the socket and receptacle. Guide pins are employed for both the fluid line coupling and the electrical panel assembly to ensure alignment. All these operations appear feasible.



PROBE AND DROGUE DOCKING MECHANISM
- 12-IN. DEPLOYMENT OF SOFT PROBE
- 4 LOCATIONS

CABLE ACTUATED LATCHES AND SHEAR PINS
- 12 LOCATIONS

FLUID LINE COUPLING
- 3-IN. DEPLOYMENT
- DUAL SEAL FLANGE

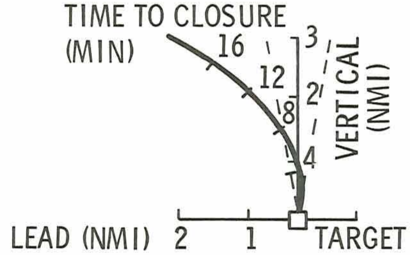
ELECTRICAL PANEL ASSEMBLY
- 9 CONNECTORS
- 826 PINS TOTAL

Figure 5-9. Orbital Assembly Interface

Rendezvous constitutes arrival of the orbiter in the proximity (500 ft) of the RNS staging and assembly area. Two phases of terminal rendezvous are closed loop, utilizing radar acquisition of the RNS assemblage. A stable orbit closure trajectory is used which terminates the closure maneuvers within the shadow cone provided by the NERVA radiation shield (Figure 5-10). The orbital transfer mode is essentially line of sight over the 500 ft range from the orbiter to the RNS. Sensor and thrustor accuracies were evaluated and found adequate for automated operation. The cold-gas attitude control system of the propulsion module stabilized the assembly during CCM replacement and was sized to accommodate missed docking operation.

Propellant resupply is a major orbital support operation. For propellant resupply, a stable orbit maneuver is used to keep the dose received by the first crew, docking 48 hours after shutdown and staying 24 hours, to about 1 REM. Before initiating the mission, propellant is vented to reject the heat from propellant chilldown and orbital heating during refueling. For propellant transfer, a linear acceleration transfer is utilized with thrust provided by the space shuttle. Transfer line chilldown is accomplished

STABLE ORBIT CLOSURE TRAJECTORY



- TARGET IN VERTICAL ATTITUDE
- TERMINATE CLOSURE WITHIN RADIATION SHIELD SHADOW CONE
- LINE OF SIGHT CHANGES < 4 DEG/SEC

PROPULSION MODULE STABILIZED FOR ASSEMBLY

- ACCOMMODATE MISSED DOCKING OPERATION
- MODULE ASSEMBLY OR CCM REPLACEMENT

SENSOR AND THRUSTOR ACCURACIES ADEQUATE FOR AUTOMATED OPERATION

	LASER RADAR	10 LB-SEC IMPULSE TO PAYLOAD/CCM
VELOCITY (FPS)	0.016	0.02
PITCH (DEG/SEC)	0.01	0.04
ROLL (DEG/SEC)	0.01	0.3

Figure 5-10. Rendezvous and Docking

during the settling period. A two thrust settling program is used where the first settles the propellant gently and a second larger thrust dissipates the turbulence.

Checkout of orbital assembly interfaces is provided by the CCM or space tug during the assembly operations. The RNS performs autonomous onboard checkout for the orbital countdown. Component functional check is utilized to avoid the consumption of expendables and NERVA criticality associated with simulated operations. Except for a small increase in instrumentation no additional components or subsystems are required to accomplish RNS checkout. Checkout capability is provided with bulk storage of procedures. The processor rate requirements are small and can be handled off-peak.

5.1.6 Flight Operations

An autonomous navigation and guidance capability was selected over a ground-directed system. The attitude reference is common for this approach and represents only a modest increase in software. Sufficient accuracy is provided with an autonomous approach, and an independent ground tracking backup is provided.

The RNS provides onboard data evaluation. Evaluation of processor requirements indicated that stage functions could be satisfied with a single state-of-the-art processor. Data compression to the ground would be utilized in earth orbit to transmit to ground stations without requiring a relay satellite. Ground data processing would be employed to accomplish fault prediction.

Since the propulsion module participates in all operations and contains all of the propellant management functions required for the stage, it is key to the RNS hybrid configuration. The RNS propellant management operations are shown with reference to the propulsion module in Figure 5-11.

The feed system for both the stage and engine are conditioned during the startup operation employing an integrated stage/NERVA chilldown system. A separate pump is also located in the feed system to refill the run tank, if required, before startup. Settling is completed at high thrust using the NERVA startup thrust ramp. A thrust hold is integrated into the startup ramp at the throttle point to permit propellant settling with zero NPSP. During the autogenous startup operations, the small volume of the propulsion module run tank reduces the pressurant demand on NERVA. The 10,800-lb

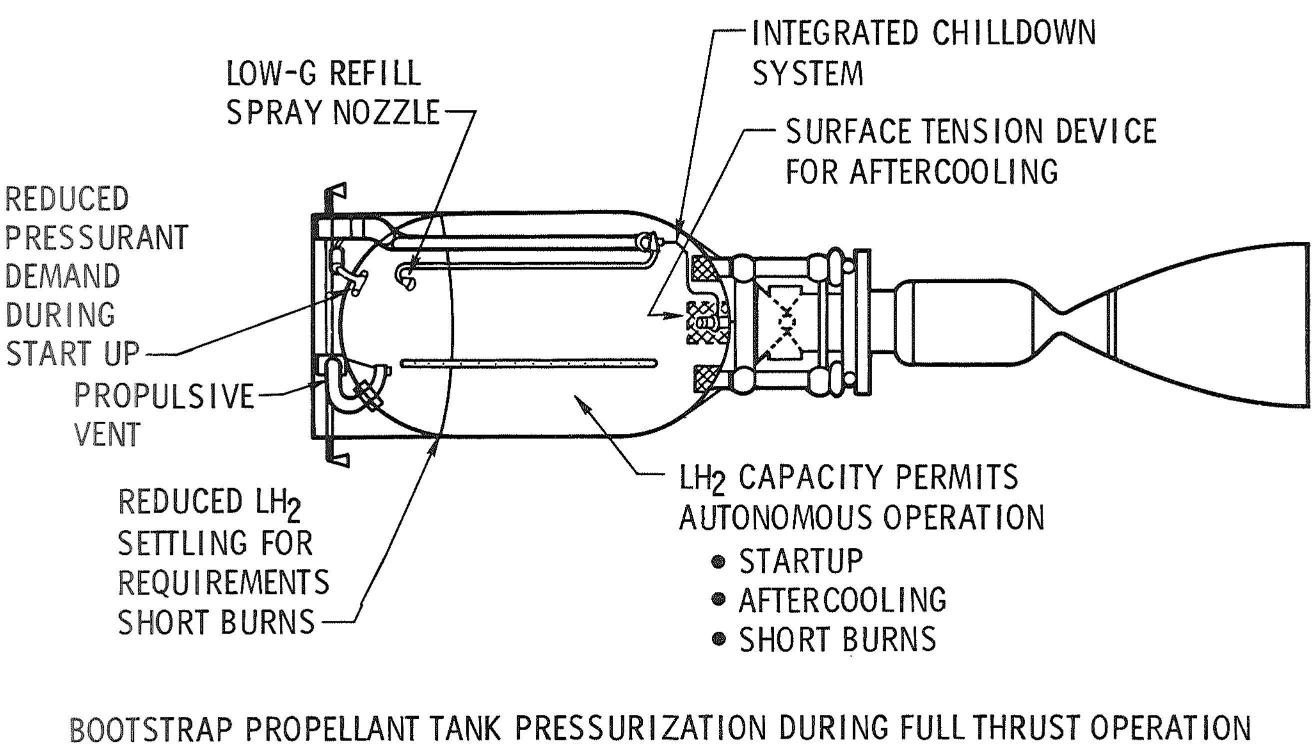


Figure 5-11. Propellant Management Operations

LH_2 capacity of the run tank is sufficient to permit autonomous operation during startup, aftercooling, and short burns. Its limited volume reduces LH_2 settling requirements for short burns. The autonomous operation of the run tank permits bootstrapping the propellant tank pressurization during NERVA full-thrust operation. Propellant level control is utilized in the run tank and its depletion during startup is limited (5,000-lb LH_2 minimum) to retain its benefit for reducing the radiation dose to equipment located at the top of the run tank.

Propellant acquisition for aftercooling is provided with a surface tension device. This operation is also simplified by the reduced run tank volume. MDAC adopted the ground rule of only supplying saturated liquid conditions during aftercooling since major advantages were found in being able to operate at reduced pressures and saturated conditions, and no reason was identified as to why it was not attainable with the current engine design. The surface tension pulse basket concept was adopted as a low weight, least complicated system. The study identified the potential for an 8,400-lb improvement in payload delivery through use of the cooldown impulse. If the cooldown requirement were somehow eliminated, the further potential payload improvement would be 23,540 lb. An evaluation of thermal radiator effectiveness indicated that a system capable of rejecting only 100 to 250 kw would achieve most of the potential gain.

A simplified propulsion module control system was devised which permits independent operation of the propulsion module and accommodates startup and shutdown ramps with minimum additional pressure head built into the system. This system is based on knowing only where the liquid level is located. Dynamic simulations of malfunction modes established that liquid level overshoot during tank refill could be controlled and the system would operate well if the NERVA flow rate demand was reduced.

For this study 36 attitude maneuvers were assessed for the reference mission profile with a resultant requirement of 145,000 lb-sec. An assessment of total APS impulse requirements for all operations totaled 450,000 lb-sec.

5.1.7 End-of-Life Disposal Operations

A reusable tug approach was adopted as a baseline mode for disposal of the propulsion module (Figure 5-12).

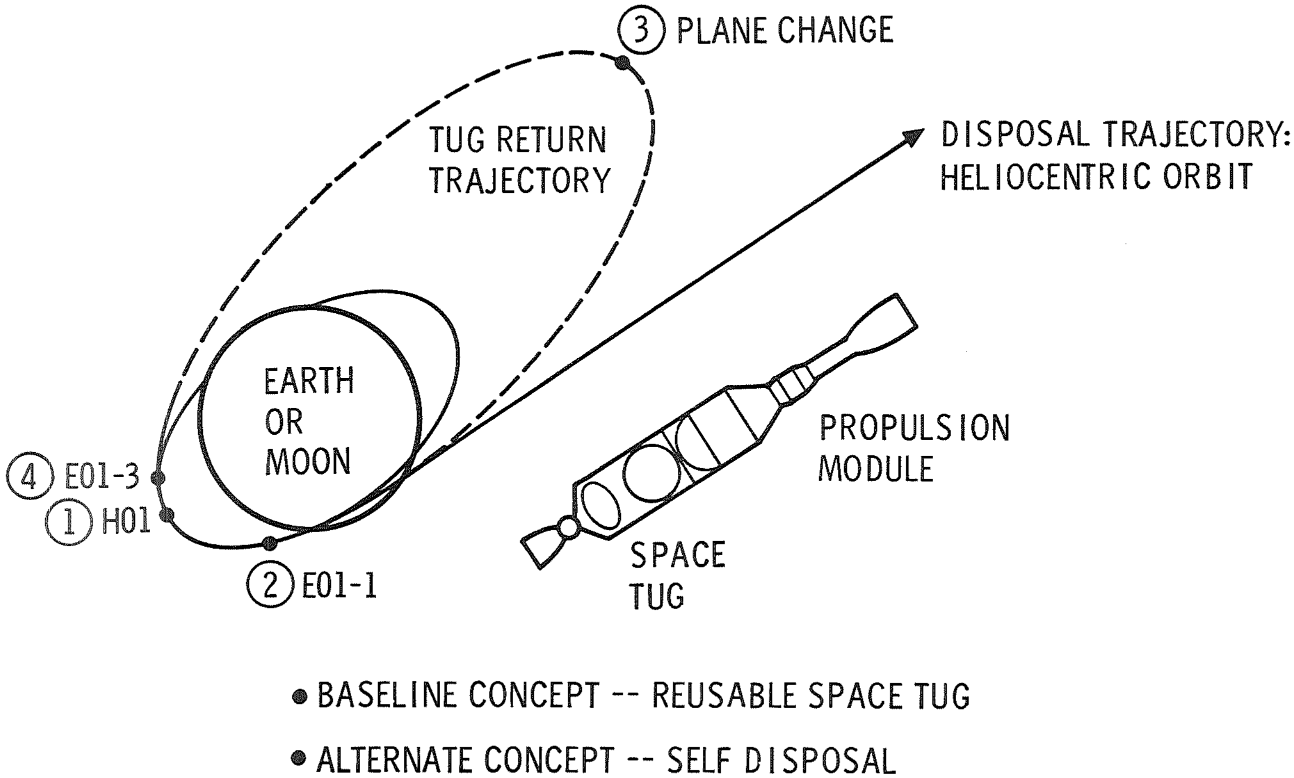


Figure 5-12. NERVA End-of-Life Disposal

5.2 CLASS 1-HYBRID

This section contains a brief description of the reusable nuclear stage (RNS) Class 1-Hybrid concept. As discussed in the preceding section, it is maintained and replenished in earth orbit by the space shuttle. Both the Saturn V INT-21 launch vehicle and the space shuttle are utilized for initial deployment.

A sketch of the reference configuration is shown in Figure 5-13. The three distinct modules, which can be assembled and disassembled in space, are shown. The propulsion module contains NERVA and a small run tank of propellant. The propellant module provides the main propellant tankage and minimal propellant management subsystems. The command and control module (CCM) is located at the forward end of the stage and contains most of the functional equipment and all of the expendables except for mainstage LH_2. The auxiliary propulsion engines are located on outriggers on the CCM. The pitch, yaw, and roll motors are all of a common size of 50-lb thrust. This module is replaced between missions in earth orbit, thereby effecting a replenishment of expendables and all scheduled maintenance.

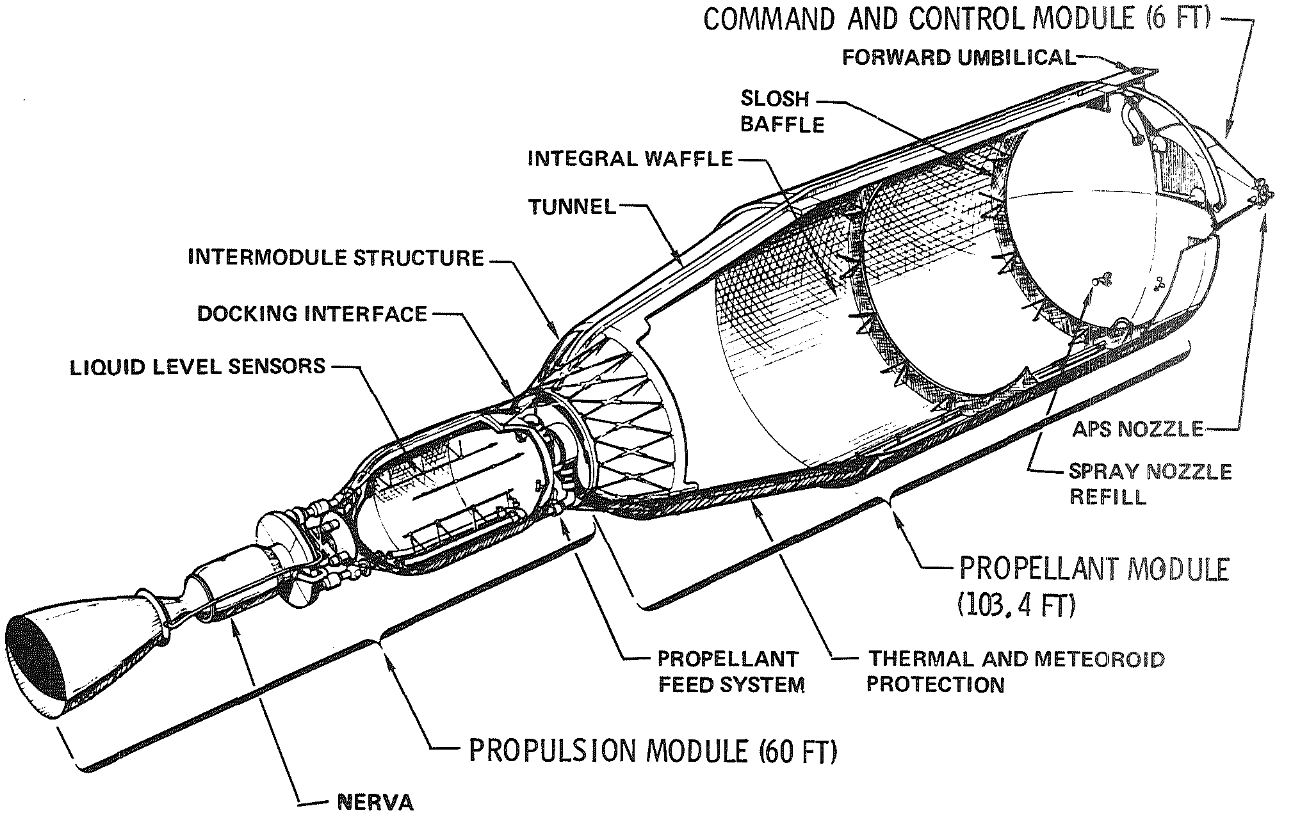


Figure 5-13. Class 1 Single-Module Hybrid RNS

This provides effective maintenance because over 90 percent of potential RNS failures and most lifetime-limited equipment are located on this module.

Both the propulsion module and the CCM are designed to be transported to earth orbit within the cargo bay of the space shuttle. This facilitates replacement of the CCM as noted, and of NERVA, as might be required because of failure or to extend the lifetime of the RNS beyond that of the engine. The RNS is resupplied with LH_2 in earth orbit by the space shuttle. All modules are designed for automated, remote assembly in earth orbit under the control of the CCM. A probe/drogue docking system is employed. A laser radar ranging system is provided on the CCM for this operation with optical corner cubes contained on the other modules to aid in alignment and rendezvous operations.

The total propellant capacity of the stage is 300, 000 lb LH_2, of which 10, 850 lb is contained in the run tank on the propulsion module. The modules are contained within a 10-degree half-angle cone subtended by the NERVA reactor, determined from a combined optimization of structural and shield weights.

However, separate launch of all modules allows the propellant module to be launched on the Saturn V INT-21 launch vehicle without imposing the requirement for structural modifications. Both tanks are fabricated from integrally stiffened aluminum alloy. The forward dome of the propellant module tank and both domes of the run tank are hemispherical for minimum weight. Isogrid structure is used on the CCM to aid equipment mounting. Fiberglass composite structures are employed for load transmission between modules and for the thrust structure in order to limit heat transfer to the propellant while providing an efficient structural configuration. Thermal insulation is provided by three blankets of high-performance insulation consisting of alternate layers of doubly aluminized mylar and dacron net. Meteoroid protection is provided to the tank and to this insulation by a layer of flexible foam and an outer fiber glass shroud. This system was selected on the basis of hypervelocity impact tests on this and other candidate protection schemes.

Nearly autonomous operation of the propulsion module is provided with the propellant module function limited to resupply of the run tank during full power operation. All startup, shutdown, and aftercooling operations are performed autonomously by the propulsion module. Redundancy is employed in all of the propellant management components. A unique feature of this design is the provision of a pump-fed recirculating chilldown system for conditioning both NERVA and the RNS feed ducting prior to startup. Operation of this system is integrated with the startup sequence utilizing the autonomous capability provided by the run tank on the propulsion module.

The propulsion module contains a simplified stored gas attitude control system which uses hydrogen gas and is recharged from the NERVA engine. A control system incorporating gyros and control logic is provided.

An autonomous navigation capability is provided in the CCM. Two sets of accelerometers are used to cover impulse management during aftercooling as well as full-power operation. Redundant centralized processors, capable of satisfying all stage and NERVA processing requirements, are connected to a central high-speed memory to form the RNS processing complex. A bulk storage, auxiliary memory unit holds all operational and checkout procedures and data for fully autonomous functional and checkout operation of the RNS. A data bus system is used for communication between these processors and other subsystems on the CCM and the other modules. Two data bus terminals are dedicated to NERVA. One is provided for the NDICE on the CCM with the other provided on the propulsion module for NERVA. The data bus system is configured on the bases of systems being developed for the space shuttle.

The primary power source, consisting of dual fuel cells, is contained on the CCM. Additional secondary power for peaking and emergency power is provided by rechargeable AgZn batteries on the CCM and on the propulsion module. Fuel cell reactant storage is common with that of the cryogenic APS propellant. Both the fuel cell and auxiliary propulsion system utilize equipment being developed for the space shuttle.

An independent, hardwired emergency detection system providing emergency commands as well as astronaut display and manual override is provided. Ground telemetry and uplink communications are performed by redundant transmitters and receivers compatible with current space communications networks.

A weight statement for the RNS Class 1-Hybrid concept is given in Table 5-1. A comparison with the Class 3 concept described in the next section is also shown.

5.3 CLASS 3 RNS

This section contains a brief description of the RNS Class 3 concept. It is launched, maintained, and replenished in earth orbit by the space shuttle.

A sketch of the reference configuration is shown in Figure 5-14. It consists of three distinct types of modules designed for launch to orbit inside the 15-ft diameter by 60 ft cargo bay of the space shuttle, which can be assembled and disassembled in space. The propulsion module contains NERVA and a

Table 5-1

RNS WEIGHT STATEMENT

ITEM	WEIGHT (LB) CLASS 1-H	CLASS 3
STRUCTURE	23,130	30,470
METEOROID/THERMAL	7,070	10,750
DOCKING/CLUSTERING	640	3,320
MAIN PROPULSION-STAGE	1,010	4,550
NERVA	27,800	27,800
DISK SHIELD	2,900	0
AUXILIARY PROPULSION (WET)	2,360	2,360
ASTRIONICS	2,505	3,170
CONTINGENCY	1,830	2,590
RESIDUAL PROPELLANT	9,470	4,160
TOTAL OPERATIONAL WEIGHT	78,715	89,170
PROPELLANT MASS FRACTION	0.788	0.771

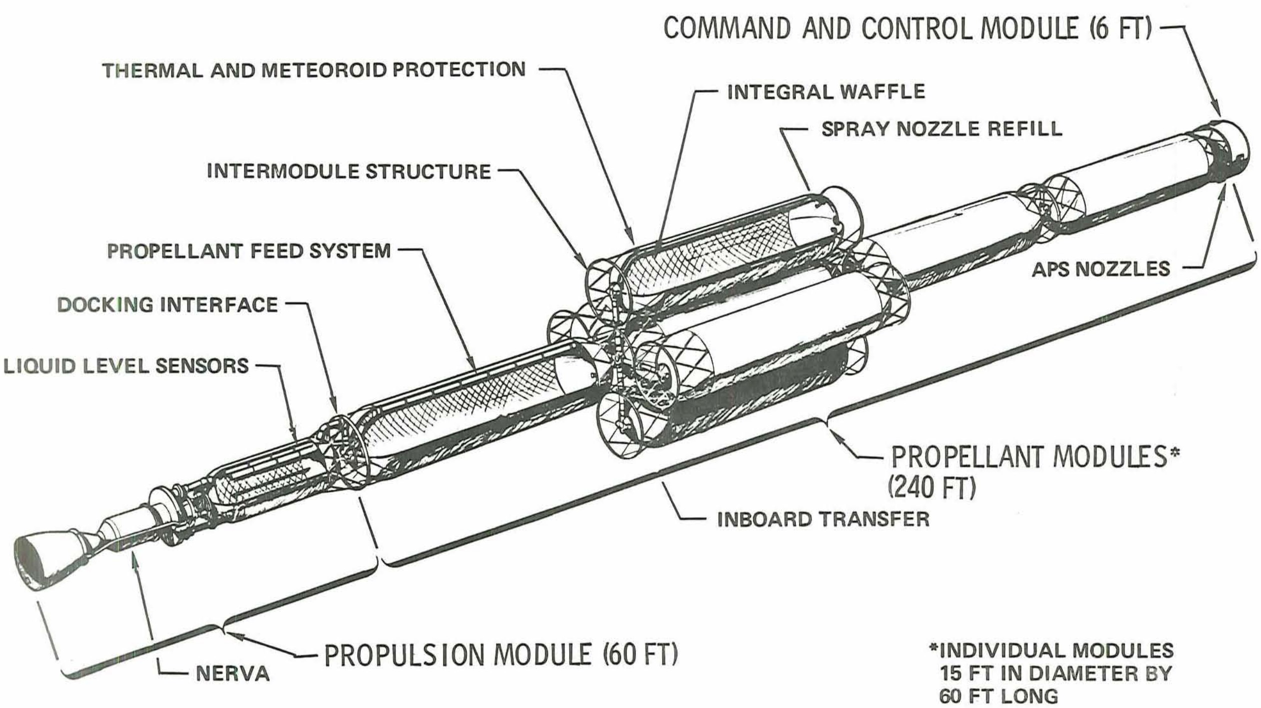


Figure 5-14. Class 3 Multi-Module RNS

small run tank of propellant. This facilitates replacement of NERVA, as might be required because of failure or to extend the lifetime of the RNS beyond that of the engine. A CCM is located at the forward end of the stage. It contains most of the functional equipment and all of the expendables except mainstage LH_2. This module is replaced between missions in earth orbit, thereby effecting a replenishment of expendables and all scheduled maintenance. Primary propellant is contained in the multiple propellant modules. These contain minimal propellant management subsystems. The main feed system provides communication from any propellant module to the run tank on the propulsion module. It can be seen that this concept is similar to the Class 1-Hybrid concept described in the preceding section with the multiple propellant modules here performing the same function as the single propellant module did there.

The vehicle configuration displayed was selected to optimize the combined effects of biological shield weight, which favors maximum vehicle length; maximum stability and controllability, which favors minimum length; and minimum assembly operations associated with the outboard modules. The baseline configuration employs four tandem propellant modules which, in conjunction with the small solid angle subtended by the run tank on the propulsion module, precludes the requirement for any biological shield. A fully adequate margin of safety is maintained for vehicle stability and controllability. The cruciform array of outboard propellant modules simplifies assembly and clustering operations.

The RNS design and operations concept minimizes orbital support requirements. The space shuttle is employed to deliver replacement modules and resupply propellant. A space tug is utilized to support assembly and replacement of modules and to safely dispose of expended propulsion modules. No permanent, manned, orbital facilities are required for maintenance or propellant resupply.

Equipment selection for the Class 3 concept paralleled that for the Class 1-Hybrid described in Section 5.2. Maximum efficiency is required of the structural/thermal/meteoroid protection designs resulting from the increased number of modules and surface area. Functional subsystem definition again made extensive use of equipment being developed for the space shuttle since this is considered to be a leading program element. All capability attributed to the CCM and propulsion module for the Class 1-Hybrid is also provided for Class 3.

Table 5-1 shows the weight penalty associated with Class 3 which must be traded against the lower launch costs. The first four entries (structure, meteoroid/thermal, docking/clustering, and main propulsion) show a significant advantage for the single module concept. This results from the inherent inefficiencies of the multiple-module configuration including the increased surface area and multiple equipment required for assembly and hookup. On the other hand, the Class 3 concept has no biological shield requirements and significantly lower propellant residuals.

Despite this weight disadvantage the RNS Class 3 configuration still has good performance capability, excellent mission flexibility through variation in number of propellant modules, and presents no serious feasibility questions.

5.4 PROGRAM SUMMARY

Preliminary development programs were defined for both versions of the RNS. Based upon the program guidelines and constraints and the times required to accomplish major development activities, a period of 5 years will be required to bring an RNS system to flight test status following Phase D ATP. Moreover, the early availability of E/STS-2 for battleship tank installation and facility checkout, beginning in early 1976, is crucial to accomplishing systems development testing at NRDS on a timely basis for providing systems design information.

5.4.1 <u>RNS Program Activities</u>

5.4.1.1 Class 1 Hybrid

The major activities for the Class1-Hybrid RNS are depicted in the context of the Continental United States, along with an indication of the methods of transportation used between the activity centers in Figure 5-15. The

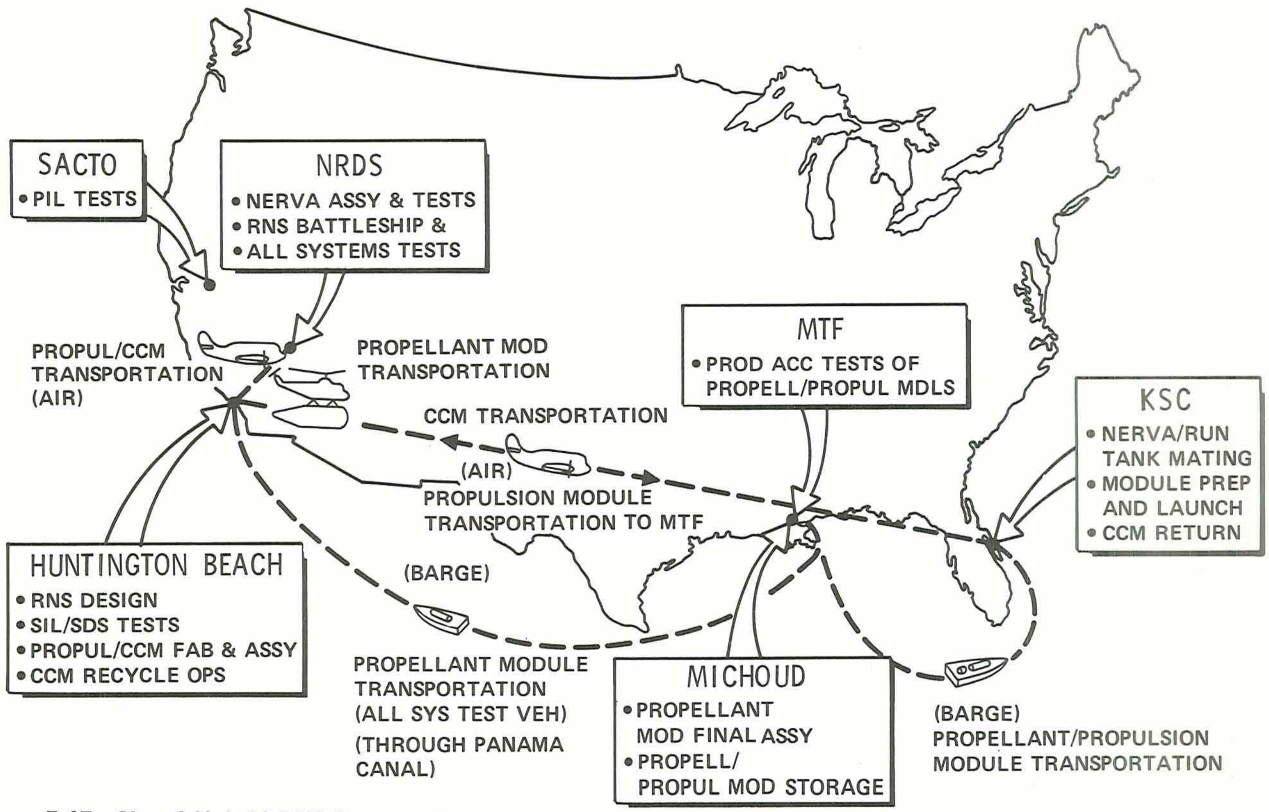


Figure 5-15. Class 1 Hybrid RNS Program Activities

engineering design of the RNS modules and the integrated system is envisioned as being done in the existing Space Systems Center facilities at Huntington Beach. Additionally, Systems Integration Laboratory (SIL) and Special Docking Simulator (SDS) test activities are planned for Huntington Beach to be easily available to engineering personnel. The SIL will consist of an active mockup to define electromechanical interfaces and aid in the design of the GSE. The propulsion module run tank assembly and the CCM would be manufactured within existing facilities at Huntington Beach, and the recycling of operational CCM will be performed on the same production line to avoid having to provide duplicate capability at KSC.

The Class 1-Hybrid RNS program as currently defined will use the NASA-Michoud facility for final assembly of the propellant module, since the Huntington Beach facilities will not accommodate 33-ft-diameter modules without modifications. Following final assembly and a dry functional system checkout at Michoud, the propellant module will be transported to MTF for LH_2 cold-flow production acceptance tests, and subsequently taken by barge directly to KSC for launch or returned to Michoud for storage.

One propellant module will be transported to Southern California by barge for use in the all-systems test program at NRDS. It will be moved from the Seal Beach barge dock to NRDS by helicopter.

Test programs have been identified at Sacramento, where Propulsion Integration Laboratory (PIL) activities will be conducted in a modified Beta test complex, as well as NRDS, where all NERVA power tests will be conducted. The PIL will consist of a mockup which simulates the physical arrangement of propulsion system components. It will be used to assess physical interfaces and fluid dynamic characteristics of LH_2 in the plumbing and tanks. The NRDS testing will be performed with the engine hardware operated separately, as well as in conjunction with stage battleship and all-systems test hardware.

Activities at KSC will include NERVA/run tank mating to form the completed propulsion module, as well as the preparation and launch of RNS modules and the return of the CCM in the space shuttle orbiter for transportation to Huntington Beach for refurbishment.

The primary transportation modes used for the RNS modules are barges and aircraft, such as the Guppy. The CCM will be transported exclusively by aircraft, and barges will be used exclusively for transporting the propellant module, with the exception of the helicopter for moving the all-systems test hardware to NRDS. The propulsion module run tank assembly will be moved by aircraft from Huntington Beach to NRDS and Michoud/MTF, and will be moved to KSC by barge with the propellant module after they complete production acceptance testing at MTF.

5.4.1.2 Class 3

The major program activities for the Class 3 RNS are depicted in Figure 5-16 and located on a map of the Continental United States, along with illustrated methods of transportation used between the activity centers.

The major center of activity for the Class 3 program is planned to be at the MDAC Space Systems Center in Huntington Beach, where the RNS design activities will be conducted, as well as the fabrication and final assembly of

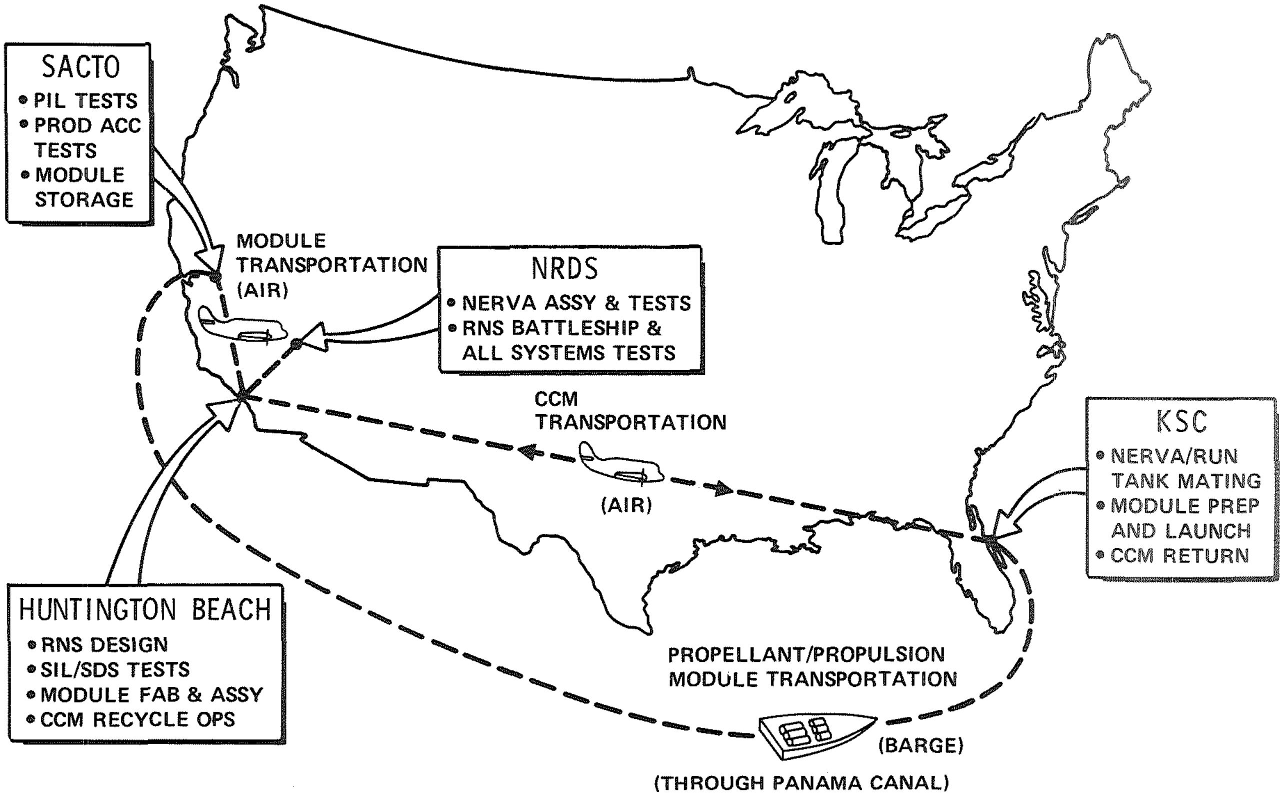


Figure 5-16. Class 3 RNS Program Activities

all modules. The maximum 15-ft diameter of the modules is compatible with the capabilities of existing manufacturing facilities at Huntington Beach, which will provide the proximity of production activities to engineering personnel for efficient operation. For the same reason of proximity to engineering, the Systems Integration Laboratory (SIL) and Special Docking Simulator (SDS) test activities are also planned for Huntington Beach, as well as command and control module recycle operations.

Test programs have been identified at Sacramento, where Propulsion Integration Laboratory (PIL) activities and production acceptance testing of modules will be conducted in a modified Beta test complex, as well as NRDS, where all NERVA power tests will be conducted. The NRDS testing will be performed with the engine hardware operated separately, as well as in conjunction with stage battleship and all-systems test hardware. RNS modules will also be stored at Sacramento.

Activities at KSC will include NERVA/run tank mating to form the completed propulsion module, as well as the preparation and launch of RNS modules and the return of the command and control module in the space shuttle orbiter for transportation to Huntington Beach for refurbishment.

The primary transportation modes used for the RNS modules are barges and aircraft, such as the Guppy. The command and control module will be transported exclusively by aircraft, and barges will be used to transport the propellant modules and propulsion module run tanks from Sacramento to KSC following production acceptance testing. Aircraft will be used to ferry single propellant modules and propulsion module run tanks from Huntington Beach to Sacramento for production acceptance testing. Aircraft will also be used exclusively for transporting RNS modules from Huntington Beach to NRDS for all-systems testing.

5.4.2 RNS Program Schedule

An abbreviated version of the RNS program schedule is shown in Figure 5-17, with activities time phased relative to the IOC date. Separate program schedules were formulated for the Class 1-Hybrid and Class 3 RNS during the Phase III effort, but they are almost identical except for slight differences

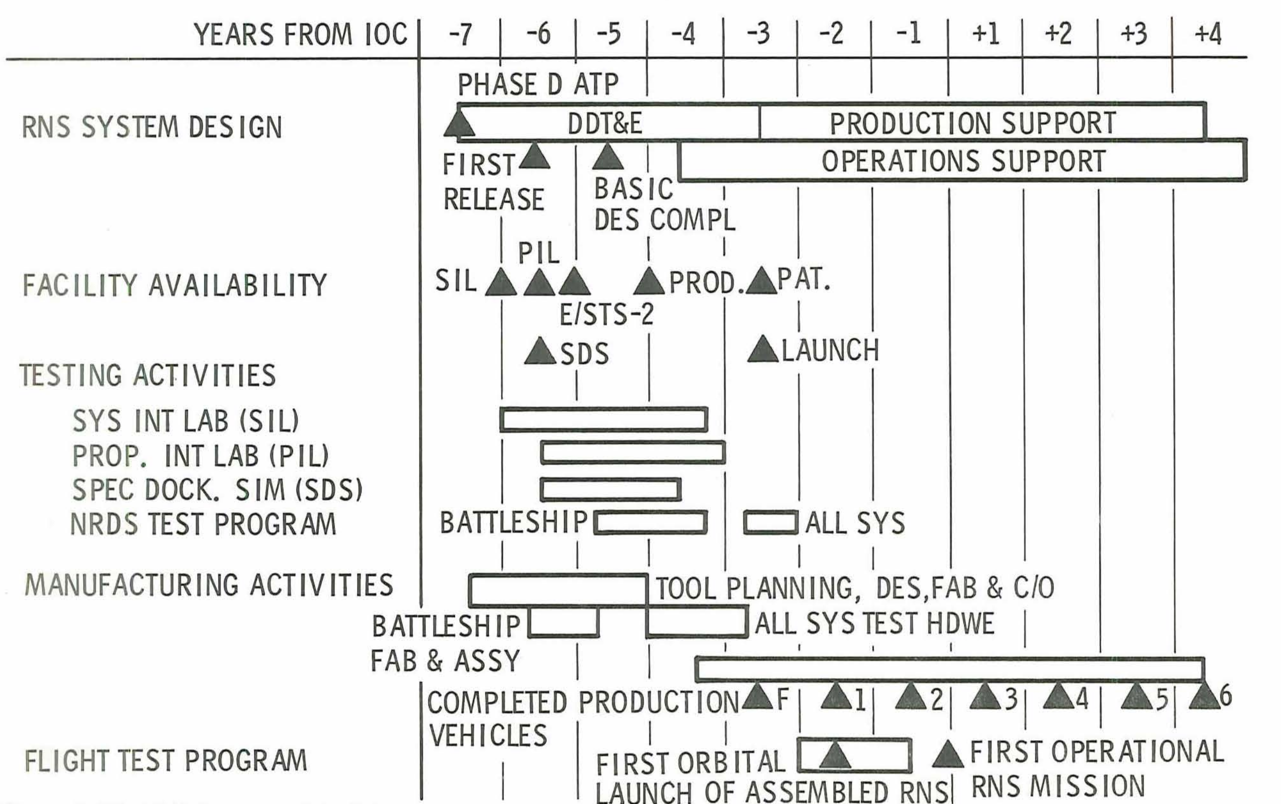


Figure 5-17. RNS Program Schedule

in production acceptance testing activities, etc. The schedule shown here is applicable to either RNS concept. A period of 5 years from Phase D ATP to first flight has been identified, as well as another period of 1-1/2 years between first flight and the IOC date.

Milestones for availability of important test, manufacturing, and launch facilities are shown, and are compatible with entries on the major milestone chart. The test program schedules are predicated upon the availability of the required facilities. The battleship and all-systems test programs at NRDS are comprised of an initial cold-flow checkout phase with a NERVA simulator, followed by full-power tests using NERVA. The battleship will also serve as a ground test module for subsequent engine development tests.

The manufacturing activities feature the field fabrication of battleship test hardware for the Class 1-Hybrid, with field fabrication being optional for Class 3. In either case, the schedule is the same. The all-systems test hardware production and the flight test article production activities overlap by approximately 9 months, implying a higher production rate to satisfy both requirements. For the Class 3, this would not require two complete vehicles, since all-systems test vehicle uses only one propellant module. The production rate shown is one RNS per year, and the total number of RNS systems produced reflects a program with a mission rate of six per year.

The flight test activities include a 6-month period for launching the RNS to orbit, assembling the mission vehicle, checking it out, etc. This is more important for a Class 3 system. After the first launch, a year is provided to perform a series of test objectives, evaluate the test data, perform an earth orbit turnaround of the RNS, and perform a repeat series of tests prior to committing the RNS to its first operational mission.

5.4.3 Costs

The RNS program cost summary (level 2) is presented in Table 5-2 for the Class 1-Hybrid and Table 5-3 for the Class 3. The data are presented as a function of candidate mission rates of 2, 4, 6, and 8 missions per year.

The nonrecurring (DDT&E) cost is a summation of the one-time expenditures associated with the engineering, fabrication, and testing of the RNS and its

Table 5-2

CLASS-1H PROGRAM COST SUMMARY*

	Mission Rate			
	2/Yr	4/Yr	6/Yr	8/Yr
Nonrecurring DDT&E	(965.5)	(965.5)	(965.5)	(965.5)
Launch Vehicle Project	109.3			
Launch Operations Project	58.4			
Reusable Nuclear Stage Project	728.7			
Mission Operations	69.1			
Recurring (Production and Operations)	(1,539.8)	(2,993.2)	(4,440.3)	(5,886.6)
Launch Vehicle Project	192.5	384.6	576.5	768.2
Launch Operations Project	115.4	230.8	346.1	461.5
Reusable Nuclear Stage	221.2	354.0	486.7	618.8
Mission Operations	1,010.7	2,023.8	3,031.0	4,038.1
Program Total	2,505.3	3,758.7	5,405.8	6,852.1

*All costs in millions of 1971 dollars.

Table 5-3

CLASS-3 PROGRAM COST SUMMARY*

	Mission Rate			
	2/Yr	4/Yr	6/Yr	8/Yr
Nonrecurring (DDT&E)	(842.3)	(842.3)	(842.3)	(842.3)
Launch Operations	61.8			
Reusable Nuclear Stage	706.3			
Mission Operations	74.2			
Recurring (Production and Operations)	(1,367.2)	(2,649.7)	(3,926.4)	(5,201.9)
Launch Operations	121.8	243.6	365.4	487.2
Reusable Nuclear Stage	230.0	373.0	516.1	658.1
Mission Operations	1,015.4	2,033.1	3,044.9	4,056.6
Program Total	2,209.5	3,492.0	4,768.7	6,044.2

*All costs in millions of 1971 dollars.

supporting projects. The cost estimates were made at the subsystem and assembly levels and summed to yield total program cost.

Included in the DDT&E estimate is the charge for one flight test article and the support required to perform two simulated test missions. The DDT&E for the RNS-1H program is $965.5 million while the Class 3 requires $842.3 million. The major difference is the requirement for the launch vehicle project (INT-21) for the Class 1-Hybrid.

Of the recurring costs, mission operations is the largest expenditure. As in the case of the DDT&E, the primary cost difference is a result of the launch vehicle project requirement for the INT-21.

The RNS project costs are defined to the system level (level 4) in Table 5-4 for the Class 1-Hybrid and Table 5-5 for the Class 3 RNS's. The Class 1-Hybrid DDT&E cost is $728.7 million while the Class 3 requires $706.3 million. The two configurations differ primarily in the system level testing (hardware and operations) and the development associated with the respective propellant module(s). The Class 3, because of its multiple-module configuration, requires more extensive system level tests and associated test hardware. However the eight propellant modules associated with this configuration have sufficient similarity to allow common development. As a result, although more expenditures are required for system level testing, this is offset by reduced propellant module development costs. The net result is a lower Class 3 development cost.

The total program funding for the two RNS configurations is shown in Figure 5-18. The primary difference between the funding schedule associated with the two candidate configurations is the requirement for the purchase of INT-21 launch vehicles. As a result a peak funding of $523 million is required in fiscal year 1982 for the Class 1H. During later years (fiscal year 1984 and beyond) the funding requirement averages about $350 million. These data are for a baseline 6 mission per year rate. As the mission rates are varied, the average funding requirement is changed by about $60 million per year for each additional mission per year. Figure 5-18 also presents the RNS project level funding schedule. Only one schedule is shown since the

Table 5-4

CLASS-1H PROJECT COST SUMMARY*

	Mission Rate			
	2/Yr	4/Yr	6/Yr	8/Yr
Nonrecurring (DDT&E)	(728.7)	(728.7)	(728.7)	(728.7)
Propulsion Module	42.5			
Propellant Module	91.1			
Command and Control Module	149.2			
Test Hardware	109.4			
Test Operations	49.3			
Facilities	64.1			
Ground Support Equipment	145.0			
SE&I	51.6			
Project Management	26.5			
Recurring (Production and Operations)	(221.2)	(354.0)	(486.7)	(618.8)
Propulsion Module	35.5	68.2	101.0	133.3
Propellant Module	26.5	45.3	63.4	81.0
Command and Control Module	64.1	113.3	161.8	210.1
Test Operations (Acceptance)	1.4	2.9	4.3	5.8
Ground Support Equipment	22.1	27.3	31.3	36.1
SE&I	62.8	82.9	105.6	127.8
Project Management	8.8	14.1	19.3	24.7
Total	949.9	1,082.7	1,215.4	1,347.5

*All costs in millions of 1971 dollars.

Table 5-5

CLASS-3 PROJECT COST SUMMARY*

	Mission Rate			
	2/Yr	4/Yr	6/Yr	8/Yr
Nonrecurring (DDT&E)	(706.3)	(706.3)	(706.3)	(706.3)
Propulsion Module	42.5			
Propellant Module	45.6			
Command and Control Module	149.2			
Test Hardware	129.0			
Test Operations	63.9			
Facilities	56.4			
Ground Support Equipment	142.4			
SE&I	51.6			
Project Management	25.7			
Recurring (Production and Operations)	(230.0)	(373.0)	(516.1)	(658.1)
Propulsion Module	35.5	68.2	101.0	133.3
Propellant Module	32.2	57.8	82.7	106.7
Command and Control Module	64.1	113.3	161.8	210.1
Test Operations (Acceptance)	4.7	9.3	14.0	18.7
Ground Support Equipment	21.5	26.6	30.5	35.2
SE&I	62.8	82.9	105.6	127.8
Project Management	9.2	14.9	20.5	26.3
Project Total	936.3	1,079.3	1,222.4	1,364.4

*All costs in millions of 1971 dollars.

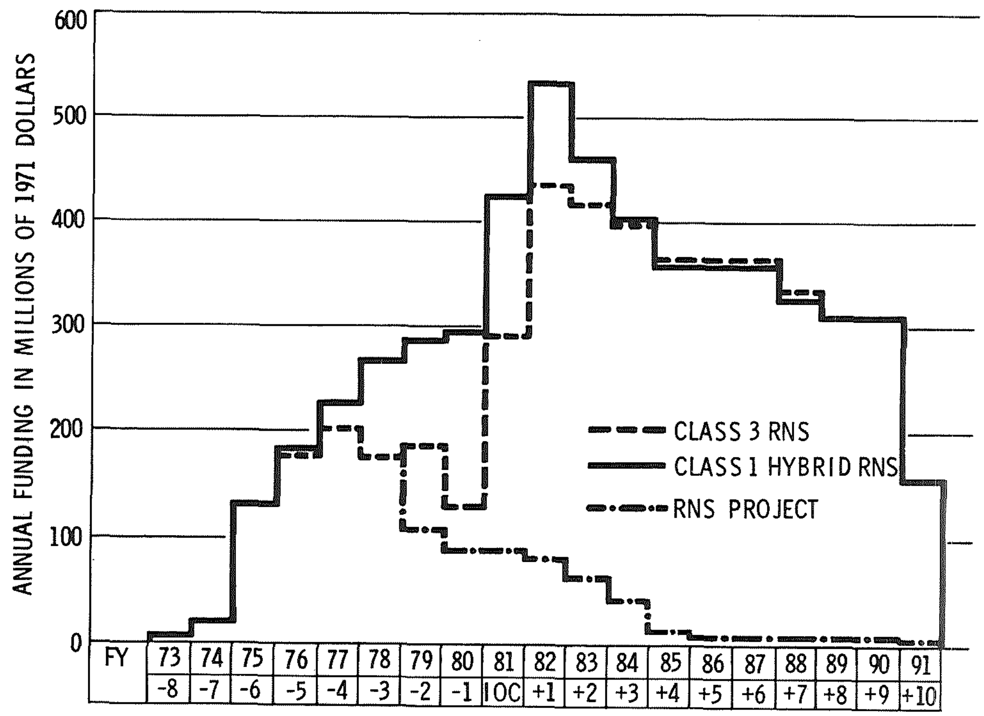


Figure 5-18. RNS Program/Project Funding Schedule—6 Missions/Year

funding requirements are virtually identical. It can be seen that the RNS project is only a small fraction of the total funding requirements.

The cost effectiveness of the RNS-1H configuration, measured in terms of dollars per pound delivered, was based on a minimum energy lunar mission. The payload delivered, assuming a 20,000-lb payload return is 128,000 lb for the RNS-1H and 108,000 lb for the RNS-3. The average recurring program cost per flight varied between \$73 and \$76 million for the Class 1 Hybrid and \$65 and \$68 million for the Class 3 reflecting mission rate of 8 per year and 2 per year respectively. The corresponding transportation cost is \$575/lb and \$602/lb for the Class 1 Hybrid and \$602/lb and \$634/lb for the Class 3. Increasing the space shuttle capability from 33,000 lb to 50,000 lb into earth orbit (260 nmi by 31.5 degrees) while keeping the cargo volume the same, results in an average reduction of \$10 to \$15 million per flight with a corresponding reduction of \$80 to \$88/lb in transportation cost for the RNS-1H and RNS-3 respectively.

Section 6
STUDY LIMITATIONS

The two main factors limiting results from the Phase III RNS system definition study concerned interfaces with the earth launch vehicle and with NERVA. Adequate study guidelines were provided to define these elements and their characteristics so as not to negate the study effort. However, these uncertainties limited the scope of the study. Most of the additional study effort suggested in Section 8 is directed toward resolution of these uncertainties either through direct study activities or through utilization of data generated on complementary programs.

Use of the nuclear stage in a shuttle mode operating out of low earth orbit is dependent upon the logistics support of the space shuttle. However, conception and definition of the space shuttle has had substantial impact upon the current stable of earth launch vehicles. As discussed in Section 4 under method of approach, the Phase III study was limited to two RNS concepts: one launched into earth orbit by the Saturn V INT-21 launch vehicle and the other launched within the cargo hold of the space shuttle and assembled in orbit. This limitation in study scope was necessary because launch vehicle and launch mode data sufficient to complete the definition of a Class 2 RNS system concept were not available at that time.

Some incompatibilities exist between the current NERVA interface design as defined by the engine contractor and the desired characteristics defined under this Phase III study. Some of these incompatibilities are due to the changing concepts in the transportation mode from earth to earth orbit (i. e., space shuttle vs INT-21 launch environment) and some are due to the fact that the engine definition leads the stage definition by such a wide margin.

Additionally, a 10, 000-lb disk shield is being designed for NERVA and, although removable, space and structural capabilities are being provided for it. Current RNS concepts do not require this size shield to provide man rating. In fact, the Class 3 concept requires no biological disk shield at all. Other major uncertainties exist with respect to the location and autonomy of NDICE, the location of multiplexing and signal conditioning of NERVA data, and whether NERVA is disassembled from the stage in one or several subassemblies in orbit, or whether it becomes an integral part of a propulsion module employing a standard docking interface with the other RNS modules. An arbitrary definition of some of the physical interface details concerning structural attachments and fluid line locations has been necessary in order to allow NERVA to proceed as a development item. However, some significantly different recommendations are made as a result of this Phase III study.

Section 7
IMPLICATION FOR RESEARCH

No feasibility problems have been found which would prevent a commitment to development of the RNS. However, there are supporting research and technology questions concerning some of the baseline subsystem features. In general these consist of uncertainties in the design criteria which are applied and would be reflected as variations in the system weight. These items will be identified and described briefly.

The top priority SRT items will be discussed first. Further SRT in the area of high-performance insulation will have a major impact on the RNS. It will be necessary to establish certainty on the performance of current systems and to establish design criteria for full-scale installation. Fiber glass tank supports have been selected for the RNS to enhance propellant storage, but data is lacking on the mechanical properties and fatigue of these structures in a radiation environment and a vacuum at cryogenic temperatures. An integral armor concept has been selected for the RNS using low density polyurethane foam and a fiber glass primary bumper. Additional effort is required to establish precise damage criteria for meteoroid protection.

Titanium tankage has the possibility of a major RNS weight improvement, about 10 percent of the inert weight, compared to the current baseline material of 2014-T6 aluminum. The minimal requirement to achieve this weight improvement would be SRT in the areas of fracture toughness and large scale manufacturing.

There is a variety of SRT items concerning propellant dynamics and propellant management. Data are required on propellant settling criteria applied to the prestart settling for the RNS. Aftercooling propellant acquisition utilizes a surface tension device and confirmation of the criteria for these is required. A lack of data on boiling heat transfer in low gravity conditions provides uncertainty concerning chilldown processes for two situations: prestart feed system chilldown and propellant resupply.

Prolonged orbital coast periods will make propellant stratification a significant consideration for the RNS design. The implications of nonequilibrium heating of the ullage gas must also be established. A major factor for these propellant technology issues will be to accomplish them in early orbital experiments on propellant fluid dynamics and thermo dynamics. Various experiments have been proposed in the past (Project THERMO) and further consideration of such experiments should include RNS requirements.

The major astrionics SRT requirement is a space resident computer system which would achieve a substantial increase in the MTBF from approximately 10, 000 hours at current technology to 50, 000 hours for RNS requirements.

Additional data are required concerning the effects of the NERVA radiation environment on a variety of materials considered for the RNS design. In this context it should be emphasized that the RNS design configuration has greatly reduced the impact of the radiation environment on its subsystems.

A variety of technologies have been identified which provide product improvements for the RNS, largely based on the development requirements for leading programs such as space shuttle. These include fracture mechanics development to assure reliable proof testing, improvement of weld joints, failure prediction techniques, dormant failure rate data, evaluation of long life characteristics for components, and surface coating performance in space. The cryogenic APS system technology developed for space shuttle would be applicable to the RNS. Although not a part of the RNS design criteria, development of efficient propellant transfer technology will significantly affect RNS transportation costs.

Section 8
SUGGESTED ADDITIONAL EFFORT

Major emphasis for subsequent study effort should be directed toward resolution of the uncertainties noted in Section 6. These were: (1) definition of an RNS concept consistent with alternative launch vehicles now being defined as part of the space shuttle definition effort and (2) resolution of both the functional and physical interface discrepancies between NERVA and the RNS. Another category for additional study effort results from reassessment of the role of the nuclear stage, based on NERVA, in the future NASA space program and potential evolutionary modes for NERVA deployment.

As discussed in Section 4 an attractive concept, designated as RNS Class 2, was identified during Phase II. Class 2 systems are particularly important in view of the questionable availability of the Saturn V launch vehicle which would eliminate the current concept for Class 1. However, an RNS concept employing a single propellant module but launched by an alternative launch vehicle can be considered in conjunction with the further definition of Class 2.

A set of candidate launch vehicle configurations compatible with the Class 2 RNS vehicle which span multiple module to single module configurations are shown in Figure 8-1. Concept A shows two concepts for placing 260 in. diameter modules in low earth orbit where they can be assembled as an RNS. The one on the left uses an S-IVB size stage with solid strapons and the one on the right is a stretched 260-in. diameter stage. Concept B depicts two possible orbit insertion stages to place a large 33-ft-diameter propellant module in orbit. This would lead to an RNS configuration similar to the Class 1 Hybrid. Concept C is a modification which uses the RNS propellant modules to contain the liquid hydrogen for launch. Therefore the Orbit Insertion Stage hardware is only represented by an oxygen tank and engine. An evaluation of these alternatives would lead to an optimum Class 2 configuration which can be taken to the same level of depth as the Class 1H and 3 configurations.

The second major area recommended for future study involves resolution of the NERVA stage interface—both functionally and physically. Table 8-1 lists the major areas of uncertainty in the functional and physical interface between

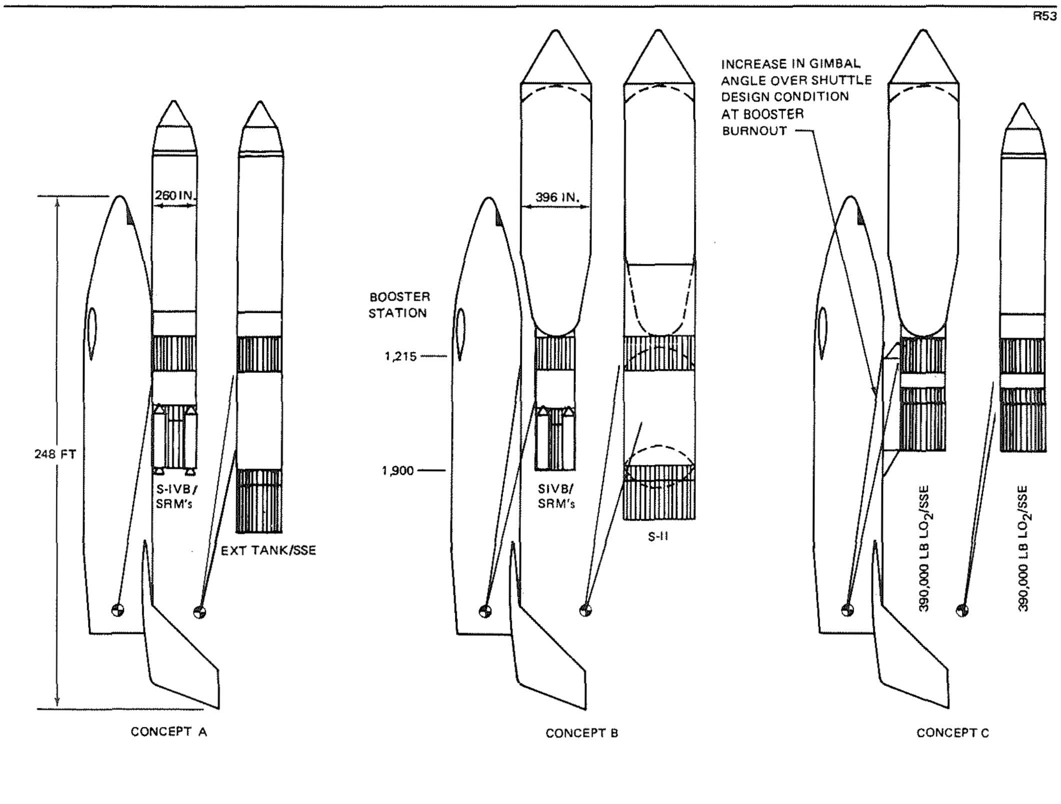


Figure 8-1. Candidate Ground Launch Concepts

Table 8-1

NERVA/STAGE INTERFACE UNCERTAINTIES

Functional	Physical
Structural dynamics during launch	Structural
Engine conditioning	Manufacturing and assembly tolerances
Biological shield requirements	Fluid line number, location, and valving
NDICE integration	Electrical line transition

NERVA and the stage. The first entry under the functional interface, structural dynamics during launch, is important since NERVA was designed for launch on the 33-ft-diameter module by the Saturn V INT-21 launch vehicle. The launch mode and launch support for the current RNS concepts which launch the engine in the cargo bay of the space shuttle should be considered in establishing structural dynamics loading for NERVA. During Phase III, a chilldown system was defined which would condition NERVA before engine startup. This system, or derivatives from it, should be considered for inclusion in definition of the NERVA interface. Additionally, engine conditioning requirements on the launch pad during launch and in earth orbit should be derived and included in establishing NERVA requirements. The current launch mode, in which the propulsion module is launched in the dry condition, represents a significant departure from the present requirements. The third functional interface listed, the biological shield requirements which are imposed upon NERVA to meet nuclear stage capability for man-rating, should be resolved considering current candidates which have much lower shield weight than heretofore. The final functional interface uncertainty involves consideration of the integration of NDICE with the RNS astrionics systems. This includes the location for multiplexing engine signals as well as the actual location for the NDICE module. The physical interface items listed are relatively self-explanatory. Their resolution will require, however, selection of an RNS configuration and particularly the level of assembly and disassembly of the stage/NERVA physical interface.

The third category of items suggested for additional study effort derives from current and projected programmatic considerations for both the nuclear stage and NERVA. Consideration of recent funding changes in the NERVA program will require redefinition of the NERVA development schedule which, of course, impacts the RNS development schedules contained within this Phase III study. Additionally, the role that a nuclear stage based upon NERVA can play in all of the future space missions should be assessed and related to the new NERVA development schedule. This can include consideration of the use of the nuclear stage for earlier precursor missions, such as injection of large unmanned planetary probes, and then subsequent evolution to a full RNS capability. Timing of the space shuttle development and its applications needs to be considered in this evaluation since the RNS, particularly its propellant, represents a major cargo for the space shuttle.

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