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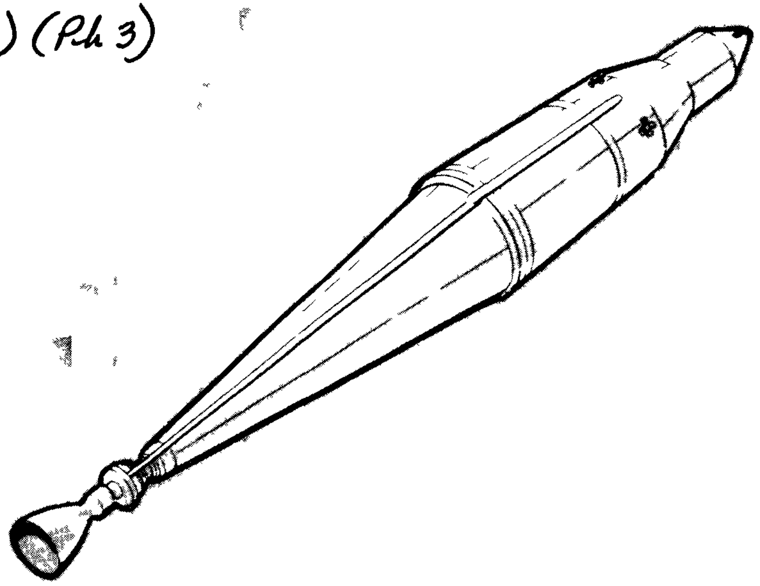
NUCLEAR FLIGHT SYSTEM DEFINITION STUDY

PHASE III FINAL REPORT

VOLUME I
EXECUTIVE SUMMARY

PREPARED FOR
GEORGE C. MARSHALL
SPACE FLIGHT CENTER

CONTRACT NO. NAS8-24975
SD71-466-1 (Vol. 1) (Ph 3)



APRIL 1971

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PHASE III FINAL REPORT

Volume I - Executive Summary

Prepared For

George C. Marshall Space Flight Center
National Aeronautics and Space Administration
under Contract NAS8-24975

April 1971

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FOREWORD

The final report on the Phase III Reusable Nuclear Shuttle (RNS) study was prepared by the North American Rockwell Corporation through its Space Division for the National Aeronautics and Space Administration's George C. Marshall Space Flight Center in accordance with Appendix A of contract NAS8-24975. The contract directed a study of mission requirements, design concepts and definition, performance, operations, facilities, and development activities for the RNS with associated funding and scheduling requirements.

This report is submitted in six volumes with Volume II consisting of three separate books:

I. ✓	(SD 71-466-1)	Executive Summary
II.		Concept and Feasibility Analysis
A. ✓	(SD 71-466-2)	System Evaluation and Capability
B. ✓	(SD 71-466-3)	Baseline System Definition
C. ✓	(SD 71-466-4)	System Engineering Documentation
III. ✓	(SD 71-466-5)	Program Support Requirements
IV.	(SD 71-466-6)	Cost Data (Limited Distribution) MSC didn't get thi
V. ✓	(SD 71-466-7)	Schedules, Milestones, and Networks
VI. ✓	(SD 71-466-8)	Reliability and Safety Analysis

This volume summarizes the information contained in the other five volumes.

ACKNOWLEDGEMENT

C. C. Priest, the NASA-MSFC contracting officer's representative, provided valuable guidance and direction throughout the Phase III study. The assistance of D. R. Saxton and other MSFC personnel is also gratefully acknowledged.

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1 0 INTRODUCTION

With the successful completion of the nuclear rocket engine technology program, focus has shifted to the development of a reusable flight engine of the 75, 000 pound thrust NERVA solid core reactor class. Specific impulse is targeted at 825 seconds for a ten-hour operating lifetime. When coupled with a suitable stage, the overall system offers attractive performance due to the high payload-to-propellant mass ratio. This, in turn, translates into cost benefits in transporting heavy payloads in space since propellant delivery to orbit is the major cost driver. In order to synthesize feasible stage design concepts and explore the potential of NERVA propulsion, NASA-MSFC initiated nuclear flight system definition studies (Phase I) in July 1969 System requirements were defined for an early expendable nuclear vehicle to be used as a third stage of the Saturn V with subsequent growth to an advanced configuration suitable for reusable shuttle and manned planetary applications.

During the latter part of 1969, program analyses were conducted within the NASA and by the Presidential Space Task Group (STG) to define an integrated program plan(s) for achieving desired goals in the next two decades of space exploration. These analyses concluded that new, low-cost transportation systems would be needed to carry out any progressive space exploration program. One of the major new transportation systems identified in the NASA and STG integrated program options was a reusable nuclear shuttle (RNS) This resulted in the reorientation of the Phase I effort to concentrate on (1) establishing system requirements for a nuclear shuttle, and (2) conducting preliminary feasibility studies on the variety of concepts previously identified. The resulting Phase II effort emphasized the evolution of both 33-foot diameter and modular RNS concepts. The 33-foot diameter concepts employed the INT-21 booster as the launch vehicle, and the modular types were designed compatible with the space shuttle cargo bay of 15-foot diameter by 60-foot length.

NR-SD defined a 33-foot diameter integral tank dual cell configuration during the Phase II study incorporating a 10-foot diameter cylindrical inner cell for radiation attenuation and propellant location control. This concept was evolved in the search for a tank geometry with high volumetric efficiency, minimum impact on the INT-21 employing an integral NERVA-RNS tank launch configuration, high radiation attenuation with minimum engine external shielding, and improved propellant management under zero gravity.

Results of the investigations indicated that the goals could be met with the concept outlined. However, subsequent detailed radiation field mapping has indicated that payload location is quite sensitive in such stage designs due to radiation scattering from propellant vapor and tank bottom. This effect would probably be too restrictive in designing practical manned payloads for RNS transport. Therefore, a number of alternate RNS configurations and launch modes were identified for subsequent Phase III study to extend the search for more attractive designs.

A modular configuration also was developed during Phase II, consisting of eight 14.2-foot diameter modules, 59.5 feet in length, arranged in two tiers with a single module in the lower tier, and the upper tier modules clustered symmetrically about a core module. This configuration was defined to the degree necessary to permit preliminary performance and cost comparisons with the 33-foot diameter counterparts. The results (Reference 1) showed the modular design to be quite attractive. However, an in-depth study was required to determine the impact of the complex design on orbital assembly operations and reliability.

The principles of a repetitive lunar shuttle cycle were established and desirable mission characteristics identified. In addition, the concept of a no-plane-change flight was developed, and the cyclic mission windows were identified. Performance capability was determined for lunar and synchronous orbit shuttle missions, as well as for unmanned injection missions using a variety of flight modes for this latter case. The cooldown impulse contributions to earth and lunar orbit departure and arrival velocity requirements were established in detail. The results confirmed the diminishing effectiveness of cooldown impulse on escape trajectories and the near-constant effectiveness for orbit insertion on a spiral path. In addition, propulsion and tank module size requirements were defined for several manned Mars mission configurations and a mission model developed which identified the various Mars mission events and times. In general, results pointed to the possibility of a uniform 300K LH_2 module.

Reference 1. SD70-117-3, Nuclear Flight System Definition Study, Phase II Final Report (August 1970).

2.0 PHASE III STUDY OBJECTIVES

As in the preceding effort, the basic goal of the Phase III study was to define attractive RNS concepts capable of providing low-cost manned/unmanned space transportation in the early 1980's. Progressive growth in a cost-effective manner to meet later manned planetary applications represented an important adjunct requirement. A high degree of reusability combined with maximum practical dependence on commonality is essential if RNS costs are to be kept low. The major space program elements which will contribute to the attainment of this goal are shown in Figure 1.

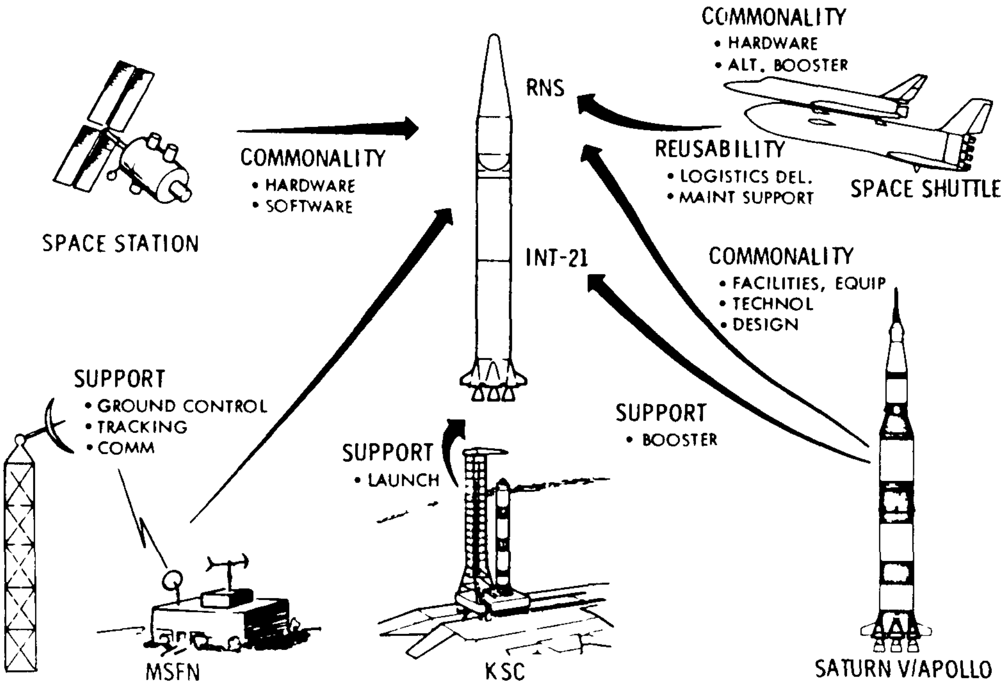


Figure 1. Major Contributors to RNS Program

Within this framework, specific objectives of the study were directed to (1) complete preliminary technical definition of attractive RNS concepts including design criteria, engineering drawings, functional schematics, system/subsystem trade-offs, and a system specification; (2) establish integrated program requirements for the baseline RNS including development schedules and costs as well as requirements/plans for operations, reliability and flight safety, quality assurance, manufacturing, facilities, test, and support R&T; (3) conduct specialized analytical studies in support of related NERVA program and other efforts; (4) provide RNS mission and performance data in a format suitable for general mission planning; and (5) identify preliminary design and operational interfaces with other planned or proposed space system elements (i.e., space shuttle, space tug, data relay satellite system, maintenance element, propellant depot, etc.).

3.0 RELATIONSHIP TO OTHER NASA EFFORTS

The Space Task Group in its study of future directions in space made recommendation that this nation accept the basic goal of a balanced manned and unmanned space program conducted for the benefit of all mankind. In order to achieve this goal, it is necessary to develop new systems and technology for space operations with emphasis upon the critical factors of: (1) commonality, (2) resuability, and (3) ecomony through a program directed initially toward development of a new space transportation capability and space station modules which utilize this capability.

The transportation complex that will make possible more economical orbital, lunar, and planetary operations employs the space shuttle in combination with the reusable nuclear shuttle (RNS) and the space tug. Space shuttles will provide the means for achieving low cost transportation to earth orbit. The RNS is intended to extend this capability to all space missions requiring delivery of heavy payloads. Space tugs can be used in many roles including operational support of the RNS and as an expendable stage on the RNS for deep space missions.

Figure 2 portrays the planned and postulated interfaces conceived at this time for the RNS. The INT-21 launch vehicle can be utilized to launch the RNS stage to earth orbit (study ground rule) whereas the NERVA engine will be delivered by the space shuttle. All logistic support from earth to low altitude orbit will be provided by the space shuttle.

The space shuttle will carry passengers and cargo directly to the RNS or to the space station in low earth orbit. There they can be transferred by a space tug to the RNS for flights to other stations, either in geosynchronous orbit or in lunar polar orbit. Space tugs will be located at each station to carry automated spacecraft into other orbits, for flights to service and repair automated equipment, and to retrieve equipment, film and "hardcopy" information for return to earth. The space tug at the orbiting lunar station (OLS) also will be employed for transportation to any point on the lunar surface and back to the OLS or RNS.

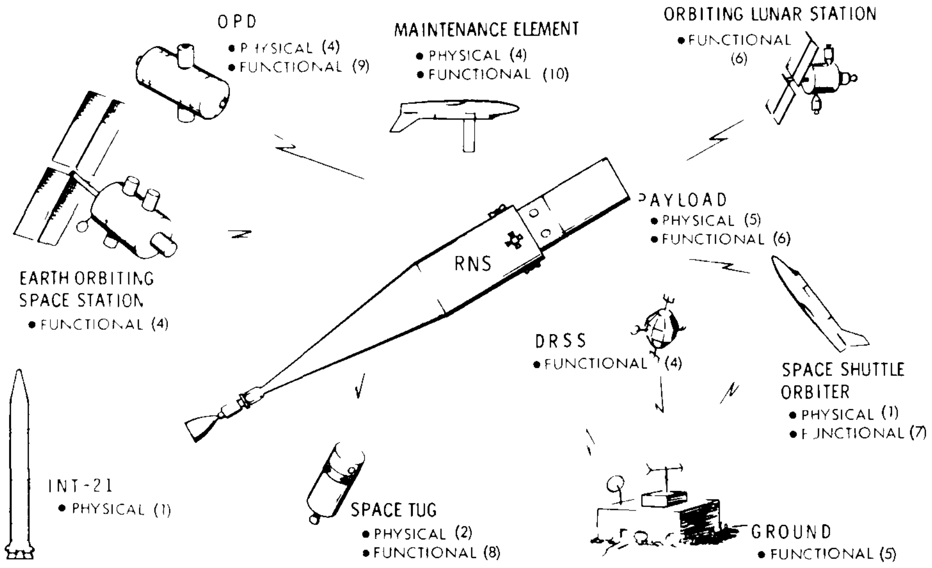


Figure 2. Interfaces With Other Program Elements

Exploration of the solar system will employ both unmanned and manned payloads. Unmanned payloads in the range of 100-200,000 pounds can be injected by the RNS on low energy missions to Mars and Venus with return of the RNS to earth operations orbit for reuse. Manned planetary missions projected in late 1980's and beyond would utilize multiple RNS modules to launch the vehicle on a trajectory to Mars. The RNS modules utilized for earth departure would be returned to low altitude orbit for reuse while the remaining module provided the propulsion for planetary arrival, departure, and earth orbit return.

Other space program elements which may be used with the RNS include an orbiting propellant depot to accommodate propellant loading during high traffic rates. In addition, an orbital maintenance element (initially an extension of the space shuttle capability) would be utilized to service the RNS including replacement of expendables (e.g., RCS and fuel cells propellant) and restoring/replacing malfunctioning or limited life components. The Data Relay Satellite System (DRSS) will relay communications (data and voice) between RNS and other space program elements.

Some of the interfacing systems discussed above may not come into being whereas other new interfaces may be established as the space program evolves. For example, propellant transfer directly from the shuttle orbiter is possible early in the program when RNS shuttle traffic rates are low. However, with higher frequency lunar logistic flights, it may be necessary to utilize an orbiting propellant depot. The Phase III study considered all the interfaces outlined above taking into consideration the effects of traffic density variations.

4.0 METHOD OF APPROACH AND PRINCIPAL ASSUMPTIONS

STUDY LOGIC

The approach employed in the Phase III study is shown in logic format in Figure 3. An integrated design definition investigation of attractive RNS concepts was performed, increasing the analytical depth with each succeeding step. Design configurations were baselined for the Class I missions (lunar/synchronous orbit shuttle) with the adjunct capability of satisfying Class II (unmanned planetary) with evolution to Class III (manned planetary) in a multistage arrangement. A key task was the determination of requirements with emphasis on orbital and mission operations and interfaces with other planned systems. In addition, engine-stage and stage-booster interfaces, supporting research and technology requirements, and cost trade-offs interacted to influence the shaping and screening of the evolving designs. System engineering support, necessary for timely programmatic decisions, was conducted in parallel with the main investigations.

Iterative loops (omitted in Figure 3. for clarity), occurred at numerous places in the analytical effort to maintain an integrated design evolution and provide the data necessary for subsystem evaluation and selection with NASA-MSFC concurrence. The technical analyses on each candidate system/subsystem concentrated on the following areas of prime significance to overall system definition:

1. Space operations including logistics and interfaces with other systems and facilities; orbital assembly, associated rendezvous, docking, and checkout requirements throughout the mission profile; maintenance and maintainability, and refurbishment necessary to support a reusable system; engine operations and control requirements taking into consideration failure modes and the interaction with guidance and navigation systems; and radiation effects on equipment, facilities, and space personnel.

2. Ground and flight test requirements as influenced by development plan alternatives and a minimum cost criterion.

3. Propellant handling and conditioning including temperature conditioning, location control, and orbital fueling.

4. Nuclear safety/reliability and quality assurance requirements and specifications taking into consideration cost and design criteria interactions as well as mission dependent factors.

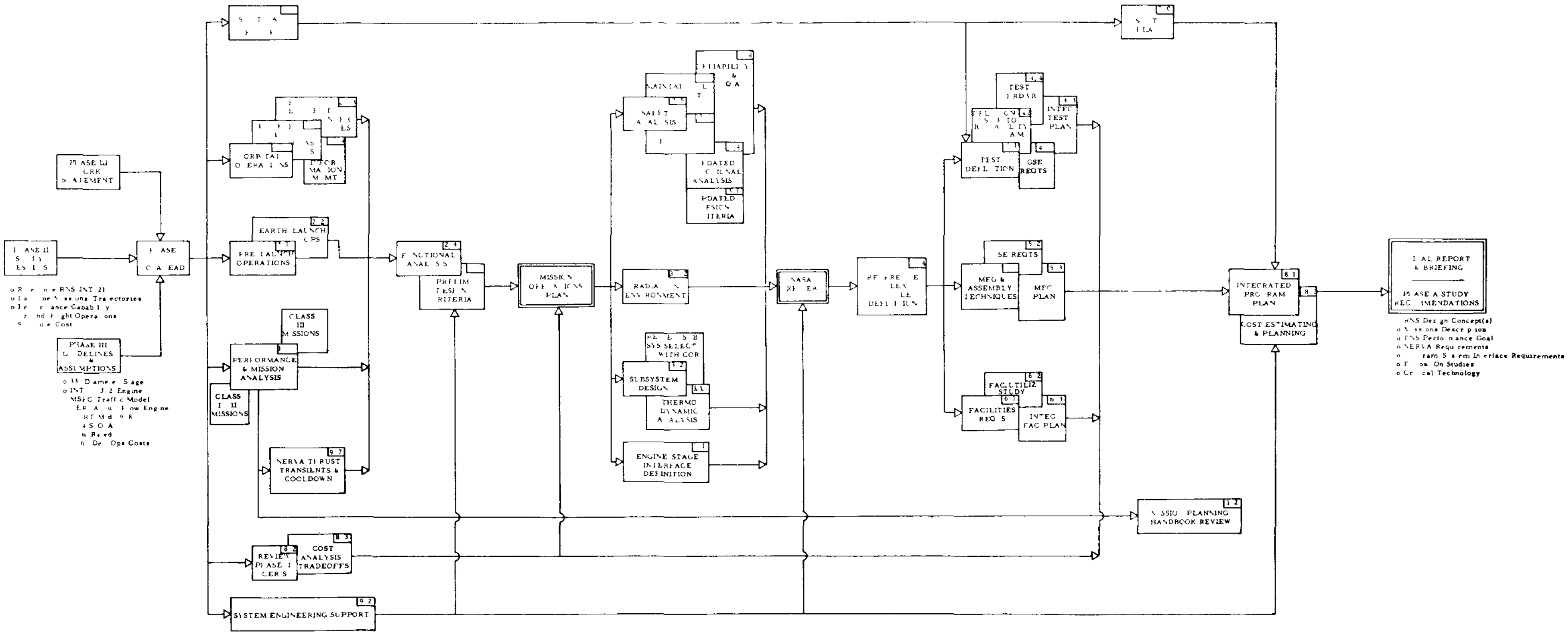


Figure 3. Nuclear Flight System Definition Phase III Program Logic

Finally, the Phase III effort concluded with a recommended RNS design concept (plus attractive alternatives), design criteria, operational requirements, mission descriptions and performance capability, integrated program plans, detail cost estimations, areas for cost avoidance, proposed changes to NERVA requirements, other program operational interface requirements, and critical technology activities.

ASSUMPTIONS

The principal guidelines and assumptions used in the Phase III study are as follows.

1. RNS concepts were limited to those characterized by a primary 33-foot diameter propellant tank, but including configurations with an attached propulsion module (designated hybrids) containing a small tank and the NERVA engine. Total LH_2 propellant capacity was baselined at 300,000 pounds, with 5% ullage.

2. All RNS designs were to employ 1974 technology, be man-rated by the time of IOC (initial operational capability) in CY-1981 and have an operational lifetime of 3 years with maintenance. Tank top integrated radiation dose was limited to 10 rem per shuttle round trip flight.

3. Launch to orbit of the primary RNS was by INT-21 with standard J-2 engines (currently designated as the MSFC baseline). The space shuttle, with cargo bay dimensions of 15-foot diameter by 60-foot length, was to deliver the propulsion module (or NERVA alone if required), propellant, payload, and all other supplies.

4. The baseline RNS earth operations orbit was 260 n mi circular at an inclination of 31.5 degrees with shuttle flight to a 60 n mi lunar polar orbit considered as the reference mission.

5. Minimization of development and operational costs was of paramount importance as long as key mission objectives and program milestones were not jeopardized. Emphasis was to be given to the maximum practical use of existing facilities and equipment.

6. Pertinent NERVA and other study documents were specified in Reference 2.

Reference 2. MSFC Document PD-SA-P-70-63, Guidelines and Constraints Document for Phase A Nuclear Shuttle Systems Definition Study, Revision No. 3 (February 1, 1971).

5.0 BASIC DATA GENERATED AND SIGNIFICANT RESULTS

The Phase III Nuclear Shuttle Definition study was performed with the prime objective of identifying the most economical RNS program commensurate with an operational mode and efficient stage design which can evolve from earth-lunar orbit shuttle missions to advanced manned Mars mission propulsion roles. High commonality with existing and programmed space elements was ground ruled at the outset to explore potential performance and operational benefits. To this end, the study was directed to parametric and tradeoff analyses covering missions/performance; ground and orbital operations including definition of interfaces and subsystems requirements; logistics and maintainability requirements associated with reusability and long space life; stage concepts and subsystems design; manufacturing, testing and facilities requirements definition; and recurring and non-recurring cost analyses/tradeoffs.

Some of the support systems, facilities, and hardware that are expected to interact with and contribute to the RNS program are depicted in Figure 1. For example, many astrionic equipment and software items necessary for RNS autonomy in orbit-to-orbit operations were derived from the space station and other programmed space elements. Additionally, ground control and backup capability to support orbital and mission operations is provided by the existing manned space flight network.

The space shuttle derived benefits are both operational and technological in nature. The vehicle serves as the low cost logistics system for delivery of propellant, payload, replacement parts, and support equipment such as a shuttle-based maintenance element. It is also the source of programmed technology benefits in high performance insulation, reaction control subsystem, and fuel cells for primary electrical power.

The Saturn V/Apollo will supply facilities, manufacturing techniques, as well as tooling and support equipment. The INT-21, on the other hand, results in a constraint due to its strength limitations. This constraint can be nevertheless obviated by launching the RNS less NERVA in an inverted position. The slender cone of the baseline RNS tank (necessary for radiation attenuation to the payload) yields aerodynamic loads well within the booster capability. The non-integral launch requires in-orbit mating and checkout of the engine or propulsive module with the main LH_2 tank, but it must be remembered that NERVA design criteria specify engine and stage assembly and disassembly capability in earth orbit. To effect this capability a neuter docking system designed for the space station (and adapted by other space elements) has been employed on the RNS.

Another space element which has been beneficial in the RNS program definition is the space tug. This system can be employed to assist the RNS during its return from the lunar mission resulting in a dramatic increase in payload capability. It also can be employed for end-of-life removal and disposal of the NERVA as well as in performing other orbital tasks such as delivery to and removal of payloads from the RNS.

The approach outlined above yields an economical RNS program which is fully integrated with the current space transportation system.

MISSION/PERFORMANCE ANALYSIS

Traditional and important objectives of mission and performance analysis are to test design alternatives on a payload basis and to provide a reference mission framework for subsystems analysis. Results in these areas are seen in the recommended RNS design, wherein payload capability has been a major selection factor. A broader objective, of particular importance in the present climate of competing space transportation concepts, has been to demonstrate the RNS to be an efficient transportation system element. Maximum competency as an earth-lunar inter-orbit shuttle has been the primary concern. The RNS defined by lunar mission requirements provides very high performance for geosynchronous orbit and transplanetary injection missions and is adaptable to the advanced manned Mars mission propulsion role. Effort toward meeting the broader objective has yielded a better understanding of how missions should be configured for best use of the projected transportation system. A corollary result is a more realistic definition of mission requirements to be met by the RNS.

Progress in defining mission requirements has come primarily through analysis of the lunar shuttle mission and its powered maneuvers. The demonstrated feasibility of minimum energy coplanar maneuvers assures that there is no penalty inherent in the concept of repetitive shuttle flights between established terminal orbits at earth and moon. Figure 4 presents a typical pattern of flights following the assumed delivery of an orbiting lunar station (OLS) early in 1985 (payload values do not reflect maximum outbound delivery capability). Translunar injection opportunities occur approximately every nine days with a nearly identical, high payload mission repeating every sixth opportunity (54.6 days). The minimum energy repeatable mission has been selected as a baseline for performance evaluation and reference mission definition. Figure 5 compares payload capability of four mission models considered and indicates a lunar delivery payload of 200,000 pounds for the final baseline RNS, far higher than originally contemplated for a 300,000 pound LH_2 capacity stage.

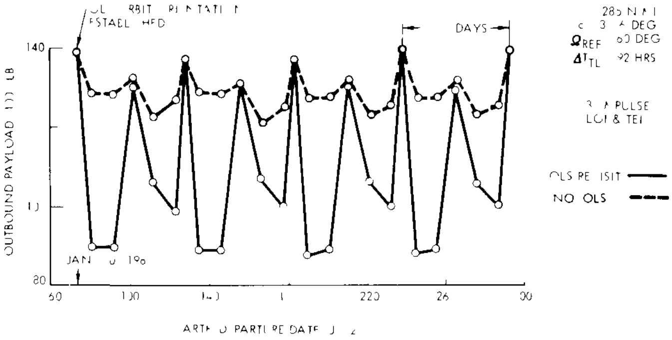


Figure 4. Lunar Shuttle Revisit Mission Payload

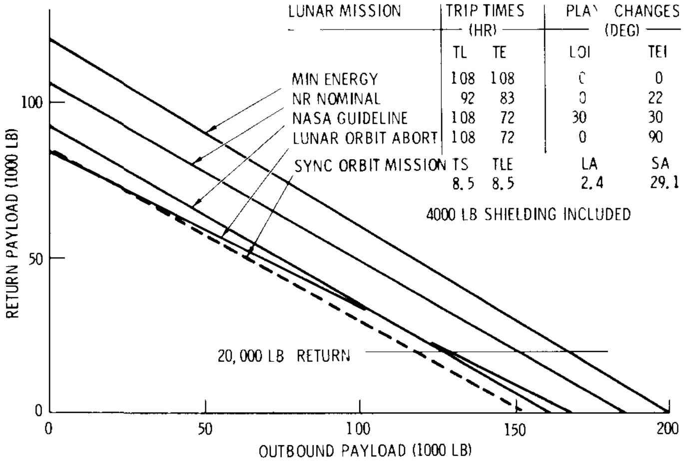


Figure 5. RNS Shuttle Payload Capability

A dramatic increase in payload capability follows when a space tug is used to assist the return of the RNS at the end of a lunar mission. By refueling the RNS in elliptical orbit, the tug permits an 80 percent increase in maximum lunar payload delivery. If the tug simply retrieves the RNS, using tug propulsion only, a 50 percent gain is still possible. Figure 6 illustrates the gain in terms of propellant quantity (RNS and tug) per pound of delivered payload. More important than the increase in the already large payload capability is the indication that an RNS sized for moderate mission requirements could occasionally employ an alternate flight mode for handling much larger payloads or for emergency non-optimum flights.

Alternatives to the 300, 000 pound LH_2 capacity also were considered from the viewpoint of payload-to-gross weight ratio. While a larger stage is inherently more efficient, it cannot match the tug assistance modes. The dotted bars in Figure 6 represent an RNS alone scaled up to provide the same payload as the combination of 300, 000 pound capacity RNS and tug.

Manned missions to geosynchronous orbit, although not studied to the extent that lunar missions have been, promise ultimately to create additional demand for shuttle vehicle flights. Requirements imposed on the RNS do not differ substantially from those of the lunar mission except in regard to mission phase durations, which are much shorter. A space station module of over 160,000 pounds could be delivered by the baseline RNS on an unmanned flight (with no external shielding).

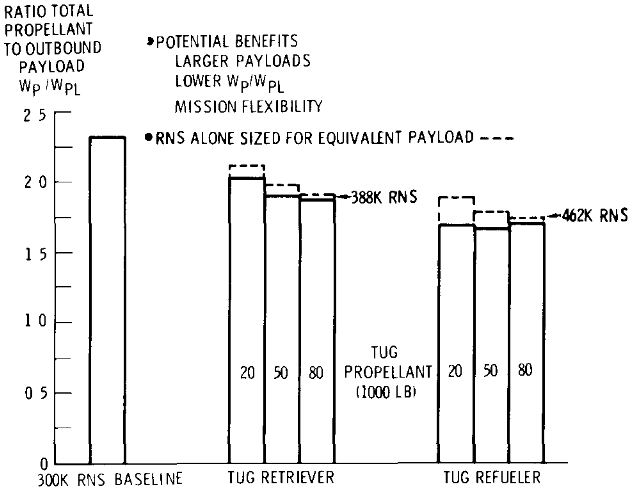


Figure 6. RNS and RNS/Tug-Assist Performance Effectiveness

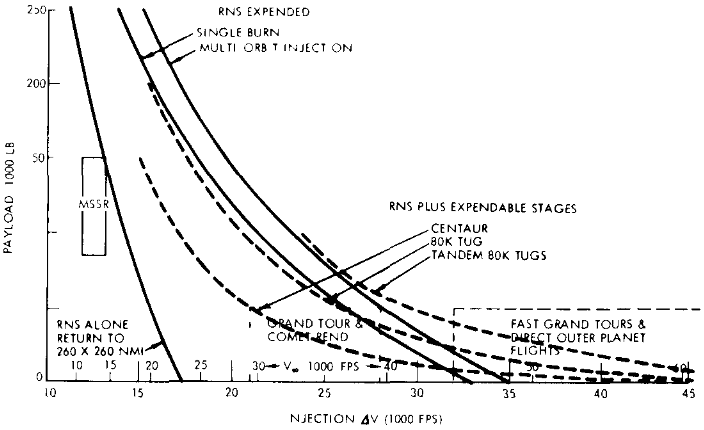
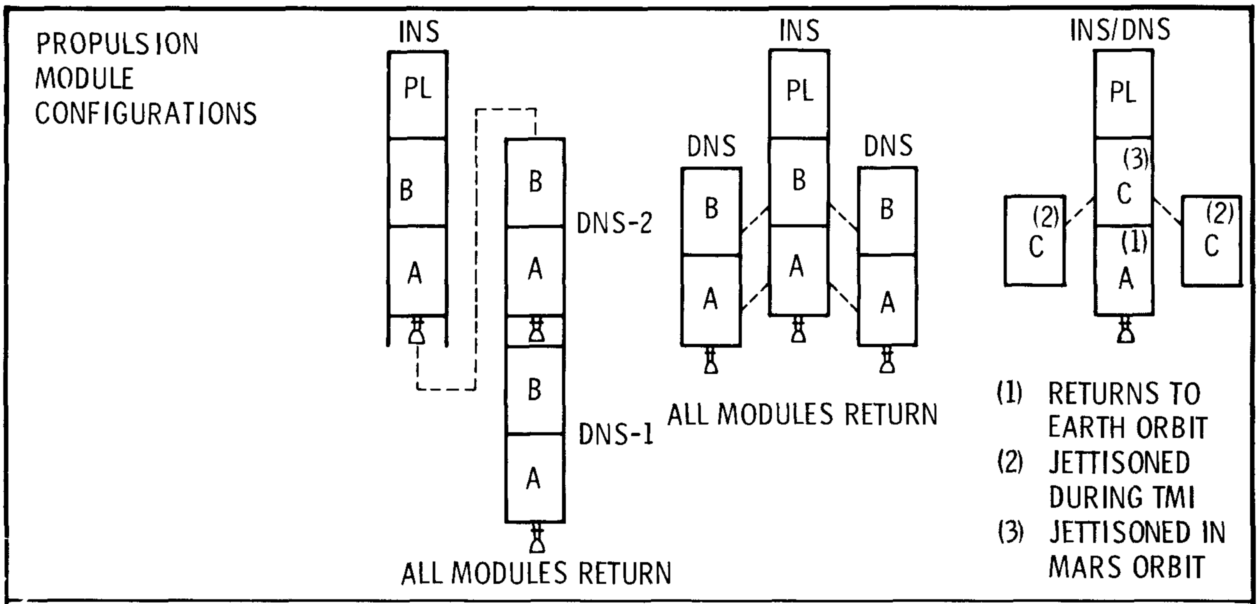


Figure 7. Transplanetary Injection Capability

As an injection stage for unmanned planetary missions, the RNS can function effectively in a variety of flight modes as shown in Figure 7. For low energy missions to Mars and Venus, the RNS offers 100-200,000 pound payload capability when used alone and returned to the earth operations orbit. Expending the RNS on an injection flight, at the end of its useful life, pushes its capability up to the energy level of outer planet missions and beyond. Greater importance, however, was given to extending the energy range as a reusable injection stage by coupling with a high performance chemical expendable stage. The simplest flight mode, a single continuous boost from circular orbit, provides capability beyond 30,000 fps. The large velocity loss on such a flight can be significantly reduced by the multi-orbit injection technique with a 1500 to 2000 fps gain in injection velocity as shown in the figure. Self-return to a 260 n mi circular orbit following payload injection seriously reduces the mission velocity level the RNS can reach. However, the addition of expendable upper stages, typified by Centaur and space tug, bring fast Grand Tour and outer planet direct flights well within reach.

In the area of manned Mars missions, there is a continuing concern to correlate lunar shuttle configurations and sizing with planetary propulsion requirements, to assess advanced subsystems requirements, and to explore the interaction of planetary mission design with propulsion requirements. The Phase III study addressed these problems in a limited way by sizing 33-foot-diameter modules in three configurations and for two contrasting mission models (1986 opposition and 1990 conjunction). One of the chief subsystems alternatives - high performance insulation (HPI)/boiloff reliquefaction - was explored, as was the effect of tug assistance for RNS retrieval.

The trends observed in initial mass requirements are not unexpected. Reliquefaction appears to be moderately attractive, tandem departure stages excel over parallel stages due to the benefits of multi-orbit injection, and tug refueling of returning stages is desirable up to the limit of tug utilization (escape velocity). Figure 8 illustrates sizing of propulsion and propellant modules for a 1986 outbound Venus swingby (OVS) mission when HPI without reliquefaction is used for the interplanetary nuclear stage (INS). Modest tailoring of configuration and mission assumptions results in modules readily compatible with the baseline RNS size.



LH_2 CAPACITIES (10^3 LB)			
DEPARTURE STAGE (DNS)	549(A+B)	639(A+B)	297 EACH
INTERPLANETARY STAGE (INS)	602(A+B)	602(A+B)	(A, C, C, C)
INITIAL MASS IN EARTH ORBIT (10^3 LB)	2,363	2,562	1,666

Figure 8. Stage Sizing for 1986 OVS Manned Mars Mission

Each type of mission proposed for the RNS offers the possibility of reduced theoretical velocity requirements with multi-impulse maneuvers. However, the degradation in NERVA performance associated with shorter burns (reduced specific impulse and increased total cooldown loss) has caused concern that the RNS cannot realize its full theoretical potential. Results throughout this study have nevertheless shown that multi-impulse maneuvers can substantially increase payload; that is, NERVA performance degradation is generally outweighed by efficient mission design. In powering a typical lunar shuttle mission, NERVA achieves an overall effective specific impulse of 775 seconds when startup, shutdown, and cooldown phases are accounted for. This represents a six-percent loss from the nominal steady-state value of 825 seconds, a loss comparable to that suffered by LOX/LH_2 propulsion systems when the effects of chilldown, line loss, and inherently greater boiloff are included. Accurate modeling of NERVA performance has been included in all the quoted payload evaluations.

15x60

40k+

Another type of performance penalty, of potentially serious proportions, involves the efficiency of space shuttle operations in support of RNS flights. Since the largest component of RNS earth orbit logistics requirements consists of low density LH_2, the cargo volume of the shuttle (15 foot diameter x 60 foot length) is a limiting factor. With early shuttle designs this was not the case, but subsequent trends point to an ultimate shuttle payload capability considerably in excess of the 40,000 plus pounds of LH_2 which can be accommodated in the ground ruled cargo bay. Several ways to ameliorate this problem await further investigation (including use of an alternate operating orbit and transport of mixed cargo with a higher average density than LH_2) (Figure 9).

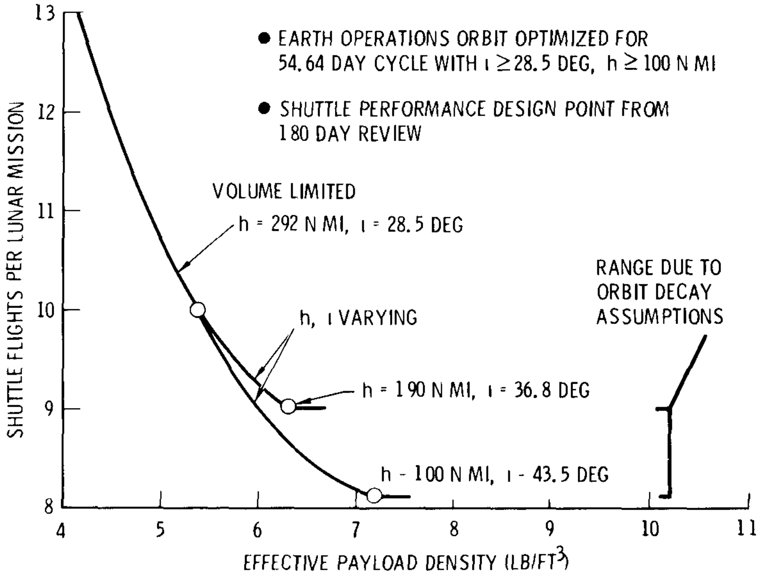


Figure 9. Effect of Payload Density on Space Shuttle Utilization

The magnitude of the penalty which can result from a cargo volume limit may be judged from a recent space shuttle design point (47,000 pounds of payload delivered to 270 n mi, 55 degrees). The number of space shuttle flights required to support one RNS lunar mission increases 25 to 40 percent, because of the volume limit, over the unconstrained case. The range noted reflects uncertainties in the constraints on earth orbit selection, primarily those associated with orbit decay between missions.

OPERATIONS REQUIREMENTS

The operations analysis for the RNS covered activities from prelaunch to end-of-life disposal, (Figure 10) keeping in mind the basic objective of providing a reusable and economical transportation system. Although the detailed analysis considered launch of the RNS both in integral (stage and NERVA mated) and non-integral (stage and NERVA launched separately) configurations, emphasis is placed in this summary on the operations associated with the latter alternative.

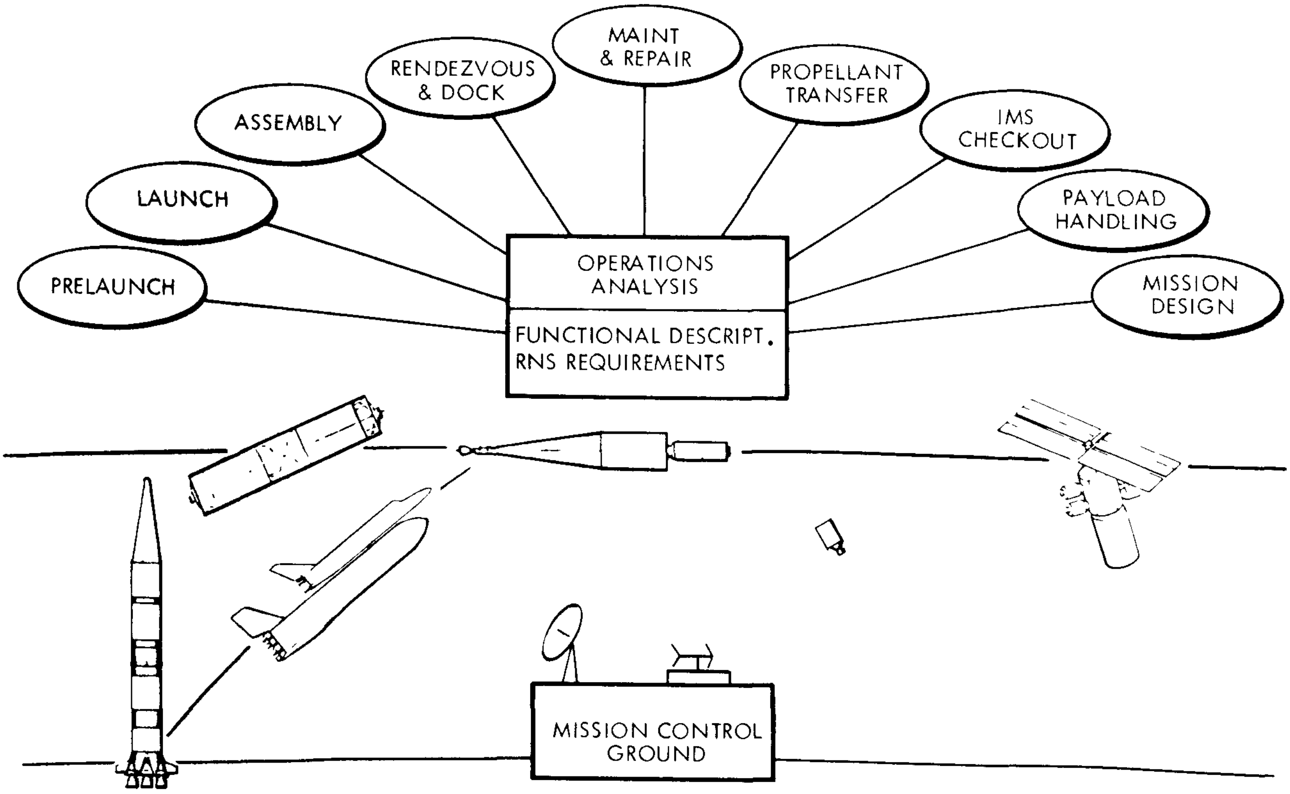


Figure 10. Mission Operations

The prelaunch operations considered activities beginning with transportation of the RNS from the fabrication site to KSC where operations in the Vertical Assembly Building (VAB) are conducted for launch to orbit. Transportation to KSC will be accomplished in the same manner as the S-II with only minor modifications required to the transporter to accommodate the increased tank length between support rings. Initial investigations show that vertical mating of the RNS tank and NERVA in the high bay aisle (for interface check) is the most attractive because of mating simplicity, as well as minimizing the GSE and facility modification requirements. Following tank/NERVA mating, the stage will be subjected to a leak and functional verification test. This will be followed by an overall system test performed by the onboard checkout (OBCO) equipment under control of the stage computer to verify total system operational capability. Upon completion of this activity, the RNS will have demonstrated readiness for the mating operation with the INT-21 which will be accomplished after the RNS tank and NERVA are demated. While the RNS tank is being mated with the INT-21, the NERVA will be prepared for loading aboard the space shuttle orbiter for launch to earth orbit. Major checkout operations associated with launch of both the RNS tank/INT-21 and NERVA/space shuttle have been identified in the study.

Orbital operations are initiated at the time the RNS tank is inserted into the operations orbit and terminated when the vehicle departs on its shuttle mission. Post-boost operations, prior to mating NERVA to the RNS tank, include removal of protective shroud(s) not jettisoned during boost and removal or safing of range safety devices. Launch of the NERVA engine is made with poison wires installed and control drums locked in the "scram" position, in keeping with safety considerations. The primary functions of the poison wires is to prevent the reactor from going critical if it should be immersed in water or liquid hydrogen. When the shuttle achieves orbit, the poison wires may be removed from the reactor by use of a retractable boom which is part of the engine delivery system.

In order to facilitate the orbital assembly of NERVA to the tank, a neuter docking system is provided wherein the active assembly is mounted on the tank and the passive assembly on the NERVA. During the docking operations, the RNS tank assumes an attitude-hold condition while the shuttle orbiter with NERVA deployed performs the rendezvous and docking as indicated in Figure 11. Following engagement of the docking system and verification of lockup of NERVA to RNS tank, the engine delivery system releases NERVA and is returned to the stowed position in the shuttle. Having achieved engagement and lockup, the active docking ring on the RNS will be retracted to locked position. Fluid and electrical connections then will be made through retractable interface plates. Upon completion of this operation, a functional checkout is performed on the total system employing OBCO to verify system operational readiness.

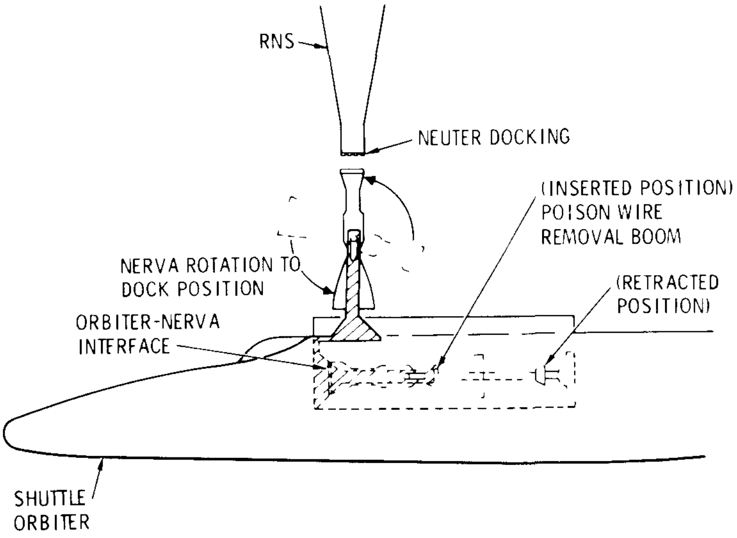


Figure 11. Poison Wire Removal and Engine Mating Concept

In addition to verifying system operational readiness, requirements and criteria include detection of malfunctions and isolation of the faults in flight replaceable unit (FRU) commensurate with the orbital maintenance concept. Malfunction detection is not restricted only to checkout of the RNS in operations orbit but is maintained active throughout the entire mission. In order to accomplish this, continual monitoring of subsystem status will be performed throughout the mission by sampling subsystem sensor outputs. Systems having redundant switchable components will utilize the malfunction detection capability to initiate the switching from the malfunctioning unit to the redundant unit. Although not ground ruled for the study, the design goal for electrical and electronic subsystems is fail operational/fail operational/fail safe (FO/FO/FS) capability. The mechanical subsystems, on the other hand, are based on a fail operational/fail safe (FO/FS) condition. Failure prediction is postulated at this time to be achieved through support from ground facilities to limit the size of the on-board digital computer memory units and reduce the amount of information management systems (IMS) computer programming required. The RNS IMS which integrates the checkout and communications function will be the focal point for controlling data for checkout and failure prediction. Also, in order to keep the programming of checkout routines as simple as possible, recognizing the programming function is an integral and major factor of automatic checkout, qualitative checkout (i. e., GO, NO-GO) will be performed by the OBCO equipment. If, during checkout, a subsystem is suspected of being marginal (operating near the predetermined GO, NO-GO limits), a quantitative check of the subsystem will be made in conjunction with the maintenance element equipment which has capability for display and recording of the exact values of parameters being interrogated.

Maintenance and repair work to be performed on the stage to achieve the three-years-in-space life will be accomplished in the RNS operations orbit. The maintenance/refurbishment checkout cycle shown in Figure 12 combines a logic-functional flow approach for the current RNS design maintenance and repair (M&R) approach, and checkout philosophy. The intent of the chart is to display the concept to be used during vehicle turnaround M&R operations. This concept is one which will entail the performance of corrective-type (unscheduled) M&R functions complemented with minimum preventative-type (scheduled) M&R activities. The basic philosophy used states that "If the system has just operated on the previous flight according to specification without discrepancies, then leave it alone." If all vehicle primary systems operated properly, then the M&R subsystem checkout cycle will verify the secondary or backup systems.

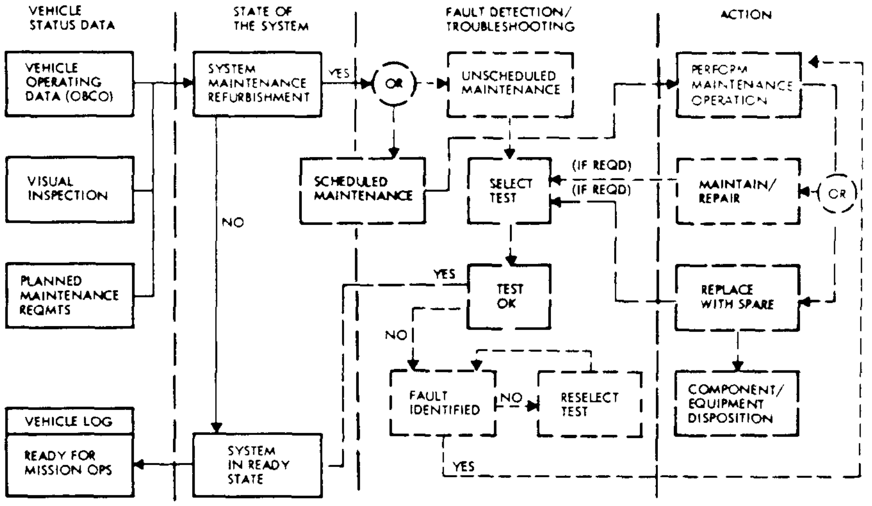


Figure 12. Maintenance/Refurbishment/Checkout Cycle

Vehicle status data output from OBCO, including visual inspection reports and planned M&R requirements, form the basis for establishing system readiness. With the system deemed ready, scheduled maintenance is performed in place or by component replacement, with the necessary testing performed to ascertain system readiness. When the system is not functioning properly, unscheduled maintenance is enacted by fault detection/troubleshooting methods to determine the problem. As the problem is defined, the action cycle (same as with scheduled maintenance) is activated with the necessary testing performed to ensure system readiness.

The two maintenance approach extremes of EVA or elaborate space hangars were ruled out during the study as being too hazardous or too costly for performing maintenance operations on the RNS. However, it is accepted that a remote maneuvering unit (such as space tug) with manipulators (teleoperators) is required to perform maintenance operations in the engine area where radiation levels exist which would be injurious to maintenance personnel.

Use of a maintenance element, with the capability of providing a suitable environment for personnel performing mainterance operations not hampered by pressure suits and reducing to a minimum or eliminating the need for EVA, is considered desirable. Two maintenance element concepts were postulated for servicing the RNS in orbit. One concept (shown in Figure 13) lends itself to delivery to the operations orbit by the shuttle on an "on-call" basis, which is very attractive for low traffic rates. It utilizes relatively simple teleoperators under manual control from the shuttle orbiter. Manipulators, together with a complement of spare equipment modules, are mounted on the maintenance element chassis. The manipulators and spares are arranged so that any modular group of components in the RNS can be exchanged with a replacement from the maintenance element. In the second concept, a 33-foot diameter maintenance element is permanently stationed in the operations orbit, with launch to orbit accomplished by the INT-21 with concurrent RNS tank delivery. This concept lends itself to high traffic rates wherein a maintenance crew would be stationed in the maintenance element. The configuration is compatible with RNS geometry in a single positioning. Inflatable seals would mate the docking and equipment bay structure enabling the equipment bay to be pressurized. In this manner personnel would have direct access to the astrionic equipment without need for EVA.

Also, replenishment of RCS and fuel cell reactants could be accomplished by a mechanism controlled from within the maintenance element and monitored through viewing ports. The design approach provides for future growth through modular expansion. Maintainability criteria resulting from these approaches are reflected in RNS subsystems design.

Evaluation of some of the more attractive propellant transfer options was performed in the study taking into consideration operational complexity, time requirements, safety, etc. In the evaluation, emphasis was given to the following design "drivers": propellant position control, storage state, logistic concepts, propellant depot configuration, RNS tank hydrodynamic and thermodynamic control, and technology development requirements. The preliminary analysis favored two methods for propellant position control during transfer: linear acceleration using source tank RCS, and centrifugal acceleration about the pitch axis.

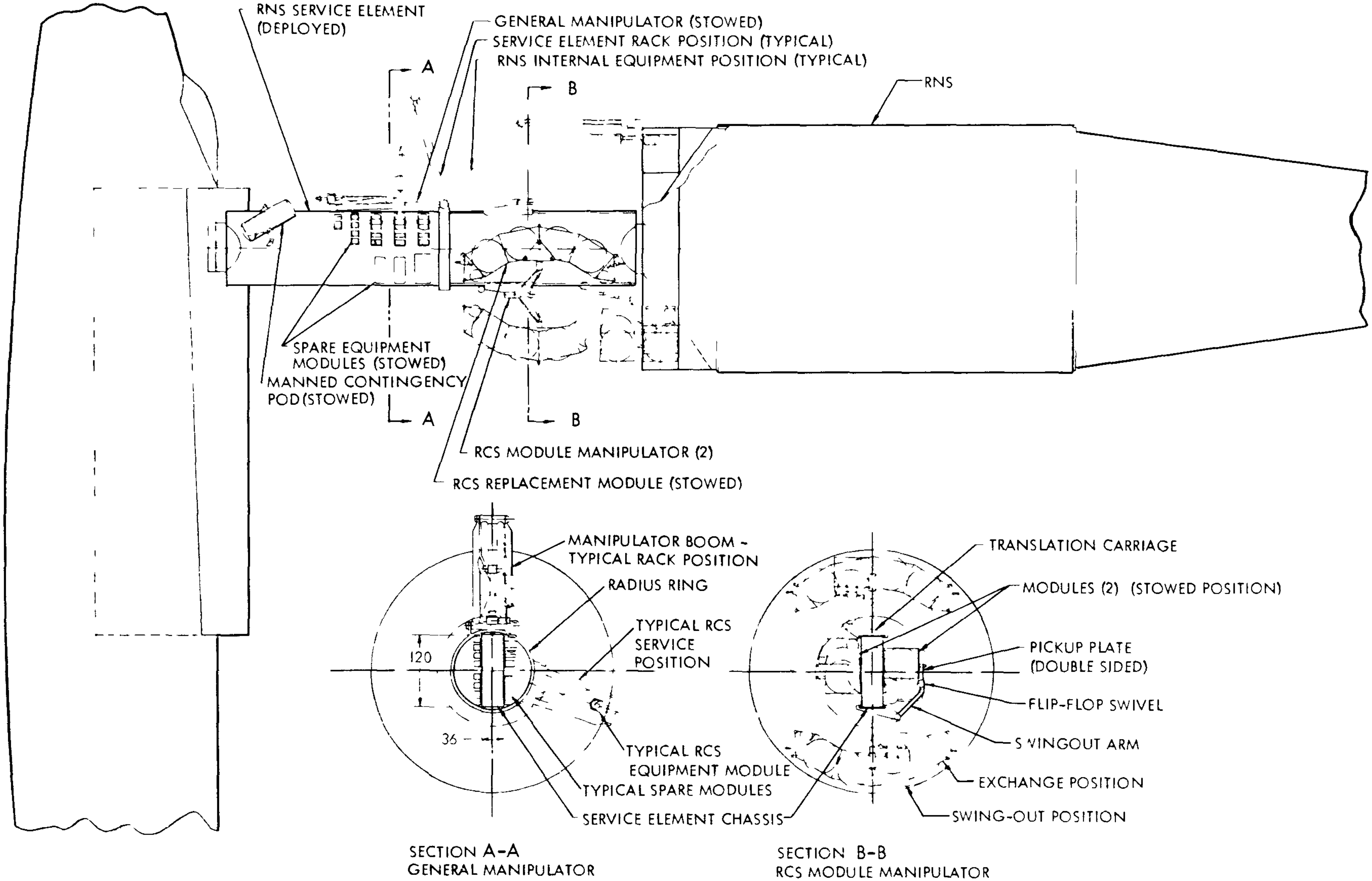


Figure 13. RNS Service Element Concept

The payload handling and related operations analysis identified a number of options oriented around the space shuttle, tug, propellant depot, maintenance element, and space station. Although the shuttle can make payload deliveries directly to the RNS, the tug appears to be the more versatile vehicle in performing the postulated transfer maneuvers.

A number of end-of-life spent stage disposal options were investigated taking into consideration disposal configuration, location from which the disposal is initiated, and the ultimate disposal location (Figure 14). Two disposal locations were shown to be attractive from the standpoint of operational simplicity, safety, and propellant requirements. The first consists of a 660-n mi orbit with an orbital life of approximately 1000 years. This can be attained from low earth orbit employing an unmanned tug (Figure 15) or with the RNS in a self-disposal mode. The second attractive disposal location consists of a heliocentric orbit, which can be economically attained if the vehicle end-of-life coincides with an unmanned planetary mission or a lunar mission with no payload return requirements.

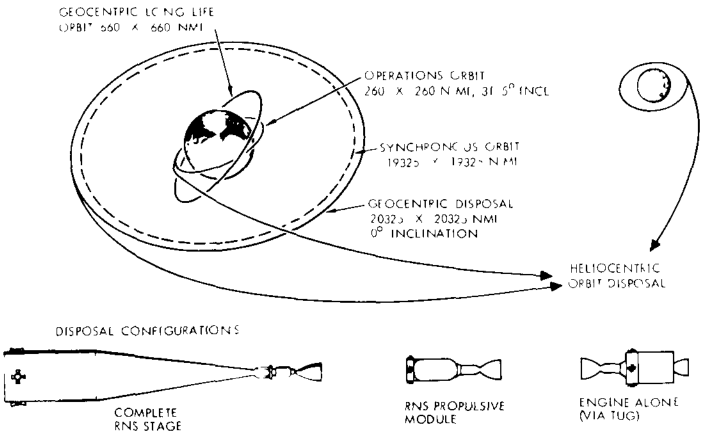


Figure 14. RNS Disposal Location & Configuration Alternates

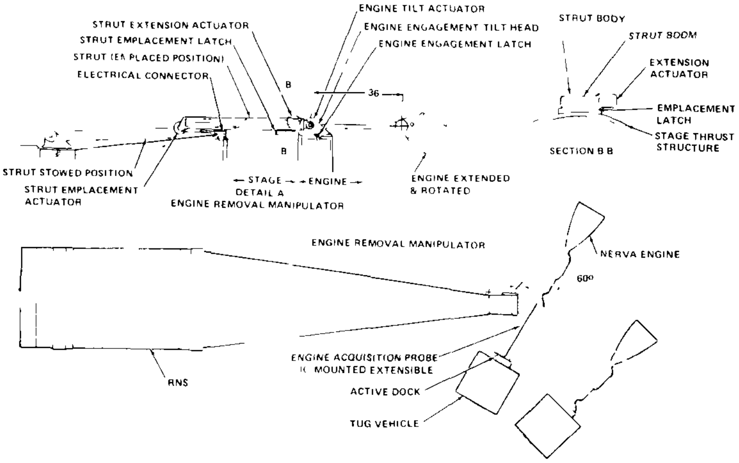


Figure 15. NERVA Removal Concept

The flight operations study activities resulted in the determination of orbital accuracy requirements, rendezvous and docking requirements, and development of an information management system concept. Rendezvous and docking modes and resulting approach patterns were investigated from which accuracy requirements were determined. Simple geometrical and error sensitivity considerations and constraints were used to establish requirements for phasing orbit accuracies prior to rendezvous transfer. The constraints are that the orbit is to be established with sufficient accuracy to allow RNS radar detection of the target vehicle within prescribed scan limits with 99.9 percent probability so that the RNS position and velocity errors are less (with 99.9 percent probability) than could be corrected by a delta-V of the same magnitude as that required for the rendezvous Hohmann transfer, and so that a non-zero closing rate will result. (The results for orbital accuracy requirements show the lunar orbit to be most severe and are identified as follows: cross range ± 3 n mi, down range ± 20 n mi, and altitude ± 1 n mi. Velocity accuracies are ± 10 fps in cross range direction and ± 15 fps in down range and radial directions.)

A rendezvous and docking example is illustrated in Figure 16 for the Hohmann transfer. In the maneuver shown, the RNS is assumed to hold an inertially fixed attitude during coast, the apparent pitch motion being caused by the 180-degree rotation of the coordinate system during the transfer. With use of +X and -X translations as shown, the nose of the RNS can point continuously in the general direction of the propellant depot (PD), thereby avoiding exposure of the depot to the high radiation emitted from the aft end of the RNS.

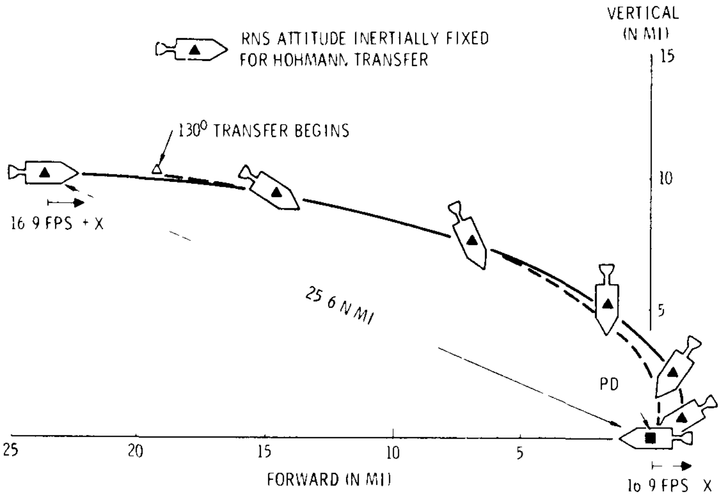


Figure 16. Motion of RNS Relative to Propellant Depot (PD) During Hohmann Transfer

The detection range requirement of 100 n mi results from the assumption that the RNS could be in a circular orbit which differs in altitude by 20 n mi from the target due to a 10 n mi insertion error. Transfer between circular orbits differing in altitude by 20 n mi begins at a range of 50 n mi. Twenty minutes of tracking adds 40 n mi. Finally, a 10 n mi range bias to allow for additional NERVA cooldown results in a 100 n mi detection range requirement. Based on the rendezvous described above, the following accuracy requirements were identified: range accuracy (3σ) ± 0.02 percent, radar range rate accuracy (3σ) ± 6 fps, SLR range rate accuracy (3σ) ± 1 percent, radar angular accuracy 0.6 degrees, SLR angular accuracy ± 0.02 degrees, and search volume 10 degrees by 10 degrees.

The information management system is intimately involved with the functions of communications, rendezvous, tracking, and checkout. The subsystem performs three major functions consisting of data handling, control, and communications. The functions overlap and are integrated into a system by digital computer software with provision for crew participation during manned operations. The digital computer accomplishes the GN&C computations, as well as communication signal routing, mission planning and event scheduling, on-board checkout, monitor and alarm logic, and operations data management. These services are accomplished through software interfaces to perform the IMS major functions of data handling, control and communications, and tracking.

Communications provides for information flow on-board the RNS, between the RNS and other vehicles, and between the RNS and ground. Bandwidth requirements for the communication and tracking links are defined as: digital data (telemetry) 12.5 KBPS for 100 (KH_z) up link and 600 KBPS for 4.8 (MH_z) down link, voice 1 channel at 4 KH_2, video (TV) 1 channel at 4.5 MH_z and tracking data PRN ranging at one MBPS for 8 MH_z.

The results of the operations requirements analyses yield the following significant conclusions:

(1) Existing facilities and support equipment can be economically utilized for transportation and prelaunch operations of the RNS

(2) OBCO can be employed for both ground and orbital checkout with limited interfacing equipment

(3) Operational compatibility of the RNS with other planned space program elements can be safely and economically effected

(4) Orbital maintenance can be performed employing a space shuttle derivative maintenance element

(5) NERVA disposal to a safe long-life orbit is within space tug's capability

(6) Self disposal of the RNS to heliocentric orbit is attractive through programming of end-of-life to coincide with an unmanned planetary mission or disposal from lunar orbit.

SYSTEM DEFINITION

The design objective during the Phase III study was to establish attractive RNS concepts. The attractiveness of the design arrangements was measured in terms of cost/performance effectiveness, which is directly relatable to components weight including external radiation shield, structure, thermal and meteoroid protection, as well as mechanical, fluid, and astrionic subsystems. Additional design drivers considered that also affect performance and cost include impact on the launch vehicle, facilities requirements, and complexity of flight operations.

The systems and subsystems analyses performed were subdivided into two separate but interrelated tasks, i. e., integrated stage design development and subsystems design. The first concentrated on the development of stage geometrical arrangements taking into consideration radiation environment, performance, interface with NERVA and launch vehicle, as well as ground and space operations including engine removal and disposal. These required parametric tradeoffs where the dimensional characteristics of stage design concepts were varied to assess their influence on structure, thermal/meteoroid protection, radiation dose to the tank top, and external shield weight. Loading impact on the launch vehicle also was assessed trading stage geometry, boost mode, and assembly mode. These analyses together with the results of interface design definition, mission operations requirements, thermodynamics, propellant management, and astrionics investigations were integrated into total systems for stage design evaluation and selection.

The subsystems were evolved concurrent with the stage configurations. The emphasis in the analyses in this case was placed in the investigation of interactions with other subsystems/systems and commonality with current NASA programmed efforts. In addition, simplicity of manufacturing, inspection and repair, as well as maintainability and reliability requirements were leading drivers in the design and selection of each subsystem, and the components thereof. Weight and performance complete the list of variables in the tradeoffs performed for stage concept evaluation, as well as for the selection of subsystems and components as applicable.

Configuration Evaluation and Selection

As previously stated, the design investigations concentrated on satisfying operational and mission performance requirements within the framework of maximizing cost effectiveness taking into consideration development cost, and development risk implications. Cost effectiveness (in terms of unit payload delivery cost) is a function of both performance and recurring expenditures. Performance is measurable in terms of radiation shield, structure, thermal and meteoroid protection and mechanical, fluid, and astrionics systems weights. Recurring cost can be subdivided into hardware and operational expenditures. The former can be minimized by simplicity of design, manufacturability, ease of quality assurance, and low maintenance of equipment and facilities while maintaining cognizance of component weight implications. Operational expenditures, on the other hand, include delivery of the stage, propellant, and spares to orbit, as well as orbital assembly and maintenance. Propellant delivery, at currently projected operating rates, is a major cost driver but its effect on the overall program can be ameliorated by improved performance of the RNS.

Low development cost can be attained by judicious use of existing technology, hardware, and facilities, as well as launch vehicle. Current technology utilization, however, must be evaluated against technology development weight reduction since it costs approximately $370/pound of inert weight added to the stage if payload is held constant (2.3 pounds of LH_2 is required for every pound of inert added to the stage). Consequently, technology development accompanied by weight reduction can be economical even when a development risk factor is added. It is, therefore, necessary to maintain a cost-conscious design development approach in the overall system optimization.

Configuration Alternates

The three configuration classes investigated are shown in Figure 17. One is a single tank design. A second is a modified dual-cell which maximizes the column of propellant available for radiation attenuation during the critical last engine burn when the radiation dose rate is reaching its peak. The third is a hybrid or two-tank design which offers the potential of aiding in end-of-life engine disposal, simplifying orbital assembly operations, improving propellant location control, and permitting early ground tests.

The analytical approach taken was to tailor tank aft bulkhead geometry to minimize payload shielding requirements. This is done by (1) controlling the angle for radiation incident on the tank, (2) using the conical aft bulkhead to achieve dual-cell benefits, and (3) taking advantage of the inverse square law to attenuate radiation beamed to the payload. These gains are achievable at the expense of reduced structural efficiency and increased operational complexity. However, radiation shielding for manned flights represents the major design driver and controlling factor in achieving best overall performance.

The analytical investigations initially optimized the performance of the single tank design for the lunar shuttle mission and then assessing the operational impact including launch to orbit. Also, the single tank optimum design point was employed to evolve attractive dual-cell and hybrid concepts, aimed at improving an already acceptable overall performance.

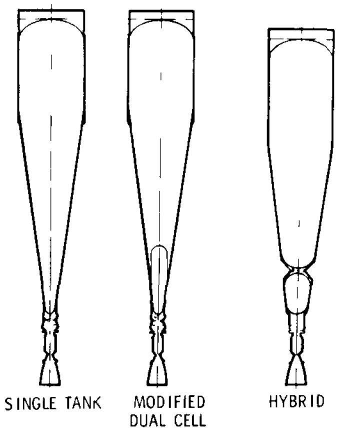


Figure 17. Alternate RNS Configuration Classes

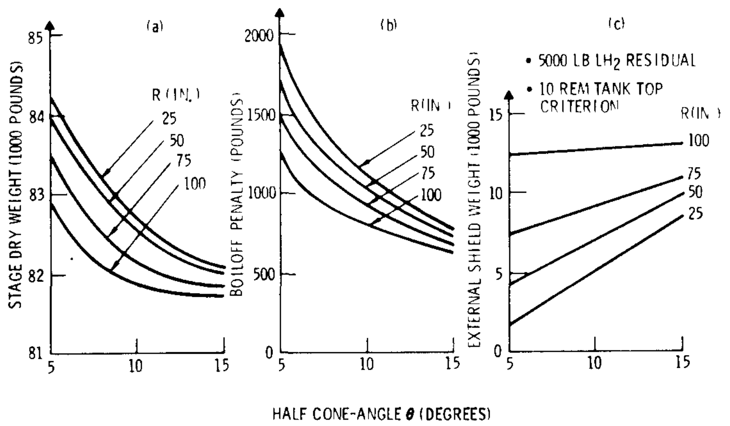


Figure 18. Stage Weight Variations

Single Tank Configuration. The parametric analyses were initiated by varying the aft bulkhead half cone-angle of the single tank configuration from 15 to 5 degrees and the end cap radius from 125 to 25 inches. A propellant tank capacity of 300,000 pounds of LH_2 was maintained with 5 percent ullage volume. The analysis consisted of structural as well as environmental protection studies, the latter including meteoroid and thermal protection, and external radiation shielding sizing. The results are presented in Figure 18 as a function of half cone-angle and end cap radius. In addition to the tank, the stage dry weight curves include forward and aft skirts; foam and high performance insulation for ground and space thermal protection; meteoroid protection for three years at

0.995 probability of no impact to the tank wall; and fixed weight components consisting of auxiliary propulsion, astrionics, thrust structure, etc. As can be seen in Figure 18, shield weight is essentially insensitive to cone-angle variations at large end cap radii ($\geq$ 100 inches). This is due to the small variation in tank length, height of propellant column towards the end of the last burn, and reactor core view angle at large cap radii.

The results of the parametric analyses including structure, thermal and meteoroid protection, boiloff penalties, and external shield are expressed in Figure 19 in terms of payload weight variation with tank geometry. An 8-degree half cone-angle with a 25-inch cap radius was found to yield near-optimum performance, It is possible that performance may continue to increase somewhat beyond this point as shown by the dotted lines in the figure; however, only parametric radiation analysis has been performed beyond the noted design point and consequently, the results need further verification.

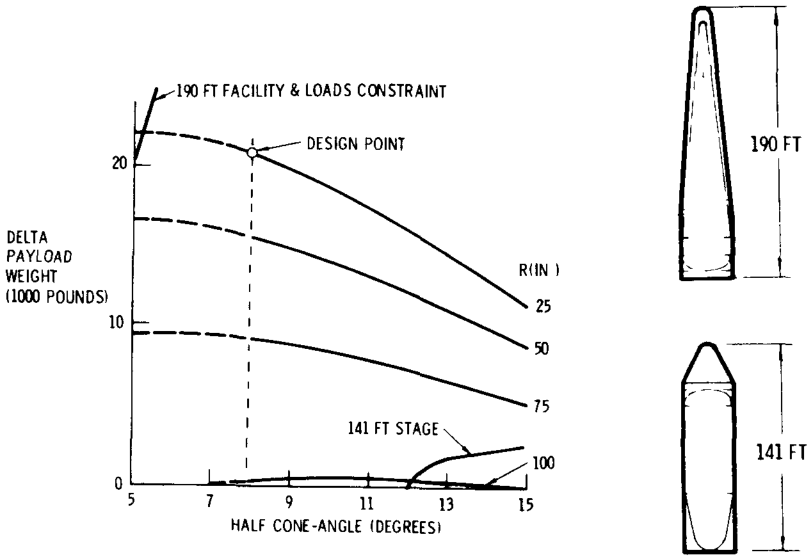


Figure 19. Design Trade-off Map With Launch and Facilities Constraints

The loading impact of the selected configuration on the INT-21 was next investigated. The proposed INT-21 has been upgraded recently by NASA to accept the loads imposed by a standard payload envelope, 33 feet in diameter and 141 feet in length including a biconic nose cone. The in-flight winds were restricted to 50 meters/sec compared to the 75 meters/sec for the Saturn V, thus reducing launch availability. This was done to minimize the uprating requirements of the S-IC and S-II. Since the selected RNS single tank configuration length, including nose cone and NERVA, is approximately 220 feet, alternate launch modes (Figure 20), were investigated to mitigate the loading impact on the INT-21. The selected approach, employs a non-integral launch mode, i. e., engine and stage delivered to earth orbit separately via space shuttle and INT-21, respectively, with subsequent mating and assembly in orbit. The stage atop the booster was, in turn, inverted, resulting in a 165-foot-long payload. A flexible body dynamic analysis at the max (q α) condition at wind speeds of 75 meters/sec for a 100 percent launch availability resulted in loadings on the INT-21 below those experienced with the 141-foot NASA baseline payload. This is due to the low air loading induced by the slender 8-degree half cone coupled to an aft movement of the center of pressure.

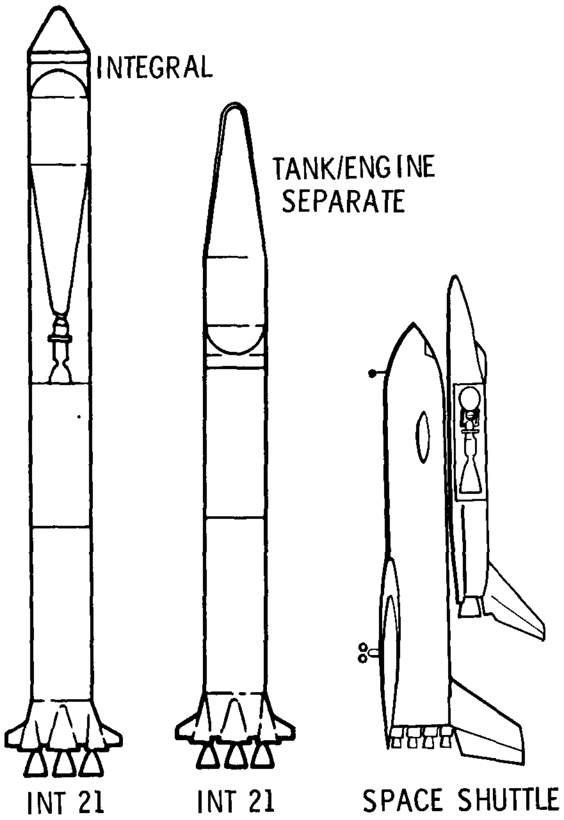


Figure 20. Alternate Launch Modes

The maximum acceptable tank length atop the INT-21 (inverted position, 8-degree half cone) is 190 feet. This, as shown in Figure 19, is also the ground facilities (KSC) constraint. The limit height of a right-side-up RNS launch configuration with no engine but with a nose cone must be restricted to 141 feet and is shown in the lower right hand side of the figure. The launch availability of this configuration is the same as that of the NASA baseline INT-21, that is, less than 100 percent. The data show that to preclude further modifications (and increased development cost) to the INT-21, this configuration must be limited to a 12-degree half cone-angle with approximately a 90-inch cap radius. Therefore, an inverted launch of the stage is necessary to maximize payload and cost effectiveness without increasing the development cost of the baseline booster. Furthermore, only with an inverted launch of the nuclear stage less NERVA, relaxation of the wind criteria, or an off-optimum performance design concept such as a larger half cone-angle and tank cap radius can the impact on the booster be avoided. It is also of importance to note at this point, that a non-integral launch requiring in-orbit mating and assembly neither creates new requirements nor violates any existing ones, because NERVA design criteria specify engine and stage assembly and disassembly capability in earth orbit.

Modified Dual Cell Configurations. The modified dual cell was evolved to improve the radiation attenuation to the tank top of the recommended single tank configuration by maintaining a higher effective propellant level within the tank during the last few critical seconds of the engine's last burn. This concept has the additional advantage of drastically reducing the available gaseous scatter volume in the vicinity of the inner cell. The latter's capacity was based on 5950 pounds of LH_2 consistent with the final cooldown propellant requirement with an allowance for vaporization. The cylindrical geometry of the inner cell was varied from 80 to 120 inches in diameter as shown in Figure 13 with the optimum falling midway at 100-inch diameter. The inclusion of the inner cell increases the ullage pressure over that of the single tank design by the sum of the dynamic head of the inner cell at main tank depletion plus pressure losses from capillary devices. The design incurs a 1450 pound structural weight penalty over the single tank configuration. This is due to the inner cell plus the pressure increase in the main tank.

Hybrid Configurations. The analyses during this phase of the study were limited to evolving attractive stage structural arrangements taking into consideration nuclear radiation, overall system weight, and space shuttle cargo bay compatibility with the propulsive module consisting of NERVA plus the auxiliary tank. A spectrum of stage configurations was synthesized as shown in Figure 17. This was accomplished by varying the auxiliary propellant tank LH_2 capacity from 3000 to 9300 pounds while maintaining compatibility with the space shuttle cargo bay geometry. The 9300 pounds propellant capacity permits engine self-disposal to high orbit altitude (660 n mi) and inclination (45 degrees). The 3000 pounds propellant capacity yields the most attractive geometry from the standpoint of radiation dose to the payload while maintaining excellent structural compatibility with the main tank Various main tank cap radii and half cone-angles were considered in the context of radiation attenuation, stage moldline continuity and intertank compatibility. The single tank study results, which indicated significant weight reductions for designs with small half cone-angles and cap radii, were employed as guide in the hybrid design screening.

The evaluation of the hybrid configurations is summarized in Table 1. The minimum empty vehicle weight, integral tank top radiation dose and external shield weight are seen to occur for the configuration employing a 3000 pound capacity LH_2 auxiliary tank (8-degree half cone-angle, 25-inch cap radius). However, its engine disposal capability is limited to high altitude orbit at inclinations that could pose future safety problems with increased space traffic. The configuration with the 7.5 degree half cone-angle represents the minimum weight system while maintaining the most versatile high earth orbit NERVA disposal capability.

Table 1. Hybrid Configuration Evaluation

CONFIGURATION(1)	EVALUATION CRITERIA				
	DISPOSAL CAPABILITY FROM LOW EARTH ORBIT	VEHICLE LENGTH (FT)	EMPTY WEIGHT (LB)	TANK TOP RAD DOSE(2) (REM)	EXTERNAL SHIELD WEIGHT (LB)
MAIN TANK - 8^0, 40 IN. R CAP AUX TANK - 77 IN. R CYL 9300 LB-LH_2	660 X 660 NMI 45^0 INCLINATION	209	80400	88	6000
MAIN TANK - 8^0, 40 IN. R CAP AUX TANK - 8^0, 25 IN. R CAP 3000 LB-LH_2	660 X 660 NMI 32.5^0 INCLINATION	211	78950	32	3800
MAIN TANK - 8^0, 77 IN. R CAP AUX TANK - 77 IN. R CYL - 9300 LB-LH_2	660 X 660 NMI 45^0 INCLINATION	193	79810	107	6600
MAIN TANK - 7.5^0, 112 IN. R CAP AUX TANK - 7.5^0, 68 IN. R CAP - 9300 LB-LH_2	660 X 660 NMI 45^0 INCLINATION	186	79230	109	6600

(1) AUXILIARY PROPULSIVE MODULE COMPATIBLE WITH SPACE SHUTTLE PAYLOAD CAPABILITY; GN&C MODULE REQUIRED FOR ENGINE DISPOSAL

(2) 5000 LB LH_2 RESIDUAL LEVEL

Alternate Configurations Comparison

Table 2 presents a brief summary of the most attractive design concept in each of the configuration classes considered. The burnout weight including shielding (directly relatable to payload performance and cost effectiveness) shows that the single tank design has an advantage of more than 6000 pounds over the hybrid, and 1500 over the modified dual cell. In the case of the latter, the weight difference is due to the higher tank design pressure discussed earlier plus the weight of the inner cell assembly.

Table 2. Candidate Systems Summary Comparison

ITEM	SINGLE TANK	MODIFIED DUAL CELL	HYBRID	
MAIN TANK HALF CONE ANGLE (DEGREES)	8	8	7 5	8
MAIN TANK CAP RADIUS (IN)	25	25	112	40
AUXILIARY TANK LH_2 CAPACITY (LB)	-	-	9,300	3,000
AUXILIARY TANK CAP RADIUS (IN)	-	-	68	25
TANK TOP RADIATION DOSE* (REM)	38	37	109	32
TANK DESIGN PRESSURE (PSIA)	*27 5*	*28 5*	28 2	28 2
EMPTY WEIGHT (LB)	75,540	77,000	79,230	78,950
EXTERNAL SHIELDING WEIGHT** (LB)	4,050	4,050	6,600	3,800
BURNOUT WEIGHT - INCL EXT SHIELDING (LB)	81,450	82,910	87,700	84,610
ENGINE DISPOSAL (HI EARTH ORBIT)				
NORMAL MODE***	TUG	TUG	AUX TANK	AUX TANK
INOPERABLE NERVA	TUG	TUG	TUG	TUG
RELIABILITY IMPLICATIONS	NO SIGNIFICANT DIFFERENCE BETWEEN CONCEPTS			
RECOMMENDED CONFIGURATION	✓			

*5000 LB LH_2 - LAST COOLDOWN PROPELLANT
**10 REM CRITERIA
***APPLICABLE FOR STAGE LIFE EXCEEDING ENGINE

The hybrid and dual cell classes show increases in stage empty weight over the single tank design. These are basically in structure and meteoroid and thermal protection, and are due to increases in surface area of both pressurized and unpressurized shells as well as a slight increase in tank design pressure due to losses accrued by transferring propellant from the main to the inner cell or auxiliary tank. From the standpoint of delivery to earth orbit, all three configurations are about equal. They all require an inverted launch on the INT-21 to preclude modifications to the latter. Engine disposal seems to favor the hybrid, until the contingency of an inoperable NERVA makes it mandatory to rely on an alternate vehicle such as the space tug for NERVA disposal.

On the basis of the data summarized in Table 2, the single tank design employing INT-21 launch of the RNS tank in an inverted attitude is the most attractive configuration while meeting current standards for on-board personnel protection and therefore has been selected as the baseline vehicle. The conclusions of the configurations evaluation and selection effort can be summarily itemized as follows: (1) The single tank design (8-degree half cone-angle, 25-inch cap radius) offers highest performance and cost effectiveness of the concepts considered; (2) Orbital mating and assembly of the stage and NERVA is feasible and necessary to maximize performance; (3) Inverted launch of the main tank is feasible and necessary to minimize development cost of the INT-21; (4) Slender cone-angle arrangements yield dynamically stable vehicle designs; and (5) The hybrid configuration employing an auxiliary propellant tank with a capacity of about 3000 pounds offers an attractive structural arrangement from the standpoint of radiation attenuation to the payload and consequently, payload performance. Nevertheless, it is less efficient than the single tank and this propellant capacity could pose problems in attaining a safe disposal orbit. Also, further work is necessary in this configuration to establish stability and control requirements for engine disposal.

Baseline Definition

The layout of the selected baseline configuration is shown in Figure 21 depicting the general arrangement of the vehicle and a summary weight statement is given in Table 3. The single tank of 33-foot cylindrical diameter and 8-degree half cone-angle with 25-inch cap radius aft bulkhead is 1827 inches long and accommodates 300,000 pounds of propellant with 5 percent ullage. Extension skirts are added to the forward and aft ends of the cylindrical portion for attachment of INT-21 booster or payload, and aerodynamic shroud, respectively. A thrust structure, also in the form

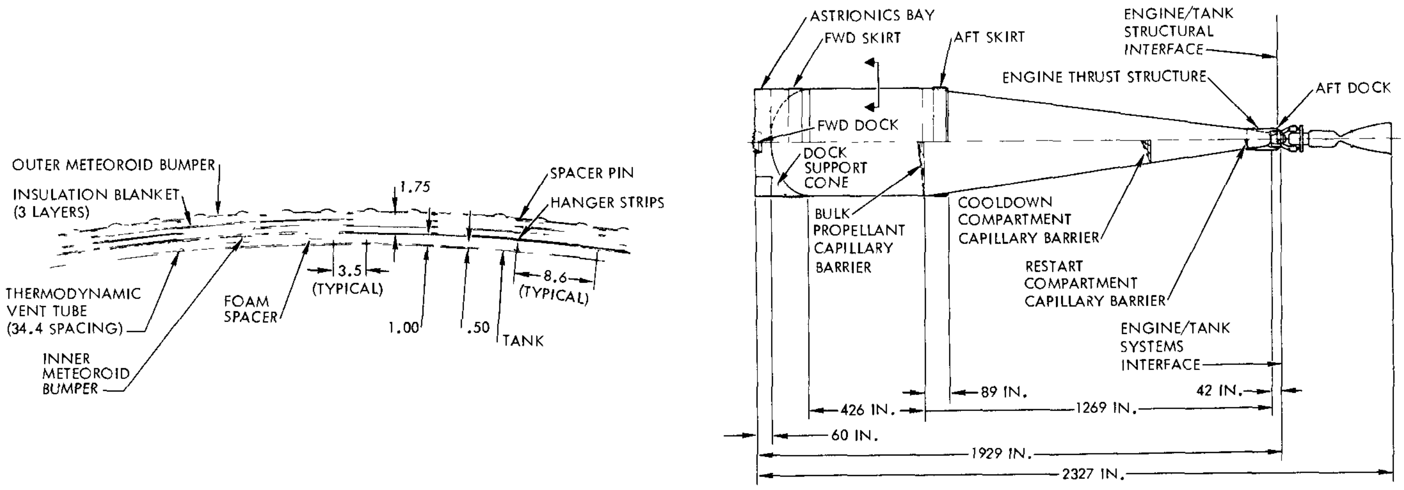


Figure 21. Selected RNS Baseline Configuration

Table 3. Recommended Single Tank RNS Weight Summary(lb)

STRUCTURE	24325		
METEOROID/THERMAL PROTECTION	13120		
DOCKING/CLUSTERING	1320		
MAIN PROPULSION	30225		
AUXILIARY PROPULSION	1320		
ASTRIONIC/ELECTRICAL POWER	5055		
SAFETY ORDNANCE SYSTEM	175		
SUBTOTAL	75540		
RCS PROPELLANT		5800	
RESIDUAL PROPELLANT		2890	
BOILOFF PROPELLANT		1360	
IMPULSE PROPELLANT		295750	
TOTAL		381340	
BURNOUT WEIGHT			
EMPTY WEIGHT			75540
LESS USABLE FUEL CELL REACTANT			1030
PLUS RESIDUAL VAPOR			+2890
TOTAL			77400

of a skirt, is provided at the end of the aft bulkhead to accommodate the engine installation. An active neuter docking system and supporting cone structure are incorporated in the forward skirt for stage docking to a propellant depot, maintenance element, or similar facility and for payload module connection. An annular astrionics bay for installation of the stage auxiliary subsystems is also integrated into the forward skirt structure. Another active neuter docking system is built into the thrust structure to facilitate orbital installation of the engine, as well as for orbital handling of the stage and NERVA during removal and disposal operations. The passive assembly of the neuter dock is attached to the engine forward thrust structure and the active assembly is attached to the stage thrust structure. The tank is compartmentalized by three perforated capillary barriers and a bottom screen to facilitate propellant management during space operations.

Structure Subsystem

The material employed in the fabrication of the tank is aluminum alloy 2014-T6. Waffle construction with a 0-90 degree rib orientation was selected for stiffening of the cylindrical sidewalls, sized for an ultimate loading intensity of 365 lb/in. occurring at max (qα) and an LH_2 temperature of -423 F. Monocoque construction was chosen for the forward and aft bulkheads since the design condition is pressure only. To minimize heat leak to the tank, the forward and aft skirts incorporate four-foot heat blocks consisting of an 0.04-inch fiber glass faced sandwich with a 2.0 inch HRP honeycomb core.

Other than the heat blocks, the basic construction selected for the skirts and astrionics bay structure is integrally, longitudinally stiffened aluminum alloy 7075-T83. Both the material and method of fabrication for the tank and skirts were selected based on minimum cost taking into consideration development and payload performance implications. Past studies on the Saturn V, to determine cost influencing parameters or drivers,' have shown that the lowest specific cost in structural components is associated with the integrally stiffened propellant tank cylinder. This is due to the few parts contained in the component, which more than compensates for the fact that it is constructed from large expensive pieces that are machined and welded together. The reduction in cost with number of parts for a given component is traceable to the reduction in manufacturing steps, and the associated reduction in inspection and documentation.

The stage thrust structure is a cone frustum approximately 107 inches long to which is attached the active docking ring of the neuter dock concept developed by the NR space station program for potential application to interfacing space program elements. Again, the selection of the docking system design was based on reduced cost development without compromising the RNS operational capability and/or performance. Because of thermal considerations, the material selected for the thrust structure is 6 AL-4V titanium alloy which has a substantially lower conductivity than aluminum. The upper edge of the thrust structure is bolted to a ring which is integral with the aft conical bulkhead.

Thermal/Meteoroid Protection

The thermal/meteoroid protection subsystem covers most of the exposed surfaces of the RNS. Details of the installation are given in Section A-A of Figure 21. The design represents an integrated HPI/meteoroid protection subsystem wherein the high performance insulation functions not only to thermally protect the hydrogen but to form a plurality of meteoroid shields to increase the efficiency of the meteoroid protection system. In addition, the integral nature of the concept provides (1) protection for the HPI from aerodynamic heating and wind loads, (2) dynamic damping of the meteoroid bumpers, (3) a scalloped area for the distribution and release of HPI purge gases during the ground hold and launch phases of the mission, (4) a more stable region for structural support of the HPI than afforded by the tank wall which undergoes dimensional changes due to internal pressures and cryothermal contraction, and (5) ease of manufacturing, installation, inspection, and repair of the subsystem.

The double bumper concept, employed over the tank sidewalls, consists of two layers of fiber glass, 0.030 and 0.010 inches thick for the outer and inner shields, respectively, encasing 1.5 inches net of GAC-9 in three separate panels, 0.5 inches each. Both bumpers are continuous cylinders with the outer sheet beaded to impart enough stiffness to prevent local flutter. The foam substrate shown in the figure provides thermal protection during ground hold and boost, and is scalloped to facilitate purging of the HPI.

GAC-9 was selected as the baseline high performance insulation with SUPERFLOC as an alternate SUPERFLOC exhibits higher performance than GAC-9, but the latter currently offers a higher degree of development, as well as better handling, installation, inspection, and repair characteristics. However, it is of importance to note that this choice could change depending on the results of current NASA funded technology studies, as well as the space shuttle development program.

Propellant Management

Of the various propellant management concepts considered, passive propellant management (passive stratification) was selected based on the possible residuals reduction -- hence significant payload gains over the other candidates. Furthermore, when combined with a judicious capillary device design for propellant feed and location control, the integrated system results in improved thermal control and overall operational simplicity.

The pressurization analysis has shown that hot pressurant flow during bootstrapping and feedout acts to create a stratified ullage. Temperature gradients so induced are not necessarily undesirable and, indeed, may be desirable if effectively utilized. A hot ullage, if maintained, results in low pressurant residuals at mission termination. The higher tank wall temperatures decrease heat leaks. In addition, a substantial decrease in boiloff per unit of heat leak can be gained by venting superheated rather than saturated hydrogen. To derive these benefits, propellant sloshing and intermixing with the ullage must be prevented. This is achieved by a two-pronged approach: (1) RCS engine sizing and operational logic that minimizes vehicle disturbances, and (2) a system of capillary devices to control propellant even if maximum vehicle perturbations do occur. Therefore, a design utilizing capillary devices in a bulk propellant control scheme has been developed to provide feedout during restart, steady burn, and cooldown; to assure slosh control; and to provide efficient thermal control, venting, and pressurization. The design is shown in Figures 21, and 22. Capillary barriers have been used to divide the tank into four major compartments, named to denote their major function. Beginning at the forward end of the tank, they are: (1) ullage compartment, (2) bulk propellant compartment, (3) cooldown compartment, and (4) restart compartment.

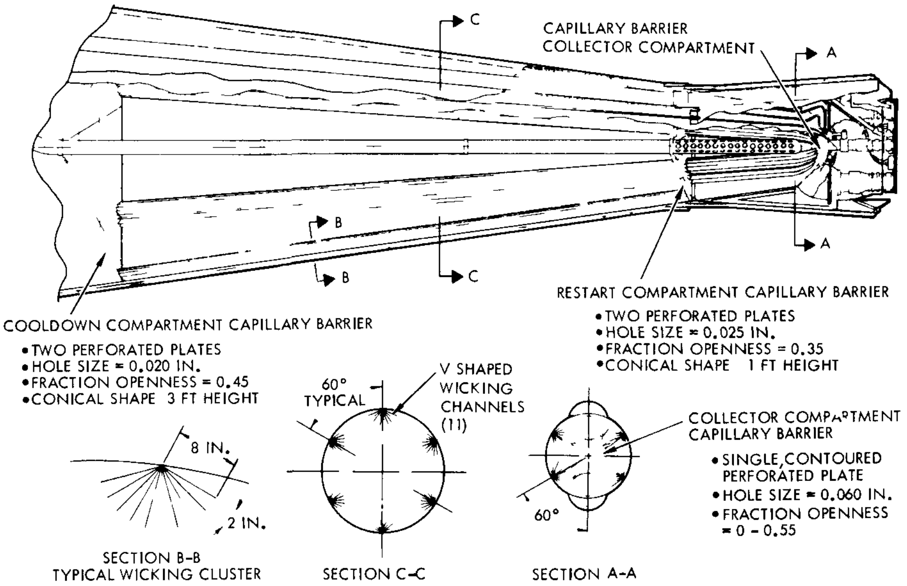


Figure 22. RNS Aft Section

The bulk propellant capillary barrier is mounted and supported at the intersection of the cylindrical and aft bulkhead at a plane just above the propellant level after the TLI burn. The barrier consists of two perforated plates one-half-inch apart with 0.060 inch chemically milled holes. The fraction of open area to total plate area for each plate is 0.1. The plates are supported by radial and circumferential frames, conically shaped for structural purposes, with the apex located two feet above the base. This barrier will prevent all but inconsequential gas-liquid interchange between compartments for rotation rates and lateral, negative, and centrifugal accelerations due to vehicle maneuvers and perturbations.

The restart and cooldown compartments assure adequate propellant flow at each engine restart. Hole size and fraction openness differ from that of the bulk capillary barrier. They are, respectively, 0.020 inches and 0.45 openness fraction for the cooldown compartment, and 0.025 inches and 0.35 openness fraction for the restart compartment. The cone height of the cooldown compartment capillary barrier is three feet. Each compartment is cooled by a thermal conditioning unit which is part of the "thermodynamic" vent system. The restart compartment, which has a capacity of 500 pounds, supplies vapor-free propellant at each engine restart. This compartment is also designed to assure adequate feedout for the last phase of the last engine cooldown. During cooldown, propellant is fed from the restart compartment to the collector compartment (Section A-A, Figure 22).

The cooldown compartment supplies the bulk of the cooldown propellant during the mission and is sized for "worst case" hydrodynamics for the lunar mission. As the bulk compartment is partially depleted, propellant could be dislocated to the upper end of the compartment which would lead to vapor passage from the bulk to the cooldown compartment as cooldown flow proceeds. To preclude vapor passage to the restart compartment, V-shaped wicking clusters have been added and are shown in the main view and in Sections B-B and C-C, in Figure 22. These clusters are sized to provide cooldown flow to the restart compartment under zero to minus 10^{-5} g. Wick size and shape have been determined using data from NR in-house studies.

Feedout during the last cooldown requires wicking clusters in the restart compartment also. Therefore, the four V-shaped clusters are extended to lead fluid into the collector. V-shaped channels are specified as they are self emptying, thereby reducing trapped residual in the compartment. The collector capillary barrier is contoured to the aft bulkhead cap geometry with cutouts to avoid the two-pump outlet lines. Fraction openness is designed to increase from 0 to 0.55 with increasing distance from the centerline. This is done to prevent vapor pull-through (interface dip) over the outlet line. Perforation size is 0.060 inches.

The vent system originates at the aft end of the conical aft bulkhead as shown in Figure 23, where the thermodynamic vent tubes are manifolded and, in turn, connected to the cooldown line by way of a throttling valve. The tubes emanating from this aft manifold have a hemispherical cross-section and run in parallel the length of the vehicle to intermediate manifolds until they reach the most forward manifold which discharges overboard through two symmetrically placed vent heads. This design, which is in effect an open-loop refrigeration system, operates by withdrawing liquid through the cooldown line and expanding the liquid to a lower temperature and pressure. The system is activated by both tank pressure and liquid temperature.

In conjunction with the propellant management system, ground and orbit fill ports, ground pressurization, and vent and autogenous pressurization lines are shown in the forward end of the stage. The ground fill line doubles as an emergency vent during orbital operations while the orbital fill line is used as

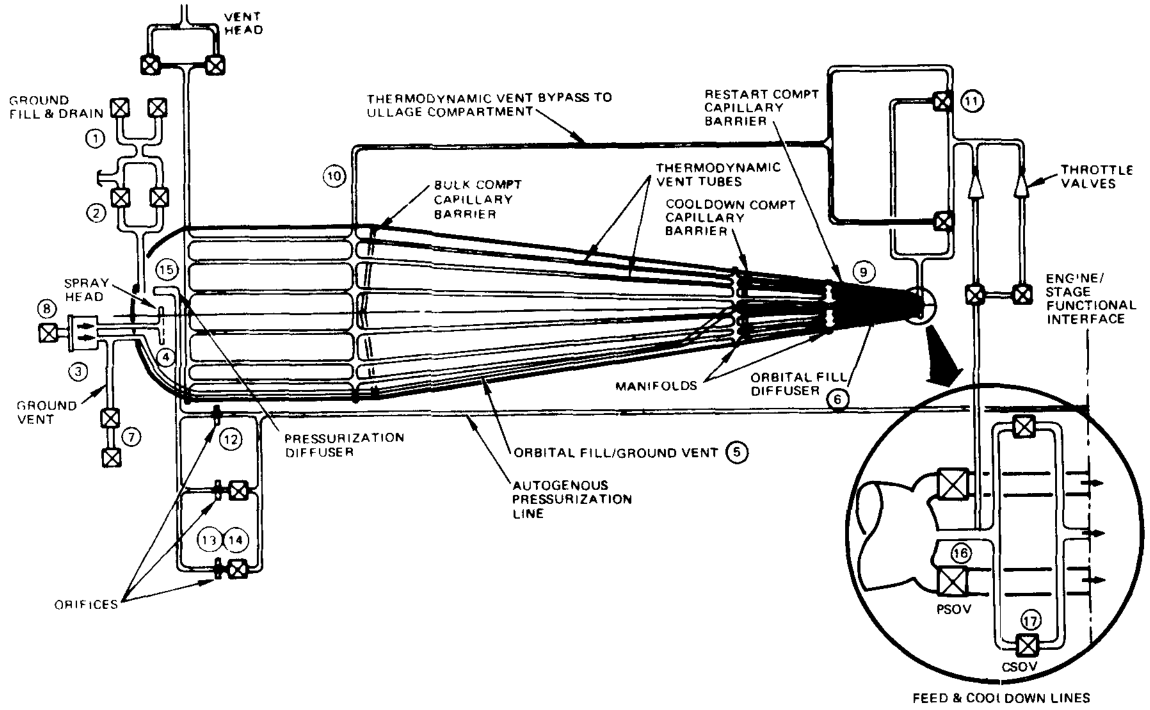


Figure 23. RNS Propellant System

a ground vent standpipe during prelaunch and launch operations. This is possible since the standpipe extends to the apex of the aft bulkhead and is, therefore, not covered by propellant during launch because the stage is inverted. The autogenous pressurization line runs the length of the vehicle and interfaces with NERVA. It is a 2.25 inch diameter line located within the systems tunnel and ends in a diffuser in the ullage compartment. Ground pressurization uses the same diffuser as shown in the top view of the stage.

Astrionics and Auxiliary Propulsion

The astrionics bay shown in Figure 24 contains all the electronic equipment including guidance, navigation, controls, communication, and the NERVA NDIC. In addition, RCS, electrical power system, and environmental control are housed in this area. The distribution of the equipment both within and without the astrionics bay is displayed in the figure. All instrumentation and components identified during the course of the study are shown.

The majority of the inside surface is covered by the two RCS propellant tankage quadrants with a third quadrant occupied mainly by the three fuel cells required with their associated inverters and controls. Also shown are the two batteries required during peak NERVA operations. The NDIC is located next to the electrical power system. The last internal quadrant is used for the instrumentation connected with horizon sensors, communication, station-keeping and docking, IMS computer and RACU's. Four inertial measuring units are shown; however, six are now required based on subsequent reliability analysis.

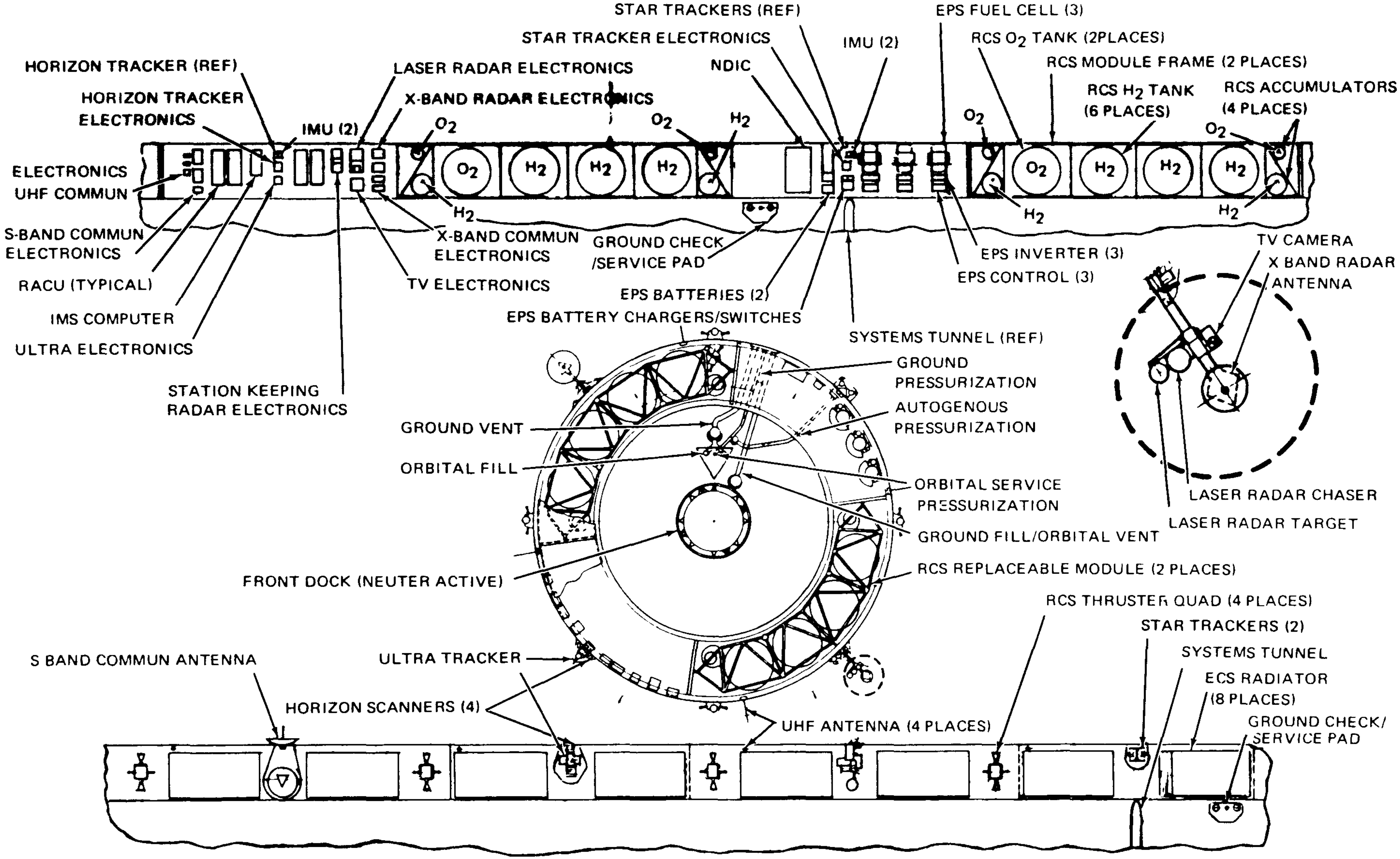


Figure 24. RNS Astrionics Bay

The external surface of the astrionics bay is mostly covered with the environmental control system radiators and by the four RCS pods. In addition, the star trackers, the communication antenna, ULTRA tracker, four horizon sensors, and the rendezvous and docking equipment (consisting of TV camera, laser radar chaser and target, and the X-band radar antenna) occupy the remaining available space.

As can be seen, the surface and volume occupied by electronics and equipment other than the RCS and its propellants is relatively small. Their relocation to suit additional or new maintenance requirements can be readily accommodated.

An autonomous guidance and navigation system has been defined for the RNS to provide maximum flexibility for carrying out lunar/geosynchronous orbit shuttle missions. The capability minimizes the need of earth based operations other than for monitoring, flight scheduling, and resupply. Another obvious advantage to providing the RNS with a completely autonomous capability is that redundant equipment is provided for backup by the MSFN during orbit-to-orbit transfers, including trans-earth and translunar flights, and by both the MSFN and another autonomous vehicle during rendezvous and docking.

For the RCS, a supercritical storage gaseous O_2/H_2 system is recommended because the concept exhibits a minimum amount of development problems. The supercritical storage concept for both hydrogen and oxygen has been used in previous spacecraft so valuable development experience is already available. Additionally, this type of system eliminates the problem of propellant acquisition since supercritical storage assures single phase delivery regardless of the gravitational conditions.

Of the electrical power systems considered, the fuel cells/battery concept was found to be particularly attractive since reactant supply could be available from the propellant depot between mission cycles and reactant tankage requirements combine with those of the RCS. Therefore, O_2/H_2 fuel cells have been selected to supply the primary load throughout the RNS mission cycle. This selection has been made considering that fuel cells are a space proven energy source, exhibit a low specific weight for the mission durations of interest, and generally have non-catastrophic failure modes and measurable degradation factors with relatively long life. Current designs exhibit active lifetimes of 2,000 hours with some laboratory evidence that lifetime can be potentially extended to 10,000 hours. In-orbit replacement and/or maintenance can be effected more readily than for solar array power sources. Degradation due to radiation effects will be less severe for a fuel cell concept than for a solar array. Additionally, fuel cells allow greater system flexibility and growth factor to meet varying load requirements since most of the subsystem weight is due to the reactants required to meet load energy requirements.

RELIABILITY AND SAFETY

Investigations in these areas were oriented to analyses of the major subsystems in the alternate stage configurations with emphasis on the selected baseline design, i. e., a single tank conical configuration with an aft bulkhead geometry employing an 8-degree half cone-angle and a 25-inch end cap radius. Additionally, reliability and safety analysis techniques were utilized throughout Phase III to ensure both a high probability of mission success for candidate RNS missions and to eliminate potentially hazardous mission operations that could endanger the safety of the earth's population and/or personnel in space.

Reliability studies of the major subsystems and components resulted in the elimination of all single point failures, with the exception of the main propellant tank. Reliability logic diagrams , fault tree analysis, and failure mode and criticality analyses (FMECA) were the principal tools employed in reliability analyses of the subsystems based on current NASA-accepted fail operational/fail safe (FO/FS) and fail operational/fail operational/fail safe (FO/FO/FS) criteria for mechanical and electrical components, respectively. Typical FMECA's are shown in Table 4.

Table 4. Typical Failure Modes, Effects, & Criticality Relationships

SUBSYSTEM	COMPONENT	FAILURE MODE	POSSIBLE FAILURE EFFECT					CRITICALITY CATEGORY
			THRUST LOSS	ENGINE DISASSEMBLY	ELEC POWER LOSS	CONTROL LOSS	PROPELLANT LOSS	
MAIN PROPULSION	MAIN LH2 TANK	RUPTURE	X	*			X	I
	PROPELLANT SHUTOFF VALVES	OPEN/CLOSED	X				X	II
	COOLDOWN CONTROL & SHUTOFF VALVES	OPEN	X				X	II
		CLOSED		X			X	
	PRESSURIZATION CONTROL VALVE	OPEN/CLOSED	X				X	II
RCS	PROPELLANT TANKS	RUPTURE				X	X	II
	GAS GENERATOR PRESSURE REGULATOR	CLOSED				X	X	II
	RELIEF & ISOLATION VALVES	OPEN				X	X	II
EPS	FUEL CELLS	INOPERATIVE	X		X	X		III
	BATTERIES	INTERNAL SHORT STRUCTURAL	X		X	X		III
	AC BUS	COMPLETE FUNCTION LOSS	X		X	X		III
G N &C	IMU	GYRO FAILURE				X		III
	STAR TRACKERS	INOPERATIVE				X		
	HORIZON SENSOR	HEAD FAILURE				X		
	MULTIPROCESSOR COMPUTER	PARTS OR CIRCUIT FAILURE	X	*		X		

*EFFECT FOLLOWS LOSS DURING MAIN BURN OR COOLDOWN

FMECA's for the major subsystems were performed for the three criticality categories utilized in the Phase II study (ranging from failures that downgrade a mission to those capable of causing personnel injury or mission loss). In addition to the main propellant tank single point failure, the electrical power subsystem did not fully meet the FO/FO/FS criterion and would require the addition of a fourth inverter and a fourth fuel cell. However, it was recommended that a decision in this regard be delayed pending availability of additional test and failure rate data for these components.

A highly redundant capability was incorporated into the major components for the GN&C subsystem (Figure 25). Most of these components can perform dual functions, thereby assuring at least degraded performance even with the highly improbable total loss of a major component. Similarly, redundancy was incorporated into the major components of the main propulsion subsystem and the RCS. For example, it was determined that the loss of an oxygen tank in the RCS would result in a deficiency of several hundred pounds reactant capacity in order to assure safe return from the lunar shuttle mission after a 17-day stay period at the moon, once the commitment for earth return is made. Since the installation of a small third O_2 tank was determined feasible, it was recommended that it be added to the RCS to assure adequate propellant reserve.

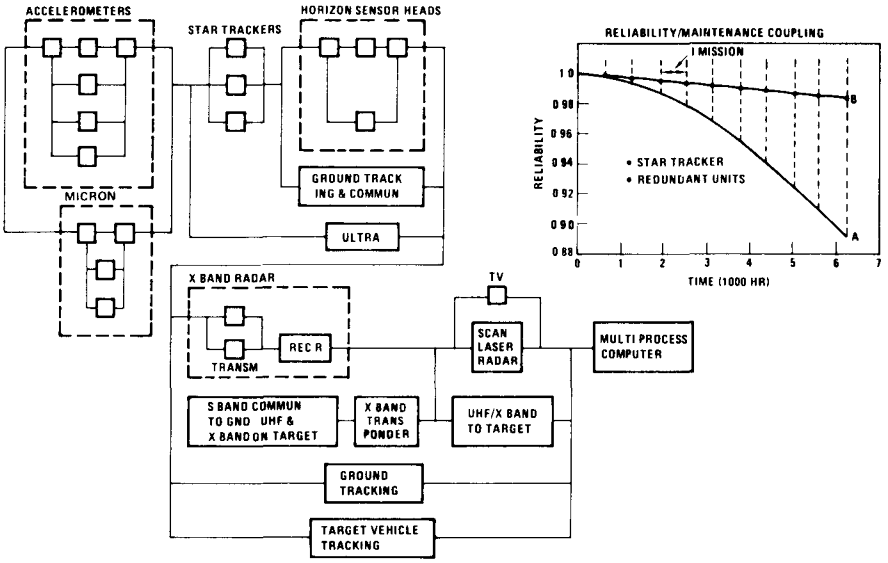
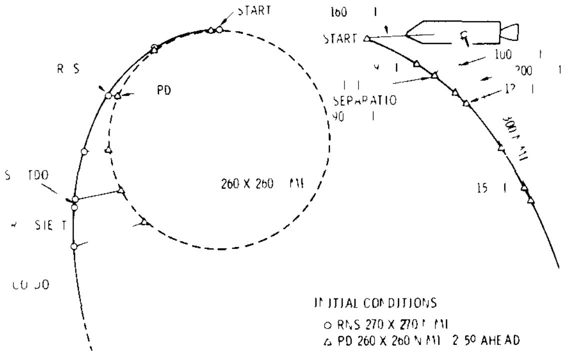


Figure 25. GN&C Failure Avoidance Through Redundancy and Maintainability

A review of the reliability apportionment performed during the Phase II study was accomplished and indicated no necessary changes at this time, particularly in view of increasing emphasis on the FO/FS criterion as a means of providing reliable and safe mission operations. Additionally, the maintainability concept for RNS lunar shuttle application was designed to include provisions for replacement of parts and components such that unscheduled component replacement can be accomplished in case of a random failure. Consequently, this approach to maintainability was also found to enhance total mission success probability as shown for redundant star trackers in Figure 25. Curve B in the figure demonstrates the increase in mission reliability attainable over a span of ten missions by effecting the necessary maintenance between missions as compared to Curve A for an unmaintained system.

Both the nuclear and non-nuclear safety implications of RNS launch operations at KSC were investigated. The well-established safety procedures and exclusion areas for Saturn V launch vehicles were found to be adequate for both the space shuttle and INT-21 launch operations of the RNS. The current nuclear safeguards employed by the NERVA engine for the ground test program appear adequate to eliminate potentially hazardous occurrences during launch operations.

Normal flight operations were shown to be within established radiation safety criteria for representative RNS missions. NR concepts for RNS mission trajectories were tailored to avoid NERVA engine firings in the vicinity of other space program elements (Figure 26). Prior to departing an RNS operations orbit, separation distance (altitude and orbit phasing) between the stage and other space program elements (propellant depot, orbiting lunar station, or synchronous orbit space station) is achieved through use of the RCS. Ancillary operations such as rendezvous and docking, crew transfer, orbital refueling, and maintenance have been shown feasible for the RNS baseline design if conducted at the forward end of the vehicle. However, operations near the aft end of the tank and in the area of the engine/stage interface were shown to be limited due to the NERVA post-shutdown radiation environment. However, additional shielding can be minimized if sufficient decay time is allowed after the last engine firing prior to scheduled operations. For example, a decay time of 24 hours will effect a reduction in gamma kerma rate of 1.4 to 1.6×10^5 compared to the normal NERVA operating power level. Additionally, an unmanned space tug affords a potentially attractive method for performing certain space operations in the aft end of the vehicle (e.g., engine disposal).



NERVA FULL POWER DOSE RATE (REM/HR)					
DISTANCE (MILES)	FORWARD	RADIAL AT CORE CENTER		AFT	
		γ	n	γ	n
1	NEGLIGIBLE	4.3×10^2	4.3×10^3	2.9×10^2	7.9×10^3
3	NEGLIGIBLE	48	480	31	870
5	NEGLIGIBLE	17	170	11	310
10	NEGLIGIBLE	4.3	43	2.9	79
15	NEGLIGIBLE	2	19	1.2	34

Figure 26. Operations Related to Engine Run Radiation

Performance and trajectory analysis of lunar shuttle missions for abnormal or emergency operations involving degraded propulsion capability could conclude with the RNS in a highly elliptical earth or lunar orbit. It was determined that safe return of the RNS crew to the earth operations orbit or to an OLS by means of a space tug (80,000 pounds LH_2 propellant capacity) is possible. However, complete loss of NERVA propulsion in the aforementioned phases of the mission could possibly result in loss of the RNS although crew module propulsion (life boat concept) could alleviate a number of these situations. However, the preliminary assessment of feasible abort modes shown in Table 5 indicates that most of the emergency situations can be accommodated for the lunar shuttle mission. Additionally, an emergency or abnormal operations matrix was developed for the lunar shuttle mission to implement the contingency planning process.

Analysis of potential earth impact accidents for lunar missions indicated that the most hazardous conditions could arise during the EOI maneuver as a result of (1) thrust at the wrong attitude, and (2) failure to shut down NERVA after the EOI burn. However, it was concluded that provisions for diagnostics within the GN&C subsystem (e.g., incipient failure detection, manual override

Table 5. Abort Maneuvering Alternatives for Lunar Shuttle Mission

AVAILABLE PROPULSION MISSION PHASE	NERVA NOMINAL PERFORMANCE	NERVA EMERGENCY MODE	RCS TRANSLATION NOMINAL PERFORMANCE	PROPULSIVE VENTING	SPACE TUG 80K SINGLE STAGE (WITH RNS PROPELLANT TANK EMPTY)	CRITICAL AREAS
Translunar Injection	Direct return to Ops EO	Direct return to Ops EO for $\Delta V<8000$ fps. to ell EO for $\Delta V = 78{,}000$ fps	Reduce full EO period if main propulsion fails at end of TLI	Same as RCS	Retrieve RNS + PL up to 3500 fps, CM up to 10,000 fps	Loss of main propulsion at near parabolic speed
Translunar Coast	Direct return to ell. EO. Circumlunar return to ell. EO. Proceed to LO.	Direct return to ell. EO. Circumlunar return to ell. EO Proceed to LO.	None - Keep attitude control	None	Retrieve RNS + PL after abort to ell. EO Hyperbolic retrieval of CM to LO	
Lunar Orbit Insertion	Proceed to LO Circumlunar return to ell. EO	Proceed to LO Circumlunar return to ell. EO	None - Keep attitude control	Reduce speed slightly to aid rescue	Complete LOI with RNS + PL Hyperbolic retrieval of CM to LO	Failure to thrust
Lunar Orbit Coast	Immediate return to ell. EO with or w/o PL exchange	Immediate return to ell. EO after PL exchange	None - Keep attitude control	None	Return RNS + PL to 12 hr EO Return CM to 3 hr EO	
Transearth Injection	Direct return to circ LO Proceed to ops EO	Direct return to cir. LO	Complete TEI if main propulsion fails near end	Same as RCS	Return RNS to LO after subparabolic abort. Retrieve RNS + PL in ell. EO up to 5500 fps, CM up to 10,000 fps	Loss of main propulsion at hyperbolic speed
Transearth Coast	Proceed to Ops EO Return to ell. LO if early abort	Proceed to ell. EO Return to ell. LO if early abort	None - Keep attitude control	None	Retrieve RNS + PL after abort to ell. EO Retrieve to EO as above	
Earth Orbit Insertion	Proceed to Ops EO	Proceed to ell. EO	Reduce ell. EO period if main propulsion fails at beginning of EOI	Same as RCS	Complete EOI with RNS + PL or CM	Failure to thrust

capability on the NERVA reactor control circuitry, etc.) could preclude the most hazardous earth impact accidents and their subsequent consequences to the earth's population.

MANUFACTURING REQUIREMENTS

The Phase III study was oriented towards evaluation of alternate stage configurations exhibiting high fineness ratio conical aft bulkheads and alternate launch modes (inverted RNS tank attitude on INT-21 with shuttle delivery of NERVA to orbit). The major areas requiring evaluation included manufacturing feasibility utilizing production techniques applicable to MAF and Seal Beach as well as utilization of existing S-IC and/or S-II tooling, facilities, and GSE. A number of alternate fabrication techniques for a long RNS tank were evaluated to take advantage of existing facilities and equipment. The most attractive and cost effective technique was found to be weld joining the tank cylinder assemblies circumferentially, the conical aft bulkhead longitudinally, and stage closeout in a horizontal attitude (Figure 27). With this fabrication/assembly technique, maximum utilization of S-IC and/or S-II tooling, facilities, GSE, and technical skills is provided. This approach allows for an increase in major assembly size, and consequently this will reduce the number of structural components which contributes to cost avoidance.

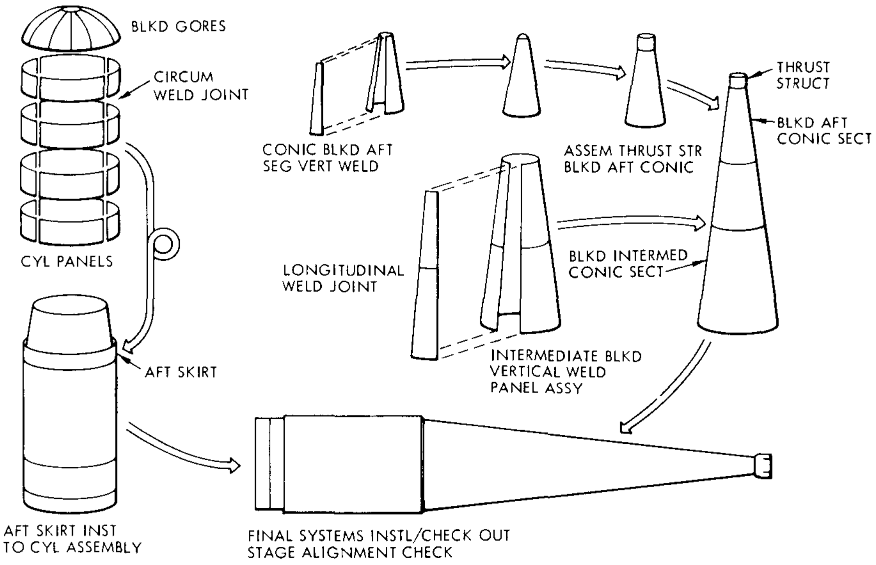


Figure 27. Tank Manufacture and Assembly Flow Sequence

The application and processing of spray foam insulation on the tank will be accomplished by utilizing the existing S-II equipment. However, new facilities and tooling will be required for the scalloping required on the spray foam and for the installation of the high performance insulation (HPI). The manufacturing process and requirements for the buildup of GAC-9 HPI blankets will follow techniques currently being developed under contract by NR (Figure 28).

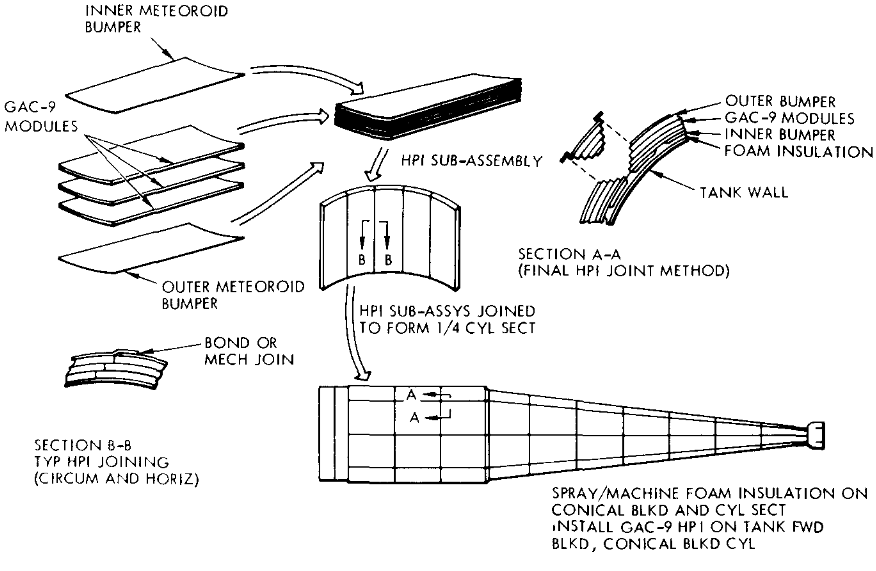


Figure 28. HPI and Meteoroid Shield Installation

The limited analysis conducted with reference to the installation of the HPI, including the meteoroid protection shield, shows that subassembly sections (approximately five feet by ten feet, composed of an inner barrier, three GAC-9 blankets, and an outer barrier) will have edges stepped to provide necessary joint overlap when attached to the next subassassembly. Joint overlap area and configuration will be determined by insulation system design. The size and configuration of the preformed subassemblies is dictated by location on the stage.

To maximize use of available tooling, facilities, and skill, the panel subassemblies will be joined into larger subassemblies prior to installation onto the stage. All insulation, except spray foam, will be installed while the stage is in a horizontal position. Generally, maximum size panel subassembly buildup will be used to minimize the number of individual segments installed on the stage.

TEST REQUIREMENTS

The primary objective of this effort was to establish test program groundrules as an aid in defining design operational requirements, test facilities, test articles, and a preliminary test schedule compatible with the study guidelines first flight test in mid-CY 1979 and IOC in CY 1981. Within this objective was the development of test criteria and the rationale necessary to attain the required operational confidence at each test level commensurate with program goals of low cost transportation, flexibility of operation, reliability, and safety. To accomplish these goals, four alternate ground test programs were evaluated. The alternates employed differently configured test articles as summarized below:

1. The baseline program employes four stages of all flight hardware. One article, RNS-TA-1, is used for both cold flow and hot test programs.
2. The boilerplate concept uses a full-size tank fabricated of heavy gauge material (non-flight weight) for both cold flow and hot tests. Other test articles are common with the baseline program.

3. In the mini-stage approach, an S-II forward bulkhead and one cylinder section with a new flight configured conical aft bulkhead are used for structural, cold flow, and hot testing. This alternate program requires a dynamic test article, RNS-TA-2, and an engineering mockup constructed of wood.

4. The ground test module (GTM) alternative employs a composite cold flow/hot test stage of regular size fabricated from existing S-II hardware and a new flight configured conical aft bulkhead. Other hardware is common with the baseline.

Evaluation of the alternate test programs indicated that the baseline approach, with all stages built to flight hardware specifications, has a lower cost for the targeted reliability (95-percent) and confidence level (90-percent) than the other alternatives. Additionally, it reflects the most attractive time span and testing sequence used in the development of the schedule, but does not quite meet the guideline IOC date. Preliminary variable and fixed costs of facilities, test articles, GSE, and test operations and durations were incorporated in the analysis. The results showed cost reductions for the baseline flight configured development test program on the order of 8 percent less than the GTM, 33 percent less than the boilerplate, and 46 percent less than the mini-stage programs.

The development test program approach requires independent hydrostatic testing of the forward and aft bulkhead with several combinations of cylindrical sections. These assemblies then will be mated with the necessary tank cylinders to form the basic flight tank and will be pneumostatically tested to permit early identification of weld assembly deficiencies and provide assurance that the completed assembly will meet design requirements.

The structural test article (RNS-S) then will be reallocated for ultimate use as an engineering dimensional simulator at the manufacturing site to provide a configuration mockup of major subsystem components, wire harnesses, bracketry, tubing, and other stage interfaces. This approach will permit early identification of possible configuration interferences and other potential engineering design deficiencies. This, in turn, will minimize flight article engineering design changes and their associated costs. Engineering data acquired from this article will be used to support the design and assembly of the cold flow and hot test article. The primary utilization cycle of the structural test article is depicted in Figure 29.

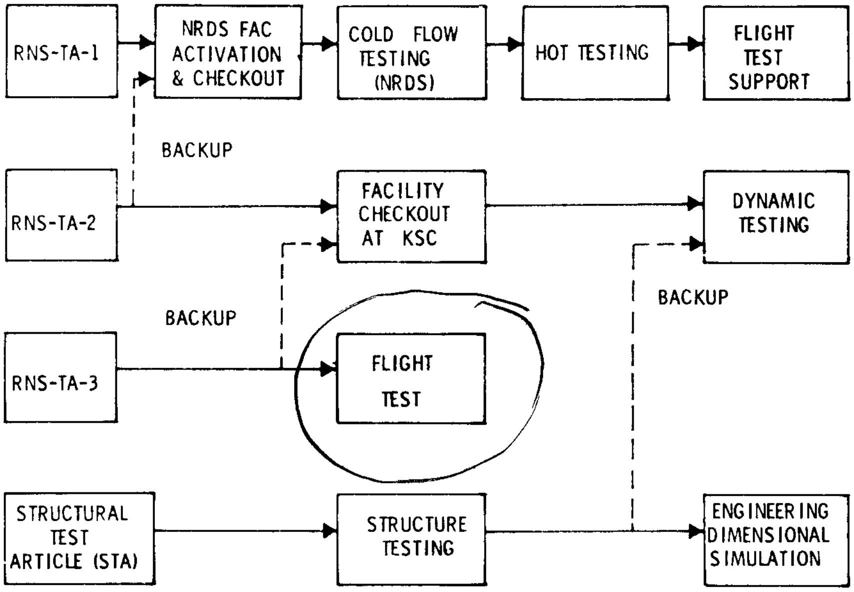


Figure 29. Test Article Utilization Cycle

The cold flow/hot test article (RNS-TA-1) will be fabricated and assembled by the same techniques developed and certified for the structural test article and dimensional simulator. Following this, the stage will be pneumostatically tested and configured to the prototype flight configuration during the systems installation phase of the manufacturing process. Then the completed stage will be subjected to a post-manufacturing integrated systems checkout test which verifies the functional performance of all vehicle systems and their interactions.

As shown in Figure 29, RNS-TA-1 first will be used for facility activation and checkout at NRDS. Upon completion of the facility activation, the article will be used for the cold flow testing program at NRDS. Upon completion of cold flow testing, RNS-TA-1 will be hot tested on the same test stand (E/STS-2). The RNS-TA-2 vehicle will provide backup for RNS-TA-1 in case of damage during cold flow or hot testing. While acting as backup, the RNS-TA-2 will be used to activate Kennedy Space Center (KSC) and then shipped to Marshall Space Flight Center (MSFC) for dynamic and acoustic testing in conjunction with INT-21. If RNS-TA-2 is required for completing the tests at NRDS, the flight stage (RNS-TA-3) will be used for KSC activation and checkout and the structural test article, which was previously scheduled to become the engineering dimensional simulator, will be cycled to MSFC for dynamic testing. In this case, a dimensional simulator could be fabricated of wood at the manufacturing facility.

The RNS development test program includes exposure of the flight test article (RNS-TA-3) to cryogenic environment at launch pad 39 while the RNS is stacked on top of the INT-21 (propellant tanking during countdown demonstration test). This approach eliminates the necessity for a special off-pad cold flow acceptance testing facility. This recommendation is based on the confidence and experience derived from the Saturn program, and predicated on the following: (1) early laboratory cryogenic tests, (2) extensive cold flow and hot test programs at NRDS, and (3) the manufacturing technique which includes structural testing of individual tank sections, in-process testing, and post-manufacturing checkout.

FACILITIES DEFINITION

Preliminary results of facilities requirements and utilization analyses showed that the RNS tank can be manufactured at either MAF or Seal Beach. Cost estimates of necessary new and modified facilities indicated a negligible total cost difference. Irrespective of the location for manufacturing of the RNS tank (MAF, Seal Beach, or both), a requirement exists for new tooling for the manufacture and assembly of the conical aft bulkhead section of the tank. Apollo tooling is a good candidate for producing the 8-degree half cone-angle and 25-inch cap radius section, up to a length of ten feet. This cost savings was not credited to the RNS during the facility and tooling utilization analysis.

A preliminary cost estimate of the major facilities and GSE requirements for the cold flow/hot testing and flight operations is presented in Table 6. The estimated costs are based on major items that require modifications, or are not available and have to be acquired. All costs are budgetary and are for funding projection purposes only, and are not intended to reflect final non-recurring costs. Indicated manufacturing costs exclude manufacturing checkout equipment.

Table 6. Facility Cost (ROM) Summary

FACILITY AND GSE	COST $M
MANUFACTURING FACILITY* (MAF OR SEAL BEACH)	2.0
MANUFACTURING GSE*	2.5
NRDS FACILITY	64.0
NRDS GSE	10.0
VAB GSE	5.5
MOBILE LAUNCHER (GSE)	5.5
LAUNCH PAD (LH_2 STORAGE)	1.0
DYNAMIC TEST FACILITY	(TBD)
ROUTE MODIFICATIONS (SEAL BEACH TO NRDS)	2.0
	92.5

*MANUFACTURING COSTS DO NOT INCLUDE MODIFICATION AND/OR NEW TOOLING AND POST-MANUFACTURING CHECKOUT EQUIPMENT.

The baseline RNS program schedule, Figure 30, depicts the integrated set of activities and events necessary to accomplish the development and operational phases. The schedule covers all major development activities from Phase A-IV (follow-on to this study) through the completion of flight testing and a ten-year operational program. To assure consideration of the most promising program alternatives, schedules were prepared for the four alternate development/test programs. However, only the baseline schedule is summarized here.

The following major groundrules and assumptions were used in the preparation of the integrated program schedule. They are derived from NASA study guidelines and the results of Phase III technical analyses: (1) NASA dates for the first test flight (mid CY-1979) and IOC (CY-1981) are treated as guidelines but not as constraints; (2) a 12-month spacing between the starts of Phases A-IV, B, and C was used ; and (3) a nine-month period was assumed for Phase C, with Phase D commencing immediately at its conclusion and with continuous NASA review throughout the program rather than a three-month gap between phases.

A maximum of three RNS/S-II stages per year can be produced with a single set of tooling. Furthermore, the production of two articles per year is considered the minimum economical rate, due to utilization of manpower and maintenance of technical skills. To minimize the cost and time span for DDT&E, a combined production rate of three stages per year during development was employed. Six operational RNS stages (and six S-IC/S-II sets for INT-21 boosters are required. Each RNS flies ten missions evenly spaced in time at an annual rate of six per year. As a compromise between storage time and production rate economy, it was assumed that one RNS and one S-II would be produced annually in the same facility.

The minimum times in months required for major system tests as derived in the test planning study are as follows:(1) cold flow - 9, (2) hot tests - 24; (3) dynamic tests - 12; (4) facilities checkout - 6; and (5) flight tests - 18.

The baseline program development schedule reflects the desired manufacturing time spans and testing sequences within the aforementioned constraints but does not quite meet the guideline IOC date of CY 1981 (denoted by dot on Figure 22). The IOC date could be realized by shortening the length of the hot test and/or flight test period, or shortening Phases A-IV and/or B. However, the time spans used are the best current estimates of realistic requirements.

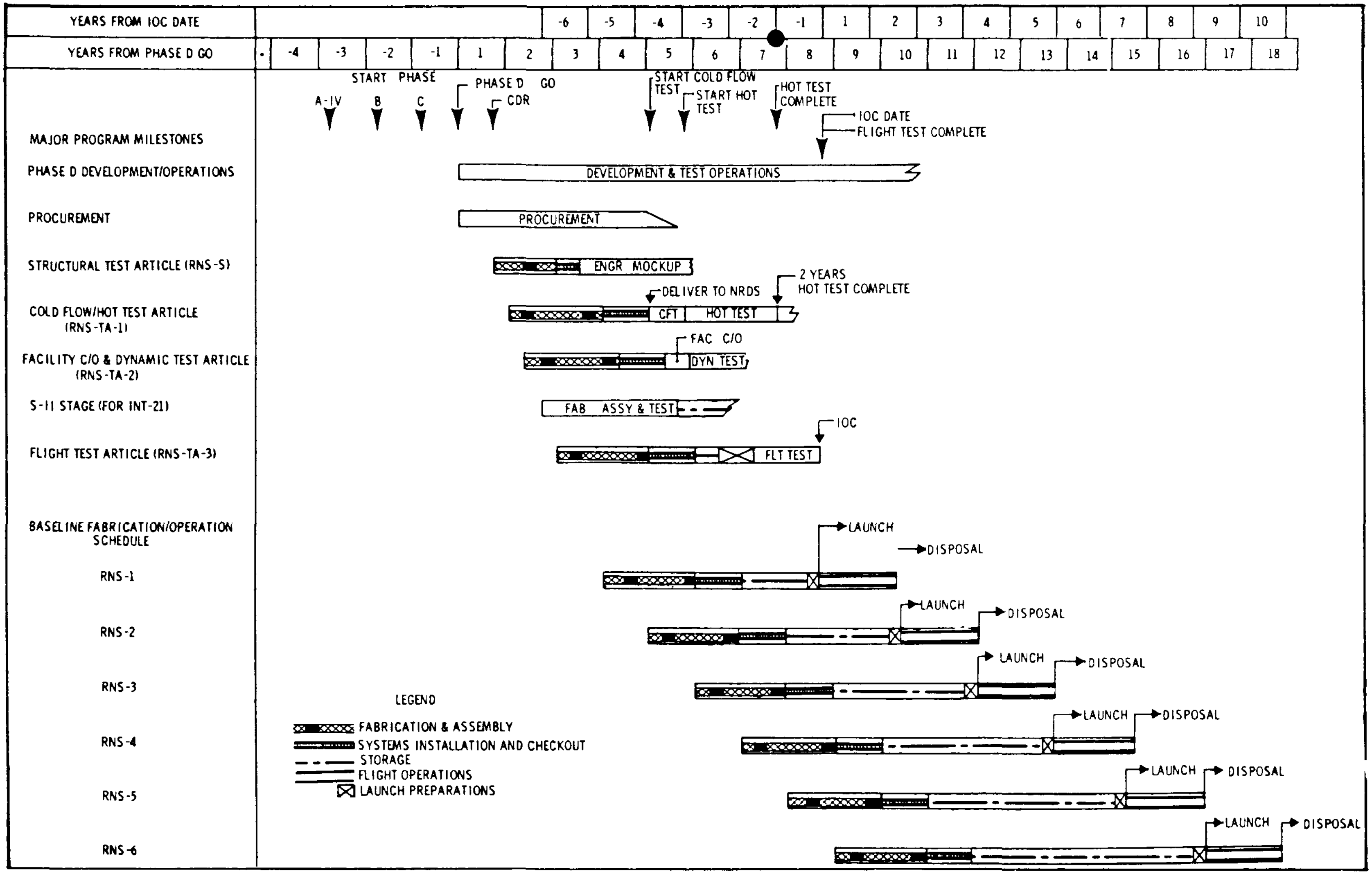


Figure 30. RNS Program Schedule

A functional block diagram presented in a logic network form was prepared to complement the program schedule. It is program-phase oriented and can be used as a baseline for developing detailed schedules and work plan tasks. The required data, including the principal tasks and their interfaces, are described and discussed in the detailed reports as part of the system engineering process.

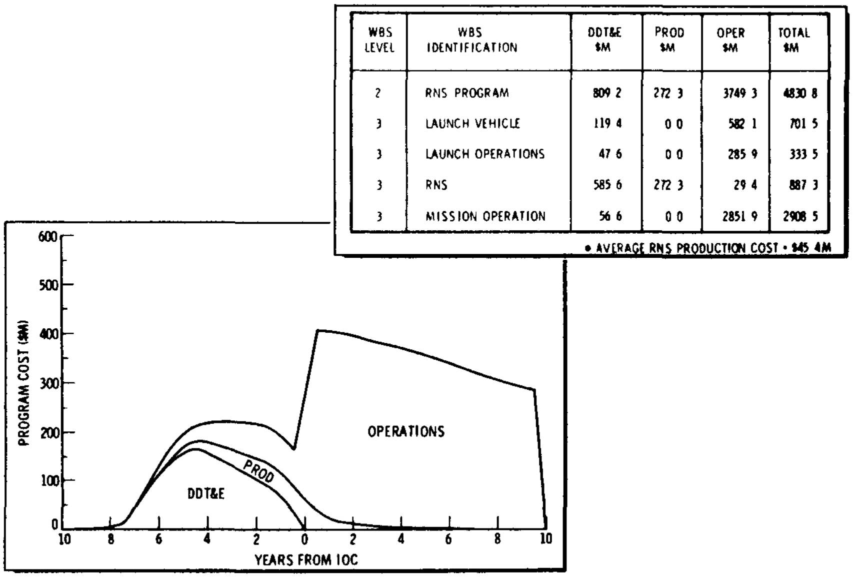
COST ANALYSIS

A primary guideline employed in the conduct of the RNS Phase A study has been to achieve the most attractive design at the least cost. This principle was applied in the formulation of design concepts, development plans, and operating procedures whether or not accompanied by quantitative cost evaluations or trade studies . Detailed program cost data were developed for the baseline and alternate configurations covering a wide range of operating conditions. The accuracy of these data has been improved considerably over the Phase II results by greater depth of engineering analysis and definition of cost estimating relationships (CER's) down to as low as the seventh level of the work breakdown structure (WBS).

Analyses and tradeoffs also were conducted to assure cost minimization at all levels within the bounds of overall study objectives, guidelines, and constraints. Quantitative data have been developed wherever practical, limited only by the availability of appropriate input information and study resources. Major cost drivers were identified along with alternatives for achieving significant savings in both cost and cost effectiveness -- the latter being expressed in terms of either dollars per flight or dollars per pound of maximum payload delivered to lunar orbit.

The costing analysis confirmed the attractiveness of the single tank (8-degree half cone-angle, 25-inch end cap radius), design over all others considered. Furthermore, the benefits to be gained through lower space shuttle logistics delivery cost and use of a fully reusable or partially reusable booster to launch the RNS tank were delineated. Significant savings also appear possible by commonality of hardware/software, facilities, GSE, and support equipment with other space programs (concurrent and past); design optimization considering propellant capacity, propellant management (stratification), and subsystems; and improvement in stage lifetime.

The top level costs for the baseline single tank configuration (six production units, delivery of NERVA and logistic supplies to orbit by the space shuttle at a cost of $162/lb., boost of RNS tank in inverted attitude on INT-21) are shown in Figure 31 with a plot of annual funding requirements. These data are expressed in terms of 1971 dollars and exclude NERVA and INT-21 DDT&E. RNS production cost averages $45.4 M, including $13.0 M for NERVA. The operational program covers a period of ten years.



WBS LEVEL	WBS IDENTIFICATION	DDT&E $M	PROD $M	OPER $M	TOTAL $M
2	RNS PROGRAM	809 2	272 3	3749 3	4830 8
3	LAUNCH VEHICLE	119 4	0 0	582 1	701 5
3	LAUNCH OPERATIONS	47 6	0 0	285 9	333 5
3	RNS	585 6	272 3	29 4	887 3
3	MISSION OPERATION	56 6	0 0	2851 9	2908 5

• AVERAGE RNS PRODUCTION COST • $45 4M

Figure 31. Baseline RNS Program Funding Requirements

A comparison of the baseline RNS with the two most attractive hybrid designs is shown in Table 7. Although there are only modest differences in DDT&E and Prod/Oper costs, there are sufficient differences in structural and external shielding weight to show payload benefits for the baseline which in turn translates into better cost effectiveness. For the hybrid designs to deliver the same maximum outbound lunar payload (200,000 pounds) as the single tank, there is an additional cost per flight of 3.0 and 6.5 million dollars for the 8-degree and 7.5-degree hybrids, respectively. Furthermore, the 8-degree hybrid (in comparison to the 7.5-degree design) has a more limited capability for self-disposal using the auxiliary propellant tank.

Table 7. Cost Comparison of Alternate Configurations

CONFIGURATION	DESIGN FEATURES	DDT&E $M	PROD/OPER ($M/FLT)	RELATIVE PAYLOAD DELIVERY COST (1)
SINGLE TANK	8° x 25-IN.	809.2	67.03	1.00
HYBRID	8° x 40-IN. MAIN TANK, 3000 LB LH_2 AUX TANK	839.8	67.29	1.06
HYBRID	7.5° x 112-IN. MAIN TANK, 9300 LB LH_2 AUX TANK	832.0	67.23	1.11

(1) BASED ON MAXIMUM OUTBOUND PAYLOAD TO LUNAR ORBIT WITH ZERO RETURN PAYLOAD

The transport of logistic supplies -- particularly RNS propellant -- represents a major fraction of program cost. If the space shuttle delivery cost can be reduced to $100/lb (50,000 pound payload capability to 260 n mi x 31.5 degrees at $5M/flight) from the baseline study value of $162/lb, RNS cost effectiveness would be improved by 26.7 percent. On the other hand, if shuttle orbital delivery cost is $200/lb, it would increase the cost of moving payload to lunar orbit by 16.4 percent. The parametric data are presented in Figure 32.

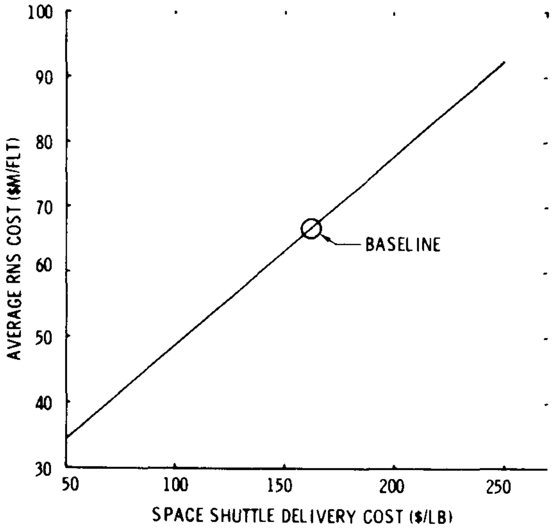


Figure 32. RNS Sensitivity to Space Shuttle Delivery Cost

Another way to reduce RNS cost may be possible if a vehicle other than the expendable INT-21 is employed for launch of the RNS tank to orbit. One promising approach is to use the space shuttle booster with an expendable second stage (ESS). Another alternative is to temporarily configure the RNS as an ESS (designated here as CPS-chemical propulsion stage) by adding an LO_2 tank and a space shuttle engine. Since the engine/LO_2 tank module would be recovered for reuse by a later regular shuttle flight after it delivers the NERVA, this concept is equivalent to a fully reusable system. Table 8 compares the baseline launch mode with the ESS and CPS. As can be seen, the potential reductions in lunar delivery cost are 8.1 percent and 14.3 percent, respectively.

Table 8. Cost Comparison of Alternate RNS Tank Boost Modes

LAUNCH VEHICLE	COST IN $M DDT&E	PROD	OPER	TOTAL	$M/FLT
INT-21(BASELINE)	809.2	272.3	3749.3	4830.8	67.0
EOS BOOSTER + ESS	762.9	272.3	3471.2	4506.4	62.4
EOS BOOSTER + CPS	720.2	272.7	3210.0	4202.9	58.1

200K w/t
335 $/LB

RNS service life was assumed to be ten equivalent lunar round trips during a three-year period. The effect of varying mission cycles (without changing the maximum time in space, which influences meteoroid protection and thermal coating requirements) was determined and the results are plotted in Figure 33.

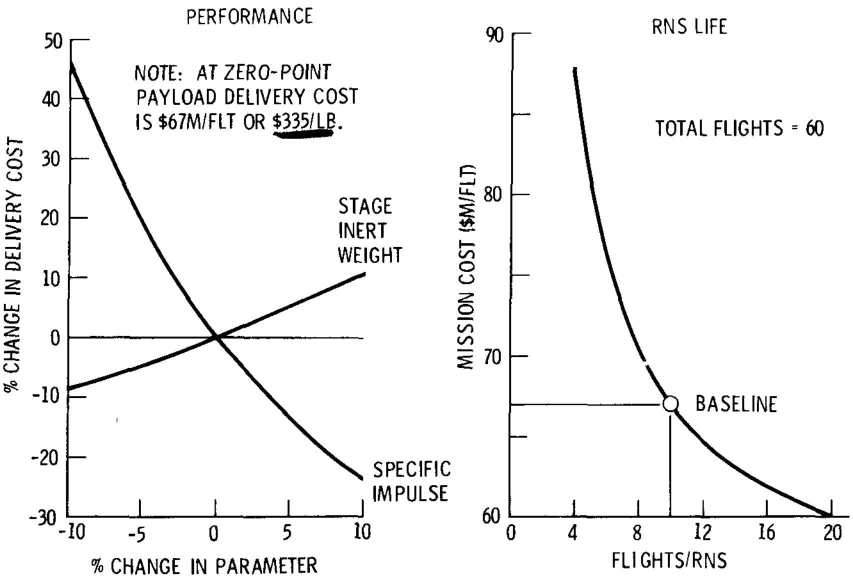


Figure 33. RNS Program Cost Sensitivity

The sensitivity of cost to service life reduction below the baseline value is quite evident, particularly below 8 flights/RNS. Some cost benefit may be possible by extending lifetime beyond 10 flights if it does not impose undue maintenance requirements or degrade safety/mission success probability.

Performance studies have indicated that cost effectiveness is most sensitive to NERVA specific impulse. Thus, a ten-percent increase in I_{sp} would reduce lunar payload delivery cost by nearly 25 percent (Figure 33). Since the Los Alamos Scientific Laboratory is currently developing carbide-type fuel elements which have a potential I_{sp} well over 900 seconds, the economic benefit is apparent. Higher specific impulse can be even more significant than NERVA lifetime. Thus, an eight-percent increase in I_{sp} is equivalent to the $13 M production cost of a complete engine. Stage inert weight, while not as strong a cost driver as specific impulse, neverthless offers important benefits (or penalties). The sensitivity of cost to weight is nearly a 1:1 ratio. (% [illegible]) On the other hand, with the use of the multi-perigee thrusting technique for minimizing RNS gravity losses, the low thrust of the 75K NERVA imposes only a small performance penalty. Thus, thrust level will have a negligible effect on cost effectiveness.

The RNS production rate is an important cost factor since it affects operating efficiency as well as requirements for facilities, tooling, and special test equipment. During Phase II, it was estimated that a rate of two stages per year (two RNS's or one RNS plus one S-II) would increase production costs by about 13 percent compared to the optimum rate of three at the Seal Beach facility. A reduction to one per year would nearly double the unit production cost. On the other hand, the number of production units was determined to have no appreciable effect on recurring cost over the range considered in this study (2-10) if lifetime is considered to be constant. However, if DDT&E is amortized over the production run, there is a substantial impact when only a few operational stages are built.

An important factor in design optimization is RNS size. Due to the current absence of firm mission requirements, the major study effort was concerned with a nominal LH_2 capacity of 300,000 pounds -- based on previous mission studies. However, the effect on performance and cost of changing the size was evaluated (Figure 34). The cost data shown excludes DDT&E. Significant improvement in cost effectiveness with size is quite evident and would justify development of a larger stage if heavier payloads are needed. Overall program economies should dictate sizing the RNS based on the anticipated traffic density and payload weight range. If there is need to carry a heavier payload only occasionally, alternate flight modes are available (such as tug-assist on the return to earth orbit). Future studies need to more fully explore this area, including the economics of flying the RNS with off-loaded propellant.

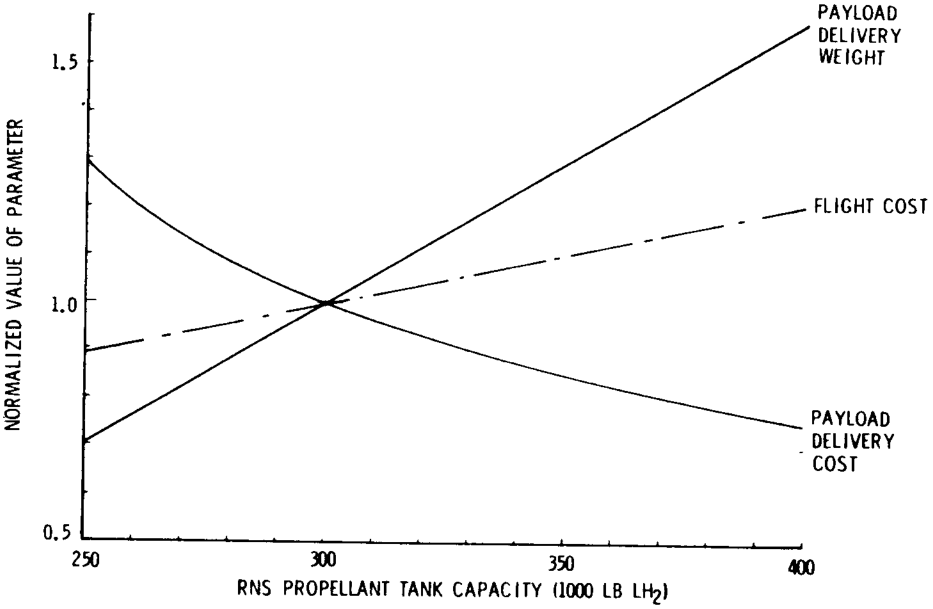


Figure 34. Cost and Performance Sensitivity to RNS Size

6.0 STUDY LIMITATIONS

The Phase III NR study has clearly met its intended objective of defining an attractive RNS program as described earlier in this report. However, there were a number of important limitations imposed by (1) study guidelines and constraints, (2) available data, and (3) depth of analysis. While it is believed that none of the limitations impact the overall assessment of the RNS program, they could possibly affect design, operations, programmatic, or cost results.

GUIDELINES AND CONSTRAINTS

Probably the two most significant study constraints were the use of a 33-foot diameter main propellant tank and its launch by INT-21. Phase II preliminary investigations by NR clearly demonstrated the competitiveness of a multi-tank concept, compatible with the cargo bay of the space shuttle, and assembled in orbit into a complete stage. Furthermore, recent in-house NR studies (including cost analyses) on shuttle booster assisted launch of 33-foot diameter tanks indicated that significant savings are possible by temporarily configuring the RNS tank as a chemical second stage which injects itself into orbit.

Another important limitation stems from the size of the space shuttle cargo bay: 15-foot diameter by 60-foot length. Due to the low density of the hydrogen propellant, full advantage cannot be taken of currently projected shuttle payload capability unless mixed cargos are practical.

In accordance with study guidelines, one complete RNS flight stage and its associated launch costs were charged to the DDT&E program. However, on the basis of the test program definition, it appears quite likely that this stage can be added to the operational inventory following flight testing. In addition, it may be practical to deliver unmanned payloads during the test program and thus obtain a further "credit" against development cost.

AVAILABLE DATA

The limited "hard data" on RNS payloads and the absence of a mission model precluded determination of an optimum RNS size and detail assessment of operational requirements imposed by traffic rate. RNS size is of particular importance since it affects both cost and cost effectiveness.

Commonality benefits from other space program elements are expected to play an important role in RNS cost avoidance. During Phase III, specific items accounted for included docking and electrical subsystems. However, even larger benefits should be realizable if the RNS uses the same HPI as the space shuttle and employs a high degree of commonality with shuttle and space station in the areas of electronic equipment, software, and operating practices. Thus, further reduction in RNS development and production costs should be possible. On the other hand, substantial gains were credited to the RNS program based on the anticipation that Saturn V/Apollo facilities, tooling, and other equipment will be avaiable in the post-1974 time period as required by the RNS. If this assumption proves to be incorrect, there will be a serious impact on program cost.

STUDY DEPTH

A number of areas received only preliminary attention. Hardware lifetime was assumed to be three years in space (or ten missions) with maintenance. However, little is known about the long term environmental effects on RNS structure and other subsystems. In addition, limited data are available on the producibility of the environmental protection system employing high performance insulation. Converting laboratory and small scale experience to suitable procedures for handling, installing, protecting, and transporting HPI on a large stage represents a major extrapolation. A degree of uncertainty also exists regarding the survivability of the complex environmental protection structure during boost - particularly with respect to the flutter phenomenon.

In subsystem definition, a propellant management system was defined which employs a stratified ullage to effect substantial reductions in residual propellant weight and thus accrue a large benefit on performance. However, due to the complex nature of the analysis, further study and probably testing will be required to verify the attractiveness of this concept.

Other areas which received limited consideration include reliability (which was studied to the depth permitted by subsystems definition), safety (particularly in the areas of abort, crew rescue, and RNS recovery); and maintenance in the vicinity of the engine as well as engine removal and disposal by a space tug.

7.0 IMPLICATIONS FOR RESEARCH

The necessary research and technology for the RNS program can be best accomplished by time-phasing it to two technology design periods. The critical activities necessary to solve the near-term development problems are shown in Table 9 . taking place in the three years preceding Phase D (development/operations). These cover analytical and testing investigations in most of the technical disciplines and are intended to serve as the basis for the initial stage design.

Some of the more significant activities in this category include the development of a flutter free thermal/meteoroid protection design integrating an efficient and easy to produce, maintain, and repair high performance insulation. Additionally, passive propellant management employing a stratified ullage to minimize residuals has shown potential payoffs that are worthy of concentrated investigation. Another area needing immediate attention is the definition of an economical in-space maintenance operations concept that benefits all the currently programmed space elements.

Table 9. Supporting Research and Technology Program/Funding

TASK DESCRIPTION	ANALYSIS	TEST	COST - $1000		
			-3	-2	-1
STRUCTURES, MATERIALS AND MANUFACTURING			(1100)	(1300)	(1400)
Meteoroid Protection	X	X	100	100	100
High Performance Insulation	X	X	300	300	300
Aluminum Alloy Under Cyclic Loading	X	X	100	100	100
Flutter Analysis and Tunnel Testing	X	X	200	300	300
Application of Composite Materials to Large Structures	X	X	300	300	300
Space Fabrication, Assembly, Testing, and Refurbishment	X	X	100	200	300
NUCLEAR RADIATION			(450)	(550)	(650)
Radiation Analysis Techniques Development	X		150	150	150
Materials and Components Radiation Effects	X	X	300	400	500
PROPULSION AND PROPELLANT MANAGEMENT			(1700)	(1600)	(1500)
Capillary Devices for Propellant Management	X	X	250	250	200
Internal Thermodynamics	X		200	150	100
Orbital Refueling	X	X	250	200	200
In-Orbit Venting	X	X	250	250	200
Destratification	X		150	150	-
Propellant Gauging	X	X	300	300	200
Reaction Control System	X	X	300	300	300
Hydrogen Reliquefaction System	X	X	-	-	300
ASTRIONICS			(350)	(250)	(150)
Navigation Accuracy and Instruments Mounting	X		100	100	-
Guidance Equations Generation	X		100	-	-
Thrust Vector Control Simulation	X		75	-	-
Information Management System Development	X		75	150	150
ORBITAL OPERATIONS			(500)	(550)	(650)
In-Space Maintenance Operations	X		250	250	250
Incipient Failure Detection	X		100	100	100
Computer-Aided Space Transportation Model	X		150	200	300
TOTAL			(4100)	(4250)	(4350)

Continuing investigations during Phase D will serve to improve the initial design and/or to evolve into an advanced system for manned planetary missions. Some of the more significant efforts in this latter category include the development of boron-epoxy for application to major structural components. Also, a continuing improvement in high performance insulation taking into consideration ease of manufacturing, installation, inspection, and repair would be beneficial to both initial and advanced stage designs. Additionally, continuing development in space fabrication, assembly, testing, and refurbishment could be of significant benefit to all future space systems.

8.0 SUGGESTED ADDITIONAL EFFORT

In keeping with its Phase A status, the NR investigation has defined in considerable detail an attractive RNS concept. The benefits of reusability, commonality, design and operational simplicity, and autonomy were exploited to the maximum practical extent to achieve space flight economy safely and reliably. With a capability of satisfying a wide range of proposed manned and unmanned shuttle missions, combined with an inherent growth potential for manned planetary exploration, the RNS represents a truly versatile space transportation system for the 1980s and beyond. However, in spite of being judged technically feasible and economically attractive, considerable room remains for additional pre-Phase B studies to (1) expand the base for RNS applications; (2) better definitize its role in space; (3) further reduce non-recurring and recurring costs through design and operating improvements with emphasis on hardware/software commonality; (4) resolve outstanding technical questions by specific analytical and experimental efforts; and (5) increase confidence in the design/program recommendations through greater depth of analysis as well as concurrent SR&T.

MISSION ANALYSIS

Primary emphasis has been devoted to the lunar shuttle mission. Repetitive realistic cycles have been established - employing precision flight mechanics techniques - with payload delivery capabilities equal to or exceeding the requirements identified in other studies. Significant improvements in capability or performance effectiveness were indicated by preliminary analysis of tug-assist modes. To a lesser degree, flights to synchronous orbit, injection of unmanned payloads toward planetary targets, and manned missions to Mars were investigated. However, there is a definite need for more specific details on applications, flight modes (particularly in conjunction with use of other stages like space tug), payloads, interface requirements, and mission/traffic scheduling. Such data are essential to the establishment of a realistic RNS size coupled to expected demand but with sufficient flexibility to permit economic delivery of smaller as well as larger size payloads than nominal.

DESIGN DEFINITION

Within the limitations imposed by study guidelines (33-foot diameter RNS tank and INT-21 booster), a high fineness ratio single tank geometry combined with an inverted tank launch mode appeared to be the best overall compromise considering all pertinent factors. However, in parallel with the Phase III effort, NR performed sufficient design definition and cost analyses to establish that superior economics should be possible with the single large tank RNS design if a semi-reusable or fully reusable launch mode is employed. This entails using the space shuttle booster with either an expendable second stage for boosting the RNS or temporarily configuring the nuclear tank as a chemical orbital injection stage by the addition of an oxygen tank and shuttle engine. Further exploration of this approach should be pursued.

Prior investigations during Phase II lead to the synthesis of an attractive multi-tank concept assembled into a stage in orbit from individual tanks delivered by the space shuttle orbiter. The benefits available from a low cost fully reusable earth-to-orbit logistics system demand further consideration of the multi-tank concept.

A potential impact to space shuttle LH_2 orbital delivery economics was identified due to cargo bay volume constraints in current designs. It is therefore recommended that high priority be given to an assessment of methods for ameliorating this key problem.

Major benefits in cost avoidance, operational simplicity, and reliability appear likely by applying the principal of commonality to the RNS. Gains are possible in the areas of technology development, hardware, software, facilities, tooling, equipment, and operating procedures from today's space programs as well as expected developments by space shuttle, space station, and other space program elements. Implementation of numerous cost saving items was made during Phase III, notable from the Saturn/Apollo program. However, this effort needs to be expanded to consider commonality benefits for such cost drivers as high performance insulation, astrionic equipment and software, orbital operating procedures (particularly maintenance and OBCO), and ground testing (typically common NERVA-stage hot testing).

In the area of design there is also need for better definition of subsystems to permit establishment of realistic lifetime goals and to better determine test requirements and overall system reliability. The weight saving potential and improved propellant management control and conditioning through use of a stratified ullage and thermodynamic venting needs to be validated by further analysis and probably experimentation. The RNS thermodynamic vent system is analogous to that currently being considered for the space shuttle.

High performance insulation needs additional design analysis to assure that producibility is practical, flight through the atmosphere will not create a serious flutter problem, and maximum commonality benefits can be derived from space shuttle developments. Wind tunnel tests will probably be required in connection with the flutter evaluation.

Other design-oriented studies should include integration of the NERVA NDIC into the stage IMS, diagnostic techniques and sensors for subsystems status monitoring and failure prediction, and the various SR&T activities summarized in section 7.0.

OPERATIONS AND FACILITIES

As a result of the Phase A studies to date, a considerable amount is known about RNS ground operations and supporting facilities/equipment ranging from fabrication to launch. No significant problem areas have been uncovered although numerous uncertainties exist and will persist until the RNS program reaches a greater state of maturity. Typically, current manufacturing/assembly facilities offer suitable choices for RNS production but their status in the post-1974 time period remains in doubt. The same is true for GSE, tooling, and other items of applicable Saturn/Apollo equipment. Subsequent studies should focus on defining commonality of RNS requirements with those of other IPP elements which will precede it, thus providing a more realistic picture of what is likely to be available in support of the nuclear shuttle program.

The RNS study groundruled use of the space shuttle for logistics support, including NERVA delivery. Additional studies are required to better define handling, packaging, loading, delivery, and unloading operations. Further attention is necessary to expand the preliminary definition of orbital operating procedures in the presence of the space/NERVA radiation environment; this is particularly necessary to assure safe, practical, maintenance procedures, especially in the vicinity of NERVA and at the tank bottom, as well as engine removal and disposal. Operation of the RNS near other space program elements also should be considered in greater detail.

Concurrent with the HPI design studies, detail procedures and supporting equipment requirements must be established for fabrication, assembly, handling, transportation, protection, and repair.

Additional test program options should be investigated including changing the mix of fixed (facilities, equipment) and variable (test time) cost items. Program risk needs to be assessed for the specified minimum test article plan. Better visibility is necessary for the ground and flight tests required to validate the maintenance concept - including techniques for non-destructive testing and sensing of incipient failures.

The aforementioned suggestions have briefly touched on the more significant areas where additional studies should be beneficial. Obviously others can be and will be considered as the RNS program evolves and more substantive information becomes available from other interfacing programs. However, it should be noted in concluding that subsequent studies are expected to lead us in the direction of further improvements in an already attractive concept for space transportation in the 1980 period and beyond.