# Nuclear Shuttle for Interorbital and Transplanetary Applications

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**A reusable nuclear shuttle (RNS) operating out of low Earth orbit is a major element of the planned space program to provide low-cost transportation beyond Earth orbit. RNS concepts based on the 75,000 lb-thrust NERVA engine are identified which range from a large single module launched by a Saturn INT-21 to highly modularized concepts configured to be launched by the space shuttle and assembled in orbit. Operations and system implications for orbital maintenance and tanking are described. Maintenance by large-scale module replacement and direct propellant resupply by the space shuttle eliminate the requirement for expensive, permanent, manned orbital support facilities. The economic premium for reusability is established and sensitivity shown for various system parameters. The impact of the RNS and its radiation environment on associated system elements is discussed.**

## Introduction

A NEW era of space transportation, based on reusability, is in sight.[1] This paper addresses the reusable nuclear shuttle (RNS) which is envisioned as a major segment of this transportation system. The RNS extends the economics of reusability to missions beyond Earth orbit. Previous concept formulations for the nuclear stage have been directed toward successively improving system economics. From early customized nuclear rocket concepts, the modular concept emerged which proposed performing diverse missions with a single, modular stage and a minimum number of different size propellant modules.[2] The utility of this concept was extended, and the need for propellant modules removed, by the nonintegral burn concept, which proposed restart of the nuclear stage to perform all or part of successive propulsive maneuvers.[3] The next logical step is to reuse the nuclear stage for successive missions by returning it to Earth orbit and resupplying propellant which is delivered by the space shuttle.

## Mission Applications

The principal mission applications currently considered for the RNS[1] are the lunar shuttle, the geosynchronous orbit shuttle, transplanetary injection of unmanned payloads, and the manned Mars landing mission. Execution of these by the RNS will be briefly described.

A typical concept of the lunar shuttle mission employs the RNS for transfer of cargo and men to and from a station located in a 60 naut miles polar lunar orbit, operating the RNS from a low circular earth orbit. Logistics from lunar orbit to the lunar surface would be provided by a reusable chemical lander stage. A circular Earth orbit at 259 naut miles altitude and an inclination of approximately 31.5° provides phase compatibility with the lunar orbit, as well as rendezvous compatibility with the Earth's surface. For this orbit, mission geometry repeats on a 54.6 day cycle. Generally, opportunities for transfer not requiring plane change maneuvers (and thus single burns for lunar arrival and departure) occur twice during this 54.6 day cycle.

The geosynchronous shuttle mission envisions transfer of space station modules, crew rotation modules, and equipment between a low circular Earth orbit and geosynchronous (19,325 naut miles) orbit altitude. It is functionally analogous to the lunar shuttle mission, with four main-stage maneuvers per mission roundtrip.

For transplanetary injection of unmanned payloads the RNS would typically inject the mission spacecraft to the required hyperbolic transfer trajectory with a single burn. After injection the RNS separates from the spacecraft, operates a second time to inject itself into a buffer ellipse, and then reinjects into the initial circular operational orbit. An expended chemical kick stage could be required for some high-velocity applications, but the indicated RNS operational mode would be unchanged.

Execution of the manned Mars landing in a reusable mode by the RNS varies across the range of mission opportunities. The approach can be characterized heuristically by considering a mission vehicle consisting of a manned mission spacecraft (weighing about 250,000 lb) and four RNS stages. Starting from the low Earth operational orbit, two of the RNS stages would inject the vehicle into a highly elliptic orbit, separate, and return themselves to the initial orbit. One of the remaining RNS stages would complete injection toward Mars and operate again for arrival at Mars, where it would be expended. The remaining RNS stage would complete Mars arrival injection, perform Mars departure, and return to earth, injecting the vehicle into a highly elliptic orbit. Both the manned spacecraft and RNS would then be recovered by an RNS, which captures and returns them to the initial earth operations orbit. In this scenario, all but one of the RNS stages were fully reusable. The one expended stage could have been previously employed on reusable shuttle missions. Alternatively, if the stages were large enough, only three would be required and they could all be fully reusable on the mission. A typical roundtrip would take about 600 days. A full discussion of the multiple mission modes, assembly orbits, and RNS sizing and staging (including tankage jettison) implications is beyond the scope of this paper.

## System Requirements

A key system affecting the operational characteristics and economics of the RNS is the space shuttle. This is generally considered as a two-stage to orbit vehicle, with both the booster and orbiter being fully reusable $LOX/LH_2$ stages capable of flying back to the launch site. A variety of configurations and performance capabilities have been considered for this system. In the present study it is assumed to have a payload capability of 50,000 lb to the RNS operational orbit and has a payload compartment with a 15 ft diam by

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60-ft-long volume. Its nominal launch cost is assumed to be \$5 million per launch or 100 \$/lb to orbit.

A variety of space program models have been proposed, such as those of the President's Space Task Group, having manpower levels of up to 12 (and ultimately 50) men in geosynchronous orbit, 12–25 men in lunar orbit, and 12–50 men on the lunar surface, during mature years of the programs. The Earth orbit space station currently being studied is intended to house 12 men for 180 days and has a reference launch weight of 110,000 lb and a 33-ft diam. It is launched to orbit (262-naut miles, 55° inclination as a reference) by the Saturn Intermediate 21 (INT-21). Its capacity and capability might be augmented for geosynchronous or lunar stations. Space shuttle launched modules could be added. Alternatively, the entire stations could be constructed from clusters of modules launched by the space shuttle.

A typical crew rotation module designed to fit in the space shuttle cargo bay capable of providing life support for a crew of 12 for up to 14 days is estimated to weigh about 13,500 lb, including contingencies and returned experiment packages.

Chemical propulsion systems which would be associated with the RNS in operations of the space transportation system include the lunar lander, kick stage, possibly an orbit to orbit shuttle or lifeboat and a space tug to support RNS orbital operations.

## Transportation System Economics

Some of the system concept assumptions and economic implications of the RNS have been investigated focusing on the lunar shuttle mission, which is most demanding in the terms of transportation system economics, expected payload delivery requirements, or traffic rates, and over-all system design requirements prior to manned planetary applications.

The sensitivity of the cost of delivered payload to lunar orbit was assessed for major parameters within a range of expected values. In the subsequent examples the baseline RNS has a 300,000-lb propellant capacity and an operational weight of 80,000 lb. This weight is higher than current estimates for either RNS concept.

Figure 1 shows the sensitivity of payload cost in lunar orbit to the cost of the space shuttle logistics system $\alpha$, which resupplies the RNS propellant and expendables and delivers payload to low Earth orbit. This parameter is the dominant factor in determining RNS transportation costs. An initial launch and procurement cost $\beta$, of \$286 million is used as a baseline corresponding to the RNS launched by the INT-21 at a rate of 2/yr. The representative space shuttle logistics cost of 100 \$/lb is indicated on the INT-21 curve as a nominal case.

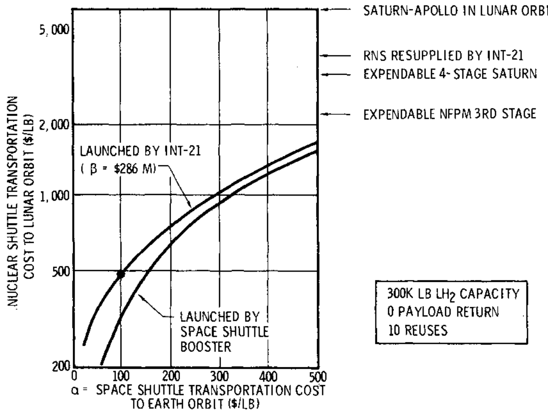


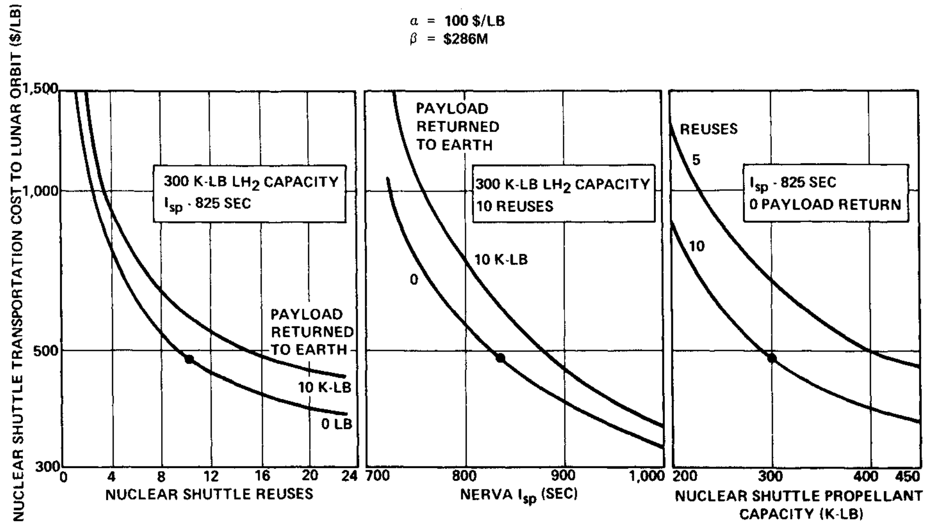

**Fig. 1 Effect of space shuttle on nuclear shuttle transportation cost.**

The alternative of launching the RNS to orbit with the space shuttle at the transportation cost of space shuttle logistics is also indicated, showing the substantial savings which may be obtained (about 30% for the nominal case). The transportation cost for current Saturn/Apollo transportation to lunar orbit is shown at the right as about 6000 \$/lb. Thus, employing an RNS together with the space shuttle logistics system would indicate a potential reduction in transportation cost to lunar orbit of an order of magnitude or more. Other system options are shown on the right. None approaches the economics of the RNS for the range of $\alpha$'s of interest.

Figure 2 shows the sensitivity of lunar transportation cost to the number of RNS roundtrips. There are diminishing returns beyond about 8 or 10 roundtrips, which must be traded against the cost of maintaining the RNS to keep it operational for longer lifetimes.

The sensitivity of transportation costs to the specific impulse of the NERVA engine is indicated in Figure 2. Increasing the $I_{sp}$ from the nominal 825 to 900 sec would result in a typical transportation cost reduction of 20%. A strategy for increasing engine lifetime has been considered, consisting of reducing engine operating temperature (and therefore, specific impulse). This figure indicates that a 100 sec reduction in $I_{sp}$ from 825 sec would approximately double the transportation costs. In view of the low benefit which was indicated for performing additional roundtrips which could utilize the increased engine lifetime, it is considered undesirable to sacrifice specific impulse for this purpose. Furthermore, an increase in the average specific impulse is most desirable. This encompasses parasitic elements such as start-up and aftercooling propellant. Considering the potential of low-cost engine replacement utilizing

**Fig. 2 Nuclear shuttle transportation cost sensitivities.**



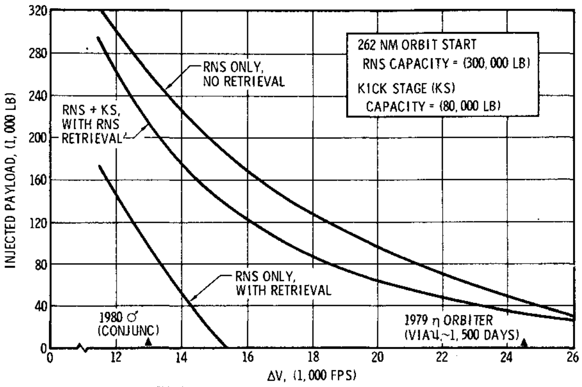



**Fig. 3 RNS escape injection performance.**

the space shuttle, frequent engine replacement is expected to be most economical on a long lived RNS system.

There is a monotonic decrease of transportation cost with propellant capacity as shown in Fig. 2, so it would always appear beneficial to increase the propellant capacity. However, the increased payload delivery capability associated with larger propellant capacity is only meaningful if the additional payload delivered is actually useful. Consequently, the implications of various program models and payloads have been evaluated. These indicated that a propellant capacity in excess of 300,000-lb $LH_2$ would be desired in a mature program.

Although the total mission velocity requirement is similar, the geosynchronous mission appears to have less impact on the RNS. This is attributed to both the lower expected payload requirements and the additional transportation leg between lunar surface and lunar orbit, which applies leverage to the surface payload weights. Thus, a smaller RNS capacity could be favorable for geosynchronous missions, depending on crew rotation requirements and possible use of a chemical shuttle for that purpose.

Transplanetary injection modes are compared in Fig. 3 for a nominal 300,000-lb $LH_2$ capacity stage, showing a fully reusable RNS, expendable nuclear stage, and an RNS with an expendable chemical kick stage having an 80,000 lb propellant capacity. A kick stage would be required for $\Delta V >$ 15,000 fps. Currently envisioned unmanned payload requirements could be easily accommodated with this reusable system capability. Also, manned flyby missions to Mars and Venus could also be readily accomplished with the capability of a single RNS.

A comprehensive evaluation of RNS performance on the manned Mars landing mission is beyond the scope of the present study. A preliminary assessment is reported in Ref. 4. The reusable and fully expendable mission modes are not completely comparable, inasmuch as propulsive capture by the RNS would be utilized for arrival at Earth in the reusable mode, whereas an aerodynamic braking would typically be utilized for the expendable mode. Neglecting retrieval of the RNS and spacecraft in Earth orbit, about 15–20% more propellant is required in orbit to operate the system. Depending on the launch approach for the RNS and mission spacecraft, an RNS with a capability of 10 reuses would permit a reduction in over-all transportation cost for the mission by a factor of 3–5 compared to a completely expendable system. Net transportation costs to Mars orbit of well below 1000 $/lb are possible.

An RNS could perform several types of missions as precursors to the manned planetary mission. Utilization of the RNS for Earth-centered applications can provide a basis for long-term operations and reliability assurance for manned planetary missions. Further, performing flight tests in a reusable mode reduces the costs of introducing the multiple stage orbital launch vehicles for manned planetary missions.

Definitive sizing and selection of functional characteristics of the RNS will be dependent on the characteristics of payload modules and program traffic requirements of an integrated space program plan. Lunar shuttle and manned Mars landing missions would dominate these considerations. Conceivably, the RNS could evolve from a capacity in the 300,000 to 340,000-lb $LH_2$ size initially to a larger size as program requirements increase. A nominal RNS capacity of 300,000-lb $LH_2$ will be used for the subsequent evaluations.

## RNS Design Concepts

The implications of reusability encompass nearly all aspects of the design of the nuclear shuttle system. The mission modes for RNS applications typically require multiple engine burns with attendant cooldown and restart operations. Multiple reuses require a long lifetime capability which impacts thermal and meteoroid protection requirements and functional reliability. Also, the performance premium for low stage weight is propagated by the number of reuses.

The existence of the space shuttle logistics system can have a dominant impact on the RNS configuration as well as those operations which are required to maintain, repair, and replenish expendables, including orbital tanking of $LH_2$, for each mission. Engine removal and replacement in orbit will be required if NERVA lifetime capability is not commensurate with that of the stage systems. The RNS can be launched to orbit unmanned without a payload. All of these affect design of the RNS and definition of an economical system approach for orbital support.

Two general RNS design concepts will be discussed here which are distinguished by their approach for launch of the RNS to Earth orbit. The Class 1 RNS is characterized as a 33-ft-diam stage compatible with launch to orbit by the INT-21 launch vehicle, consisting of the S-IC and S-II stages. The second approach is called the multiple module RNS, which is characterized by launch of all modules comprising the RNS within the cargo bay of the space shuttle.

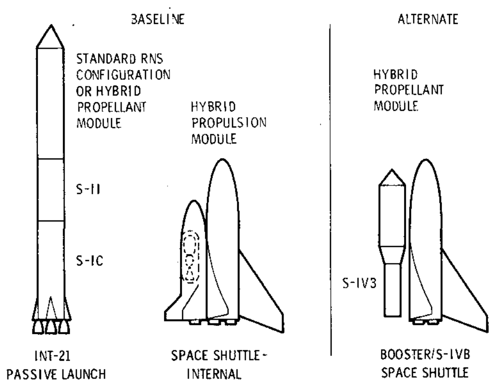



**Fig. 4 Launch to orbit—Class 1 RNS.**

## Class 1 RNS Design

Two concepts have been considered for the Class 1 RNS design. The standard Class 1 RNS employs a single module and retains a standard interface between the stage and NERVA. The Class 1 Hybrid consists of a propellant module, launched by the INT-21, and a propulsion module which consists of NERVA plus a small run tank. The propulsion module would be launched to orbit within the cargo bay of the space shuttle. A standard docking interface would be provided between the two modules. Potential configurations for launch to Earth orbit are depicted in Fig. 4. The Saturn V INT-21 can be used to launch either the hybrid propellant module or the standard RNS, both offloaded. An attractive alternative is also indicated in the figure which utilizes the space shuttle booster with the S-IVB stage replacing the reusable orbiter. The feasibility of this configuration deserves further investigation because it can utilize the launch economies of the space shuttle system. Neither concept requires a suborbital start of NERVA. The hybrid is used as a baseline for the Class 1 RNS concept because of its advantage for engine removal and replacement. Both concepts have comparable propellant mass fractions.

Optimization of the radiation shield and structural configuration have a large impact on the RNS design. A number of configurations were evaluated which varied the aft dome shape, engine separation distance and included internal tanks within the main tank to locate the propellant most effectively for shielding purposes. A 10° half-angle conical aft dome was found to be optimum. This configuration yielded substantial dose reductions from the height of the $LH_2$ residual as well as the $LH_2$ terminal drop rate which decreased the time of exposure to high radiation levels. This optimization considered the combined effects of the tank structural weight, thermal and meteoroid protection, and shielding. Similar data was obtained for both the standard and the hybrid configurations. The tankage geometry for both the propellant and propulsion modules in that case are such that the $LH_2$ is contained within a cone angle subtended by the radiation shield of the engine module.

Two design approaches for maintenance in orbit were considered: in-situ repair and module replacement. The design impact on the RNS for these approaches is different in terms of equipment packaging, interconnection, and checkout. In-situ repair would require some relatively complex operations which would be performed either by EVA or a sophisticated teleoperator system. A large number of orbital disconnects must be included and all components must be readily accessible. The checkout system would need to be capable of isolating faults to the level of replacement. For module replacement, however, the functional equipment could be packaged in a limited number of replaceable modules which could be removed remotely by a maintenance unit (as a kit on the space tug). This approach requires automatic disconnects. Module replacement appears to be potentially the most simple and imposes the minimum penalty to the RNS design. Definition of optimum replacement modules and their design is still in process. One possible approach would locate all replaceable functional subsystems of the RNS forward skirt in a single replacement module which could be carried by the space shuttle.

Alternative methods of replenishment of expendables have been evaluated, including fluid recharge and replacement for APS propellants and the power system (a fuel cell is the lunar shuttle reference primary power system). The present approach identifies replacement of the entire fuel cell module to minimize fluid disconnects and is analogous with maintenance operations.

An equipment layout with replacement modules in the RNS forward skirt is depicted in Fig. 5. All the maintenance modules would be inserted into structure mounted on the forward docking support cone. The modular concept appears to be adaptable to all of the functional subsystems. The maintenance unit could be docked with the RNS using the standard forward docking mechanism and the modules would be removed and replaced with a turntable mechanism.

A sketch of the RNS Class 1 Hybrid is shown in Fig. 6. A weight statement for this configuration is shown in Table 1. The structural weight includes an integrally stiffened 2014-T6 aluminum tank. Fiber glass honeycomb is used for skirts and the forward payload adapter to minimize heat leaks. The orbital interstage between the propellant tank and the engine module consists of fiber glass struts. The thermal protection system consists of 54 layers of doubly aluminized mylar with a nylon net spacer (DAM/Net). Meteoroid protection is provided by surrounding this with flexible foam and a fiber glass outer shroud which is tensioned

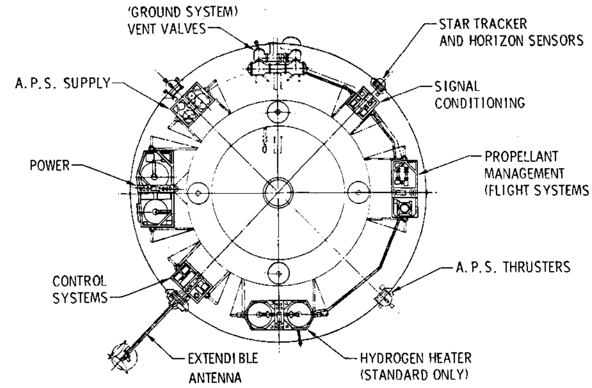



**Fig. 5 RNS Class 1 equipment placement—forward skirt.**

during launch to transmit loads to the tank sidewall. The astrionics and propulsion functional subsystems are of advanced design but represent current stage technology. Lifetime, reliability, checkout, and provision for maintenance are major requirements governing functional subsystem configurations.

## Multiple Module RNS Design

The concepts for the multiple module RNS which fully utilizes the space shuttle for launch-to-orbit are analogous in many respects to the selected Class 1 Hybrid approach, keeping the propulsion module and employing multiple propellant tanks instead of a single large tank. This approach would be motivated by the potential reduction in launch costs, although partition of the propellant container into many small modules could be expected to penalize the mass fraction. Consideration of functional requirements, reliability, maintenance and replenishment requirements resulted in selection of three discrete types of modules for this concept. The command and control module performs the navigation and guidance functions for all RNS operations, the processing of all data, data management (including capability for both up and down links to ground or Earth satellites), flight control, NERVA control functions, electrical power (primary and secondary), and the auxiliary propulsion subsystem functions for RNS control. It contains all consumables except main-tank $LH_2$. The propulsion module includes a run tank which acts as the propellant supply for NERVA, the engine prepressurization capability, and a minimum capability for stabilization and control during maintenance and assembly operations. This module is identical to that already discussed in conjunction with the Class 1 Hybrid concept. The propellant module provides propellant storage only; it is totally responsive to external control.

The reference launch approach for the multiple module RNS uses the space shuttle with an internal launch (within the cargo bay of the orbiter) for each of the three types of RNS modules. The mass fraction of the RNS could be improved by using larger modules. One multiple module configuration was investigated utilizing larger modules, typically 22 ft in diam and with up to 150,000-lb $LH_2$ capacity. These required launch by an expendable launch vehicle such as the

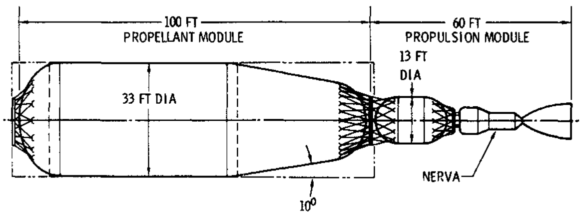



**Fig. 6 Nuclear shuttle Hybrid-1.**

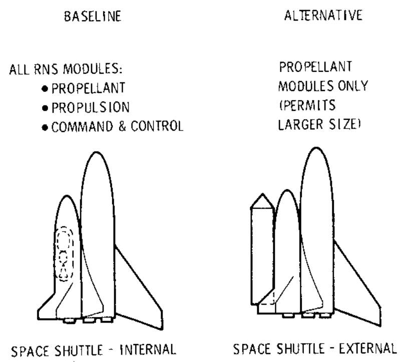



**Fig. 7 Launch to orbit—multiple module RNS.**

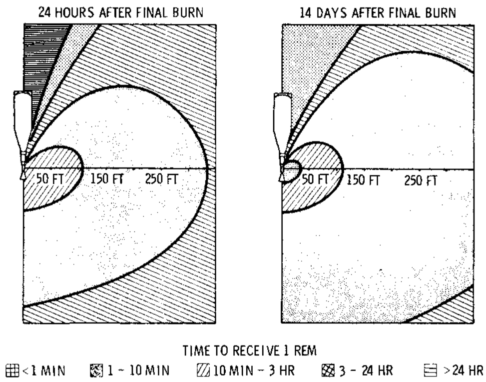



**Fig. 9 Radiation level after shutdown.**

Saturn IB. This approach suffers from launch vehicle availability and high launch costs. A potentially attractive alternative is indicated in Fig. 7 which depicts larger propellant modules launched external to the space shuttle orbiter. Because of the potential performance gain the feasibility of this approach deserves further investigation.

The maintenance and replenishment policy for the three types of modules differ in frequency. It is anticipated that maintenance operations would be performed by total module replacement in an operation identical to initial RNS assembly operations. Replenishment exclusive of the $LH_2$ is confined to a single module. The command and control module containing the expendables would be replaced in Earth orbit each roundtrip and returned to the ground by the space shuttle for refurbishment and recycling into the program. The propulsion module would be replaced periodically consistent with the limited NERVA lifetime or upon failure. Infrequent replacement is anticipated for propellant modules, based on the absence of expendables, simplicity, and its inherent high reliability. Thus, in many respects the multiple module RNS configuration would be similar to the Class 1 concept except for the geometry of the tankage.

Four of the multiple module configurations studied are shown in Fig. 8. The tandem configuration permits end-to-end docking and assembly. Payload to engine distance is maximized reducing shielding requirements. The planar configuration requires side-by-side clustering operations to be performed after end docking. Cross-feed ducting is required for $LH_2$ flow. Payload to NERVA distance is reduced, thus increasing radiation levels. The two clustered configurations are similar to the planar except for an increase in operations required for clustering and propellant feed and a reduction in separation distance. The major factors to be considered in selecting the RNS configuration are the radiation shielding implications, the assembly and operation implications, and vehicle stability, including flight control and structural stability. Both the tandem and planar configurations satisfy

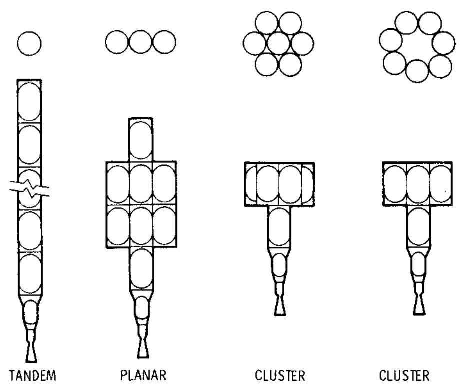



**Fig. 8 Multiple module configuration candidates.**

the radiation dose criteria without additional shielding for the reference space shuttle cargo bay dimensions. However, stability for powered flight attitude control requires the planar configuration for the reference module size. A tandem configuration could be employed if the module diameter exceeded approximately 18 ft for the reference RNS capacity of 300,000-lb $LH_2$. Thus, the planar configuration was selected as a baseline. The propellant feed system approach used with this concept permits isolation and independent access to each tank.

A weight statement for the multiple module RNS with eight propellant modules designed to fit within the reference space shuttle cargo bay dimensions of 15 ft diam by 60 ft long is shown in Table 2. The weight penalties associated with this configuration include the multiple docking and clustering subsystems, greater area for thermal and meteoroid protection, and the multiplicity of "plumbing." Comparing these weights to those for the Class 1 Hybrid in Table 1, the multiple module RNS avoids the radiation shield penalty and incurs a much lower residual propellant weight penalty. The latter results from a large, cold gas residual in the large tank associated with multiple restart operations. This residual is largely eliminated in the multiple module case, because depleted tanks can be isolated and vented while still containing hot expulsion pressurant.

## Orbital Tanking

Propellant resupply is required to perform multiple missions with the RNS. It is a major operation affecting orbital support of the RNS and the overall economics of the space transportation system. There are a number of system approaches (space shuttle tankers, propellant modules, orbital tank farms) and propellant transfer systems (acceleration, dielectrophoresis, etc.) to be considered together with the option of refilling or replacing depleted tankage. Requirements for these systems and their characteristics will be discussed briefly together with their implications for the design of the RNS.

A reservoir of propellant tankage in orbit, either as a tank farm or large RNS fleet, is required to smooth out propellant delivery to orbit and minimize the number of relatively expensive space shuttle vehicles which must be dedicated to propellant resupply for the RNS. The cases considered suggest that such a strategy would prove economical for RNS traffic exceeding four flights per year, which occurs in the first year or two of the program models investigated. If a tank farm were employed, it would be constructed most economically from RNS tankage. However, use of a larger RNS fleet is most attractive since it provides reservoir capacity as well as mission flexibility.

The implications of propellant transfer system technology were assessed for the RNS, and a set of transfer system designs were formulated considering a 300,000-lb $LH_2$ orbital tanker

**Table 1 RNS Class 1 Hybrid weight statement, lb[a]**

| Item | Propellant module | Propulsion module | Total |
|---|---|---|---|
| $LH_2$ Capacity | (290,300) | (9,700) | 300,000 |
| Structure | 23,450 | 1,280 | 24,730 |
| Thermal/meteoroid | 7,250 | 660 | 7,910 |
| Propellant handling | 570 | 250 | 820 |
| Secondary propulsion | 940 | 160 | 1,100 |
| Astrionics | 3,010 | 80 | 3,090 |
| Shield | | 2,600 | 2,600 |
| NERVA | | 23,000 | 23,000 |
| Contingency | 1,810 | 120 | 1,930 |
| Total dry weight | 37,030 | 28,150 | 65,180 |
| RCS propellants | 1,780 | 70 | 1,850 |
| Propellant residuals | 9,030 | 440 | 9,470 |
| Operational weight | 47,840 | 28,660 | 76,500 |

[a] Propellant mass fraction, $\lambda' = 0.793$.

vehicle. Five transfer system concepts were evaluated: linear acceleration, rotating acceleration, surface tension, dielectrophoresis (DEP), and bladder expulsion. A linear acceleration transfer is considered most economical and compatible with the RNS system. The liquid residual for acceleration transfer is reduced by employing flow control and other design strategies to minimize suction dip. The impact of acceleration on the orbit is reduced to only a slight wobble by orienting the thrust vector perpendicular to the orbit and transferring the propellant in an integral number of orbits.

The dimensions of the space shuttle cargo bay must be compatible with its payload weight delivery capability to achieve an economical propellant resupply approach. The relation between this volume and weight is an important consideration in defining the characteristics and approach to utilization of propellant modules for a space shuttle tanker. The major alternatives considered are: 1) a module deployed from the space shuttle which would be delivered to the RNS or tank farm by a space tug, and 2) an integral tank module which would entail deployment of a propellant transfer line from the space shuttle to engage the receiver tank. The integral configuration could make greater use of the available volume within the space shuttle cargo bay. For the baseline space shuttle, the net $LH_2$ capacity, after subtracting residuals, is about 6000 lb greater with the integral tanker. This results in savings of about $6 million per RNS mission using the integral tanker mode. It also involves fewer operations than module replacement. For a weight limited space shuttle, similar conclusions are obtained from about a 3000-lb difference in weight between the two concepts. Thus, the integral tanker concept is recommended.

**Table 2 Weight statement (lb) for multiple module RNS—clustered configuration (configured for 15-ft-diam × 60-ft space shuttle cargo hold)**

| Item | Propulsion module | Command control module | Propellant module | Total configuration[a] |
|---|---|---|---|---|
| $LH_2$ Capacity | (9,700) | 0 | (36,500) | 301,700 |
| Structure | 1,280 | 970 | 3,400 | 29,450 |
| Thermal/meteoroid | 660 | 140 | 1,000 | 8,800 |
| Propellant handling | 250 | 30 | 470 | 4,040 |
| Secondary propulsion | 160 | 850 | ... | 1,010 |
| Astrionics | 80 | 2,870 | 50 | 3,350 |
| NERVA | 23,000 | ... | ... | 23,000 |
| Contingency | 120 | 240 | 240 | 2,280 |
| Total dry weight | 25,550 | 5,100 | 5,160 | 71,930 |
| RCS propellants | 70 | 1,290 | ... | 1,360 |
| Propellant residuals | 440 | ... | 465 | 4,160 |
| Operational weight | 26,060 | 6,390 | 5,625 | 77,450 |

[a] Based on 8 propellant modules. Propellant mass fraction $\lambda' = 0.793$.

A spray nozzle inlet is recommended for the RNS tank to provide ullage collapse and allow propellant tanking without RNS venting. The propellant resupply mode selection should also consider the performance advantage obtained by jettison of expended tankage on a multiple module RNS. No advantage was indicated for jettison, which must be further penalized by additional orbital assembly operations and space pollution by discarded tanks, although it would prove economically attractive for the manned Mars landing mission.

The RNS applications which have been evaluated typically result in a supporting traffic by the space shuttle consisting of 75% $LH_2$ resupply. Additional propellants would be supplied for the lunar lander. Thus, propellant delivery would represent a major role for the space shuttle.

## Radiation Environment

The radiation environment of NERVA does not appear to pose a major problem to mission operations of the RNS except possibly for engine removal. A radiation map following shutdown in shown in Fig. 9 for the hybrid concept. It can be seen that the forward region of the stage is available for tanking and maintenance during this period without a radiation hazard. The approaches identified for start-up and rendezvous of the RNS minimize the impact of its radiation environment on the associated system elements. For start-up the APS system can be used economically to separate the RNS about 13 naut miles above and 160 naut miles behind the orbital facility so that it will fly by at a safe distance (about 90 naut miles) during full thrust operation resulting in a dose to the facility of less than 0.05 rem.

The reference rendezvous approach assumes that the RNS is active and performs the closure maneuver. A coelliptic rendezvous can then be utilized coming from a location about 10 naut miles above and 50 naut miles ahead of the facility to a location at the same altitude and plane about 10 naut miles in front of the facility. This approach permits a stable orbit closure to be accomplished with a small rate of change in the line of sight between the two vehicles during the final phase. This allows the RNS to keep the orbital facility within its shadow column and within the capabilities of the guidance system. During the last few miles of closure, the RNS would be oriented radially toward the orbital facility.

## Disposal

Several alternatives for disposal of NERVA or the RNS at end of life or in the event of failure have been considered. It would be desirable before the last operation of the RNS system, to inject an unmanned payload from the operational low Earth orbit into a heliocentric trajectory to minimize costs. Since NERVA replacement can be anticipated during the life of the RNS system, a separate approach is required for the propulsion module. One possibility would employ the space tug to provide the propulsion capability for heliocentric injection of the propulsion module. It could be operated in a reusable mode from either the low Earth assembly orbit or the target orbit (if failure occurred there). This approach is considered desirable on the basis of safety, orbital debris, and system economics.

## Conclusions

A propellant capacity of about 300,000-lb $LH_2$ is identified for the initial RNS configuration, pending further clarification of integrated space program plans, with potential evolutionary growth to larger capacities. The various RNS design concepts can result in comparable system performance, so development and launch implications will dominate selection. Employing a NERVA propulsion module facilitates the engine replacement in orbit and provides favorable operational characteristics. Relatively advanced stage technology would be employed on the flight configuration of the RNS, but no major feasibility problems have been identified. The capability developed for initial Earth-centered applications would be directly applicable to providing a manned Mars mission capability.

The approach for RNS design has focused on simplicity and large scale module replacement to minimize the equipment and crew required to support the RNS in orbit. A major manned orbital maintenance facility does not appear warranted, and it is also conceivable that an orbital tank farm could be obviated by the space shuttle. The potential of the space shuttle should be exploited to support the RNS. In addition, a space tug could fill a useful role for assembly, maintenance, and engine removal/disposal operations.

Inasmuch as NERVA characteristics were largely selected in an environment of expendable systems, some review would be desirable, particularly to improve its aftercooling characteristics. However, thrust, lifetime, specific impulse, and operating pressure deserve reconsideration specifically for the RNS concept.

The space shuttle has a major impact on the RNS through both space shuttle compatible design configurations for the RNS and propellant resupply operations and economics. Thus, an integrated system definition is essential to achieve a fully effective transportation system.

In conclusion, the RNS, together with the other system elements discussed, has the potential of providing Earth-centered interorbital and lunar transportation at costs that are an order of magnitude below Saturn-Apollo, and even manned Mars landing capability at costs well below current lunar transportation.

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# Alternating Current Operation of a Colloid Source

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**The generation of charged colloids by electrostatic spraying has been adopted to a novel thruster concept in which metal capillary needles are subjected to an a.c. voltage which generates positive and negative current pulses of similar shape and magnitude. This mode of operation may eliminate the need for an electron neutralizer. At thrust levels on the order of $10^{-4}$ lb, the required neutralizer power for the conventional direct current (d.c.) colloid thruster is relatively large compared to the beam power; thus, it would be an advantage to eliminate the requirement for an electron neutralizer for the low-thrust colloid source. Feasibility of this concept has been explored by examining single needle capillary operation. Tests were performed in a bell jar vacuum system and a time-of-flight circuit was built so that thruster parameters could be calculated for the positive and negative pulses. Positive and negative charge-to-mass ratios were obtained in the range of 10,000 coul/kg at a specific impulse on the order of 1000 sec and a beam efficiency of 40%. Results, to date, are encouraging and indicate that a simple, reliable low-thrust system may evolve from this concept.**

## Nomenclature

$g$ = acceleration due to gravity
$L$ = distance from needle tip to collector
$\dot{m}$ = mass flow rate, $dm/dt$
$q/m$ = charge to mass ratio
$T$ = thrust
$t$ = time
T.O.F. = time-of-flight
$V$ = colloid particle velocity
$\epsilon$ = dielectric constant
$i_0$ = needle current
$I_{sp}$ = specific impulse
$V_0$ = accelerating potential

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## Introduction

THE electrohydrodynamic spraying of charged liquid droplets (colloids) from metal capillary needles subjected to high voltages has been extensively investigated with a smaller effort on slit geometry sources and generation of negatively charged colloid beams. The bipolar concept proposed by R. Hunter,[1] expels simultaneously positive and negative charged droplets from metal capillary needles. The bipolar concept presently requires two feed systems, two power supplies, and two propellant types. If the a.c. mode of operation can be perfected, these requirements for elimination of the electron neutralizer will be reduced, and the present study was directed toward this end.

Individual needles have been operated at beam currents above 10 μamps, $10^4$ coul/kg, and distribution efficiencies of 75%.[2] TRW Systems recently ran an 18-needle d.c. module for 1000 hr at an $I_{sp}$ = 975 sec, 69% efficiency, and 31.3 μlb