THE INFLUENCE OF RADIATION SHIELDING ON REUSABLE NUCLEAR SHUTTLE DESIGN

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The nuclear rocket's unique energy source affords unusually high performance while requiring special protection for manned flights. If maximum capability is to be achieved without compromising development or operating costs, stage designs must employ efficient methods for minimizing radiation shield requirement. With this objective, alternate reusable nuclear shuttle (RNS) configurations were synthesized and evaluated. Particular attention was given to design factors which reduced tank exposure to direct and scattered radiation, increased payload-engine separation, and improved self-shielding by the LH_2 propellant. The most attractive RNS concept in terms of cost effectiveness (unit payload delivery cost) consists of a single conical aft bulkhead tank with a high fineness ratio (eight-degree half cone-angle with a 25-inch cap radius). Launch is accomplished by the INT-21 with the tank positioned in the inverted attitude. The NERVA (nuclear engine for rocket vehicle application) engine is delivered to orbit separately where final stage assembly and checkout are accomplished. This approach is consistent with NERVA definition criteria and required operating procedures to support an economically viable nuclear shuttle transportation program in the post-1980 period.

The attractiveness of a space transportation system is usually measured in terms of performance, nonrecurring cost, cost effectiveness (i.e., dollars per pound of payload delivered), and development risk. Achievement of a promising design concept requires effecting a compromise between diverse factors (e.g., technology, stage geometry, launch vehicle compatibility, maintainability, and end-of-life disposal). The nuclear rocket, no exception to this logic, is unique among space propulsion systems due to the radiation field inherent to this compact, high efficiency energy source. Thus, protection of on-board personnel, sensitive equipment, other in-space personnel, and earth's population is of paramount importance. This paper is addressed generally to the task of designing a reusable nuclear shuttle (RNS) for safe, post-1980, manned space transportation while meeting the criteria of attractiveness. Of specific concern is the interaction between requirements for protecting payload-carrying personnel, launch of the stage to earth orbit, and subsystems design.

For the past 20 months, the Space Division of North American Rockwell (NR) has been conducting a Phase A study (Nuclear Shuttle System Definition Study, Contract NAS8-24975) for NASA's Marshall Space Flight Center. The study's objective is to establish conceptual definition for a 1974-technology RNS with emphasis on minimizing development and operating cost. Candidate concepts are characterized by a 33-foot diameter propellant tank launched integrally to orbit by a Saturn V INT-21 booster. Total propellant (LH_2) capacity is baselined at 300,000 pounds. The RNS is powered by a 75,000 pound thrust full-flow NERVA engine with a nominal specific impulse of 825 seconds. To provide logistics support for the RNS, the earth-to-orbit shuttle (EOS) is assumed to deliver expendables (including main propellant), engines, and stage spare parts.

A convenient method for classifying candidate RNS concepts (employing the above guidelines) is to use the Saturn V as the standard of reference. Thus, one configuration category (I) contains all single tank designs with forward and aft elliptical bulkheads. These designs permit launch of the stage as an integral unit (engine plus tank) by the currently designated NASA INT-21 baseline (Reference 1). The other category (II) employs some form of conical tank bottom and encompasses designs which may require alternate launch and operational modes. Early studies (Reference 2) indicated that the simplest Saturn-type (viz, S-II) configuration is most efficient geometrically (and weight-wise) as a propellant container; however, it is limited to unmanned missions unless a severe weight penalty is accepted in supplementary radiation shielding. This deficiency can be partially overcome by modifying the internal tank geometry to increase the effectiveness of the LH_2 propellant as a radiation shield. Such designs, designated dual cell, control the flow path of hydrogen so that a column of propellant is interjected between the tank top and engine especially during the critical period just preceding the last run engine shutdown (Reference 3). However, detail 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.

Category II configurations, the subject of this paper, tailor tank aft bulkhead geometry to minimize payload shielding requirements. This is done by (1) controlling the incident angle for radiation interception of 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 operating complexity. However, radiation shielding for manned flights represents the major design driver and controlling factor in achieving best overall performance and cost effectiveness.

Stage design concepts attractiveness can be measured in terms of development cost and cost effectiveness maintaining cognizance of the design considerations. Low development cost can be attained by maximizing use of existing technology, hardware, and facilities, as well as by minimizing modifications to the launch vehicle. Cost effectiveness (in terms of unit payload delivery cost) is a function of both performance and recurring expenditures. Performance is measurable in terms of components weight which include radiation shield, structure, thermal and meteoroid protection, as well as mechanical, fluid and astrionic subsystems. 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. Recurring costs include delivery of the stage, propellant, and other supplies to orbit. as well as orbital assembly and maintenance. Propellant delivery, even using the EOS at currently projected operating rates, is a major cost driver.

A number of attractive RNS design concepts have been synthesized and these are compared to illustrate how the radiation environment can be accommodated while maximizing performance and cost effectiveness for manned shuttle applications.

CONICAL AFT BULKHEAD DESIGN CONCEPTS

In the conical design, radiation attenuation to the tank top is attained by the shadow shield cone created by the aft bulkhead, depth of LH_2 column at any given point in the mission, and distance from the radiation source.

The three Category II configuration classes investigated are shown in Figure 1. 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 was conceived with the primary objective of aiding in end-of-life engine disposal while minimizing radiation dose to the payload.

The analytical approach taken was to optimize the performance of the single tank design for the lunar shuttle mission and then assess the operational impact including the launch to orbit. Also, the single tank optimum design point has been employed to evolve attractive dual cell and hybrid concepts, aimed at improving an already acceptable overall performance.

The design issues shown in Figure 2 relate to performance and cost evaluation criteria and serve as guides in design investigations. For example, stage length is inversely proportional to the aft bulkhead cone angle and end cap radius. As stage length increases so does surface area and weight. On the other hand, the weight of the external shield required for radiation dose attenuation to the payload decreases with increase in fineness ratio of the cone. Consequently, the tradeoff yields a point of minimum total weight which denotes the stage design with the highest flight performance. Yet, to complete the tradeoff, the resulting stage geometry has to be evaluated for impact to the launch vehicle, orbital operations, and facilities in order to arrive at a realistic and attractive solution.

Other design issues that must be considered in the system evaluation include stage and engine interface and NERVA disposal requirements. As shown in Figure 2, interface design must respond to a wide range of considerations when applied to hybrid and single tank designs. These include the inherent complexities associated with mating fluid lines and electrical receptacles in earth orbit. Engine disposal also presents a wide range of design considerations when related to a hybrid stage concept. In this case, the maximum propellant capacity that can be accommodated in the EOS with the engine is 13,200 pounds. However, this results in an auxiliary tank geometry which is unattractive for radiation attenuation to the payload. Additionally, 13,200 pounds of propellant is inadequate for heliocentric orbit disposal of the engine from a low altitude earth orbit, if this is desirable. On the other hand, it is larger than necessary for safe high altitude earth orbit disposal.

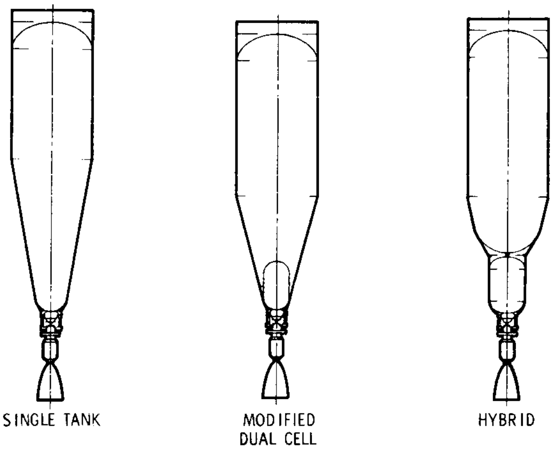


Figure 1. RNS Configuration Classes

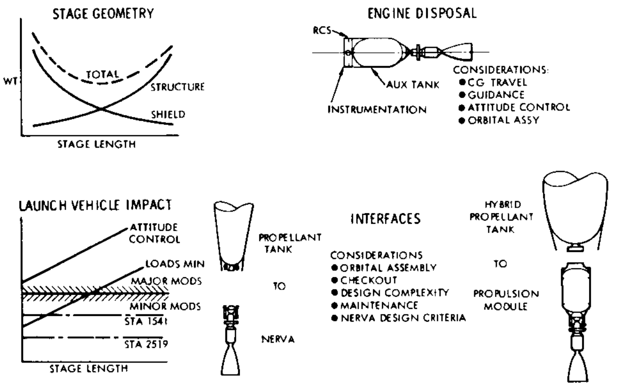


Figure 2. Design Issues

SINGLE TANK

The necessary parametric analyses were initiated by investigating the influence of aft bulkhead geometry variations on stage height and surface area. The bulkhead half cone-angle was varied from 15 to 5 degrees and the end cap radius from 125 to 25 inches. The propellant tank was sized for 300,000 pounds of LH_2 with 5 percent ullage volume. The tank configuration employed consists of three segments: forward elliptical bulkhead of 1.5 aspect ratio, cylindrical section 33-feet in diameter, and a conical aft bulkhead. The resultant stage length variation, including engine and astrionics bay, is presented in Figure 3(a). Stage length maximum variation is approximately 90 feet (190 percent) between the 5 degree half cone-angle with a 25-inch cap radius and the 15-degree counterpart with a 125-inch cap radius, accountable to both the change in half cone-angle and cap radius. The tank total surface area variation over the range of the parameters considered is less than 25 percent as shown in Figure 3(b). Since surface area can be related to weight, this result implies that a relatively small weight variation can be expected between the tank geometries under study.

This is evident in the stage weight variation as a function of the half cone-angle and cap radius shown in Figure 4(a). The weight includes forward and aft skirts with four-foot long heat blocks, foam and high performance insulation (HPI) for ground and space thermal protection, double wall 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.

The resultant weights indicate that the maximum difference between extremes is approximately 2,600 pounds and that the majority of this weight difference is in the meteoroid and thermal protection system which responds to the surface area variation. In addition, the variation in surface area increases the heat input to the tank and, therefore, increases weight in terms of boil-off. The boil-off penalty presented in Figure 4(b) is shown to have a maximum variation of approximately 1,300 pounds between geometry extremes.

Figure 4(c) presents the external shield weight required for a tank top integral dose criterion of 10 rem. The shield weights were derived from pressure vessel and reactor assembly (PVARA) and external on-axis integral tank top dose contributions for an initial LH_2 tank capacity of 300,000 pounds. An LH_2 residual capacity of 5,000 pounds at the termination of the tank drain (for after-shutdown cooling requirements) was also assumed. The shield weights vary from approximately 2,000 pounds for the 5-degree half cone-angle and 25-inch cap radius to 13,000 pounds for the 15-degree, 100-inch cap radius design point. The reduction in tank top radiation dose and external shield weight is principally due to (1) greater source-to-tank

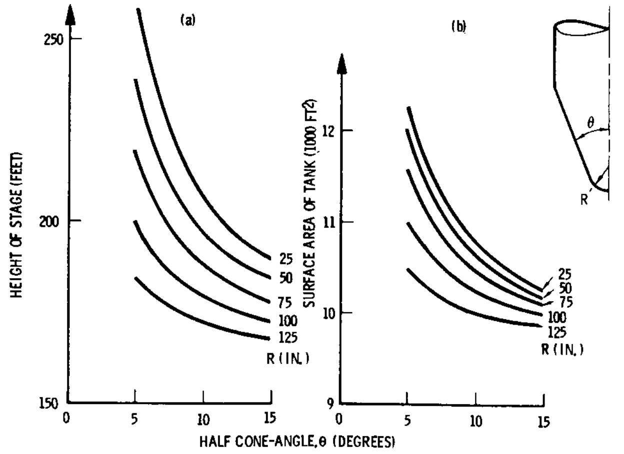


Figure 3. Stage Length and Surface Area Variations

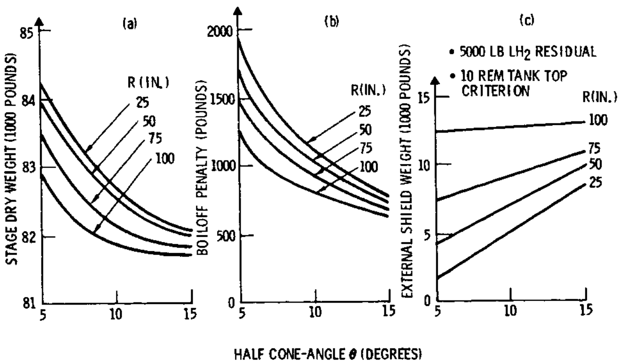


Figure 4. Stage Weight Variations

top detector separation distance (high fineness ratio tank), (2) reduced effective energy deposition and scattering centers in the aft end of the propellant tank, and (3) greater depths of the LH_2 propellant column for radiation attenuation at any given time during the draining cycle, for a fixed propellant capacity. As can be seen in Figure 4(c), the shield weight is essentially insensitive to cone angle variations at large end cap radii ($\geq$100 inches). This is due to the very small variations in the three radiation factors at large cap radii.

The results of the parametric analyses including structure, thermal and meteoroid protection, boil-off penalties, and external shielding are expressed in Figure 5 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.

The data as depicted in Figure 5 show the 8-degree half cone-angle, 25-inch cap radius configuration to have a 21,000 pound payload gain over the reference 15-degree half cone-angle x 100-inch cap radius. This payload gain results from a 9,000 pound variation in external radiation shield weight between the two designs, less a 1,300 pound increase in structure weight for the longer tank. The net weight difference of 7,700 pounds, with a lunar mission payload exchange factor of approximately 2.8 pounds of payload per pound of equivalent inert weight (fixed weights plus effective boil-off), yields the gain previously quoted. The 2.8 pounds exchange ratio is derived by letting the moon-bound payload vary with the performance mass ratio of the vehicle while maintaining the return payload constant.

The resulting single tank baseline is shown in Figure 6. The 396-inch diameter cylindrical section is 426 inches in length and the total tank length is 1,827 inches. Retaining the distance of 200 inches between the engine core center and aft end of the tank results in a 42-inch separation between NERVA and tank interface. With the 60-inch astrionics unit length added at the forward skirt, the total stage length less the engine is 1,929 inches (approximately 160 feet); and with the engine is 2,326 inches (194 feet).

Both facility size (maximum permissible height in KSC VAB) and INT-21 strength capability constraints were then imposed on the selected single tank design. The former consideration limits RNS launch configuration to 190 feet. NASA-MSFC has recently established a baseline INT-21 booster consisting of the S-IC, the S-II and a 33-foot diameter, 141-foot long payload with a biconic nose cone, and retaining the present Saturn V attitude-attitude rate control system (Reference 1). This launch configuration results in increased loading at max (qα) over the present boost stages, requiring therefore, structural modifications. To minimize these modifications on the current S-IC's and S-II's, NASA established a lower wind criterion of 50 meter/sec maximum wind profile. This reduces the launch availability to certain months of the year.

Although the INT-21 has been ground-ruled in this study as the RNS boost vehicle, consideration can be given to integral (engine-stage mated on ground) as well as nonintegral launch as shown in Figure 7. In the latter case, the main propellant tank is launched by the INT-21 (preferably inverted to minimize aerodynamic loads including flutter) and the NERVA or propulsive module (in the case of the hybrid configuration) is launched by the EOS. The nonintegral 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 the active assembly of a neuter docking system designed for the Space Station (and adapted by other space elements) has been attached to the stage thrust structure. The passive assembly of the docking system has been in turn adapted to the NERVA upper thrust structure. In this manner, orbital mating is accomplished employing the EOS, and demating, if necessary is done with the space tug.

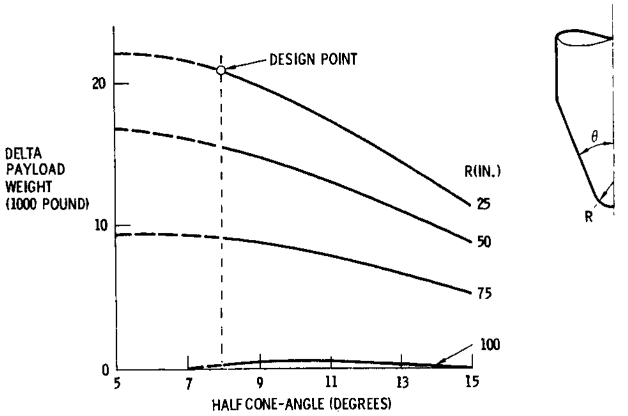


Figure 5. Design Trade-Off Map

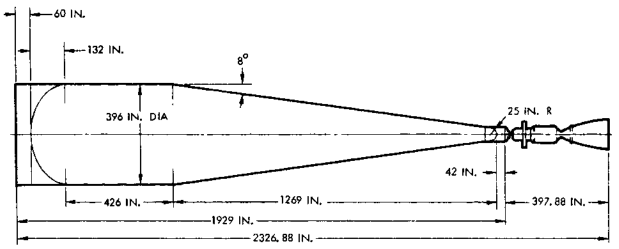


Figure 6. Single Tank Baseline Configuration

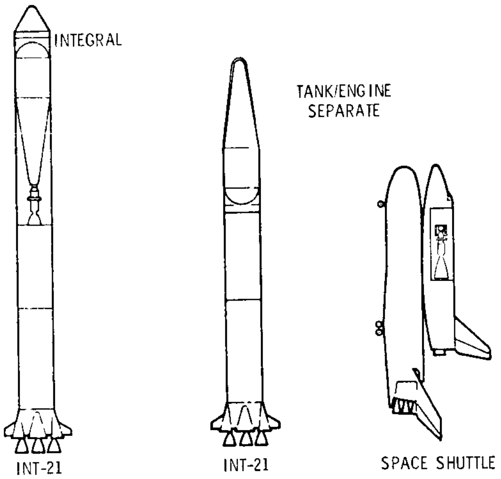


Figure 7. Alternate Launch Modes

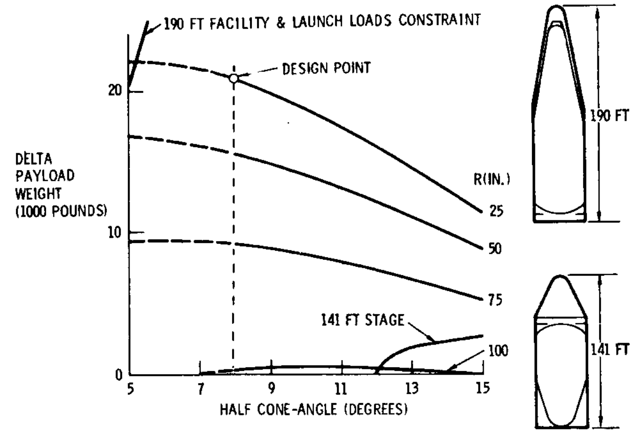


Figure 8. Design Trade-Off Map with Launch and Facilities Constraints

In employing the baseline INT-21, the acceptable size of an RNS tank with inverted launch and 8-degree, 25-inch cap radius aft bulkhead is 190 feet, as shown in Figure 8. This height capability is due to the lower combined air loads resulting from the slender 8-degree nose cone and the aft shift in center of pressure. It should be noted that the loads derived for this configuration are compatible with the 75 meter/sec wind profile (or 95 percent probability of no occurrence) corresponding to 100 percent launch time availability during the year.

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 corner of Figure 8. 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 cost) to the INT-21 baseline, 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.

MODIFIED DUAL CELL

Figure 9 depicts the configurational arrangements of the RNS using an inner cell with a capacity commensurate with the last cooldown plus residual propellant requirements, identified as 5,950 pounds. The objective is dual in nature: (1) by trapping propellant within the inner cell, propellant management during periods of zero gravity might be simplified, and (2) the resultant column of propellant could be used effectively as a radiation attenuation shield in the critical latter seconds of burn when tank top radiation dose rate is reaching its peak.

Since the single tank baseline of 8-degrees and 25-inch cap radius was shown to be optimum, the inner cell concept study was confined to that configuration only. A number of inner cells geometries were considered by varying the radius of the cylinder. The limiting upper radius is 60 inches when the bulkhead becomes tangent to the side walls of the cone.

The optimum cell geometry is based on the minimization of the algebraic sum of the tank and inner cell structure as it increases with pressure, and of shield weight as it reduces with increasing inner cell height. The pressure increase is equal to the propellant transfer line height from outer to inner cell, multiplied by the density and acceleration, and reaches a maximum when the outer cell is near depletion. Losses in and at the transfer line intake are relatively small. The results of the analysis indicated that the optimum configuration has an inner cell top radius of 50 inches.

HYBRID

The hybrid class of RNS configurations was conceived primarily to aid in engine end-of-life disposal. After the last operational flight, the auxiliary tank is filled with LH_2 and the propulsion module - consisting of the small tank, NERVA, guidance and navigation, and reaction control system - propels itself to a safe disposal orbit. Other potential benefits include ground mating of the engine with the small tank resulting in reduced orbital assembly operations, and amelioration of start-up pressurant requirements when the main tank has a large ullage.

In addition, consideration must be given to other significant design drivers that affect stage cost effectiveness. These include nuclear radiation, system weight, and EOS cargo bay compatibility for the auxiliary tank. A spectrum of hybrid configurations as shown in Figure 10 was synthesized for an initial screening prior to a more detailed tradeoff study to identify the most attractive candidate in this class. As also shown in the figure, a wide range of auxiliary tank geometries and capacities was screened on the basis of EOS cargo bay dimensional compatibility, producibility, radiation scattering, LH_2 capacity in relation to disposal capability, and interface compatibility with the main tank. Various main tank cap radii and half cone-angles were considered in the context of radiation attenuation and stage moldline symmetry.

The results of the single tank study—indicating significant weight reductions for designs with small half cone-angles and cap radii—were used to guide the hybrid design screening.

The evaluation of the most promising hybrid vehicle configurations is summarized in Table 1. The evaluation criteria include vehicle length and weight, external shield weight, and disposal capability from low earth orbit. The minimum empty vehicle weight, integral tank top radiation dose and external shield weight are seen to occur for the hybrid configuration employing a 3,000 pound capacity LH_2 auxiliary tank (8-degree half cone-angle, 25-inch cap radius). Shielding weight advantages of about 2,800 to 3,400 pounds are derived from the 25-inch end cap radius in the lower auxiliary tank of this hybrid configuration as well as the overall vehicle length of 208 feet. However, the reduced LH_2 capacity of 3,000 pounds precludes the possibility of engine disposal to a safe orbit. If the dual requirements for 9,300 pounds of LH_2 tank capacity for engine end-of-life disposal and an allowable cargo volume of 15-foot diameter by 60-foot length for the EOS are to be satisfied, one of the other three hybrid configurations listed in the table must be selected. Therefore, the hybrid configuration employing an auxiliary tank with a 7.5-degree half cone-angle and 68-inch end cap radius aft bulkhead geometry and a 7.5-degree half cone-angle, 112-inch end cap radius aft bulkhead geometry for the main tank affords the optimum selected hybrid arrangement. This configuration represents the minimum weight system while maintaining a high earth orbit NERVA disposal capability.

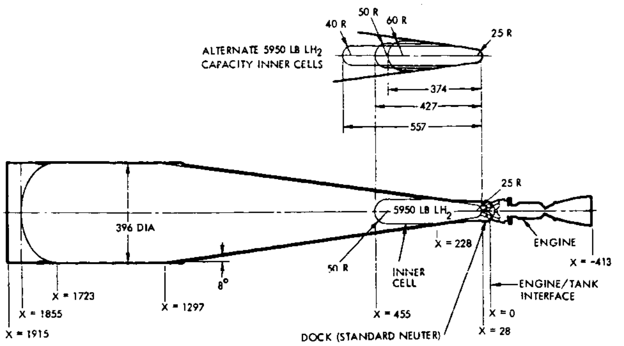


Figure 9. Modified Dual Cell Configuration

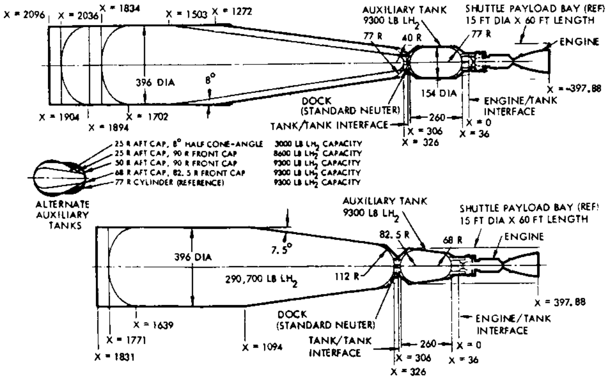


Figure 10. Hybrid Configurations

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°, 40 in. r cap Auxiliary tank - 77 in. r cyl - 9300 lb-LH_2	660 x 660 n mi 45° inclination	208	81310	88	6000
Main tank - 8°, 40 in. r cap Auxiliary tank - 8°, 25 in. r cap - 3000 lb-LH_2	660 x 660 n mi 32.5° inclination	208	79870	32	3800
Main tank - 8° 77 in. r cap Auxiliary tank - 77 in. r cyl - 9300 lb-LH_2	660 x 660 n mi 45° inclination	193	80730	107	6600
Main tank - 7.5°, 112 in. r cap Auxiliary tank - 7.5°, 68 in. r cap - 9300 lb-LH_2	660 x 660 n mi 45° inclination	186	80150	109	6600

[1] Auxiliary propulsive module compatible with EOS payload capability; Guidance Navigation and Control module required for engine disposal.

[2] 5000 lb LH_2 residual level.

ALTERNATE CONCEPTS 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 over 6,000 pounds over the hybrid, and 1,500 over the modified dual cell. In the case of the latter the weight difference is due to the higher tank design pressure resulting from the additional losses in feeding propellant to the top of the inner cell plus the weight of the inner cell assembly.

Over 2,500 pounds of the penalty for the hybrid are due to the higher external shield weight as shown in Table 2. The other 3,500 pounds are due to increases in stage empty weight over the single tank design. These are basically in structures, 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 auxiliary tank.

Of concern also is design compatibility with operational requirements, particularly those derived from earth launch of the RNS plus its logistic supplies, and orbital activities to support a program dependent on reusability to substantially reduce cost. It is particularly pertinent to determine if there are critical operational drivers which favor certain designs.

As previously indicated, the MSFC booster baseline configuration, employing Saturn V's attitude and attitude rate control mode, does not constrain the RNS length as long as the tank is boosted in the inverted position. Although this approach necessitates a separate NERVA launch with orbital mating and checkout, no requirements are imposed beyond those to support a reusable shuttle program. Furthermore, NERVA design criteria specify engine assembly and removal capability in earth orbit. Engine replacement may be necessary due to limited lifetime or unrepairable damage considerations and many common operations exist in payload mating and checkout, propellant transfer, maintenance and repair, etc., requiring development of similar in-orbit capabilities. Lastly, the limited benefit of an integral engine-tank launch (permiting ground mating and checkout) must be weighed against use of a new flight control approach—load minimum— or alternately more extensive structural design changes to the INT-21 even for the shortest conical RNS.

Like the recommended single tank concept, the hybrid design employs a separate engine launch. However, since the engine is attached to an auxiliary tank on the ground, somewhat fewer connections should be required in orbit for mating with the main tank. A preliminary assessment did not show any significant reliability benefits. A main attraction of the hybrid is the built-in auxiliary tank to permit NERVA end-of-life self-disposal. Maximum tank size is limited by EOS cargo bay dimensions and radiation attenuation requirements. Nevertheless, 9,300 pounds can be efficiently accommodated and is sufficient for a safe high altitude earth orbit engine disposal. If the disposal module is to be autonomous, it will require addition of astrionics equipment and an RCS system for flight stabilization, guidance, and control. Unless these items can be designed for installation initially with the auxiliary tank (which imposes stringent radiation-hardened and lifetime requirements), they will have to be mated in orbit just prior to disposal. This requires support by another vehicle such as the tug. With all of the other concepts, either the disposal tankage/equipment must be delivered and mated to the engine just prior to disposal or the tug can be used to deliver NERVA to a safe location. Although the choice is not clear-cut for a normal disposal, if NERVA is inoperable the tug appears to be the only practical alternative. With this contingency as the key driver, tug disposal is recommended under all conditions, thus eliminating any significant operational benefit in the hybrid design.

One additional factor of concern is the effect of using a high fineness ratio tank with a small end cap radius. Interface studies indicate that a suitable coupling can be made without impacting NERVA requirements. Furthermore, the slender conical tank geometry should aid in zero g propellant control through migration and retention of the LH_2 at the aft end.

Payload delivery cost (cost effectiveness) is perhaps the most significant parameter in concept evaluation. The three bar charts shown in Figure 11 indicate the relative worth of the three alternate designs. As can be seen, the 8-degree single tank concept (1) is superior in terms of maximum performance and minimum payload delivery cost. On the basis of current RNS performance and cost estimates, this could amount to a savings of 10-15 million dollars per lunar shuttle flight. Although the modified dual cell (2) affords somewhat better radiation protection, it is more complex, structurally heavier, and thus more costly than the single tank design.

On the basis of the data summarized in Table 2 and Figure 11, the single tank design employing INT-21 launch of the RNS tank in an inverted attitude is clearly the most attractive configuration while meeting current standards of on-board personnel protection.

REFERENCES

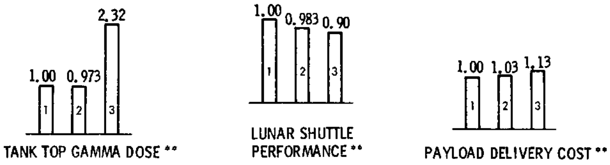
1. Preliminary Design Loads INT-21, D5-15806 (10 August 1970)
2. Nuclear Flight System Definition Study–Phase I Report, SD 70-118 (March 1970)
3. Nuclear Flight System Definition Study–Phase II Final Report, SD 70-117 (August 1970)

Table 2. Candidate Systems Summary Comparison

Item	Single Tank	Modified Dual Cell	Hybrid
Main tank half cone-angle - (degrees)	8	8	7.5
Main tank cap radius - (in.)	25	25	112
Auxiliary tank LH_2 capacity - (lb)			9,300
Auxiliary tank cap radius - (in.)			68
Tank top radiation dose* - (rem)	38	37	109
Tank design pressure - (psia)	27.5	28.5	28.2
Empty weight - (lb)	76,450	77,900	80,150
External shielding weight** - (lb)	4,050	4,050	6,600
Burnout weight - including external shielding - (lb)	81,930	83,400	88,180
Engine disposal			
Maximum capability	Heliocentric (limited only by EOS capability)		High earth orbit (unless extra tank added)
Inoperable NERVA	Tug	Tug	Tug
Reliability implications	No significant difference between concepts		
Recommended configuration	✓		

*5000 lb LH_2 last cooldown propellant
**10 rem criteria

CONCEPT	CONFIGURATION	LAUNCH MODE TANK/ENG SEPARATE
(1)	SINGLE TANK 8° X 25" R	✓
(2)	MODIFIED DUAL CELL	✓
(3)	HYBRID	✓



** VALUES RELATIVE TO CONCEPT (1)

Figure 11. Comparison of Alternate RNS Concepts