

IMPACT OF RADIATION DOSE ON NUCLEAR SHUTTLE CONFIGURATION

C. A. Goetz and M. P. Billings
McDonnell Douglas Astronautics Company – West
Huntington Beach, California

ABSTRACT

This paper assesses the impact of nuclear radiation (from the NERVA propulsion system) on the selection of a reference configuration for each of two classes of the Reusable Nuclear Shuttle (RNS). One class was characterized by a single propellant tank, the shape of whose bottom was found to have a pronounced effect on crew radiation levels and associated shield weight requirements. A trade study of shield weight versus structural weight indicated that the minimum-weight configuration for this class had a tank bottom in the shape of a frustum of a 10°-half-angle cone. A hybrid version of this configuration was found to affect crew radiation levels in substantially the same manner.

The other class of RNS consisted of a propulsion module and eight propellant modules. Radiation analyses of various module arrangements led to a design configuration with no external shield requirements.

CREDIT

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INTRODUCTION

Current interest in space nuclear propulsion is centered on the Reusable Nuclear Shuttle (RNS). Prospective missions include transportation of large payloads between low earth and synchronous orbits and between low earth and lunar orbits. Interaction with other vital components of such a transportation network is illustrated in Figure 1 for the lunar shuttle mission.

Two classes of the RNS are under consideration, these being a single-module class and a multi-module class, as shown in Figure 2. Each class has a total propellant capacity of about 300,000 pounds of liquid hydrogen. They may be distinguished as follows:

Single-module class—A single propellant tank, 33 ft in diameter (or a hybrid version using a small run tank in combination with the single main tank), placed in earth orbit by the Intermediate-21 launch vehicle

Multi-module class—An arrangement of a propulsion module plus 8 propellant modules, each of which is compatible with the 15-ft-dia by 60-ft-long cargo hold of the Space Shuttle, which transports them into earth orbit for subsequent assembly there

Radiation analyses were conducted on these concepts to identify the effects of propellant tank geometry on crew radiation levels and consequent shield weight requirements. Results from these investigations had a substantial impact on the selection of a reference configuration for each RNS class.

NUCLEAR SHUTTLE SYSTEM OPERATIONS

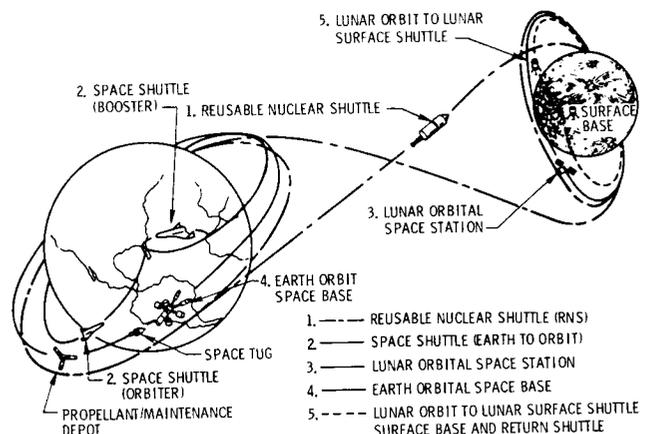
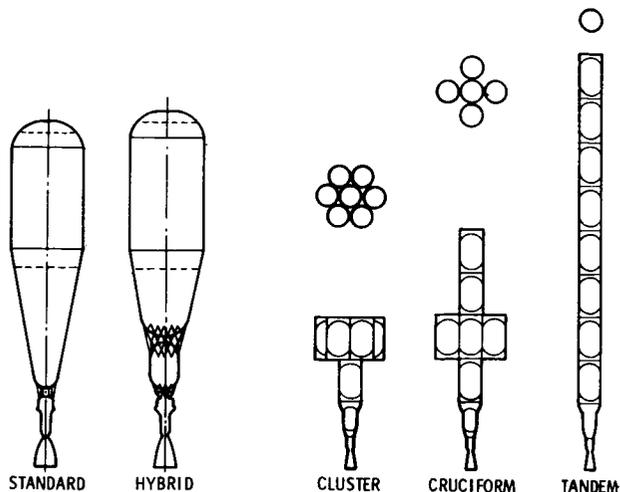


FIGURE 1. NUCLEAR SHUTTLE SYSTEM OPERATIONS

SINGLE - MODULE CLASS

MULTI - MODULE CLASS



SELECTION OF POINT KERNEL METHOD

- EASE OF USE FOR SURVEY WORK
- ACCORD WITH EXPERIMENTAL DATA ON SIMULATED NUCLEAR ENGINE/LH₂ TANK CONFIGURATION

PATCH CODE FEATURES

- DIRECT EVALUATION OF UNCOLLIDED RADIATION ^① TRANSMITTED THROUGH PROPELLANT TANK
- AUTOMATED CALCULATION OF SCATTERING ^② AND SECONDARY EVENTS IN PROPELLANT TANK
- DETECTOR RESPONSE TALLIED BY SHIELD ZONE ^③ TRANSMISSION

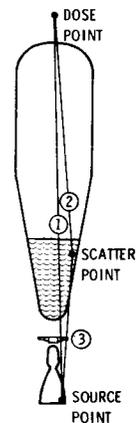


FIGURE 4. PATCH POINT KERNEL CODE

The potential influence of tank geometry on crew radiation levels arose from the fact that the propellant could provide significant reduction of crew dose due to nuclear engine radiation over the entire time period of the mission. Thus there was an incentive for effective utilization of the propellant to reduce the weight of shielding needed to meet the stipulated crew dose.

CALCULATION METHODS

The calculational techniques shown in Figure 3 were used in these analyses. Data on the engine and its radiation sources were based on the May 1969 Common Radiation Analysis Model,¹ except as modified in Reference 2. These data, together with data providing a model of each propellant tank design, were supplied as input to the PATCH point kernel code³ (or the SOBER Monte Carlo code*) to calculate dose rate as a function of propellant level in the tank. These dose rate data were broken down into the contributions from each particular zone of a disk shield, located between engine and tank, through which the radiation had been transmitted (Figure 4).

The next step in the procedure was to equate propellant *level* to drain *time* and to use the DOSE code to perform an integration of the dose rate over time. The resulting dose by shield zone was then coupled with data on shield geometry and shield material attenuation and, using the Lagrange multiplier formulation incorporated in the ZONER code, an optimum distribution of shield material was calculated for the external disk shield. The final result was payload dose as a function of shield weight.

The bulk of the dose rate analyses were accomplished using point kernel techniques. Selection of this method was based on (1) the utility of the point kernel technique for survey work and (2) the general accord shown between point kernel calculations and experimental data on simulated nuclear engine/propellant tank configurations.⁴ The PATCH code (see Figure 4) provided the requisite utility and accuracy and, in addition, offered unique features of particular benefit to this study:

- (1) direct evaluation of the dose from single-scatter and secondary production events in the tank, as well as the usual calculation of line-of-sight contributions,
- (2) tallying of detector response by the specific shield zone through which the radiation had been transmitted,
- (3) rapid determination of fluxes at scattering centers by interpolating tabular data in lieu of integration over all volume sources.

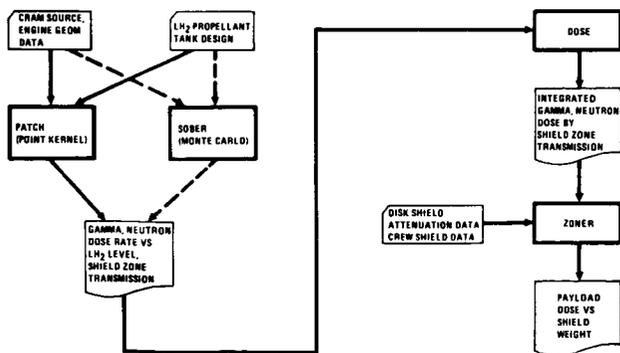


FIGURE 3. MDAC COMPUTER CODE OPERATIONS SEQUENCE

*A McDonnell Douglas adaptation of the FASTER Code⁵.

EFFECTS OF CONFIGURATION ON DOSE RATE

Detailed calculations of crew dose rate, integrated dose and attendant disk shield weight requirements were performed for a number of candidate configurations for each RNS class. For the single-module configurations, this activity necessitated a continuing, intensive evaluation of results in order to develop an understanding of the effect of the tank configuration on the radiation protection requirements. Through this understanding, a family of tank configurations of interest with respect to potential reduction of shield weight were identified for detailed evaluation.

Single-Module Class

The configurations investigated for potential application in the single-module class are illustrated in Figures 5 and 6. The designs shown in Figure 5 were distinguishable solely by the shape of the tank bottom, which was either ellipsoidal (with a $\sqrt{2}:1$ ratio of radius to depth) or basically conical (with a half-angle of 8, 10, 15 or 30 degrees). The tank designs shown in Figure 6 employed baffles which retained a portion of the propellant in a configuration which enhanced its time-integrated shielding worth.

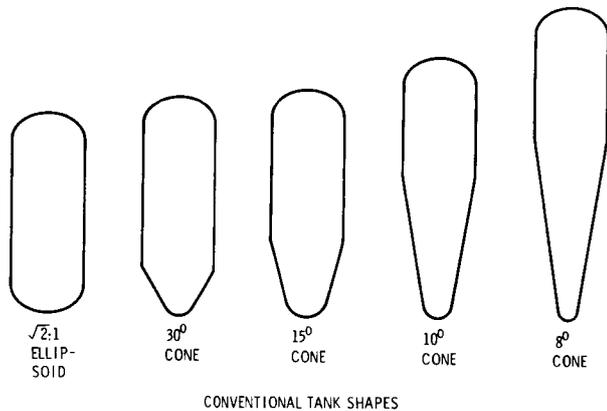


FIGURE 5. CANDIDATE LH₂ TANK CONFIGURATIONS

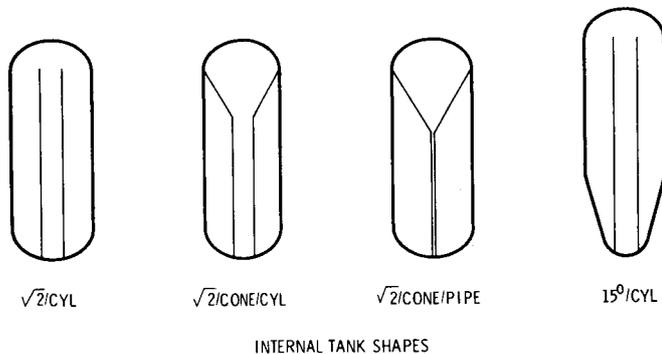


FIGURE 6. CANDIDATE LH₂ TANK CONFIGURATIONS

Tank geometrical differences were found to affect the crew dose and attendant shield weight requirements in several ways. Figure 7 exhibits one of these geometrical effects: the difference in terminal dose rate due to tank bottom shape. The data displayed correspond to a residual propellant weight of 3,500 lbs. This represents the minimum amount of liquid hydrogen reserved for final aftercooling of the engine. The shape of the tank bottom determines the level of this liquid in the tank. The narrower tank bottoms result in higher LH₂ levels and correspondingly lower direct radiation levels above the tank.

Figure 8 illustrates another important geometrical effect: differences in the rate at which the propellant is decreasing. A rapid drop rate means that less time is spent at high radiation levels. It should be noted that the configurations with the highest drop rates are the same ones which have the lowest terminal dose rates.

The configurations shown in Figure 6 represented a conscious attempt to exploit such phenomena. These so-called internal tank designs employed baffles which retained a portion of the propellant in a configuration which enhanced its time-integrated shielding worth. The idea was to simulate the behavior of the narrow-angle tank bottoms by artificially producing a fast drop rate and low radiation transmission through the inner tank near the end of engine burn. These configurations had the possible advantage of reducing overall stage length relative to the low-angle conical designs.

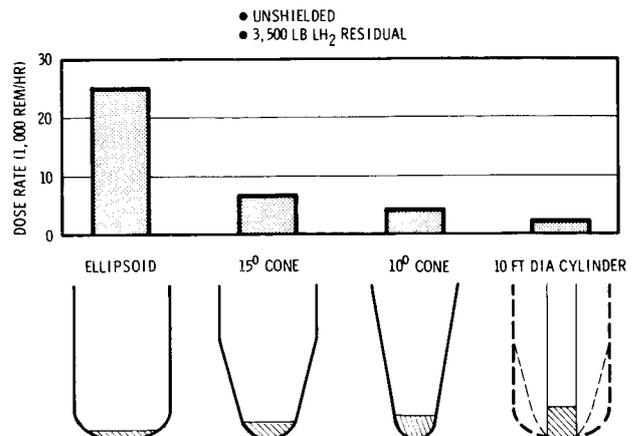


FIGURE 7. TERMINAL DOSE RATE

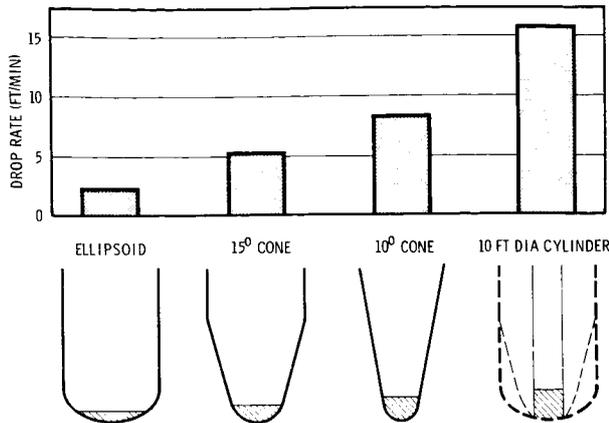


FIGURE 8. TERMINAL LH₂ DROP RATE

Comparison of Figures 9 and 10 shows the different variation with time of the dose rates for configurations with and without an internal tank. The direct dose rate represents the radiation which reaches the dose point without making any collisions in the propellant tank. The variation of this dose rate with LH₂ level is identical in both configurations. The variation of this dose rate with drain time, however, is substantially different. This difference is solely attributable to the difference in drop rates between the liquid in the central column in one case and the liquid in the un baffled tank in the other.

TIME DEPENDENT DOSE RATES - 15-DEGREE CONE

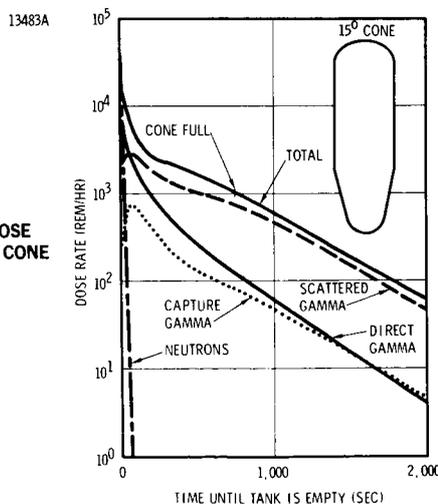


FIGURE 9. TIME DEPENDENT DOSE RATES - 15-DEGREE CONE

TIME DEPENDENT DOSE RATES - 15-DEGREE CONE WITH INTERNAL TANK

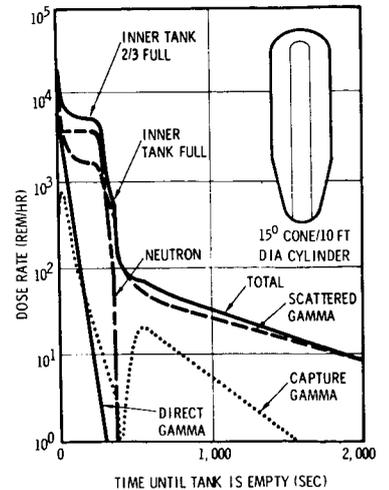


FIGURE 10. TIME DEPENDENT DOSE RATES - 15-DEGREE CONE WITH INTERNAL TANK

The advantage of the internal tank design in reducing the direct dose is partially offset, however, by scattering events. Such scattering is particularly significant during drainage of the inner tank, when the outer tank is empty (or nearly so). During this time period, radiation scattered from the walls of the empty outer tank can reach the dose point without interference from the propellant in the inner tank, except when the latter is nearly full. Hence there is a plateau in the scattered dose rate, extending over a wide range of propellant levels in the inner tank - from the nearly-full condition to the nearly-empty situation, where direct transmission through the inner tank propellant begins to dominate.

Multi-Module Class

Radiation analyses of configurations for the multi-module class RNS concentrated on the effects of module arrangement on crew dose rather than the effects of individual tank shape. The module diameters were restricted by launch considerations to 15 feet, at which value the effect of tank shape on crew radiation protection requirements was significantly diminished from that associated with the single-module class. In the survey of several candidate designs for a reference configuration for this RNS class, two key factors which affected crew radiation levels were identified:

- the 8 propellant modules should be arranged so that a minimum of two propellant modules, plus the run tank, are between the engine and crew while outboard tanks drain
- the crew dose is then due almost entirely to dose transmitted through these in-line tanks as they drain and, hence, is directly related to engine/crew separation distance.

These findings are illustrated by the dose rate data for various inboard tank arrangements shown in the following table. The indicated dose rates would be obtained throughout the period when the outboard tanks are draining, this being ~400 seconds/tank.

Number of Inboard Modules	Dose Rate Transmission Through Inboard Tanks, Rem/hr	
	Cluster	Cruciform
1 + Run Tank	16	3
2 + Run Tank	0.5	< 0.1
1	~ 37	~ 9
2	~ 1	~ 0.1

RESULTS

Single-Module Class

An overall comparison of the relative shielding merits of a representative selection of tank configurations is provided by Figure 11. These results demonstrate that conventionally designed tanks which subtend large solid angles (with respect to the engine source center) require impractically large shield weights. This result is particularly evident for the ellipsoidal tank bottom configuration and, to a lesser extent, for the 30° half-angle design.

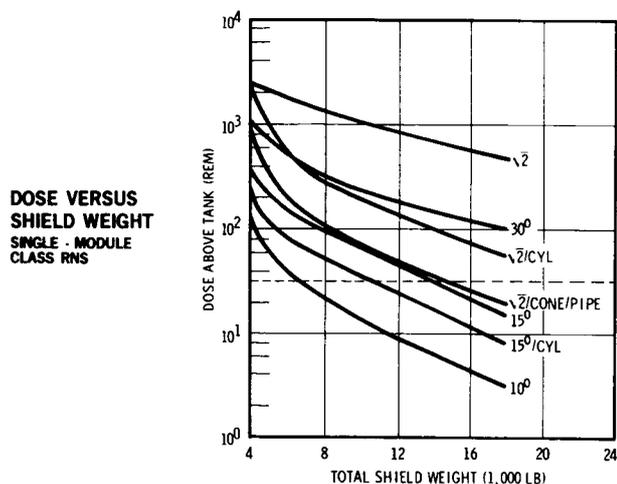


FIGURE 11. DOSE VERSUS SHIELD WEIGHT Single - Module Class RNS

It can also be seen that the use of internal tanks is an effective means of reducing shield weight requirements. Part of this reduction is offset, however, by increased structural weight and by supplementary shield weight to reduce off-axis doses. Such weight penalties are not shown in this illustration.

The simplest and most effective means of achieving the radiation criterion is through the use of narrow-bottom tanks. Reduction of the tank bottom cone angle produces the following effects, which act in concert to reduce shield requirements:

- Lower terminal dose rate due to higher level of residual LH₂
- Decreased time of exposure to high dose rates due to faster LH₂ drop rate
- Increased separation distance
- Smaller fraction of engine leakage radiation intercepted by LH₂ tank and scattered to the crew location
- Smaller cross sectional area of external disk shield

A trade study of structural and shield weight indicated a broad minimum in total weight below a cone half-angle of about 10°. A hybrid version using a small tank in combination with the main tank showed similar effects on crew radiation levels while conferring some operational benefits in the area of propellant management. This configuration, shown in Figure 12, was selected as the McDonnell Douglas reference design for the Class 1 (or Single-Module) RNS.

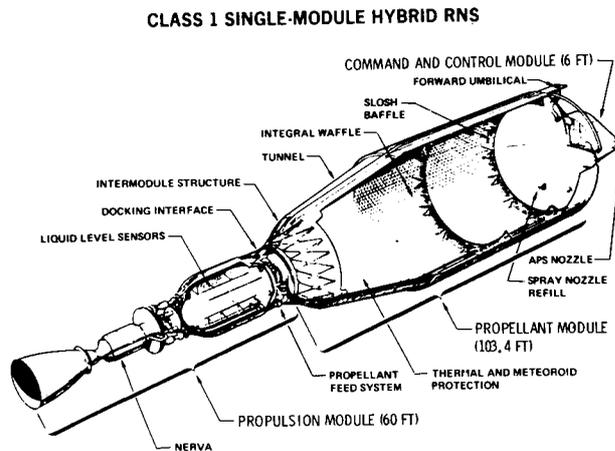


FIGURE 12. CLASS 1 SINGLE-MODULE HYBRID RNS

Figure 13 shows the variation of dose rate with time for the reference design. Figure 14 presents the minimum shield weight requirements as a function of radiation level forward of the main tank. These data reflect no credit for inherent radiation attenuation by the crew compartment structure and equipment and neglect secondary gamma radiation due to neutron capture in the disk shield (estimated at approximately 3 rem⁶).

In determining disk shield weight, a radiation criterion of 30 rem was used, based on a crew allowable dose of 10 rem per mission and a crew compartment dose attenuation factor of 3, which is representative of a modified Apollo command module.

Allowing for a 10 percent uncertainty in the calculated dose, the total shield weight needed to reduce the crew dose to 10 rem is 6,200 lb, signifying a disk shield weight of 2,900 lbs. This result is based on (1) a 3,500-lb LH₂ residual; (2) a 3-zone disk shield with radii of 25.5, 40 and 50 inches; and (3) a 160-in.-dia run tank. Table 1 compares the required shield weights for other values of propellant residual and run tank diameter.

SHIELD WEIGHT REQUIREMENTS VS DOSE

NO. OF SHIELD ZONES	SHIELD ZONE RADII
2	0-30", 30-50"
3	0-30", 30-40", 40-50"
4	0-25.5", 25.5"-30", 30-40", 40-50"

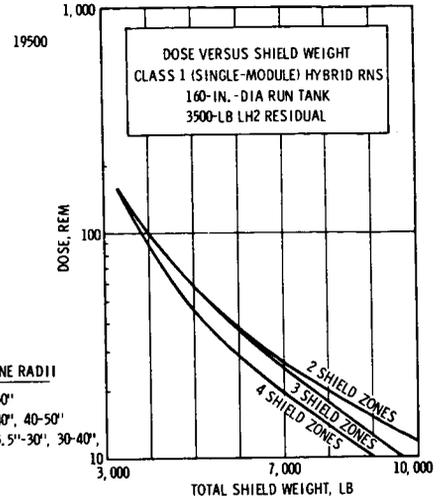


FIGURE 14. SHIELD WEIGHT REQUIREMENTS VS DOSE

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SHIELD WEIGHT REQUIREMENTS FOR SINGLE-MODULE CLASS HYBRID RNS

RUN TANK DIAMETER, IN.	112	112	112	160	160
PROPELLANT RESIDUAL, LB	0	3,500	7,500	3,500	7,500
TOTAL SHIELD WEIGHT,* LB	6,200	5,700	5,500	6,200	5,700

*SHIELD WEIGHT TO REDUCE CALCULATED DOSE 11 FT ABOVE TANK TO 27 REM, USING A 3,300-LB INTERNAL SHIELD AND AN EXTERNAL 3-ZONE DISK SHIELD WITH RADII OF 25.5, 40 AND 50 IN.

TABLE 1. SHIELD WEIGHT REQUIREMENTS FOR SINGLE-MODULE CLASS HYBRID RNS

TIME DEPENDENT DOSE RATES

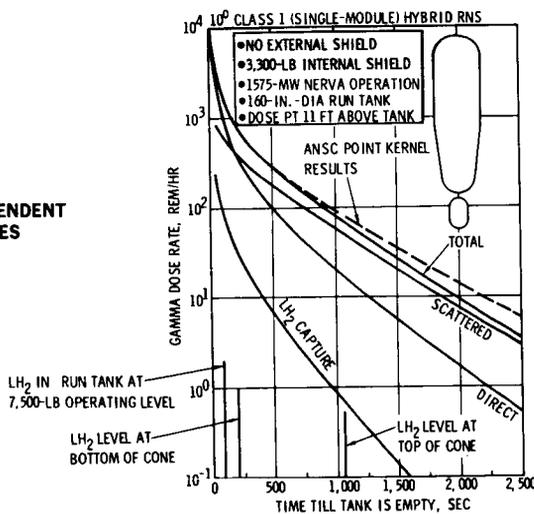


FIGURE 13. TIME DEPENDENT DOSE RATES

Multi-Module Class

Several arrangements of propellant modules, in conjunction with a propulsion module, were investigated for potential application to the multi-module class. A comparison of the unshielded doses to the multi-module class. A comparison of the unshielded doses 11 feet in advance of the forward propellant module of each of three different configurations is provided in Table 2. The difference in dose between different configurations is due to the difference in separation distances, which, as indicated, has a major effect.

DOSE PER MISSION FOR MULTIMODULE CLASS RNS CONFIGURATIONS

MODULE ARRANGEMENT	CLUSTER DESIGN	CRUCIFORM DESIGN	TANDEM DESIGN
ENGINE/CREW SEPARATION	169 FT	289 FT	529 FT
GAMMA DOSE			
DIRECT	39 REM	14 REM	4 REM
INBOARD SCATTER	33	8	2
INBOARD CAPTURE	9	1	0
OUTBOARD SCATTER	6	1	0
TOTAL GAMMA	87 REM	23 REM	6 REM

*DOSE CORRESPONDING TO 3500-LB LH₂ RESIDUAL, 3300-LB INTERNAL SHIELD AND NO DISK SHIELD

TABLE 2. DOSE PER MISSION FOR MULTIMODULE CLASS RNS CONFIGURATIONS

The results in Table 2 are based on a drainage sequence in which the outboard propellant modules are drained first. The reverse situation would expose the crew to high dose rates over the drainage period of the outboard modules. Such high dose rates would result from the transmission of radiation through the empty inboard modules. As noted previously, the time-integrated crew dose is essentially due to dose transmission through the inboard propellant modules, this being accumulated during the period of drain of the run tank and the last two full inboard modules. This result is illustrated for the cluster configuration in Figure 15 and is invariant with module arrangement for the configurations indicated.

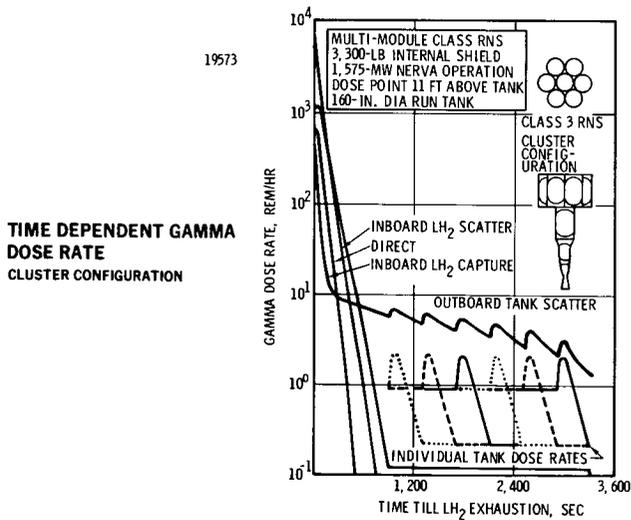


FIGURE 15. TIME DEPENDENT GAMMA DOSE RATE Cluster Configuration

The cruciform configuration was selected as the McDonnell Douglas reference design for the multi-module class RNS. This configuration, illustrated in Figure 16, meets the crew dose criterion without the need for external shielding.

Figure 17 shows the variation of the gamma dose rate with LH₂ drainage time for the reference design. The neutron dose rate is not shown as it is appreciable only when the propellant is nearly exhausted and is not a significant contributor to the overall dose.

Most of the dose is due to radiation which is transmitted without collision through the inboard tanks or which undergoes some scattering or capture interaction there. A recognizable but small (~ 1 rem) dose contribution is due to scatter from the structural materials of the empty outboard tanks. Most of this contribution is accumulated during the drain period of the last three inboard modules plus the run tank. When the fourth, most forward inboard module is full, it provides appreciable attenuation of this scattered radiation. Thus scatter from propellant and structural materials in the outboard modules is insignificant during the entire period of drain of the outboard tanks.

CLASS 3 MULTI-MODULE RNS

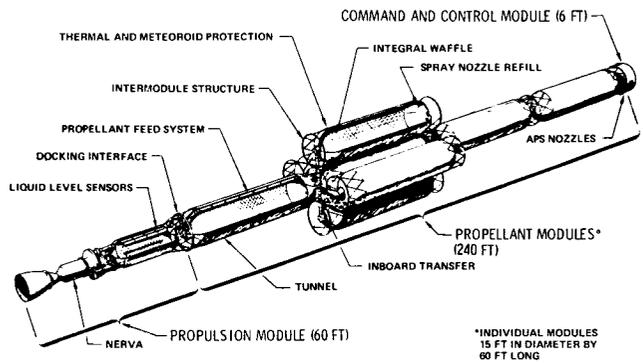


FIGURE 16. CLASS 3 MULTI-MODULE RNS

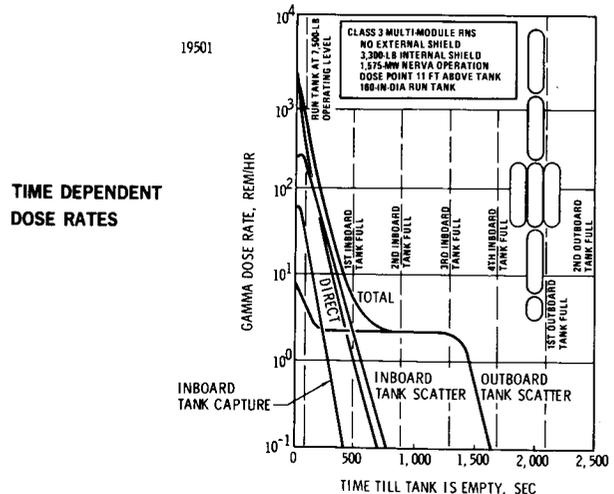


FIGURE 17. TIME DEPENDENT DOSE RATES

CONCLUSIONS

This study was initiated when it became evident that the RNS propellant provided potentially significant attenuation of radiation emitted by the nuclear engine. It was recognized that large shield weight savings could be realized by the effective use of the propellant in protecting the crew. Consequently shielding analyses were made to identify the effects of propellant tank geometry and drainage sequence on crew radiation levels and attendant shield weight requirements.

The results of this study clearly demonstrated that overall weight savings were possible through enlightened design of propellant tank geometry and drainage schedule. The conclusions summarized in Figure 18 provided a substantial impact on the selection of a reference configuration for each RNS class. The Single-Module design ultimately showed a reduction of several thousand pounds over the previous 15° baseline design while the Multi-Module design obviated the need for an external shield.

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SUMMARY OF CONCLUSIONS IN RNS SHIELDING ANALYSES

SINGLE-MODULE CLASS

- LARGE-SOLID-ANGLE CONVENTIONAL TANK BOTTOMS REQUIRE LARGE SHIELD WEIGHTS
- INTERNAL TANKS ARE PARTIALLY EFFECTIVE IN REDUCING SHIELD WEIGHT REQUIREMENTS
- SMALL-ANGLE TANK BOTTOMS OFFER SIMPLEST, MOST EFFECTIVE WAY TO CUT SHIELD REQUIREMENTS
 - LOWER TERMINAL DOSE RATE DUE TO HIGHER LEVEL OF RESIDUAL LH₂
 - DECREASED TIME OF EXPOSURE TO HIGH DOSE RATES DUE TO FASTER LH₂ DROP RATE
 - INCREASED SEPARATION DISTANCE
 - SMALLER FRACTION OF ENGINE LEAKAGE RADIATION INTERCEPTED BY LH₂ TANK AND SCATTERED TO CREW LOCATION
- HYBRID (RUN TANK) DESIGN PROVIDES COMPARABLY LOW SHIELD WEIGHT REQUIREMENTS

SMALLER CROSS-SECTIONAL AREA OF EXTERNAL DISK SHIELD

MULTIMODULE CLASS

- INHERENT FLEXIBILITY OF CONCEPT CAN BE EXPLOITED TO ELIMINATE NEED FOR EXTERNAL SHIELD
- SEPARATION DISTANCE PLAYS A SIGNIFICANT ROLE
- MINIMUM INBOARD PROPELLANT INVENTORY SUPPLIED BY TWO PROPELLANT MODULES PLUS RUN TANK
- OUTBOARD PROPELLANT MODULES SHOULD BE DRAINED FIRST

FIGURE 18. SUMMARY OF CONCLUSIONS IN RNS SHIELDING ANALYSES

REFERENCES

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