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RADIATION EXPOSURE TO CREW DURING
OPERATION OF A MANNED NUCLEAR SPACE VEHICLE

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Radiation Exposure to Crew During Operation of a Manned Nuclear Space Vehicle

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ABSTRACT

Results are presented from a study of the radiation exposure of crew members during operation of a manned nuclear space vehicle. The various contributing components of the total radiation dose are evaluated and the effects of stage operation, engine shielding, and crew shielding are explored.

A conceptual spacecraft crew shielding configuration composed of water is proposed which can perform as a space radiation protection device during most of a prolonged mission and serve as a reactor shield during the brief period when the nuclear propulsion system is operated. The water in this shield could also serve as a combination life support system component and sanitation retention system in a compartment tank design.

It appears that the integral design of the engine shield and such a crew radiation protection system can possibly result in the design of nuclear space vehicles which have no biological shielding weight increases over that required for space shielding.

Although preliminary in nature, this study should serve to establish the general magnitude of the biological radiation problems associated with manned payloads closely coupled to the final nuclear stage of multistage nuclear rockets on missions of the Mars Man Landing type, (e.g. ASFC paper entitled "Trends in EarthPlanetary Space Transportation Systems" presented at the 4th AIAA Manned Spaceflight Meeting). The final nuclear stage is considered to be the principle onboard nuclear radiation source during operation of such a multistage configuration.

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I. INTRODUCTION

This report presents the results of an investigation of the radiation exposure to crew members of a space vehicle powered by a nuclear rocket. The reference configurations and assumptions are presented along with a discussion of the methods of calculation and the analytical results. Application of the results to a reference operating profile is made to show the relative effects of power level and propellant consumption on radiation exposure.

A. SCOPE OF STUDY

This study is limited to the prediction of radiation exposure of the crew members during operation of a nuclear space vehicle at substantial power levels. No attempt is made to analyze the radiation exposure during reactor cooldown prior to separation of the spacecraft from the nuclear propulsion system; nor is any attempt made to establish optimum shielding requirements for manned nuclear space vehicles.

The crew exposure resulting from operation of an unshielded engine is reviewed in some detail to serve as a starting point for future shielding studies. The effect of engine shielding is discussed along with shielding concepts which could control radiation from the nuclear propulsion system.

B. CONSTITUENTS OF RADIATION ENVIRONMENT

Four major reactor born radiation environment constituents are evaluated: direct gamma, scattered gamma, direct neutron, and scattered neutron radiation intensities. In addition, an assumed magnitude of space radiation is included based on a brief survey of the literature on this subject.

The relative importance of each of these radiation types is reviewed for appropriate variations of the reference configuration. The establishment of the relative importance of each of these radiation contributions was a primary objective in this study.

C. INFLUENCE OF OPERATING PARAMETERS

Sensitivity of crew dose to operating profile is an area which could affect planning of a mission profile to obtain the minimum exposure of the crew consistent with mission objectives and requirements. The results obtained in this analysis have been applied to a reference operating cycle to provide a preliminary indication of these effects.

II. REFERENCE CONFIGURATIONS AND ASSUMPTIONS

In order to arrive at meaningful radiation exposure predictions, a representative digital computer model was fabricated based on present knowledge of mission requirements, preliminary designs of the Large Diameter NERVA (LDN) engine and current literature on spacecraft shielding. The reference configurations and assumptions used in the study are described in this section.

A. VEHICLE CONFIGURATION

A sketch of the idealized vehicle configuration is presented in Figure 1. The propellant tank in this model is 33 feet in diameter and 73 feet in overall length. It includes a 45° conical bottom section which was represented as a cone cutoff at the bottom with a resulting height of 150 inches from the tank bottom to the bottom of the cylindrical segment. The tank top was represented as an elliptical section with a ratio of 2:1. The total amount of LH_2 in the tank prior to commencing nuclear operation was considered to be 235,000 lbs plus 10% ullage. The overall separation distance from the center of the reactor to the base of the shielded crew compartment is 91 feet.

IDEALIZED NUCLEAR SPACE VEHICLE

FOR DOSE CALCULATIONS

FIG. 1

B. LARGE DIAMETER NERVA ENGINE (LDN)

The 5,000 Mw LDN reactor described in Reference 1 was used as the reference nuclear subsystem for the 250,000 lb. thrust engine employed in this study. The unshielded engine condition was mocked up by voiding the radiation shields reported therein. Radiation source terms were obtained from this reference as well. It should be noted that an 8.5-inch aluminum support plate is included above the active core in this configuration. The reactor center is located 15 feet below the tank bottom.

A cylindrical region was included above the reactor to simulate the NERVA turbopump and some engine components (see Figure 1). This cylinder has a radius of 39 inches and a 36-inch height and weighs 2600 lbs. Steel attenuation coefficients are assumed to be adequate for this preliminary approximation of the shadow shielding effect of the engine's propellant feed system.

C. REFERENCE OPERATING PROFILE

The following reference operating profile was used in interpreting the significance of the analytical results for a simulated mission application.

<u>Run Portion</u>	<u>Reactor Power Level (Mw)</u>	<u>Operating Time (Sec)</u>	<u>LH₂ Flow Rate (Lbs/sec)</u>	<u>LH₂ Consumption (Lbs.)</u>
Full Power	5,000	677	300	203,000
33% Power	1,700	175	100	17,500
15% Power	750	60	100	6,000
Shutdown	--	--	--	--
After Shutdown	Variable	350	10	3,500

It will be noted that a total of 230,000 lbs. of LH_2 is consumed in this run including a 3,500 lb. reservoir at reactor shutdown, which is used for after shutdown cooling prior to and during separation of the nuclear stage from the spacecraft.

Each of the changes in power level were assumed to be step changes with no time lag. Startup transients were not reviewed because they are unimportant in respect to crew dose effects.

Figure 2 shows how the LH_2 level in the conical section of the propellant tank varies with LH_2 weight. Figure 3 shows how the LH_2 level varies as a function of operating time for the reference operating profile. The flow rate of LH_2 and the reactor power levels are also depicted in this figure. The transition from the cylindrical portion to the conical portion of the tank can be seen. Radiation exposure was calculated for the operating cycle only and not for the fractional power which exists after reactor shutdown.

D. SPACECRAFT CREW SHIELDING

A representative spacecraft shield was selected after a review of some of the available literature on space radiation protection requirements for a manned mission of the Mars Landing category^{2,3,4,5,6}. This shield weighs 20,000 lbs. and is composed of a uniform thickness of 8-inches of water over a cylindrical crew compartment 12-feet high and 10-feet in diameter. Such a water shielded compartment is reported in Reference 2 to be adequate for an eight man crew. The water could also be a portion of the life support and sanitation tank systems in the spacecraft.

Future studies of manned Mars missions with nuclear propulsion will have to include a thorough review of the space radiation shielding problem and the tradeoffs between these shielding requirements and those of the onboard

FIG. 2

FIG. 3

nuclear propulsion systems. The space radiation shield chosen for this study is based only on solar radiation protection for a Mars mission commencing in the 1982 time period. Evaluation of the dependence of the spacecraft shield configuration on the solar activity as a function of mission time period is beyond the scope of this study. It should be noted that none of the literature reviewed, in selecting the reference spacecraft shield, discussed galactic radiation contributions to the dose to the crew. The problem presented by the existence of such radiation hazards, on manned planetary missions, is a complex and little understood aspect of the space radiation shielding field. Some of the aspects of this problem are discussed in References 7 and 8.

The representative crew shield described above is assumed to result in approximately a 90 rem (roentgen equivalent man) exposure of the crew². This represents a first approximation to the dose due to anticipated solar proton activity. No attempt was made to evaluate life support system or other spacecraft component shielding effectiveness. An exact mission profile was not considered and no attempt made to evaluate the above dose estimate. It is important to note, however, that several independent investigations at various facilities^{2,3,4,5} have resulted in dose quotations of approximately this magnitude with the specified shielding. In all cases, the solar radiation was considered to be isotropically impinging on the crew compartment.

E. RADIATION EXPOSURE GUIDELINES

Exposure to ionizing radiation, regardless of source, produces deleterious effects on biological organisms. The incidence of radiation induced injury in man is a probabilistic function of dose. The Federal Radiation Council⁸ assumes that radiation injury has no threshold so that small doses entail small risks, etc.

The injurious effects of radiation can be grouped broadly into somatic and genetic categories. The genetic effects are the least understood but are appropriately not of great significance in manned spacecraft operations due to the infinitesimally small fraction of the population being exposed. The individual risks may be large from a genetic standpoint, but must be accepted if spacecraft shielding is to be kept to a reasonable minimum consistent with the other risks in manned space explorations. Somatic effects must be limited so that no lethal or incapacitating doses are received. Short of such occurrences, it is important that the spacecraft crew members safety be assured so as to not interfere with the mission. Finally, every assurance should be made that latent injuries should not occur subsequent to completion of the missions involved. The astronaut's career dose must be minimized and medical X-ray additions to this dose should not be ignored.

To this end, much work has been done recently^{8,10,11} in connection with space radiation protection. The addition of onboard nuclear radiation contributions becomes significant for manned missions involving nuclear propulsion systems. For the purposes of this study, a relatively arbitrary selection of exposure criteria has been made. This selection allows a much greater exposure from space radiation than from the nuclear propulsion system for the following reasons:

1. The nuclear reactor radiation exposure is acute (i.e. very limited time during exposure), whereas the solar radiation contribution may be received in increments over the entire mission (approximately 1-1/2 years).

2. The space radiation exposure is much more probabilistic in occurrence, whereas the reactor radiation is a certainty affected only by the ability to predict the intensity analytically.

3. Protective shielding is much lighter per unit reduction in dose when applied to the smaller diameter nuclear engine than over the entirety of the shielded crew compartment (approximately 500 sq. ft. of shielded surface area).

The exposure criteria chosen in this context is as follows:

90 rem	= solar radiation
<u>10 rem</u>	<u>= engine radiation</u>
100 rem	= total

A "rem" (roentgen equivalent man) is the unit used to express human biological doses as a result of exposure to ionizing radiation. The dose in rems is equal to the absorbed dose in rads times a factor related to the effectiveness of the type of deleterious radiation being absorbed. This factor is the relative biological effectiveness, (RBE), of damage production per unit of absorbed energy dose. An RBE of 1.0 was used for solar protons¹² and gamma rays, and an RBE of approximately 10 was used for neutrons by employing the tissue dose conversion curves of the National Bureau of Standards Handbook 63¹³.

The following data on radiation injury is intended to serve as a guide in understanding the significance of the above exposure levels, as well as the calculated values to be introduced later in this report.

TABLE I

Probable Effects of Acute Radiation Exposure

<u>Acute Whole Body Radiation Exposure (rem)</u>	<u>Probable Effect</u>	<u>Reference</u>
50	Clinically detectible blood changes	Radiological Health Handbook ¹⁴
80 - 120	Nausea and vomiting for about 1 day in 5 to 10 percent exposed. Fatigue but no serious disability.	"
130 - 200	Nausea and vomiting for about 1 day followed by other symptoms of radiation sickness in 25 to 50 percent exposed. No deaths anticipated.	"
200 - 300	Possible incapacitation (inability to perform mission required functions.)	Aerospace Medicine ⁸
300 - 500	LD ₅₀ (lethal dose to 50% exposed)	United Nations Scientific Commission on Effects of Atomic Radiation ¹⁵
400 - 600	"	National Academy of Sciences - National Research Council Committee on Biologi- cal Effects of Atomic Radiation ¹⁶
450	"	National Committee on Radiation Protection and Measurement ¹⁷

The above listed probable effects are associated with an acute (i.e. single dose over short period) whole body type of exposure. Protracted exposure such as might be the case for space radiation contributions is known to be much less severe in effects produced for the same integrated exposure level. This area of the radiation exposure problem is concerned principally with identification of recoverable versus non-recoverable injuries. It will be noted that three of the references quoted in Table I give a range from 300 rem to 600 rem for the LD₅₀ value.

The 100 rem value chosen for this study can be seen to be a relatively high figure. However, it must be remembered that the larger fraction of this number (the 90 rem from solar radiation) would most likely be received from several solar storms over a period of months.

Finally, very little is known about the combined effects of prolonged weightlessness and the other rigors of spaceflight in a radiation environment. Future studies will result in the establishment of permissible radiation exposure to spacecraft crew members by the responsible government agencies. For the present, however, the values chosen for this study appear appropriate. It should be noted that any additional shielding imposed by reductions in allowable dose from space radiation will also attenuate radiation from the reactor.

III. METHODS OF CALCULATION

The methods of calculation employed in this study are straightforward in most instances. However, there are some calculations which require some explanation since they involve combinations of computer codes and hand calculational techniques.

The sources of radiation for the reactor core are based on the data reported in Reference 1 for the Large Diameter NERVA engine. Secondary gamma sources external to the reactor core are based on a scaleup of the data used in the design of the 1100 Mw NERVA engine¹⁸ with appropriate approximations to reflect material and geometry differences between the small diameter and large diameter engines. Since most of the work reported herein is based on an unshielded engine condition, validity of the approximations involved in sources in non-core regions are not of major concern.

A. GAMMA RADIATION ANALYSIS

The gamma radiation analyses are broken down into the following three categories: direct, scattered, and capture contributions. The direct contribution includes all sources within the engine. The scattering values in this case represent tank wall scattering only. Scattering within the LH_2 is included as part of the buildup factor used in connection with the direct calculations.

The QAD computer code¹⁹ is used to calculate the direct component. A twelve group energy breakdown is employed in these calculations. Attenuation coefficients and buildup factors are based on GE/ANPD data^{20,21}. These calculations are point kernel integrations over the source arrays. Due to the very large separation distances involved, the engine could be represented as a point source except for the self-shielding effects of the propellant feed system and shape factors associated with engine shield geometries (e.g. elliptical vs cylindrical shields). The significance of this refinement will be greater in subsequent studies than in the preliminary results reported here.

The dose to the payload is determined by calculations for a number of different conditions. These include evaluations of dose as a function of LH_2 level in the tank. Reference is again made to the basic model described in Figure 1 and the LH_2 level data of Figures 2 and 3. Direct gamma radiation penetration through the reference crew shield is also evaluated by a twelve group QAD calculation. The direct fast neutron and gamma radiation intensity impinging on the tank is shown in Figure 4 for the condition where 3,500 lbs. of LH_2 (64-inch liquid level) is at the bottom of the tank. These values represent the condition for an unshielded engine. In the analysis of a candidate engine shield configuration, the secondary gamma production in the shield was simultaneously included in the direct gamma radiation calculations.

Tank wall gamma scattering was analyzed with the aid of the GGG digital computer program²². This was accomplished by breaking up the tank wall into seven annular scattering surfaces and using the single scattering Klein-Nishina calculations performed by GGG with a point source representation of the engine. Twelve source energy groups and sixteen scattered energy groups were used, ranging from 0.1 to 10 Mev. Figure 5 depicts the geometry used in the scattering analysis. The GGG calculations were normalized to QAD predictions of incident gamma radiation intensity at each of the scattering surfaces. In this manner, only the scattered leg of the GGG calculations was actually used in quoting results. Further, this series of calculations was repeated for several LH_2 levels in the propellant tank so that the scattered gamma contribution could be evaluated as a function of LH_2 level. The relatively thin tank wall (0.36 cm) lends itself to a single scattering calculation with a fair degree of certainty.

GAMMA DOSE-RATE AND FAST NEUTRON FLUX AT THE PROPELLANT TANK.

FIG. 4

GEOMETRY FOR COMPUTATION OF SCATTERED RADIATION DOSE

FIG. 5

The relative attenuation of direct and tank wall scattered gamma radiation in the LH_2 of the propellant tank is shown in Figure 6. The direct attenuation is a straight exponential function calculated with QAD using point isotropic infinite medium water buildup factors.²¹ The scattered data reflect the geometry associated with the 45° tank core bottom depicted in Figure 1 and the relationship between liquid boil and weight of LH_2 given in Figures 2 and 3. The first several thousand pounds of LH_2 (several feet) in the tank bottom have very little effect on the tank wall scattered components. For higher liquid levels in the conical bottom section the scattered component starts to assume the same attenuation as the direct component. For very large LH_2 thicknesses, the scattered component is doubly attenuated - once on the incident leg and once on the scattered leg. However, scattered gamma intensity is not sufficiently high for this effect to be noticeable in terms of total crew dose rate.

An important aspect of the scattered gamma radiation analyses is the fact that the average scattered gamma ray energy is 0.72 Mev, as compared to a direct (no shield, no LH_2) average energy of 2.8 Mev. This is an unusually high average energy for scattered gamma radiation. It results from the large separation distances involved and the angular dependence of scattered energy as a function of such small scattering angles. The significance of this relatively hard (i.e. high energy) scattered gamma component is that the crew shield is not highly attenuating for these type radiations.

Secondary gamma radiation is produced as a result of 2.2 Mev (n, γ) reactions in the LH_2 in the tank. These gamma rays are attenuated by successively higher levels of LH_2 to the same degree that the direct reactor radiation is attenuated; since their 2.2 Mev is close to the 2.8 Mev effective reactor gamma energy. Therefore the direct gamma attenuation curve of Figure 6 is applicable in this case as well. The direct gamma curve is the result of a QAD calculation.

Hand calculation techniques were used to show that the hydrogen capture gamma source strength varies from zero, with no LH_2 , to a considerable amount as the conical bottom is filled. The contribution of these sources, as a function of LH_2 level, is strongly dependent on the sources created near the tank wall rather than along the axis of the tank. This is so because a large volume of hydrogen is exposed to reactor leakage neutrons in these regions (see Figure 4). The gamma ray dose to the crew compartment from hydrogen neutron captures in the tank is large for an unshielded reactor case, but is relatively small for Lithium Hydride type engine shield configurations since the reactor neutron leakage is greatly reduced. A correlation was made between these data and the analysis of a LH_2 radiation heating experiment performed with the ASTR facility at General Dynamics/Fort Worth.²³

Hand calculations showed a negligible contribution to the payload radiation levels resulting from tank wall (n, γ) capture gamma radiation production in the tank wall.

Scheduler limitations for this study did not allow for a separate treatment of liquid hydrogen scattered gamma reactions. Employment of infinite medium water buildup factors and point isotropic sources in the engine model partially offset this limitation.

GAMMA RAY DOSE RATE VS. FLUID LEVEL IN PROPELLANT TANK

FIG. 6

B. NEUTRON RADIATION ANALYSES

The neutron radiation analyses also treat the direct and tank wall scattering components separately. The analysis of the neutron penetration through LH_2 constituted a fairly large fraction of the total study. This problem used the QAD neutron moments method. In addition to moments data for water, beryllium and carbon, effective removal cross sections were used.²⁴ Further, calculation of the deep penetration in LH_2 using Monte Carlo techniques²⁵ has been initiated. A Monte Carlo analysis of an LH_2 attenuation experiment²³ is given in Appendix A. These calculations are proceeding and will be reported separately.

Figure 7 shows how the available QAD moments data compare with a removal theory prediction²⁴ of the attenuating effect of LH_2 on the unshielded large diameter engine fast neutron leakage flux.

The direct neutron radiation intensity impinging on the propellant tank is shown in Figure 4 for the condition where 3,500 lbs. (64-inch liquid level) of LH_2 exists in the tank for an unshielded engine. A hand calculational technique was used to evaluate the fast neutron scattering off the propellant tank wall using a single scattering approximation.

The geometrical model used for the neutron scattering calculation is shown in Figure 5. The angle of scatter was specified by extending rays from the center of the reactor to the point of scatter and from there to the center of the payload.

FIG. 7

The single scattering equation for flux at the payload position is given by

$$\phi = \int dE \int \phi^1(\vec{r}_1, E) \sum_{r_2} \frac{(E) P(E, \vec{r}_1 \rightarrow \vec{r}_2)}{r_2^2} dV$$

where:

E = neutron source energy

$\vec{r}_1$ = position vector of point of scatter relative to the center of the reactor

$\vec{r}_2$ = vector distances to payload position relative to point of scatter

$\phi^1(\vec{r}_1, E)dE$ = neutron flux at r_1 and E in dE

$\sum(E)$ = macroscopic scattering cross section

$P(E, \vec{r}_1 \rightarrow \vec{r}_2)$ = probability of scattering per unit solid angle which deflects a neutron from an initial direction along r_1 to a final one along r_2

dV = differential volume of scattering medium

Because of azimuthal symmetry the spatial integration of the above equation reduces to a one dimensional integration. This integration was performed numerically with the limits of integration specified by the angles α_1 , and α_2 shown in Figure 5. That is to say, it is assumed that scattering becomes important only when the level of the propellant is below the cylindrical portion of the propellant tank, as shown in Figure 4. Scattered neutrons then arrive at the payload without attenuation by liquid hydrogen. The validity of this assumption can be verified by observing the drastic decrease of $\phi^1(\vec{r}_1, E)$ as the distance r_1 is varied across the intersection of the propellant level and the bottom of the tank.

The flux of neutrons with energies greater than 0.1 Mev incident on the tank were obtained by the QAD point kernel integration program. This flux was then weighted by the shape of the leakage spectrum as obtained by the S_n transport code to yield the values of $\phi^1(\vec{r}_1, E)$ used in the integration described above. The integration over energy extended from 0.1 to 10 Mev as a sum of contributions from 0.1 to 0.4 Mev, 0.4 - 0.9 Mev, 0.9 - 1.4, 1.4 to 3 Mev, and 3 to 10 Mev.

The scattering probability P is given by

$$P(E, \vec{r}_1 \rightarrow \vec{r}_2) = \frac{\frac{d\sigma}{d\Omega}}{\int_{4\pi} \frac{d\sigma}{d\Omega} d\Omega}$$

where $\frac{d\sigma}{d\Omega}$ is the differential elastic scattering cross section for aluminum. Representative values for each of the five energy groups were taken from Reference 26. The energy group averaged values²⁷ of $\Sigma(E)$ were substituted in the equation for ϕ given above. These fluxes were then converted to scattered neutron dose rates by applying the energy dependent flux to dose conversion factors¹³ to the group fluxes and summing for all energies from 0.1 to 10 Mev.

The resulting attenuating effects of LH_2 on the neutron dose rate at the crew compartment were evaluated. Figure 8 shows how the direct and scattered neutron dose rates vary as a function of LH_2 level in the propellant tank.

FAST NEUTRON DOSE RATE TO CREW vs FLUID LEVEL IN TANK

FIG. 8

The large amount of attenuation of the direct neutron contribution is of great significance in practical applications of these data. That is to say, the direct neutron dose to the crew would be quite high except for the fact that the LH_2 in the tank is extremely effective in attenuating neutron radiation. It can also be seen from Figure 8, that the fast neutron contribution resulting from scattering off the tank wall is unaffected by small amounts of hydrogen in the tank because of the shape of the tank bottom. The tank wall scattered neutron intensity is much more sensitive to LH_2 level than the scattered gamma data shown in Figure 6 because LH_2 is more effective in attenuating neutrons than gamma rays.

IV. ANALYSES OF RESULTING EXPOSURE AT PAYLOAD

Based on the calculations and intermediate results described above, the exposure levels at the payload during full power operation at 5,000 Mw were evaluated. The results of these analyses are reported below.

A. UNSHIELDED RADIATION ENVIRONMENT (NO LH_2 IN TANK)

The simplest condition studied was the case of an unshielded engine and an empty propellant tank. The full power radiation environment at the crew compartment (with no crew shield) is given below. It is fully appreciated that the reactor would not be operated at full power with no LH_2 in the tank. However, presentation of the results in this manner allows for direct interpretation for the small fraction of full power that would exist when the tank is nearly completely empty, most probably occurring after the spacecraft and nuclear stage have been separated. In addition, these data serve as end points for evaluations of radiation exposure vs LH_2 level in the tank. The contribution to total dose

rates of neutrons and gamma rays of each energy is shown in Table 2. The hydrogen capture gamma spectrum varies from a fraction of one Mev to the secondary source energy of 1.0 Mev due to buildup as a result of scattering interactions for various LH_2 levels.

TABLE 2

Spectrum of Unshielded Radiation Dose-Rate at Crew Compartment
(No Engine Shield, No Crew Shield, No LH_2)

<u>Direct Gamma</u>		<u>Scattered Gamma</u>		<u>Direct Neutron</u>		<u>Scattered Neutron</u>	
<u>E(Mev)</u>	<u>$\dot{D}$(rem/sec)</u>	<u>E(Mev)</u>	<u>$\dot{D}$(rem/sec)</u>	<u>E(Mev)</u>	<u>$\dot{D}$(rem/sec)</u>	<u>E(Mev)</u>	<u>$\dot{D}$(rem/sec)</u>
		.2	.3				
.3	9	.3	3.9	.33	15000	.25	130
.7	75	.7	3.0	.67	6400	.65	210
1.0	77	1.0	5.3	1.0	8100	1.0	85
1.5	82	1.5	.5				
2.0	84			2.0	5400	2.0	100
2.5	80						
2.8	60			3.0	1100		
3.5	130						
4.5	68			4.0	500		
5.5	33			5.0	240	5.0	25
6.5	26			6.0	180		
7.5	9			8.0	60		
8.5	17			10.0	20		

The data in Table 2 are summarized in Table 3. The bulk of the radiation level for this case is obviously from direct neutrons. As will be seen, this is not the case for realistic run conditions as exemplified by the reference operating profile reviewed in Section V.

TABLE 3

Full Power, Unshielded, Radiation Dose-Rate at Crew Compartment
(No Engine Shield, No Crew Shield, No LH₂)

<u>Contributing Radiation</u>	<u>Dose Rate (rem/sec)</u>
Direct Neutron	37,000
Tank Wall Scattered Neutron	550
Direct Gamma	750
Wall Scattered Gamma	13
Wall Capture Gamma	Negligible
LH ₂ Capture Gamma	0
<hr/>	
Total Dose Rate	$\sim 4 \times 10^4 \left(\frac{\text{rem}}{\text{sec}} \right)$

B. UNSHIELDED RADIATION ENVIRONMENT VS LH₂ LEVEL IN TANK

The above radiation levels, for an empty tank condition, and the LH₂ attenuation curves presented previously have been combined with the LH₂ capture gamma data to arrive at the variation in full power dose rates as a function of liquid level in the tank. These data are shown in Figure 9.

It can be seen from this figure, that the dose rate in an unshielded crew compartment, from an unshielded engine, is not influenced appreciably by the direct neutron contribution for substantial power operation with more than three feet of LH₂ in the tank (i.e. approx. 1500 lbs.). The total dose rate is

FIG. 9

composed principally of direct gamma and scattered fast neutron contributions in the range from three to eight feet of LH_2 in the tank (i.e. 1500 to 7600 lbs.). For LH_2 levels greater than eight feet, the bulk of the total dose rate comes from direct gamma and LH_2 capture gamma radiation with a small diminishing contribution from tank wall gamma scattering.

Interpretation of the significance of the data in Figure 9 as they affect total crew dose is dependent on the time duration at substantial reactor power levels and the rate at which the propellant is consumed. These effects are evaluated for a reference operating profile in a later section of this report.

C. ATTENUATION PROVIDED BY SPACECRAFT SHIELD

As can be seen in Figure 10, an eight-inch (20.3 cm) thick water crew shield has approximately a decade shielding effect on the direct and scattered neutrons, but only an effect of roughly a factor of two on direct and scattered gamma radiation respectively. The data in this figure are useful for assessing the effectiveness of other size crew shields. Polyethylene is considered, by some investigators, as an alternate to water in this connection. The shielding properties of the two are virtually identical. Other crew shield materials, such as aluminum, graphite, and beryllium, all have distinctive radiation attenuating effects on the reactor born radiation contributions. Only the water case is included here for a representative evaluation. Water is particularly attractive because of the life support requirements and its versatility as a shielding material. The full power dose rates to the crew with an 8-inch water crew shield are summarized in Table 4 for the case of an unshielded engine and an empty propellant tank.

ATTENUATION OF RADIATION BY SPACECRAFT WATER SHIELD

FIG. 10

TABLE 4

Radiation Environment with 20,000 Lb. Crew
Compartment Shield from Unshielded Engine - Empty Tank

<u>Contributing Radiation</u>	<u>Full Power Dose Rate (rem/sec)</u>
Direct Gamma	340
Wall Scattered Gamma	5
Direct Neutron	3,700
Wall Scattered Neutron	55
<hr/>	
Total $\sim 4 \times 10^3$	

D. EFFECTS OF ENGINE SHIELDING

Shielding for a NERVA engine must be designed with due consideration for the radiation limitations of the engine and an optimum vehicle performance with propellant heating as well as payload considerations. At this stage in the nuclear rocket development program, however, preliminary estimates of these requirements do not exist. There is therefore a corresponding uncertainty in the shield configuration which will ultimately be incorporated in the engine irrespective of any biological shielding considerations.

A shield has been proposed¹ based on some preliminary analyses which could be representative for the engine and vehicle requirements. It is incorporated in this study because it is well defined and because some of its effects are known. It consists of an elliptical portion weighing 3,000 lbs. and an annular portion weighing 1,200 lbs. Both parts contain lithium hydride and stainless steel and attenuate the direct and scattered gamma radiation giving a

net effect on dose rates at the crew compartment of factors of 6.7 and 4.4 respectively. In addition, the neutron leakage from the engine is greatly reduced due to the presence of lithium hydride. This has the effect of drastically reducing the contribution from LH_2 capture gamma radiation from the liquid in the tank. The reduction in direct and scattered fast neutron contributions is approximately a factor of 59 and 24 respectively. The resultant empty tank dose rates to the crew, with the 8-inch thick crew shield and this engine shield, are given in Table 5.

TABLE 5

Radiation Environment with 20,000 Lb. Crew Compartment Shield
and 4,200 Lb. Engine Shield - Empty Tank

<u>Contributing Radiation</u>	<u>Full Power Dose Rate (rem/sec)</u>
Direct Gamma	51
Wall Scattered Gamma	1
Direct Neutron	63
Wall Scattered Neutron	2
Total	<hr/> 117

The intensity of the direct and scattered gamma dose rates to the crew is seen to be not affected as greatly by this engine shield as the neutron contributions. This is because of the relatively large amount of lithium hydride in comparison with steel. For actual operating conditions, the LH_2 in the tank further reduces the neutron contributions substantially, resulting in the bulk of the crew dose being made up primarily of direct gamma radiation, and a considerable contribution from LH_2 capture and scattered gamma radiation.

V. APPLICATION OF RESULTS FOR A REFERENCE OPERATING PROFILE

The above data have been presented in such a manner as to allow application to any number of run profiles. All data are presented for the full power condition with no liquid hydrogen in the tank coupled with the appropriate curves to assess the effect of various tank liquid levels which would exist for a specific run. One such run has been analyzed and the resultant radiation exposure of the crew is reported herein.

A. EXPOSURE OF CREW FOR AN UNSHIELDED SPACECRAFT AND UNSHIELDED ENGINE

Figure 11 shows the dose rates for the last five minutes of the reference run profile which consists of the following power holds:

<u>Power Level</u> (Mev)	<u>Duration</u> (sec)	<u>LH₂ Flow Rate</u> (lbs/sec)
5,000	677	300
1,700	175	100
750	60	100
Reactor Scram	--	3,500 lbs. residual LH ₂ for cooldown

Integration under the curves of Figure 11 results in the following integrated doses for the run in question.

TABLE 6

Radiation Dose to Crew for the Reference Operating Profile

(Unshielded Engine and Unshielded Crew Compartment)

<u>Contributing Radiation</u>	<u>Integrated Dose (rem)</u>
Direct Gamma	4,000
Wall Scattered Gamma	500
LH ₂ Capture Gamma	8,100
Direct Neutrons	8
Wall Scattered Neutrons	3,400
Total	16,000 rem

FIG. 11

Although the direct neutron dose rate is very large for the empty tank cases reported earlier, it can be seen from Figure 11 and Table 6 to be a relatively minor contribution for an actual run where 3,500 lbs. of LH_2 remain in the tank for after shutdown cooling. This contribution is obviously very sensitive to after cooldown requirements. The 8,100 rem from LH_2 capture gamma production is a very misleading value due to the fact that no neutron shielding is included in the engine in this case. This value is very sensitive to relatively small weight increases if they are the result of adding a material like lithium hydride to the engine configuration.

The 16,000 rem total of Table 6 is obviously a lethal dose to the crew as described earlier in Section II. However, it is an unrealistic case involving no engine shield and no crew shield. The total dose can be seen to be made up mainly of direct and LH_2 capture gamma and scattered fast neutron contributions.

B. EXPOSURE OF CREW WITH A SHIELDED SPACECRAFT AND AN UNSHIELDED ENGINE

As reported previously, the representative water crew shield (8" thick and 20,000 lbs.) greatly attenuates the neutron radiation incident on the crew compartment but is not too effective in reducing the contributions from direct and scattered gamma radiation. Table 7 gives the integrated dose to the crew for the reference run profile with an unshielded engine but employing the representative crew shield.

TABLE 7

Radiation Dose to Crew for the Reference Operating Profile
with a 8" Water Crew Shield (Unshielded Engine)

<u>Contributing Radiation</u>	<u>Integrated Dose (Rem)</u>
Direct Gamma	1,800
LH ₂ Capture Gamma	3,600
Wall Scattered Gamma	200
Direct Neutron	1
Wall Scattered Neutron	340
	<hr/>
Total	5,900 rem

The principal radiation dose contribution is clearly from direct and LH₂ capture gamma radiation for the unshielded engine/shielded crew compartment case. However, the dose is seen to be definitely lethal to the crew with no engine shield. The 5,900 rem value is approximately twenty times the lower limit quotation of 300 rem for an LD₅₀ (lethal dose to 50% exposed) as reported by the United Nations Scientific Committee on the Effects of Atomic Radiation (see Table 1). This value (5,900 rem) can also be compared to the earlier stated radiation exposure guideline of 100 rem of which 90 rem is allocated to space radiation and 10 rem to reactor born radiation contributions (see Section II). Thus the dose from an 8-inch water shielded spacecraft with an unshielded engine can be seen to be roughly 600 times the desired value of 10 rem from the reactor born radiation.

C. EXPOSURE OF CREW WITH A SHIELDED SPACECRAFT AND A SHIELDED ENGINE

When the reference crew shield is used in combination with the engine shield chosen for this study (see Section IV), the resulting crew exposure levels are reduced from those given in Table 7 to the values reported below in Table 8.

TABLE 8

Radiation Dose to Crew with 8" Water 20,000 Lb. Crew
Shield and 4,200 Lbs. Engine Shield for Reference Run Profile

<u>Contributing Radiation</u>	<u>Integrated Dose (Rem)</u>
Direct Gamma	270
LH ₂ Capture Gamma	70
Wall Scattered Gamma	57
Direct Neutron	Negligible
Wall Scattered Neutron	14
	<hr/>
Total	410 rem

It is obvious that the combined effects of an 8-inch thick water crew shield and a 4,200 lb. lithium hydride/stainless steel engine shield are not sufficient to reduce the integrated crew exposure to the desired value of 10 rem. An additional reduction of a factor of roughly 40 is required.

D. EFFECT OF ADDITIONAL SHIELDING OR VARIABLE SPACECRAFT SHIELD UTILIZATION

The principal radiation contributions shown in Table 8 are due to direct and LH₂ capture and tank scattered gamma radiations. Therefore additional gamma ray shielding is required. Approximately six inches of steel or its equivalent would be required in addition to the 4,200 lb. engine shield to achieve a 10 rem exposure for the run profile in question. If placed over the diameter of the pressure vessel such an additional steel thickness would weigh approximately 8,000 lbs. The resulting 12,000 lbs is only a rough approximation which would require a considerably more exhaustive shielding study before a candidate shield could be proposed.

It is possible, however, that a water crew shield could be designed such that virtually all of the water could be located at the base of the crew compartment during the relatively short time period when the reactor is operating in the power range. This configuration is shown in Figure 12. Such a configuration would allow full utilization of the available 20,000 lbs. of water as a shield for radiation from the reactor. This would result in an approximate exposure to the crew of 10 rem from reactor operation if used with the reference engine shield of 4,200 lbs. Such a concept could allow design of a nuclear space vehicle involving no specifically identifiable biological radiation shielding for the onboard nuclear reactor.

During all other portions of the mission, with the exception of the reactor power run discussed above, the crew shield water would be located around the entire compartment envelope. The water would only be used in the aft location during high power operation of the 250,000 lb. thrust nuclear engine.

Provision could be made, in the design of the crew compartment, to allow for a variable thickness aft bulkhead. The normal water thickness would be 8-inches but this thickness would be increased up to 50 inches during operation of the nuclear engine. An aft sanitation tank shield looks promising.

This method of operation seems quite feasible for a number of applications. For instance, in a multistage nuclear Manned Mars Landing Mission, the final nuclear stage could be operated with the above shielding concept during the Mars Departure Maneuver. Utilization of appropriate warning devices to signal oncoming solar flares would enable operation of the nuclear propulsion unit to coincide with a period of minimum danger from solar flare occurrences. The nuclear propulsion period (for the final nuclear stage) would involve a period of a fraction of an hour during which almost no protection against solar protons would be available.

CREW COMPARTMENT WITH VARIABLE WATER SHIELD

A. CONFIGURATION DURING
REACTOR OPERATION ONLY.

B. USUAL CONFIGURATION

This concept is only one means of providing radiation protection for the crew from the on-board nuclear propulsion system. Additional studies will pursue this and other concepts.

VI. SUMMARY AND CONCLUSIONS

In summary, the crew compartment radiation environment has been evaluated for an operating manned nuclear space vehicle under various conditions. The unshielded engine configuration serves as a starting point for future shield design analyses. The representative crew shield and engine shields have been shown to have a marked effect on crew radiation exposure.

For the reference operating profile studied herein, the following integrated crew doses from reactor radiation have been found to exist.

<u>Condition</u>	<u>Crew Dose (Rem)</u>
Unshielded Engine/Unshielded Crew Compartment	16,000
Unshielded Engine/8" Water (20,000 lbs.) Shielded Crew Compartment	5,900
Engine Shield (4,200 lbs.)/8" Water (20,000 lbs.) Shielded Crew Compartment	410
Engine Shield (~12,000 lbs.)/8" Water (20,000 lbs.) Shielded Crew Compartment	~10
Engine Shield (4,200 lbs.)/50" Water (20,000 lbs.) Shielded Crew Compartment	~10

In addition to the above crew doses from reactor operation, approximately 90 rem is expected to be accumulated from solar proton radiation with a 20,000 lb. crew shield on a 1-1/2 year Mars mission.

The preliminary nature of this study should be emphasized. No attempt has been made to account for the uncertainties in the data by the use of safety factors, etc. The results are dependent in varying degrees upon the definition of the vehicle, spacecraft, run profile, space radiation shielding, and reactor shielding. Changes in the crew radiation exposure levels can be expected to be influenced by future developments in these areas.

This study establishes the general magnitude of the radiation environment of the crew during operation of a nuclear space vehicle. The relative importance of the various nuclear radiation contributions is also established along with the effects of a typical engine operating cycle. The total crew dose has been found to be reasonably controlled without addition of excessive shield weight over that required for unmanned applications.

Design of a flexible spacecraft crew shield, which can serve as a space radiation shield for most of a mission duration and double as a reactor shield, for the short period during which the engine is operated, was investigated and found to be a very promising concept for controlling crew radiation exposure.

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APPENDIX

NEUTRON ATTENUATION IN LH_2 - CALCULATION VS MEASUREMENT

RN-TM-0294

APPENDIX A

Monte Carlo Analysis of the General Dynamics (ASTR)
Experiment on Neutron Penetration Through Hydrogen

INTRODUCTION

The prediction of fast neutron dose rates at the crew compartment of the nuclear rocket vehicle involves an evaluation of transmission of radiation through various quantities of liquid hydrogen. The hydrogen is distributed with a non-uniform thickness above the engine because of the conically shaped bottom of the propellant tank. This, together with the fact the crew compartment is located at a large distance from the tank bottom, permits neutrons to arrive at the payload with small angle scattering (and hence small energy loss), and with track lengths in the propellant that are shorter than those near the axis of the tank. This situation is illustrated by the track A B C (as opposed to $A^1 B^1 C^1$) shown in the Figure below. Under this circumstance, the usual point kernel procedure for penetration calculation will tend to under-predict the actual dose rate.

An alternative to the point kernel method for the solution of the above neutron transmission problem is the Monte Carlo procedure. To provide guides helpful in an efficient application of the Monte Carlo method, a limited analysis was conducted of a General Dynamics experiment²³ on neutron penetration through

liquid hydrogen. In this analysis the leakage spectrum of the ASTR (Aerospace Shield Test Reactor) was assumed as a source and an attempt was made to theoretically reproduce the experimental flux attenuation in hydrogen of neutrons with energies greater than 2.9 Mev. The basic calculations were performed with the General Electric Flexible Monte Carlo Code - Neutron, FMC-N²⁵.

ANALYSIS

1. Preliminary Calculations

Before any analysis of the experimental results were begun, calculations were performed with FMC-N to provide a test of the "exponential transformation" as a variance reduction scheme for deep penetration calculations. In this technique, variance is reduced by a more frequent sampling of the deep penetration event by use of input parameters which adjust cross sections. The bias introduced is removed by a simple deterministic correction, given by an exponential factor²⁵. An attempt to solve these transmission problems by using a straight Monte Carlo analogue without resort to any variance reducing scheme would result in a prohibitive expenditure of computer time.

The conditions for these initial calculations were approximated with those assumed in another more detailed study²⁸. The geometry consisted of a cylindrical slab of liquid hydrogen (density 0.07 gm/cm³) whose diameter-to-thickness ratio is large. A monodirectional beam of 8 Mev neutrons are directed into the slab and the current of neutrons with energies greater than 0.01 Mev are counted. The hydrogen cross sections were obtained from BNL-325²⁹, and were chosen at a sufficient number of points, so that straight line segments connecting adjacent values yield a close representation of the actual cross section over the energy range of interest.

Slab thicknesses of 83.96 and 167.92 cm were considered. The results, represented as buildup factors (ratio of uncollided plus scattered current to uncollided current), are compared with those of Reference 28 below.

<u>Thickness, cm</u>	<u>Neutron Buildup Factor</u>	
	<u>Present Calculation</u>	<u>Reference 28</u>
83.96	4.3	4.4
167.92	6.5	6.6

The agreement is good, giving confidence in the "exponential transformation" as a scheme for calculating deep penetrations.

2. Monte Carlo Mockup of the General Dynamics Experiment

The General Dynamics experiment "was designed to simulate the radiation source and liquid-hydrogen propellant-tank of a typical nuclear rocket system design"²³. The experimental arrangement consisted of the ASTR (Aerospace Shield Test Reactor) and a 125-gal. hydrogen dewar, positioned in the ASTR tank as shown to approximate scale in Figure A1. For greater details, one is referred to Reference 23 and 30. The dewar, placed within a liner tank, is positioned so that it sits directly above the reactor. Neutron flux measurements were taken with foils at various points within the hydrogen tank.

In the present calculations the configuration was mocked up as shown in Figure A2. Only one medium of interaction is assumed, namely liquid hydrogen. Several small detector regions are defined in the system which enable the evaluation of flux from the track length tally of the FMC-N program. Actually, 33 regions and 25 surfaces were defined in the calculation, but for the sake of clarity all are not shown in Figure A2. The reactor is approximated by a point

FIG. A1

EXPERIMENTAL ARRANGEMENT

FIG. A2

MONTÉ CARLO CALCULATION MODEL OF HYDROGEN DEWAR

isotropic source located 6.73 in. from the center of the core and in the direction of the hydrogen tank. The location of this "effective" point source is taken to be that point from which an inverse distance-square relation maintains in describing attenuation of neutron flux in air. Using the data on ASTR radiation map in air,³⁰ it was found that the above location of the "effective" point source yields an inverse square attenuation that equaled the experimental attenuation to within $\pm 5\%$ between 25 and 65 inches from the core center. It should be pointed out that an "effective" source as is defined here is not a unique method for representing the source. A selection from various types of surface sources with different spacial and angular distribution can be made but the effort required to determine whether a more satisfactory choice is possible is outside the scope of this study.

A total of 11,000 neutron histories were studied with the source neutrons distributed as follows:

- a. Between $0^\circ - 9^\circ$ (measured from the reactor-tank axis), 1000 neutrons each at 4, 6, 7.25 and 8.5 Mev.
- b. Between $9^\circ - 19^\circ$, 1000 neutrons at same energies.
- c. Between $19^\circ - 26^\circ$, 800 neutrons at 4, 7.25 and 8.5 Mev, 600 neutrons at 6 Mev.

The maximum angle of 26° corresponds to the angle subtended by the tank used in the experiment.

The results of the calculations, normalized to a source strength of 2 neutrons/sec, are summarized in Figure A3. Since the detector has a threshold of 2.9 Mev, the flux values at this energy are readily obtained by the exponential

and inverse distance-square law. Except for the three top Monte Carlo values at 7.25 Mev, the results fall essentially on smooth curves.

The same results are presented in Figure A4 but now are weighted according to the ASTR leakage spectrum³⁰. It is noticed that although the high energy contribution is depressed somewhat there is still a significant contribution from source energies greater than 9 Mev for penetrations greater than around 60 cm of hydrogen. At 100.2 cm of hydrogen, it is estimated that the integral flux above 9 Mev is 40-50% of the flux from 2.9 to 9 Mev.

The flux of neutrons between 2.9 and 9 Mev has been obtained by numerically integrating the curves of Figure A4. The variation of this flux with distance in hydrogen is compared with that of experiment in Figure A5. Again, it is pointed out that the intent here is to compare penetration within hydrogen, hence the normalization indicated in Figure A5.

DISCUSSION OF RESULTS

Comparison of the final calculated results with the experimental data raises a number of questions. The major sources of the discrepancies, however, are not obscure. The cause of the difference near the origin is mostly caused by the shadowing effect of piping below the tank bottom, which are not accounted in the calculation. If one assumes the shielding effect of the piping to be approximated by that of a small-diameter, stainless steel disc of 0.32 in. thickness (as is done in Reference 4), and apply a correction based on this assumption, the difference near the origin would be only about 25% relative to the experimental point. One of the sources of discrepancy at the large thicknesses

FIG. A4

FIG. A5

is evident from the results of Figure A4; there is a sizeable contribution to flux due to neutrons above 9 Mev which are not included in these calculations. If one applies a factor of ~ 1.5 (an estimate of the correction for the contribution above 9 Mev) to the calculated value at 100 cm, there is improvement but still a factor of two discrepancy yet to be explained. The causes of the remaining difference are probably due to (a) neutrons streaming along the void spaces surrounding the hydrogen, and then being deflected laterally into the tank, thus enhancing the experimental flux at the detectors located deep within the hydrogen, and (b) the assumption of a point isotropic source in the calculation, when in reality the leakage neutrons are emitted with a preferential forward direction.