Radiation Analysis of Various Vehicle and Payload Configurations for the Reusable Nuclear Shuttle**

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Radiation analyses were performed and shielding weight requirements were estimated for various candidate vehicle and payload configurations for use with the reusable nuclear shuttle. The analyses included both Point Kernel and Monte Carlo approaches. The effects on reduced shield weight were determined for propellant tanks with pointed conical tank bottoms and for one case of a cluster of small (15 ft diameter) tanks. This later case, however, had an arrangement which had no center tank in the upper tier of tanks. This effect negated most of the gain of going to the smaller tanks. A range of shield weights is presented for various light and heavy manned payload configurations when used in conjunction with a single liquid hydrogen propellant tank, 33 ft in diameter with a 15° conical tank bottom.

I. INTRODUCTION

The importance of a minimum weight system in the nuclear rocket program requires that the maximum shielding benefit be obtained from the large liquid hydrogen propellant tank or tanks. The effects of various tank shapes and drainage patterns on the required weight of biological shielding have been examined.

The analyses were based on use of the 75,000 lb thrust NERVA* engine in a reusable nuclear shuttle between earth orbit and lunar orbit which requires a propellant tank capacity of 300,000 lbs of liquid hydrogen. The NERVA engine includes (a) an internal shield within the Pressure Vessel and Reactor Assembly (PVARA) designed to meet the requirements of protection of some of the engine components[1], and (b) provision for a mission-dependent uncooled disk shield forward of the PVARA designed to limit crew exposure during manned missions with very light payloads. A recently completed study of engine shield requirements based on a reference 33 ft diameter LH_2 tank with a 15° half-angle conical tank bottom, resulted in selection of a reference upper limit disk shield weighing 10,000 lbs.[2] This shield limits the tank top dose to 20 Rem. This is equivalent to a 10 Rem crew dose if the light payload has an attenuation factor of two. Shield weights determined for alternate propellant tank configurations were based on providing tank top radiation exposure equivalent to that predicted with the reference 15° conic tank and 10,000 lb disk shield (i.e., 20 Rem at the propellant tank top payload interface). The PVARA used in this analyses has an internal shield weighing approximately 3300 lbs.[3,4]

The transport results were obtained using two-dimensional discrete ordinates[5] to calculate the flux in the PVARA. Three-dimensional Monte Carlo calculations[6] were used outside the PVARA using the emergent flux from the PVARA as the source. Since these transport calculations require a large amount of computer time, the dependence of the tank top dose rate as a function of liquid hydrogen level for the various configurations was obtained using point kernel techniques[7]. These "drainage curves" were normalized to the Monte Carlo results at specific liquid levels. By far, the largest contribution to the tank top dose comes from the PVARA for the current engine. Therefore, for most of the transport calculations, only the PVARA source was considered.

The resulting doses for the various designs for the unshielded cases were used to estimate the shield requirements. Parameter studies with various shield thicknesses and radii were calculated with the point kernel techniques. Monte Carlo calculations were made for two cases with an external shield and for the basic configuration with no external (disk) shield.

Even though no definite payload has been defined, the attenuation of some hypothetical payloads was examined. Transport calculations for two different payloads for the 15° reference tank

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* The Nuclear Engine for Rocket Vehicle Application (NERVA) program is administered by the Space Nuclear Systems Office, a joint office of the USAEC and NASA. Aerojet Nuclear Systems Company is prime contractor for the engine system and Westinghouse Electric Corporation is principal subcontractor responsible for the nuclear subsystem.

were performed.

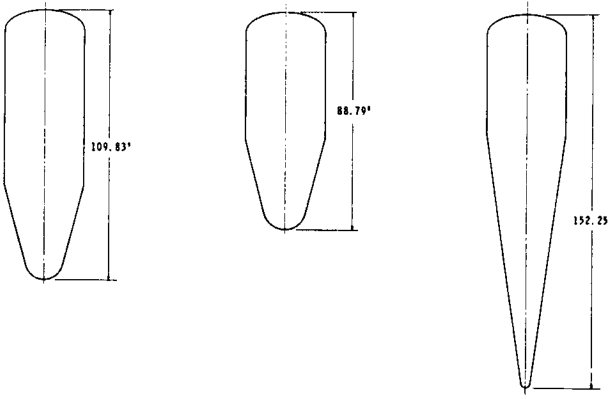
II. COMPARISON OF VARIOUS PROPELLANT TANK CONFIGURATIONS

In the course of manned shielding studies performed at Aerojet in recent years, the tank top dose has decreased from several thousand Rem predicted with a hot bleed cycle engine close-coupled to a $\sqrt{2}$ elliptical bottom tank to roughly 400 Rem with the present full flow engine with a single 300,000 lb capacity liquid hydrogen reference tank with a 15° conical tank bottom. A large part of this reduction has resulted from a concentrated effort to reduce or eliminate major propellant lines and changes in the nozzle and pump discharge line which reduced the secondary gamma sources. The shape of the tank bottom has also had a large affect on the tank top dose. For example, the tank top dose from the PVARA with a 30° half angle conical tank bottom is 1680 Rem compared to 790 Rem for a 15° half angle conical tank bottom for a 190,000 lb capacity tank. Other parameters varied included the separation distance between the PVARA and tank, amount of residual liquid hydrogen and weight of internal shield.

In support of the vehicle definition studies being conducted for the Marshall Space Flight Center by Lockheed, McDonnell Douglas and North American Rockwell, Aerojet has more recently examined various tanks for the reusable nuclear vehicle. With a reusable engine, the tanks with smaller half angles become more attractive since impact of the added interstage weight (due to the longer tank length) is greatly reduced since the engine is reused many times.

Figures 1(a) and 1(b) provides a comparison of the 15° conical bottom reference tank with a 30,000 lb liquid hydrogen capacity and one with a 170,000 lb capacity. The integral tank top dose for the larger tank is about half that of the short tank, primarily because the tank top location is further from the engine. The dose rate versus liquid level has been calculated by point kernel techniques for each of the gamma ray sources as shown in Figure 2. By far, the largest contribution to the dose comes from the PVARA. Also, over half the total dose is accumulated during the last 10% of engine operation.

FIGURE 1
SINGLE TANK CONFIGURATIONS

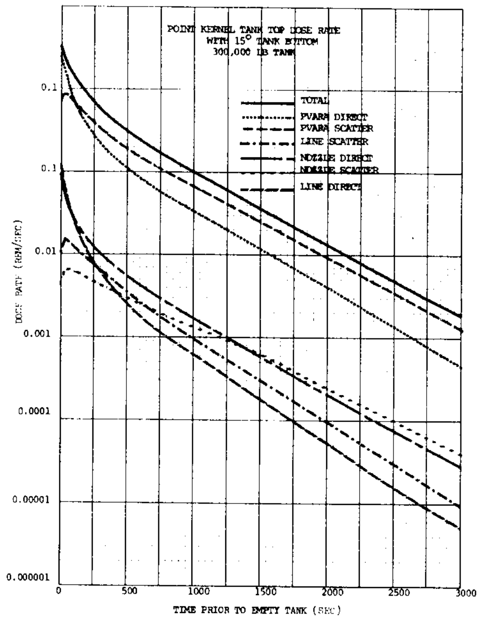


a. 15° TANK 300,000 lb LH_2

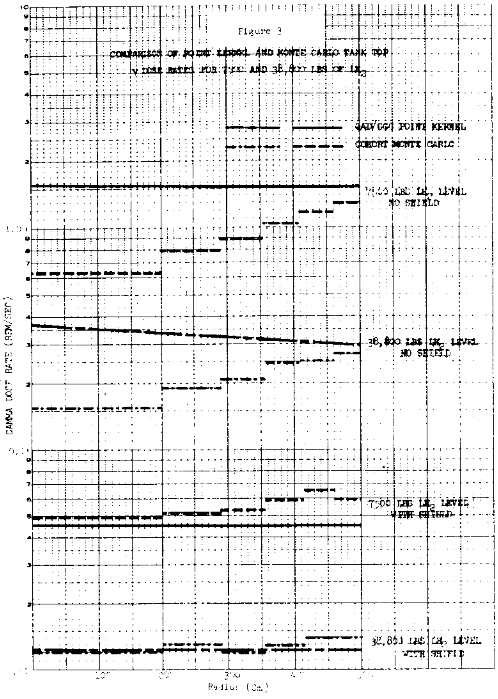
b. 15° TANK 170,000 lb LH_2

c. 8° TANK 300,000 lb LH_2

FIGURE 2



Transport calculations were made for this tank at the 7500, 38,800, and 70,000 lb liquid hydrogen levels. A comparison of the dose rates from the point kernel and transport calculations is given in Figure 3. It can be seen that the point kernel technique overpredicts the centerline dose rate but provides a good estimate of the average tank top dose rate for the case without an external disk shield. For the disk shield case, agreement is excellent both on and off axis.



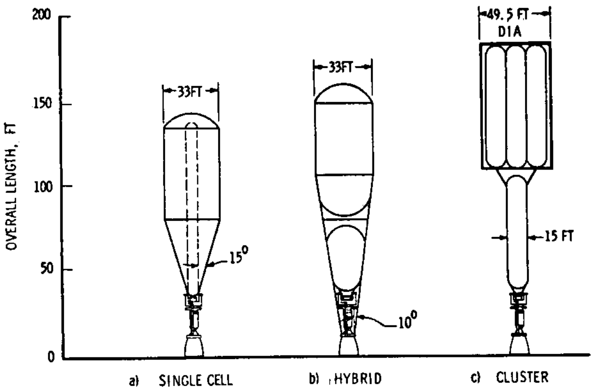
As the half angle of the tank bottom is reduced, the tank top dose is reduced by a combination of several effects. The smaller angle results in a longer tank and hence the tank top location is further from the engine. With the smaller angle, fewer particles scatter in the tank and therefore reduce the scattered contribution to the tank top dose. Also, the narrow angle results in more liquid hydrogen shielding due to a larger depth of liquid hydrogen for any given weight of propellant. Transport calculations were made for a tank with the 8° half angle tank bottom also shown in Figure 1(c). The tank top centerline integral dose from the PVARA was 33 Rem for this case compared to 210 Rem for the 15° reference tank (with no disk shield in the engine).

Several tanks with alternate drainage patterns have also been examined. A tank similar to the 15° reference tank was run with a 10 ft diameter internal cylinder or "standpipe". (See Figure 4(a)) This "standpipe" would be drained last, providing a column of a liquid hydrogen shielding. This concept was found to be effective in reducing the tank top centerline dose, but radiation levels off axis were higher than the reference tank. Also, the neutron dose which is negligible in all the other configurations, amounted to 40 Rem for the standpipe configuration.

A "hybrid" configuration consisting of a small run tank below the main tank (see Figure 4(b)) was also investigated. The small tank, which is drained last, has a liquid hydrogen capacity of about 9500 lbs. The tanks were designed such that the included half angle is 10°. The tank top centerline PVARA dose for this case was calculated to be 46 Rem. The largest factor in reducing the dose compared to the reference tank was the reduction in solid angle from 15° to 10°.

FIGURE 4

NUCLEAR SHUTTLE CONFIGURATIONS



A clustered arrangement of smaller tanks that could be launched in the Earth to Orbit Shuttle (EOS) and assembled in orbit was also investigated. The multiple tank arrangement consisted of seven tanks as shown in Figure 4(c). The tank top centerline dose from the PVARA for this case was calculated to be 138 Rem. This multiple tank configuration has a void on centerline above the lower tank; a substantial fraction of the total dose was accumulated after the lower tank was filled. The tank top dose could be reduced substantially by placing a larger column of liquid hydrogen on centerline. Such an arrangement has been considered by the McDonnell-Douglas Astronautics Company. The tank top dose was greatly reduced by this arrangement.

A comparison of the centerline tank top "point kernel" dose rates versus time for the four tank configurations is given in Figure 5. From Figure 5 it would appear that the standpipe is the most attractive design from a shielding standpoint; however, it should be pointed out that the dose rate forward of tank top and the dose rate off axis are much higher than the centerline curve in Figure 5. The multiple tank arrangement has a rather high dose rate compared to the other tanks from the initial burn to a time 500 seconds prior to empty tank condition since the depth of liquid hydrogen on axis is never greater than the length of one of the tanks in the cluster. The point kernel integral dose for these configurations is given in Table 1. The amount of residual liquid hydrogen was assumed to be 7500 lbs.

Calculations were made to determine the tank top dose with a 10,000 lb external disk shield for each of the configurations. The variables of the dose along the tank top plane for the case with an external shield is quite uniform for each of the configurations except the standpipe case. Table 2 provides a comparison of the tank top doses for each configuration with the disk shield.

FIGURE 5

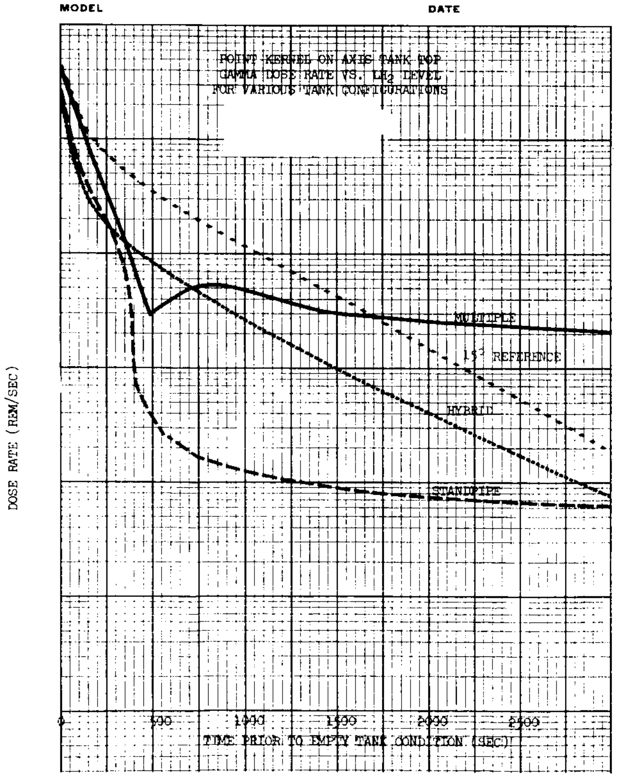


TABLE 1

COMPARISON OF POINT KERNEL CENTERLINE TANK TOP GAMMA DOSE - NO DISK SHIELD FOR ALTERNATIVE PROPELLANT TANKS

TISSUE KERMA (Rem)

	15° Dec. '69 Nozzle Sources*	15° May '70 Nozzle Sources**	15° Standpipe 10 Foot Diameter	10° Hybrid	10° Conic	Multiple Tanks 15 Ft. Diameter
PVARA DIRECT	169	169	5.9	30.5	74.7	77.5
PVARA SCATTER	250	250	57.9	72.0	80.7	120.6
LH_2 CAPTURE	12.5	12.5	0.5	8.8	5.0	10.4
NOZZLE ASSEMBLY DIRECT	2.5	0.8	0.3	1.5	0.8	1.0
NOZZLE ASSEMBLY SCATTER	26.0	3.7	2.7	4.5	1.1	9.2
PDL DIRECT	2.4	4.9	0.8	4.2	1.6	1.7
PDL SCATTER	5.9	4.5	18.2	4.0	1.7	4.1
TOTAL	468.2	445.4	86.3	125.5	165.5	224.5

*Based on QAD fast neutron flux with DOT leakage spectrum.
**Based on Neutron Monte Carlo nozzle analysis.
(NOTE: May '70 sources were used for alternative tanks)

III. COMPARISONS OF PAYLOAD ATTENUATION

Analyses were performed on typical payload configurations with the 15° reference tank to ascertain the payload attenuation[8]. The Monte Carlo technique was chosen for these studies because of the large effect of multiple scattering associated with complex geometries.

The payloads examined were the modified Apollo and the Mission B module. The Mission B module is representative of a heavy payload comprised of a manned space station module weighing over 80,000 lbs. The level of detail included in the mathematical model for the Monte Carlo calculations is shown in Figure 6 and Figure 7 for the Modified Apollo and Mission B module respectively. Kerma rate distributions at the various manned payload attenuation factors at different locations in the payload. The payload attenuation factors shown in Table 3 are defined as the ratio of the dose in the payload to the dose at tank top.

TABLE 2

COMPARISON OF POINT KERNEL CENTERLINE TANK TOP DOSE WITH 10000 LB LEAD DISK SHIELD FOR ALTERNATE PROPELLANT TANKS

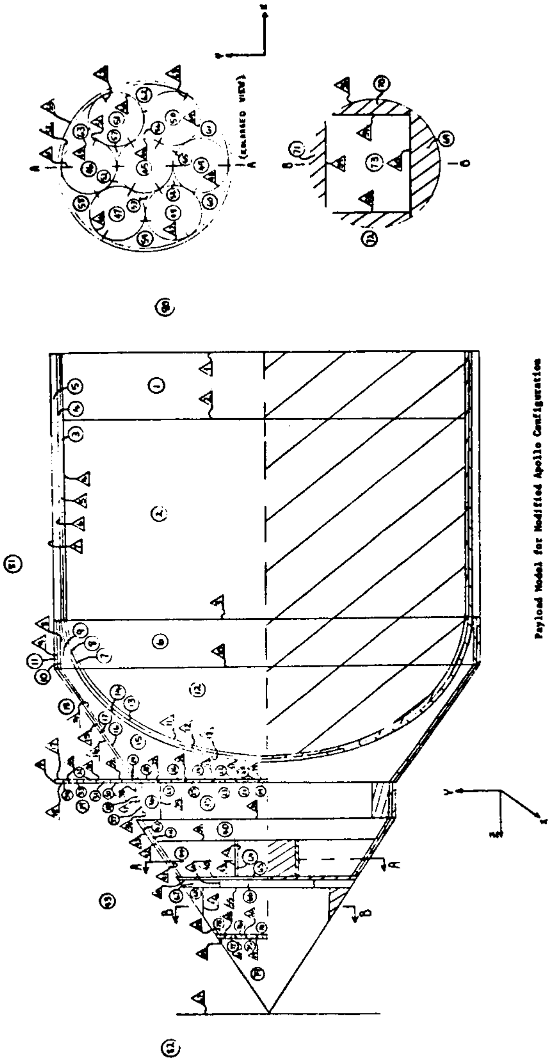
	DOSE (REM)				
	15° REFERENCE TANK	15° STANDPIPE 10 FOOT DIAMETER	10° CONIC	10° HYBRID	MULTIPLE TANKS 15 FT. DIAMETER
PVARA DIRECT	2.2	0.1	1.7	0.7	1.0
PVARA SCATTER	15.5	2.8	3.9	1.7	7.5
LH_2 CAPTURE	0.3	---	0.1	0.1	0.3
NOZZLE ASSEMBLY DIRECT	0.2	0.1	0.3	0.8	0.2
NOZZLE ASSEMBLY SCATTER	1.3	0.7	0.1	0.4	3.1
PDL DIRECT	0.3	---	0.1	0.1	0.1
PDL SCATTER	0.7	1.3	0.1	0.1	0.6
TOTAL	20.5	5.0	6.3	3.9	12.8

REPRESENTATIVE PAYLOAD ATTENUATION FACTORS FOR VARIOUS NERVA CONFIGURATIONS

Payload Configuration	Detector Level	Gamma-Ray Source		
		PVARA	PDL	Nozzle Assembly
	Without Engine Disk Shield			
Modified Apollo	Crew Location	[illegible]	[illegible]	0.488
Mission B	Crew Quarter	0.766	[illegible]	0.78[illegible]
Mission B	Radiation Shelter	0.30[illegible]	0.36[illegible]	0.41[illegible]
Mission B	Apollo Payload	[illegible]	0.010	0.021
	With Engine Disk Shield			
Modified Apollo	Crew Location	[illegible]	[illegible]	[illegible]

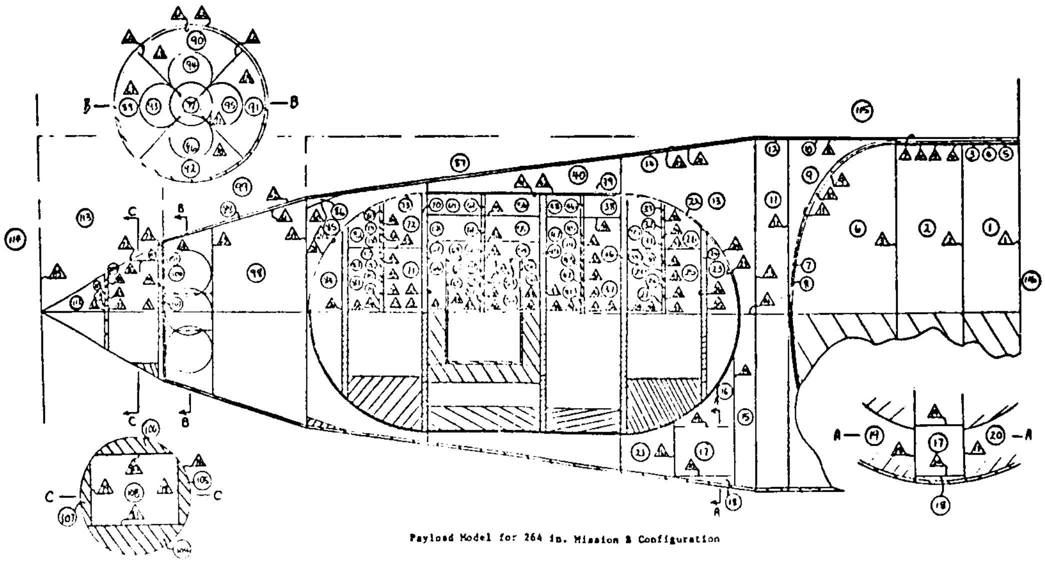
Table 3

FIGURE 6



Payload Model for Modified Apollo Configuration

Figure 7



Payload Model for 264 in. Mission B Configuration

IV. SUMMARY

(a) 15° Reference Tank

Monte Carlo calculations for the 15° conical bottom reference tank confirmed the validity of the point kernel calculations used in this analysis as well as the shielding trade studies. The point kernel results should be interpreted to be a good value for the average tank top dose for a standard tank design. The agreement between the point kernel and Monte Carlo calculations with a 10,000 lb disk shield were excellent and confirmed that this shield would reduce the tank top dose to approximately 20 Rem.

(b) Alternative Tank Designs

Investigation of various tank designs has shown that the tank top dose can be substantially reduced by alternative tank configurations. The most important parameter in this study was found to be the tank bottom angle. The 8° conic resulted in a centerline tank top dose of 36 Rem compared to 246 Rem for 15° reference tank. A 10° hybrid tank configuration resulted in a tank top centerline dose of 70 Rem.

A 15° conic with an internal standpipe concept was found to be effective in reducing the centerline tank top dose. However, it was demonstrated that the shielding requirements for locations above the tank top plane or off axis resulted in no net weight saving over the reference tank.

The results of the cluster configuration examined, indicated a disk shield weight of approximately 7600 lbs would be required. It could be seen from this analysis that other cluster configurations would result in further shield weight reductions.

The results of the tank top doses and shield weights are summarized in Table 4.

(c) Payload Radiation Attenuation

A 10,000 lb engine shield is a reasonable shield configuration to assure a 10 Rem crew dose in a 16,000 lbs six-man modified Apollo command module payload, with an approximate attenuation factor of two. The large mission module payload (>100,000 lbs) with a mission module of 82,000 lbs, results in crew doses less than 10 Rem with no disk shielding at the engine. The crew in this case was located in a modified Apollo command module located at the forward end of the payload. Payloads with weights intermediate to these would have engine disk shielding requirements which would be greatly dependent on the payload mass arrangements. In no case would they be expected to require shield weights approaching the 10,000 lbs figure.

	Tank Top Gamma Tissue Dose (Rem)									
	15° Reference Tank		15° Standpipe 10 Foot Diameter		10° Hybrid		Multiple Tank 15 Foot Diameter		8° Single Tank	
	On Axis	Off Axis	On Axis	Off Axis	On Axis	Off Axis	On Axis	Off Axis	On Axis	Off Axis
Point Kernel Tank Top Dose	455	-	86	-	126	-	[illegible]	-	-	-
Monte Carlo Tank Top Dose	246	308	70	400	70	114	[illegible]	-	36	62
Disk Shield Wt To Reduce Tank Top to 20 Rem	10,000 lbs		10,000 lbs		4,000 lbs		[illegible] lbs		3,000 lbs	

COMPARISON OF TANK TOP DOSE AND SHIELD WEIGHT FOR VARIOUS TANK DESIGNS

Table 4

V. ADDENDUM

This addendum is intended to provide a reference source of data pertaining to the 75,000 lbs thrust NERVA engine shielding weight as a function of allowed crew dose.

Table 5 appears in the National Academy of Sciences publication entitled, "Radiation Protection Guides and Constraints for Space-Mission and Vehicle-Design Studies Involving Nuclear Systems". These data should be replaced by Table 6 for reference purposes for the full flow 75,000 lbs NERVA engine with a reference 300,000 lbs capacity LH_2 tank. The earlier data reported in the NAS publication were for some earlier engine sources and an earlier tank configuration, which had a propellant capacity of 190,000 lbs. The newer data are applicable for the Reusable Nuclear Shuttle Mission.

TABLE 5

SHIELD WEIGHT FOR CREW DOSE OF 10 REM FOR

VARIOUS PAYLOAD ATTENUATION FACTORS

PAYLOAD ATTENUATION FACTOR	SHIELD WEIGHT (LBS)			
	INTERNAL ENGINE SHIELD	EXTERNAL ENGINE SHIELD	SHIELDING AT PAYLOAD	TOTAL
1	3300	10,000	9,000	22,300
3	3300	10,000	3,500	16,800
10	3300	7,300	-	10,600
20	3300	4,400	-	7,700
30	3300	2,900	-	6,200
50	3300	1,300	-	4,600
100	3300		-	3,300

Table 6

SHIELD WEIGHT FOR 300,000 LB LH_2 CAPACITY TANK
(CREW DOSE OF 10 REM WITH VARIABLE LEAD DISK SHIELD)

PAYLOAD ATTENUATION FACTOR	SHIELD WEIGHT (LBS)			
	INTERNAL ENGINE SHIELD	EXTERNAL ENGINE SHIELD	SHIELDING AT PAYLOAD	TOTAL
1	3300	10,000	5,500	18,800
2	3300	10,000	-	13,300
3	3300	8,700	-	12,000
10	3300	4,200	-	7,500
20	3300	1,900	-	5,200
30	3300	800	-	4,100
	3300		-	3,300

NOTES: 1. GRAPHITE SKIRT EXTENSION
2. Al PUMP DISCHARGE LINE

Table 7

SHIELD WEIGHT FOR VARIOUS CREW EXPOSURE CRITERIA
WITH A LIGHT PAYLOAD WITH AN ASSUMED ATTENUATION FACTOR OF TWO

CREW EXPOSURE CRITERIA (REM PER MISSION)*	SHIELD WEIGHT (LBS)			
	INTERNAL ENGINE SHIELD	EXTERNAL ENGINE SHIELD	SHIELDING AT PAYLOAD	TOTAL
5	3300	10,000	5,500	18,800
10	3300	10,000	-	13,300
20	3300	7,500	-	10,800
40	3300	5,100	-	8,400
50	3300	4,200	-	7,500

*BASED ON COMPLETE DRAINAGE OF THE 300,000 LBS OF AVAILABLE HYDROGEN WITH 7,500 LBS OF LH_2 RESIDUAL FOR COOLDOWN.

The tissue dose at the top of this larger tank is approximately 400 Rem with no engine disk shielding and 20 Rem with a 10,000 lbs engine disk shield.

Table 7 shows the shielding weight as a function of various possible crew exposure criteria per mission for a hypothetical payload with a factor of two payload attenuation (which includes both the material attenuation and the relatively minor geometric attenuation to a crew location approximately 11 ft forward of tank top).

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