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**PRELIMINARY NUCLEAR DESIGN OF
EXTERNAL DISK SHIELD**

NERVA Program, Contract SNP-1

MASTER

April 1970

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PRELIMINARY NUCLEAR DESIGN OF
EXTERNAL DISK SHIELD

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PRELIMINARY NUCLEAR DESIGN OF EXTERNAL DISK SHIELD

I. Summary

The Shielding Trade Study, completed in December 1969 (References 1 and 2), resulted in selection of an uncooled disk shield external to the pressure vessel as the best means of providing biological shielding to limit the radiation environment of the crew. The size and weight of disk shield required is variable, depending on the requirements of the mission. Engine design provides for disk shielding weighing up to 10,000 lbs (Reference 3). A disk shield as heavy as this is required only for missions with very light payloads, while little or no disk shield may be required for missions with heavy payloads. The purpose of this transmittal is to provide a preliminary nuclear design of a nominal 10,000 lb disk shield. Preliminary nuclear designs for a reference lead disk shield and a back-up borated steel disk shield are enclosed as Figures 3 and 7 respectively.

II. Approach to Design

The disk shield nuclear design has been selected on the basis of parametric studies of tank top dose versus shield weight. These studies were based on a reference configuration with a 300,000 lb capacity propellant tank having a 75° conical bottom and 200 inch separation distance between tank bottom and core center. The nuclear models and radiation sources for the engine and tank were as described in Reference 4 and were for a full flow engine configuration.

With no biological shielding at the engine, the gamma radiation environment at the top of the propellant tank varies with time during a firing as shown in Figure 1 (Reference 1). Gamma dose rates in Rem/sec are plotted versus the

FIGURE 1

Tank Top Dose Rate
with 75° Tank Bottom
300,000 lb Tank

TABLE 1

TANK TOP DOSES WITH AND WITHOUT
10,000 LB LEAD DISK
(300,000 LBS CAPACITY PROPELLANT TANK)

<u>RADIATION CONTRIBUTION</u>	<u>TANK TOP</u>	
	<u>NO DISK</u>	<u>10,000 LB LEAD DISK</u>
PVARA DIRECT	169	2.2
PVARA SCATTERED	250	11.3
LH ₂ CAPTURE	12.5	0.2
NOZZLE DIRECT	0.1	NEGLIGIBLE
NOZZLE SCATTERED	2.6	0.7
SKIRT DIRECT	2.4	0.9
SKIRT SCATTERED	23.4	10.6
PDL DIRECT	2.4	0.1
PDL SCATTERED	5.9	1.0
TOTAL	468.2	27.0

time required for complete depletion of the remaining liquid hydrogen at a rate of consumption of $9\frac{1}{4}$ lb/sec.

The dose rates were computed by point kernel analytical techniques including the QAD point kernel attenuation code for direct beam calculations and the GGG point kernel scattering code for calculations of the scattered component. It is convenient to define "direct" radiation as radiation which undergoes no collisions after emerging from the source and "scattered" radiation as radiation which undergoes one or more scatters in the propellant module, since each of these components is treated by a different analytical procedure. More sophisticated Monte Carlo calculations which have been performed for selected LH_2 levels have compared favorably with the point kernel results (Reference 5).

The results of integrating the dose rate versus time profiles of Figure 1 to a limit of 81 seconds based on 7500 lbs residual hydrogen for cooldown are shown in the tank top dose summary titled "No Disk" in Table 1. The total tank top gamma dose is 468 Rem, with direct and scattered contributions of roughly equal importance. For LH_2 residuals of this order of magnitude at end of firing, the amount of hydrogen available as neutron shielding throughout the run is such that neutron contributions to the tank top dose are negligible (Reference 6). Hence, in any manned mission, the combined effects of indigenous mass in the payload, additional distance between tank top and crew, and system biological shielding must reduce the gamma dose of 468 Rem at tank top to the permissible exposure at the crew location.

The disk shield operates toward this end by providing a cone of protection both for the crew compartment and for the propellant tank since the latter acts as a source of scattered radiation to the crew. Consequently, the model selected for the parametric studies consisted of a two-region disk having a central region

25 inches in radius, and a peripheral region of variable radius. The central region is mainly a shadow shield for the PVARA, while the peripheral region serves to limit radiation incident on the propellant tank.

The primary function of the shield is gamma attenuation. Therefore, lead was chosen as the basic shield material because of its superior gamma attenuation cross-section per unit mass and low cross-section for secondary gamma production. A two inch lamination of borated graphite was introduced between the lead and the source. This provides an initial material which has high temperature capability and which assures that relatively low energy neutrons incident upon the shield are absorbed in soft gamma-emitting (n,α) reactions with boron on the source side of the gamma shielding rather than in structural members or components between the shield and the detector. In addition, a two inch lamination of LiH was introduced above the lead. This very efficient light weight neutron shield greatly reduces the neutron transmission through the shield, thus reducing secondary gamma production above the shield, residual dose rates due to component activation, and neutron doses above the shield. Based on preliminary estimates of structural support which might be required, three .25 inch stainless steel laminations were also included in the model (see Figure 3).

The bottom of the disk shield was held fixed at 81 inches from core center. The effectiveness of the disk would increase with decreasing distance from the source; however, preliminary thermal analyses indicated that 81 inches should be clearly acceptable while smaller distances might require careful and extensive thermal analyses to assure that the requirement that the disk be un-cooled would not be compromised.

QAD point kernel analyses (Reference 5) were performed to determine transmission through the shield versus total mass thickness of shielding in gm/cm^2 for

the significant system sources. QAD/GGG/SCATBLOCK analyses (Reference 5) were employed to determine the effects of central shield thickness (gm/cm^2) and peripheral shield radius and thickness respectively upon scattered contributions transmitted through and outboard of the central disk region. Variations in total mass thickness were accomplished by varying lead thickness only and holding the neutron shielding and structural laminations fixed. Thus, a body of parametric data for variable central disk thickness and variable peripheral disk radius and thickness was generated. This data was reduced by program WANG (Reference 5) to obtain tank top dose as a function of disk shield weight.

These data were used to plot the curves of Figure 2 which shows how the 468 Rem tank top dose responds to various configurations of engine disk shielding. The weights shown are total system shield weight and include a nominal 3300 lb internal shield and preliminary estimates of non-useful structural weight required to the support disk. For each of several central disk weights the peripheral disk was varied in thickness for outer radii of 30, 40, 45, 47.5, 50, 52, and 54 inches. The more significant members of the family of curves thus generated are shown in Figure 2 along with the envelope curve of the entire family. Points on this envelope curve represent minimum dose versus shield weight solutions.

Table 2 shows the effect of combining the disk shield minimum weight envelope curve of Figure 2 with payloads having various effective attenuation factors. Note that, for payloads with effective attenuation factors greater than 30, no disk is required, while a very light payload having less than a factor of 3 attenuation requires shielding in excess of a 10,000 lb disk. The payload shield weight was estimated on the basis of a 10 ft diameter shadow shield at the crew.

FIGURE 2

Dose at Tank Top of 300,000 lb. H₂ Tank
Vs Δ System Weight for Lead Disk Shield

TABLE 2

SHIELD WEIGHT FOR 300,000 LB LH₂ CAPACITY TANK
(CREW DOSE OF 10 REM WITH VARIABLE LEAD DISK SHIELD)

PAYLOAD ATTENUATION FACTOR	SHIELD WEIGHT (LB)			
	INTERNAL ENGINE SHIELD	EXTERNAL ENGINE SHIELD	SHIELDING AT PAYLOAD	TOTAL
1	3300	10,000	5,500	18,800
3	3300	9,700	-	13,000
10	3300	4,400	-	7,700
20	3300	1,900	-	5,200
30	3300	800	-	4,100
50	3300	-	-	3,300
100	3300	-	-	3,300

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

III. Selection of Shield

The envelope curve of Figure 2 indicates that an optimally configured 10,000 lb disk shield should limit crew dose to 10 Rem with a payload having an effective attenuation factor of about 3. The preliminary disk shield nuclear design (Figure 3) was chosen with parameters closely approximating the envelope condition; i.e., a 50-inch radius disk with 3000 lb/7000 lb central vs peripheral weight distribution appears to be at or very near the minimum. It should be noted that near the envelope the dose is a slowly varying function of the disk parameters so that considerable latitude in selection is possible. This disk design was chosen from the lower end of the range of radii which appeared to afford near optimum solutions. The tank top dose contributions predicted with the shield in place are shown in Table 1. The shielded dose is almost entirely due to scattered contributions, indicating that most of the radiation is probably coming around the shield and that additional reductions in the dose would require either a larger disk shield diameter or shielding at the payload.

The dimensions shown in Figure 3 are based on the specified material densities. The total mass thickness in gr/cm^2 includes the assumed steel structural laminations. Any departures in density or differences resulting from engineered structural plates should be compensated for such that the total mass thickness in gm/cm^2 remains constant. In actual design of the disk shield, the structure should be engineered to sacrifice structural material thickness in favor of shield thickness, and wherever possible, to replace stainless steel with materials with lower neutron capture cross-sections such as aluminum.

A mission requiring less attenuation in the engine shielding would, of course, result in selection of a small, lighter disk shield configuration. For

FIGURE 3

BASELINE DESIGN - 10,000 LB. LEAD DISK SHIELD LOCATED
81 INCHES FORWARD OF CORE CENTER

DIMENSIONS BASED ON MATERIAL DENSITIES:

Lead	11.3 gm/cm ³
Stainless Steel	8.0 gm/cm ³
Borated Graphite	1.9 gm/cm ³
Lithium Hydride	.78 gm/cm ³

FIGURE 4

ESTIMATED EFFECT OF INCREASING CORE CENTER TO DISK
SHIELD SEPARATION BEYOND 81 INCHES UPON
DISK SHIELD WEIGHT REQUIRED TO PROVIDE
EQUIVALENT TANK TOP RADIATION ENVIRONMENT

FIGURE 5

ESTIMATED EFFECT OF INCREASING CORE CENTER TO DISK
SHIELD SEPARATION BEYOND 81 INCHES UPON
DISK SHIELD RADIUS REQUIRED TO PROVIDE
EQUIVALENT TANK TOP RADIATION ENVIRONMENT

example, a mission requiring a disk of about 5000 lbs (which might be a mission with an effective payload attenuation of about 9) might dictate a disk of about 45 inch radius with a 2200 lb/2800 lb split between central and peripheral weight.

Estimates have been made of weight penalties which might be incurred by fixing the disk location at distances in excess of 81 inches from core center. Figure 4 shows the additional weight and Figure 5 the corresponding radius which might be required to provide the same tank top environment as the reference disk located 81 inches from core center.

IV. Back-up Design

Parametric studies have also been performed which utilized borated stainless steel rather than lead as gamma shielding. While this is a somewhat less efficient shielding material than lead, it does offer better mechanical and thermal properties.

Present analyses (Reference 7) indicate acceptable temperatures in a lead disk shield, but should any unforeseen thermal or mechanical design problems arise, steel might be considered as a back-up material.

Parametric data developed for borated steel disk shielding is shown in Figure 6. A preliminary nuclear design of an optimally configured 10,000 lb steel disk shield is shown in Figure 7. The optimum parameters for the reference steel disk are essentially the same as for the reference lead disk; i.e., 50 inch radius and 3000 lb/7000 lb central vs peripheral split, but the tank-top dose is higher for the same shield weight (39 Rem vs 27 Rem).

V. Additional Analyses of Reference Designs

Some results of additional analyses performed on the reference disk con-

FIGURE 6

Dose at Tank Top of 300,000 Lb. LH₂ Tank Vs.
 Δ System Weight for Steel Disk Shield

Dose (Rem)

Central Disk

● 2000 lb.

▼ 2500 lb.

■ 3000 lb.

▲ 4000 lb.

Central Disk Only

R = 45 in. Peripheral Disk

R = 50 in. Peripheral Disk

R = 54 in. Peripheral Disk

Envelope

10

9

8

7

6

5

4

3

2

1

0

0

0

0

0

0

0

0

0

0

0

0

0

0

3000

5000

7000

9000

11000

13000

15000

17000

Δ System Weight (lbs)

FIGURE 7

BASELINE DESIGN - 10,000 LB BORATED STEEL DISK SHIELD LOCATED
81 INCHES FORWARD OF COFE CENTER

DIMENSIONS BASED ON MATERIAL DENSITIES:

Borated Stainless Steel	8.0 gm/cm ³
Stainless Steel	8.0 gm/cm ³
Borated Graphite	1.9 gm/cm ³
Lithium Hydride	.78 gm/cm ³

figurations will be enclosed here. These were intended to augment and support the point kernel survey analyses which led to the design selections.

Figures 8 and 9 show axial gamma KERMA rate traverses along centerline through the central shield region and at R = 37.5 inches in the peripheral shield region. These were the results of sequentially coupled 2-dimensional transport calculations (DOT/DASH/DOT, Reference 8) and were intended to verify the relative effectiveness of the lead and steel shields. It was determined from these calculations that, for equivalent support structure, a 10,000 lb steel shield could be replaced with an 8300 lb lead shield.

Tables 3 and 4 present the results of ANISN neutron transport calculations performed with 16 group Hansen-Roach cross-sections for the central disk regions of lead and borated steel disks. Leakage from the shield and neutron absorption distributions by region through the shield are given for each of 3 broad neutron energy classes. The absorptions which occur in the steel portions of the shield result in very penetrating secondary gammas.

Table 5 contains the tank top doses calculated to result from secondary sources in the 10,000 lb lead and steel disks as they were modeled for the parametric studies. These secondaries were not included in development of the envelope curves. This was based on the reasoning that (a) secondary production problems could be minimized by revising the split between neutron and gamma shielding while holding the mass thickness and therefore, the total weight, constant, and (b) engineering of the steel support regions should reduce the mass of steel, particularly for the LiH cans. These assumptions appear to be warranted, although secondaries might require fairly careful consideration in the case of the steel disk.

FIGURE 8

Revised Mission A Disk - Central Region
PVARA Gamma Attenuation in Lead and in SS
On Center-line

DOT-DASH-DOT Calculation

Gamma Kerma Rate
(Rads-C/hr)

10^5

10^6

10^7

Axial Distance Through Shield, (cm)

FIGURE 9

TABLE 3

ONE DIMENSIONAL CALCULATION OF NEUTRON TRANSPORT THROUGH
CENTRAL REGION OF 10,000 LB LEAD DISK SHIELD (S₆, 16 GROUP ANISN)

<u>Neutron Energy</u>	<u>Albedo</u>	<u>Fraction of Incident Neutrons Absorbed</u>					<u>Transmission Through Shield</u>
		<u>Bottom SS</u>	<u>Borated Graphite</u>	<u>Lead</u>	<u>LiH</u>	<u>LiH Can (SS)</u>	
Fast (E > 1 MeV)	.596	.0018	.022	.00017	.241	.0042	.133
Intermediate (.04 ev < E < 1 MeV)	.616	.0071	.178	.0004	.176	.005	.0133
Thermal (E < .04 ev)	.175	.189	.631	.00007	.0004	.0003	Negligible

TABLE 4

ONE DIMENSIONAL CALCULATION OF NEUTRON TRANSPORT THROUGH CENTRAL
REGION OF 10,000 LB BORATED STEEL SHIELD (S_6 , 16 GROUP ANISN)

<u>Neutron Energy</u>	<u>Albedo</u>	<u>Fraction of Incident Neutrons Absorbed</u>						<u>Transmission Through Shield</u>
		<u>Bottom SS</u>	<u>Borated Graphite</u>	<u>Boron in Borated SS</u>	<u>SS in Borated SS</u>	<u>LiH</u>	<u>LiH Can (SS)</u>	
Fast ($E > 1$ MeV)	.608	.0018	.014	.059	.027	.21	.004	.075
Intermediate (.01 ev $< E < 1$ MeV)	.608	.0069	.155	.10	.022	.09	.002	.009
Thermal ($E < .04$ ev)	.175	.19	.63	.0016	.0001	Negli- gible	Negligible	Negligible

TABLE 5

TANK TOP DOSE CONTRIBUTIONS BY THE DISK SHIELD*
 (300,000 LB CAPACITY PROPELLANT TANK - 7500 LBS LH_2 RESIDUAL)

<u>Material</u>	<u>10,000 lbs Borated Stainless Steel Disk</u>	<u>10,000 lbs Lead Disk</u>
Bottom CRES-347 Plate	0.83	0.43
Borated Graphite	0.21	0.13
Primary Gamma Attenuator	3.02	0.03
LiH	0	0
LiH Can (Top) (CRES-347)	0.25	0.40
LiH Can (Bottom) (CRES-347)	1.11	2.03
	<hr/> <hr/>	<hr/> <hr/>
	5.42 Rem	3.02 Rem

*Based on neutron leakage from the PVARA which included a 3,300 lbs BATH internal shield. The disk shields compared here are 81 inches above core center.

Figures 10 and 11 show comparisons between axial fast neutron flux ($E > .9$ MeV) profiles as calculated by ANISN with 16 group Hansen-Roach cross-sections and with 100 group P_3 cross-sections for the central regions of lead and borated steel disk shields, respectively. It is concluded from these data that the 16 group calculation does an adequate job of predicting fast neutron transmission through the shield.

Coupled transport calculations were performed to determine the effect of the shield on the radiation intensity at a plane forward of the disk shield location. Figure 12 shows radial gamma KERMA rate profiles and Figure 13 shows fast neutron flux ($E > .9$ MeV) profiles calculated with and without a disk shield at a plane 96 inches forward of core center. The unshielded data resulted from DOT/DASH analyses (Reference 8). The data with a disk were obtained by using DOT/DASH calculated angular fluxes at the lower surface of the disk as source input to a second DOT calculation in the disk shield. This DOT in turn produced leakage flux input to a final DASH calculation to the desired plane. These calculations were for an 8300 lb, 50 inch radius shield which, from the parametric data of Figure 2, would be expected to limit the tank top dose to about 39 Rem. The reductions in intensity due to the shield which were predicted by the DOT/DASH/DOT/DASH analyses were compared to the equivalent kernel data used in developing the parametric data of Figure 2. The point kernel and coupled transport methods were found to provide consistent results.

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