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September 1967

Westinghouse Astronuclear Laboratory

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PARAMETRIC ANALYSIS OF
NR.1 FLIGHT SHIELD CONFIGURATION

[Title Unclassified]

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PARAMETRIC ANALYSIS OF NR.1 FLIGHT SHIELD CONFIGURATION

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SUMMARY

This study has evaluated the effects of the location and geometry of a $\text{TiH}_x\text{-B}_4\text{C-Al}$ flight shield on the external radiation environment of a 5000 MW NR-1 reactor. These effects have been interpreted in terms of nuclear heating at the hydrogen propellant tanks in both single and clustered configurations, inasmuch as tank heating has been the gauge by which shields have been compared in previous studies.

Three basic shield locations considered were:

- 1) below the core support plate,
- 2) combined with the core support plate, and
- 3) above the core support plate.

The shield geometry was varied parametrically to include several thicknesses of the central portion of the shield (with radius equal to that of the reactor core) as well as several thicknesses of the peripheral shield region (located above the reflector). The shield material used throughout this analysis is $\text{TiH}_{1.8}\text{-B}_4\text{C-Al}$ (24-6-70 percent by volume).

Changes in the reactor materials and geometry from those used in earlier radiation environment studies (Reference 4) have produced some changes in the predicted magnitude of radiation levels and shield effectiveness. For example, the change in the reactor vessel material from aluminum to Inconel causes an increase in the radiation level at the propellant tank which is not significantly reduced by the shield.

The results of this analysis indicate that--

- 1) To obtain a minimum weight shield for attenuations greater than 50 percent in a single module, both central and peripheral shield components are needed. For clustered modules, both components of the shield are needed to achieve attenuations greater than 62 percent.
- 2) The combination of the central shield with the support plate may offer a slight weight advantage over the shield located below the support plate for shield weights between 2000 and 3000 pounds.

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3) For the combined shield-support plate configuration, the weight of the shield material inserts must exceed 900 pounds if the height of the structure is to be adequate to provide required mechanical strength and if the volume fraction of the shield insert material is to be large enough to prevent excessive streaming through the structural material.

The results of this study are summarized in Table 1.

This study reconfirms the findings of the NR-1 Nuclear Subsystem Parametric Study that the optimum location for the shield is below the support plate; i. e., between the core and support plate regions. Apparently the advantages of this location far outweigh the disadvantages since the radiation effects and heating rates in the shield are not considered a problem in the light of the present state-of-the-art knowledge concerning these effects on the selected TiH_x-B_4C-Al composite shield material. The uncertainties in shield thickness which presently exist because of undefined shield criteria and uncertainties in shield attenuation can be tolerated without undue weight penalty by providing additional space over some nominal requirements for potential growth of the shield.

TABLE 1
ADVANTAGES AND DISADVANTAGES OF ALTERNATE SHIELD LOCATIONS

Shield Location	Advantages	Disadvantages
Below (aft of) core support plate	<ul style="list-style-type: none"> • Near minimum weight • Low secondary gamma production in regions in and above shield (shield contribution suppressed with boron) • Protects support plate <ul style="list-style-type: none"> a) In loss of flow accident b) from high heating rate c) from high secondary gamma production • Mates with ID of peripheral shield thus providing more complete angular coverage and preventing "streaming" of radiation 	<ul style="list-style-type: none"> • Maximum radiation effects in shield • Maximum heating in shield • Mechanically complex • Most severe on shield material selection • Variation in attenuation requires adjustment of support structure and tie tubes
Combined with core support plate	<ul style="list-style-type: none"> • Minimum weight over narrow attenuation range • Low secondary gamma production in regions in and above shield (shield contribution suppressed with boron) • Mechanical simplicity 	<ul style="list-style-type: none"> • Over-diluted with Al structure for thin or thick central shields • Severe on material selection • High heating rate • High radiation effects • Design is relatively inflexible
Above (forward of) the core support system	<ul style="list-style-type: none"> • Least severe radiation environment • Widest range of allowable shield materials • Most flexible for shield redesign 	<ul style="list-style-type: none"> • Maximum weight (estimate ~ 1000 lb penalty over below-support-plate design) • Additional shield may be required to protect flange • Maximum radiation environment on major structural members-support plate, flange, tie tube plena • Highest external radiation levels for given shield weight • High secondary gamma ray production in regions above core • Minimum polar angular coverage for given shield weight

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TABLE OF CONTENTS

<u>Section</u>		<u>Page</u>
1	INTRODUCTION	1
2	ANALYTICAL METHODS	3
	2.1 Transport Calculations	3
	2.2 Point Kernel Calculations	3
	2.3 Approximate Method for Propellant Tank Heating	6
3	GEOMETRICAL MODELS	9
	3.1 Transport Model	9
	3.2 Point Kernel Model	9
	3.3 Shield Weight and Reactor Weight Increments for Various Cases Studied	10
4	RESULTS OF CALCULATIONS	13
	4.1 Transport Results	13
	4.1.1 Heterogeneous Effects of Combined Shield-Support Plate on Fast Neutron Leakage	13
	4.1.2 Photon Source Strengths and Distributions	13
	4.2 Point Kernel Results for External Radiation Environment	14
	4.3 Propellant Heating Results	15
5	DISCUSSION OF RESULTS	17
	5.1 Importance of Peripheral Shield	17
	5.2 Minimum Shield Weight for Propellant Heating	17
	5.3 Limitations on Shield-Support Plate Combination	18
	5.4 Comparison with Previous Studies	18
6	CONCLUSIONS	19
7	REFERENCES	21
APPENDIX A.	Gamma Radiation Levels from Several Reactor Components	91

~~CONFIDENTIAL~~

LIST OF ILLUSTRATIONS

<u>Figure</u>		<u>Page</u>
1	Geometrical Models for 2-D Transport Cell Study of NR-1 Shield Configurations	29
2	Basic Configuration, Shield Below Support Plate	30
3	Basic Configuration, Combined Shield-Support Plate	31
4	Basic Configuration, Shield Above Support Plate	32
5	Average Axial Gamma Source Distributions, 2-D Transport Cell Study, Combined Shield-Support Plate (Configurations 3 and 4)	33
6	Average Axial Gamma Source Distributions, 2-D Transport Cell Study, Shield Below Support Plate (Configuration 1)	34
7	Average Axial Gamma Source Distributions, 2-D Transport Cell Study, Shield Above Support Plate (Configuration 2)	35
8	NR-1 Shield Location and Thickness Study, Shield Below Support Plate Configuration--Case I-1-A	36
9	NR-1 Shield Location and Thickness Study, Shield Below Support Plate Configuration, (Polar Traverses at 30 ft from the Core Center)--Case I-1-A	37
10	NR-1 Shield Location and Thickness Study, Shield Below Support Plate Configuration, (Polar Traverses at 30 ft from the Core Center)--Case I-1-C	38
11	NR-1 Shield Location and Thickness Study, Shield Below Support Plate Configuration, (Polar Traverses at 30 ft from the Core Center)--Case I-1-D	39
12	NR-1 Shield Location and Thickness Study, Shield Below Support Plate Configuration, (Polar Traverses at 30 ft from the Core Center)--Case I-2-A	40
13	NR-1 Shield Location and Thickness Study, Shield Below Support Plate Configuration, (Polar Traverses at 30 ft from the Core Center)--Case I-2-B	41
14	NR-1 Shield Location and Thickness Study, Shield Below Support Plate Configuration, (Polar Traverses at 30 ft from the Core Center)--Case I-2-C	42
15	NR-1 Shield Location and Thickness Study, Shield Below Support Plate Configuration, (Polar Traverses at 30 ft from the Core Center)--Case I-2-D	43
16	NR-1 Shield Location and Thickness Study, Shield Below Support Plate Configuration, (Polar Traverses at 30 ft from the Core Center)--Case I-3-A	44
17	NR-1 Shield Location and Thickness Study, Shield Below Support Plate Configuration, (Polar Traverses at 30 ft from the Core Center)--Case I-3-B	45

~~CONFIDENTIAL~~

LIST OF ILLUSTRATIONS (CONTINUED)

<u>Figure</u>		<u>Page</u>
18	NR-1 Shield Location and Thickness Study, Shield Below Support Plate Configuration, (Polar Traverses at 30 ft from the Core Center)--Case I-3-C	46
19	NR-1 Shield Location and Thickness Study, Shield Below Support Plate Configuration, (Polar Traverses at 30 ft from the Core Center)--Case I-3-D	47
20	NR-1 Shield Location and Thickness Study, Shield Below Support Plate Configuration, (Polar Traverses at 30 ft from the Core Center)--Case I-4-A	48
21	NR-1 Shield Location and Thickness Study, Shield Below Support Plate Configuration, (Polar Traverses at 30 ft from the Core Center)--Case I-4-B	49
22	NR-1 Shield Location and Thickness Study, Shield Below Support Plate Configuration, (Polar Traverses at 30 ft from the Core Center)--Case I-4-C	50
23	NR-1 Shield Location and Thickness Study, Shield Below Support Plate Configuration, (Polar Traverses at 30 ft from the Core Center)--Case I-4-D	51
24	NR-1 Shield Location and Thickness Study, Shield Below Support Plate Configuration, (Polar Traverses at 30 ft from the Core Center)--Case II-2-A	52
25	NR-1 Shield Location and Thickness Study, Combined Shield-Support Plate Configuration, (Polar Traverses at 30 ft from the Core Center)--Case II-3-A	53
26	NR-1 Shield Location and Thickness Study, Combined Shield-Support Plate Configuration, (Polar Traverses at 30 ft from the Core Center)--Case II-4-A	54
27	NR-1 Shield Location and Thickness Study, Combined Shield-Support Plate Configuration, (Polar Traverses at 30 ft from the Core Center)--Case II-2-B	55
28	NR-1 Shield Location and Thickness Study, Combined Shield-Support Plate Configuration, (Polar Traverses at 30 ft from the Core Center)--Case II-2-C	56
29	NR-1 Shield Location and Thickness Study, Combined Shield-Support Plate Configuration, (Polar Traverses at 30 ft from the Core Center)--Case II-2-D	57
30	NR-1 Shield Location and Thickness Study, Combined Shield-Support Plate Configuration, (Polar Traverses at 30 ft from the Core Center)--Case II-3-B	58
31	NR-1 Shield Location and Thickness Study, Combined Shield-Support Plate Configuration, (Polar Traverses at 30 ft from the Core Center)--Case II-3-C	59
32	NR-1 Shield Location and Thickness Study, Combined Shield-Support Plate Configuration, (Polar Traverses at 30 ft from the Core Center)--Case II-3-D	60
33	NR-1 Shield Location and Thickness Study, Combined Shield-Support Plate Configuration, (Polar Traverses at 30 ft from the Core Center)--Case II-4-B	61

~~CONFIDENTIAL~~

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LIST OF ILLUSTRATIONS (CONTINUED)

<u>Figure</u>		<u>Page</u>
34	NR-1 Shield Location and Thickness Study, Combined Shield-Support Plate Configuration, (Polar Traverses at 30 ft from the Core Center)--Case II-4-C	62
35	NR-1 Shield Location and Thickness Study, Combined Shield-Support Plate Configuration, (Polar Traverses at 30 ft from the Core Center)--Case II-4-D	63
36	NR-1 Shield Location and Thickness Study, Top Shield Configuration, (Polar Traverses at 30 ft from the Core Center)--Case III-2-A	64
37	NR-1 Shield Location and Thickness Study, Top Shield Configuration, (Polar Traverses at 30 ft from the Core Center)--Case III-2-B	65
38	NR-1 Shield Location and Thickness Study, Top Shield Configuration, (Polar Traverses at 30 ft from the Core Center)--Case III-2-C	66
39	NR-1 Shield Location and Thickness Study, Top Shield Configuration, (Polar Traverses at 30 ft from the Core Center)--Case III-2-D	67
40	NR-1 Shield Location and Thickness Study, Top Shield Configuration, (Polar Traverses at 30 ft from the Core Center)--Case III-3-A	68
41	NR-1 Shield Location and Thickness Study, Top Shield Configuration, (Polar Traverses at 30 ft from the Core Center)--Case III-3-B	69
42	NR-1 Shield Location and Thickness Study, Top Shield Configuration, (Polar Traverses at 30 ft from the Core Center)--Case III-3-C	70
43	NR-1 Shield Location and Thickness Study, Top Shield Configuration, (Polar Traverses at 30 ft from the Core Center)--Case III-3-D	71
44	NR-1 Shield Location and Thickness Study, Top Shield Configuration, (Polar Traverses at 30 ft from the Core Center)--Case III-4-A	72
45	NR-1 Shield Location and Thickness Study, Top Shield Configuration, (Polar Traverses at 30 ft from the Core Center)--Case III-4-B	73
46	NR-1 Shield Location and Thickness Study, Top Shield Configuration, (Polar Traverses at 30 ft from the Core Center)--Case III-4-C	74
47	NR-1 Shield Location and Thickness Study, Top Shield Configuration, (Polar Traverses at 30 ft from the Core Center)--Case III-4-D	75
48	Incident Nuclear Heating Rate in a Single-Module Propellant Tank vs Reactor Weight Increment (Shield Above Support Plate)	76
49	Incident Nuclear Heating Rate in a Single-Module Propellant Tank vs Reactor Weight Increment	77

~~CONFIDENTIAL~~

LIST OF ILLUSTRATIONS (CONTINUED)

<u>Figure</u>		<u>Page</u>
50	Incident Nuclear Heating Rate in a Single-Module Propellant Tank vs Reactor Weight Increment (Shield Below Support Plate)	78
51	Incident Nuclear Heating Rate in the Central Tank of a 3-Module Cluster vs Reactor Weight Increment (Shield Combined with Support Plate)	79
52	Incident Nuclear Heating Rate in the Central Tank of a 3-Module Cluster vs Reactor Weight Increment	80
53	Incident Nuclear Heating Rate in the Central Tank of a 3-Module Cluster vs Reactor Weight Increment (Shield Below Support Plate)	81
54	Incident Nuclear Heating Rate in the Outboard Tank of a 3-Module Cluster vs Reactor Weight Increment (Shield Below Support Plate)	82
55	Incident Nuclear Heating Rate in a Single-Module Propellant Tank (Minimum Reactor Weight Increment)	83
56	Incident Nuclear Heating Rate in the Central Tank of a 3-Module Cluster (Minimum Reactor Weight Increment)	84
57	Incident Nuclear Heating Rate Shield Below Support Plate (Minimum Reactor Weight Increment)	85
58	5000 MW NR-1, Gamma Dose Rate from Several Reactor Regions, No Shield	86
59	5000 MW NR-1, Gamma Dose Rate from Several Reactor Regions, Central Shield Only (1370 lbs)	87
60	5000 MW NR-1, Gamma Dose Rate from Several Reactor Regions, Central and Peripheral Shields (1370 + 975 lbs)	88

LIST OF TABLES

<u>Number</u>		<u>Page</u>
1	Advantages and Disadvantages of Alternate Shield Locations	22
2	Shield Weights and Reactor Weight Increments	23
3	Comparison of Secondary Gamma Source Strengths for Three Shield Configurations	24
4	Absolute Source Strengths for Three Shield Configurations	25
5	Single Module Propellant Tank Heating for Various Shield Configurations	26
6	Heating in Central Propellant Tank of a Three-Module Cluster, for Various Shield Configurations	27
7	Heating in the Outboard Propellant Tank of a Three-Module Cluster for Various Shield Configurations	28

SECTION 1

INTRODUCTION

Three candidate locations have been considered for the flight shield in the NR-1 reactor. They are:

- 1) Above (forward of) the core support system
- 2) Integral with the core support plate
- 3) Below (aft of) the core support plate.

Figure 1 shows a sketch of the geometry for these three locations.

Previous radiation evaluations of NR-1 flight shields^{(1 through 7)*} have considered different shield materials such as LiH-steel, borated BeO-Al and $\text{TiH}_x\text{-B}_4\text{C-Al}$, from which the $\text{TiH}_x\text{-B}_4\text{C-Al}$ has been selected as the primary material.⁽⁵⁾ Studies have also considered various locations of the shield. Each phase of these early studies, however, dealt with slightly different reactor geometries and radiation sources. Also, different analytical methods were used in various parts of these studies. Thus, the purpose of the present study is to compare the effects of shield location and geometry on the external radiation environment using a consistent reactor model and method of analysis. A standard reference for comparing the effectiveness of the shields has been accomplished by the reduction of external radiation environment data to equivalent propellant heating rate by integrating over the solid angles subtended by the propellant tanks.

The effects of the heterogeneity of a combined shield-core support plate were investigated and compared with the radiation leakage from a homogeneous shield and core support plate mixture. This analysis was needed to evaluate the validity of using a homogeneous model for the combined support plate shield arrangement.

Finally, the combined shield-support plate configuration was evaluated vs the shield located above the support plate and below the support plate by comparing the calculated reactor weight increment and resulting equivalent propellant heating for each of the shield configurations considered in this parametric study.

* Superscripted numbers correspond to references listed in Section 7.

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A description of the analytical methods and the geometrical models used is contained in Sections 2 and 3. A detailed presentation of the analysis results is given in Section 4. A discussion of the results, including comparisons with previous results is presented in Section 5. The conclusions resulting from this study are given in Section 6. An appendix is included which presents the gamma ray radiation levels from various reactor source components. These data are of help in understanding the effects of the shield.

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SECTION 2

ANALYTICAL METHODS

Three analytical techniques were used in this study. They were:

- 1) Two-dimensional S_n transport method
- 2) Point kernel method
- 3) An approximate method for obtaining propellant tank integral heating.

The following is a brief description of the application of these methods.

2.1 TRANSPORT CALCULATIONS

Two-dimensional, R-Z, geometry transport analyses were made on mockups of cells for each shield location. Flux edits of the neutron distribution in each arrangement were used to obtain axial secondary gamma ray source intensities, spectra, and distributions as well as relative neutron leakage. The two-dimensional transport code, ODD-K,⁽⁸⁾ was run as an inhomogeneous calculation with a fixed source located in the first two mesh intervals within 0.2 cm from the core end of the mockup. An S_4 angular quadrature approximation to the Boltzmann transport equation was employed with a P_1 scattering cross section matrix.

A two-dimensional transport calculation in R-Z geometry was also employed for a single shield configuration (shield below support plate) to obtain fission and secondary gamma source distributions throughout the reactor system including the shield (Configuration I-3-C, Table 2). These calculations were performed by use of the shielding standard design method SSDM-III using the ODD-K and NAGS programs.⁽⁹⁾

2.2 POINT KERNEL CALCULATIONS

Point kernel techniques, employing radiation sources obtained from the NAGS code and adjusted in the regions affected by the shield, were used to calculate the radiation levels of neutrons and gamma rays outside the reactor.

The contributions to the dose rate at 30 feet from core gammas and extra-core gammas for $Z < 144.145$ cm, and extra core gammas for $Z > 144.145$ cm are presented separately for each of the 40 cases studied.

The point kernel code, KAP, was used to calculate external fast neutron and gamma ray dose rates on a polar angle traverse at 30 feet from the core center for 40 shield configurations. The polar angles ranged from 0 degree (forward centerline axis) to 90 degrees (reactor core midplane).

The Albert-Welton kernel in the KAP code was used to obtain fast neutron dose rates in rads-ethylene/hr. Fast neutron fluxes were calculated using the carbon moments data in the monovariant spectra option in the KAP code. Gamma ray calculations employed water dose buildup factors for all materials to obtain dose rates in rads-carbon/hr.

While the point kernel method is limited in its ability to predict spectral changes, it has shown acceptable agreement with previous studies involving transport and Monte Carlo methods, to permit its use for a parametric study of this type. An evaluation of the point kernel method follows, as applied to the NERVA system.

Previous calculations of gamma dose rates external to the reactor using point kernel codes have been acceptably supported by experimental data. Hence, a reasonable degree of certainty is associated with the calculated gamma dose rates. Furthermore, a Monte Carlo calculation of the total gamma dose rate at 0 degree and 90 degrees for the base case of the combined shield-support plate configuration (Case 11-3-C) was only about 20 percent higher than the point kernel result at 0 degree and less than 10 percent higher at 90 degrees.

Fast neutron flux traverses ($E > 0.1$ Mev) were obtained using the infinite media carbon moments data in the neutron monovariant spectra option of the point kernel code. These fluxes may be acceptably accurate at the reactor midplane (90 degrees) for all cases, and at other polar angles only when no hydride shielding is present since use of the non-hydrogenous moments option does not properly treat the neutron spectrum changes which occur in a hydrogenous material (i. e., the hydride shield). However, use of a hydrogenous moments data fit option will not give the proper spectrum in a non-hydrogenous medium. Consequently, the fast neutron fluxes are expected to be too high in areas shielded by the central and peripheral shields.

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Fast neutron dose rates in rads-ethylene/hr were calculated using the modified Albert-Welton kernel option in the point kernel code. These data are felt to be most reliable in regions shielded by the hydride shield but are probably an underestimate in unshielded areas. These fast neutron dose rates were integrated over the solid angle subtended by the central tank and converted to tank heating rates (assuming an average neutron energy of 1 Mev based on transport theory calculated spectra), using the method described in Section 2.3, below. Hence, the neutron heating for unshielded and partially shielded configurations is probably underestimated. The overall effectiveness of the shield in reducing tank heating is also underestimated, but to a lesser extent than the neutron heating because the neutrons contribute less than 23 percent of the total heating in the centered tank.

Some of the limitations of the point kernel technique as presently programmed and applied are now being investigated. It is anticipated that revision in the point kernel technique or development of new analytical techniques will result in some revision of the neutron radiation levels, neutron heating, and total heating data presented in this study. However, these data are believed to be accurate enough for parametric studies of this type.

Sources for the Point Kernel Program

This study utilized a consistent set of source data for the three configurations. Ratios of the source in the shield and support plate for Configuration I to the source in Configurations II and III were obtained. The relative sources calculated in the two-dimensional cell study for Configurations II and III were then normalized, using the above ratios, to absolute values for corresponding regions calculated for the complete reactor.

Gamma ray source data in all reactor regions for the base case "shield-below-support-plate" configuration were obtained from a two-dimensional transport calculation.⁽¹⁰⁾ The same sources were used in each of the 40 configurations studied, for the core and for extra-core regions below the plane of the top of the cluster plate ($Z < 144.145$ cm). Sources in regions affected by the change in shield thickness and compositions; i. e., sources above the plane of the top of the cluster plate ($Z > 144.145$), were obtained by modifying the sources obtained from the basic "shield-below-support-plate" configuration. This modification was done as follows:

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First, a two dimensional transport cell study was performed for the basic "shield-below-support-plate," "combined-shield-support-plate," and "top-shield" configurations, as indicated in Section 3.1. This study provided a consistent set of source data for the three configurations. The shield and support plate sources from the base case "shield below support plate" were multiplied by the ratio of relative integral source strengths in the base case "combined-shield-and-support-plate" configuration and the base case "top-shield" configuration to obtain source strengths for all three basic configurations. Sources thus developed for the support plate and tie tube plenum in the "top-shield" configuration were also used for the cases in which no central shield is present.

For all cases other than the base case in each configuration, the region sources (which would be expected to vary because of the change in shield mass thickness) were obtained by multiplying the sources from the base cases by the ratio of the fast neutron flux (at 30 feet, 0 degrees) for the case in question to the fast neutron flux for the base case. Hence, the assumption was made that the secondary gamma sources above the shield are proportional to the fast neutron flux leakage above the shield.

Additional adjustments were made for regions in which the region volume changes; i.e., side pressure vessel, peripheral shield, central shield, corner plenum region; and regions in which the source spatial distribution is expected to change due to changes in shield geometry; i.e., side pressure vessel, corner plenum region, and peripheral shield.

2.3 APPROXIMATE METHOD FOR PROPELLANT TANK HEATING

Some fraction of the energy incident on the propellant tank is absorbed in the propellant. The total nuclear energy incident on the propellant tank was approximated by integrating the radiation intensity distribution over the solid angle subtended by the propellant tank from the center of the reactor core as follows:

$$q = \sum_i (N\phi_{ni} + G\phi_{\gamma i}) A_i$$

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where:

q = the total nuclear heating rate to the propellant.

N and G = dose to heat conversion factors for neutrons and gammas, respectively.

ϕ_{ni} and $\phi_{\gamma i}$ = neutron and gamma dose rate at a radial distance of 30 feet from core center as a function of the polar angle

i = polar angle interval index

A_i = the projected area of the tank in the i th polar angular interval at a radius of 30 feet

= $2\pi D^2 (\cos \theta_i - \cos \theta_{i-1})$ for the centered tank.

= $2\Delta\theta \alpha D^2$ for the off axis adjacent tank

D = distance from the core center to the meridian ring on which the dose rates are calculated (30 feet or 915 cm)

θ = the polar angle measured from reactor centerline

$\Delta\theta$ = the polar angle increment = $\theta_{i+1} - \theta_i$

α = the azimuthal angle width determined by the points of tangency to the adjacent tank at the polar angle θ

The average neutron energy and total-flux/fast-flux ratio were determined from 8 groups of a 16-group transport calculation in the following manner:

$$\bar{K}(E) = \frac{\sum_{i=1}^8 K_i(E_i) \times \phi(E_i)}{\sum_{i=1}^8 \phi(E_i)}$$

K = neutron flux-to-dose conversion factor

i = flux groups contributing to the dose rate

$\phi(E_i)$ = neutron flux in each energy group i from transport calculation.

$\bar{E}$ is then found from tables or graphs of K versus E .

The ratio of total-to-fast neutrons is simply:

$$\frac{\sum_{i=1}^{16} \phi_i (E > 0)}{\sum_{i=1}^8 \phi_i (E > 0.1 \text{ Mev})}$$

The average fast flux $\bar{\phi}_n$, was assumed to vary with polar angle as the point kernel calculated Albert-Welton dose $\bar{\phi}_n = \frac{D_{A-W}}{K(1.0 \text{ Mev})}$.

Gamma energy absorbed in the propellant tank, wall and LH_2 originating from $\text{LH}_2 (n, \gamma)$ captures was estimated based on assuming an isotropic distribution of capture gamma ray emission and assuming that approximately one half of the energy escapes the tank, since most of the neutron captures occur in much less than a gamma ray relaxation length from the surface of the tank. Hence, the capture gamma energy flux is given as

$$\begin{aligned} Q &= \frac{D_{A-W}}{K(1 \text{ Mev})} \cdot \frac{\phi_{\text{total}}}{\phi_{\text{fast}}} \cdot 2.2 \text{ Mev/cpt} \cdot 0.5 \frac{\text{photon absorbed}}{\text{photon produced}} \\ &= 2.0 \frac{D_{A-W}}{K(1 \text{ Mev})} \text{ Mev/cm}^2\text{-sec} \end{aligned}$$

Adding to this the neutron kinetic heating, one has

$$Q_n = 2 \frac{D_{A-W}}{K(1 \text{ Mev})} + 1 \frac{D_{A-W}}{K(1 \text{ Mev})} = 3 \frac{D_{A-W}}{K(1 \text{ Mev})} \frac{\text{Mev}}{\text{cm}^2 \text{ sec}}$$

The gamma ray dose rate was converted to an energy flux by assuming an average dose-to-flux conversion factor for 1 Mev Photons, of

$$6.26 \times 10^5 \frac{\text{Mev/cm}^2\text{-sec}}{\text{Rad/Hr}}$$

SECTION 3

GEOMETRICAL MODELS

3.1 TRANSPORT MODEL

Relative secondary gamma source strengths and distributions were calculated in a two-dimensional transport study for a cell mockup of three shield-support plate configurations. The three configurations included: (1) shield located below the support plate; (2) shield located above the support plate; (3) combined shield and support plate. In addition, a fourth configuration representing a homogenization of configuration (3) was added to investigate the effect of the heterogeneity of the combined shield-support plate on fast neutron leakage as well as its effect on the secondary gamma source strength and distribution.

The study was performed for a 2.666 cm radius cylindrical "cell" with height approximately equal to the conceptual design thicknesses of the shield-support plate assemblies. In all cases, a hydrogen region was included above the support plate to account for the return of neutrons from the tie tube plenum. In each mockup, an additional radial region was included to account for neutrons which enter a cell from laterally adjacent areas. The geometrical description of the cell mockups for the basic configurations described above are presented in Figure 1. The shield and reactor weights were identical for all configurations in this study.

3.2 POINT KERNEL MODEL

The basic geometrical model and material composition for the NR-1 with shield below the support plate has been previously reported.⁽⁷⁾ No change in the previously reported geometry and material data was made in any region below the plane of the dome end of the core. However, in regions above the plane of the dome end of the core, the following changes were made:

- 1) The shield region in the previously reported model included molybdenum plates and plena at the dome and nozzle end of the shield. These materials were not included in the model used in the present study. Instead, there is a 3.81 cm void in this region.

- 2) The peripheral shield was moved closer to the core since Mechanical Design repositioned the ganged drive mechanism above this shield. (Since this study was completed, the configuration has been reversed again in design studies now in progress.)
- 3) The drum drive shaft region was reduced in volume to occupy the space between the reflector and the new location of the peripheral shield.

Figure 2 presents the model description for the base case with the shield below the support plate (Case I-3-C). Variation in the central shield and peripheral shield thicknesses was accomplished by varying the dome end axial boundaries of these regions. The thicknesses of regions above the central shield were held constant for all central shield thicknesses. The drive shaft plenum region was exchanged for the required peripheral shield.

Figure 3 presents the base case configuration for the combined shield-support plate (Case II-3-C). Variations in this basic configuration were made by varying the thickness of the combined shield support-plate ($1/2$ and $1-1/2$ times the base thickness) while assuming the composition remained unchanged for each thickness. The peripheral shield was varied by changing its density ($1/2$ and 2 times the base density) while assuming the thickness to remain constant. In cases for which the peripheral shield is absent, the plenum region above the peripheral shield in the base configuration was extended to replace the peripheral shield, but the density of this plenum region was not changed.

Figure 4 presents the base case configuration for the top shield design (Case III-3-C). The shields for this case have the same central region thickness as in the shield below support plate cases. However, a single step was included in the region above the peripheral shield in the geometrical mockup of the shield to approximate possible tailoring of the shield to conform to the curvature of the vessel closure. The height of this outer portion of the central top shield was made equal to half of the axial thickness of the central shield. As in the combined shield-support plate cases, the peripheral shield was varied by changing the density.

3.3 SHIELD WEIGHTS AND REACTOR WEIGHT INCREMENTS FOR VARIOUS CASES STUDIED

Table 2 presents the shield weights and reactor weight increments for each of the forty cases studied. The reactor weight increment is defined as the shield weight plus the

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change in reactor weight resulting from changing the shield design from the base case. Included are the weight of the shield, change in length of the vessel and core support structures, and change in peripheral region material.

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SECTION 4

RESULTS OF CALCULATIONS

4.1 TRANSPORT RESULTS

4.1.1 Heterogeneous Effects of Combined Shield-Support Plate on Fast Neutron Leakage

Fast neutron fluxes for $E > 0.1$ Mev were obtained as a function of cell radius at $Z = 43.8$ cm; i.e., at a position in the hydrogen plenum 7.5 cm above the top of the shield-support plate assembly. The two-dimensional transport results for the heterogeneous model were 14 percent higher than the similar results for the homogeneous case on the axis of the cell at this elevation. However, the area averaged fast flux was only three percent higher for the heterogeneous model than for the homogeneous model at this elevation.

The increase in fast neutron leakage in the heterogeneous vs. the homogeneous model as predicted by the two-dimensional transport cell study was small compared to the uncertainties in the point kernel calculations of external radiation environment. Hence, a homogeneous shield-support plate was considered acceptable in the point kernel model, and a correction to point kernel fast flux data to account for shield-support plate heterogeneity was regarded as unnecessary.

The foregoing conclusion may require further study if a support plate-shield of different geometry is considered. For example, if the degree of heterogeneity of the combined shield-support plate is increased due to larger or wider spaced shield inserts or if the shield-support plate thickness is substantially increased over the 36 cm considered here, then the effect of heterogeneity may have to be re-evaluated.

4.1.2 Photon Source Strengths and Distributions

Relative axial source distributions derived from the 2-D Cell study are presented in Figures 5, 6, and 7, for the combined shield-support plate, shield below support plate, and top shield configurations, respectively. Relative source strengths for the three basic configurations and the heterogeneous case are presented as ratios in Table 3. The absolute magnitudes of the shield and support plate sources, shown in Table 4, were obtained by applying the ratios

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from Table 2 to the shield and support plate sources previously published for NR-1 (this is discussed further in Section 2.2).

4.2 POINT KERNEL RESULTS FOR EXTERNAL RADIATION ENVIRONMENT

The effect of NR-1 shield configuration on the external radiation environment is shown in Figures 8 through 47. These figures present a consistent set of data which may be integrated over the solid angle subtended by the propellant tanks as measured from core center to obtain first order estimates of tank heating. The data are consistent in the sense that a consistent method, reactor model, and shield material were employed.

All of the radiation environment data given in Figures 8 through 47 are full power (5000 MW) normalized polar angle traverses at a radius of 30 feet from the geometric center of the reactor core.

Each figure is constructed to present the fast neutron data on the upper part of the figure and to present the gamma ray data on the lower part of the figure. A sketch of the dome end portion of the reactor model is included as an insert on each figure to identify the shield configuration. These sketches are not to scale and omit most of the detail included in the calculational model.

Fast neutron dose rates in units of rads (ethylene)/hr are presented for all configurations. Fast neutron flux (carbon moments) for $E > 0.1$ Mev are presented for most configurations.

Gamma ray dose rates in rads (carbon)/hr are presented as three components plus the total which includes all important reactor primary and secondary sources.

Figures 8 through 23 present data for the shield below the support plate configurations. Figures 24 through 35 present data for the combined shield-support plate configurations, and Figures 36 through 47 present data for the top shield configurations.

The case number designations in Figures 8 through 47 and Table 2 indicate the shield configurations. The description is in three parts:

- 1) Location--Roman numeral
- 2) Central shield thickness--Arabic number
- 3) Peripheral shield axial thickness--Letter

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The locations are:

- I) Central shield below the support plate
- II) Central shield combined with support plate
- III) Central shield above the support plate

Central shield thicknesses are:

$$1 = 0.0$$

$$2 = 17.9 \text{ g/cm}^2 \text{ for I and III; } 42.9 \text{ g/cm}^2 \text{ for II or } -7.0 \text{ g/cm}^2 \text{ shield only}^*$$

$$3 = 35.8 \text{ g/cm}^2 \text{ for I and III; } 85.8 \text{ g/cm}^2 \text{ for II or } 35.9 \text{ g/cm}^2 \text{ shield only}$$

$$4 = 71.6 \text{ g/cm}^2 \text{ for I and III; } 128.7 \text{ g/cm}^2 \text{ for II or } 78.8 \text{ g/cm}^2 \text{ shield only}$$

Peripheral shield axial thicknesses are:

$$A = 0.0 \text{ g/cm}^2$$

$$B = 21.64 \text{ g/cm}^2$$

$$C = 43.29 \text{ g/cm}^2$$

$$D = 86.58 \text{ g/cm}^2$$

4.3 PROPELLANT HEATING RESULTS

The nuclear heating rate in the propellant tank is taken to be the rate of absorption of that energy which is contained in the solid angle subtended by the propellant tank measured from the center of the reactor core. The fast neutron and gamma ray dose rates presented for the forty shield configurations (see Figures 8 through 47) were integrated over the solid angle subtended by the central tank. The resulting integral dose rates were converted to heating rates as described in Section 3.3 and are presented in the following tables and figures.

The nuclear heating rate in the solid angle subtended by the propellant tanks is plotted in Figures 48 through 54 for the several different shield configurations. The points indicated by "A" are values for the central shield only, the B's, C's, and D's refer to different weights of the peripheral shield.

*Configuration II values are for a combined shield-support plate combination. Thus for this case, if a standard support plate weight of 49.9 g/cm^2 is subtracted, the shield weight must be a negative (physically impossible) value.

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SECTION 5

DISCUSSION OF RESULTS

Figures 48 through 54 show propellant heating rates as a function of reactor weight measurements as the shield arrangements are varied. Each numbered curve of the families is for a constant central shield with the letters representing different peripheral shields. For example, "A" represents central shields with no peripheral shield; "B" represents 488 pound peripheral shield for each numbered central shield; etc.

5.1 IMPORTANCE OF PERIPHERAL SHIELDS

It can be easily seen (Figure 48) that the vertical extension (peripheral) shield offers no weight advantage for reducing propellant heating in a single module if the central shield is located above the support plate. However, for all other shield configurations (Figures 49 through 54) with shields greater than 1000 pounds for both single and clustered modules, the peripheral shield is required to achieve a minimum weight for a given attenuation of propellant heating.

5.2 MINIMUM SHIELD WEIGHT FOR PROPELLANT HEATING

The minimum reactor weight increment required to achieve a given heating rate is shown by the solid line on Figures 48 through 54. Figures 55 through 57 show only these (minimum weight) envelopes. A distinct 1000 pound disadvantage may be seen for the shield located above the support plate, as previously predicted.⁽⁶⁾

The difference between the propellant heating rates with the central shield in or below the support plate is small. Part of this difference may be due to differences in source strengths. The difference in secondary gamma source contribution between the combination support plate-shield and shield below the support plate may be due to the presence of capture-gamma-suppressing boron in the top of the support plate-shield combination (Table IV). Some of the difference may also be due to the smaller mass of aluminum structure for supporting the core. For this study, no reduction in support plate thickness or weight was made for the reduced heating in the support plate with the shield located between it and the core. This adjustment

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is expected to be up to about 1.5 inches for thick shields, of which only a part needs to be replaced by the more effective shield material as was done in the combined shield-support plate arrangement.

5.3 LIMITATIONS ON SHIELD-SUPPORT PLATE COMBINATION

Some of the cases considered for the shield-support plate combination are not mechanically possible because a certain minimum structure is required to support the core. In some instances, subtracting this minimum structure weight from the homogenized shield-support plate weight resulted in negative shield weights. This situation exists in the curves representing central shield configuration 2 in Figures 49 and 52. Further, central shield weights below 900 pounds were not considered because shield insert volumes less than 1/3 of the total shield-support plate solid volume were considered too heterogeneous to provide adequate shielding.

5.4 COMPARISON WITH PREVIOUS STUDIES

Propellant heating rates presented here for the 2,345 pound shield (Case I-3-C) were compared with those for a 4,100 pound BeO-Al shield⁽⁴⁾ which the former is intended to replace. The propellant heating given⁽⁴⁾ was based on the solid angle integral of 10 foot meridian ring data. Comparison of integral propellant heating based on 10- and 30-foot polar traverses showed the former heating to be about 60 KW lower than the 30-foot data. The Inconel reactor vessel contributes an additional 70 KW over that of an aluminum vessel. This would make the adjusted heating $317 - (60 + 70) = 187$ KW compared to the previous value⁽⁴⁾ of 156 KW. These adjustments bring the present values to about 15 percent of the previous estimates. Most other reactor differences, such as cluster plate, shield material, and location changes were taken into account.⁽⁶⁾

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SECTION 6 CONCLUSIONS

Of the three locations considered for the NR-1 flight shield (below, in, and above the core support plate), the shield below the support plate allows the greatest range of attenuations. This position allows:

- 1) Maximum polar angular coverage
- 2) Minimum secondary gamma ray production in the reactor
- 3) Maximum protection for clustered propellant tanks
- 4) Maximum radiation protection for other reactor components, i.e., seals, drum drives, etc.

These factors are dependent on position, not weight, though within the attenuation range that can be covered by any location considered, the position below the support plate offers minimum or near minimum weight. The shield-support plate combination is limited in minimum shield weight and maximum shield insert volume fraction. It is felt that the small weight advantage of this arrangement is more than offset by its disadvantages in flexibility and the unique advantages of the shield located below the support plate.

From the various combinations of central and peripheral shields studied, a peripheral shield is necessary, for shields greater than 1000 pounds, to achieve minimum shield weight for a given propellant nuclear heating rate. Central shields alone do not provide the optimum configuration for either single or clustered propellant tank configurations.

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SECTION 7

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TABLE 1

ADVANTAGES AND DISADVANTAGES OF ALTERNATE SHIELD LOCATIONS

Shield Location	Advantages	Disadvantages
Below (aft of) core support plate	<ul style="list-style-type: none"> • Near minimum weight • Low secondary gamma production in regions in and above shield (shield contribution suppressed with boron) • Protects support plate <ol style="list-style-type: none"> a) in loss of flow accident b) from high heating rate c) from high secondary gamma production • Mates with ID of peripheral shield thus providing more complete angular coverage and preventing "streaming" of radiation 	<ul style="list-style-type: none"> • Maximum radiation effects in shield • Maximum heating in shield • Mechanically complex • Most severe on shield material selection • Variation in attenuation requires adjustment of support structure and tie tubes
Combined with core support plate	<ul style="list-style-type: none"> • Minimum weight over narrow attenuation range • Low secondary gamma production in regions in and above shield (shield contribution suppressed with boron) • Mechanical simplicity 	<ul style="list-style-type: none"> • Over-diluted with Al structure for thin or thick central shields • Severe on material selection • High heating rate • High radiation effects • Design is relatively inflexible
Above (forward of) the core support system	<ul style="list-style-type: none"> • Least severe radiation environment • Widest range of allowable shield materials • Most flexible for shield redesign 	<ul style="list-style-type: none"> • Maximum weight (estimate ~1000 lb penalty over below-support-plate design) • Additional shield may be required to protect flange • Maximum radiation environment on major structural members-support plate, flange, tie tube plena • Highest external radiation levels for given shield weight • High secondary gamma ray production in regions above core • Minimum polar angular coverage for given shield weight

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TABLE 2

SHIELD WEIGHTS AND REACTOR WEIGHT INCREMENTS (IN LBS.)

Case No.	Central Shield Weight	Peripheral Shield Weight	Total Shield Weight	Reactor Weight Increment	Case No.	Central Shield Weight	Peripheral Shield Weight	Total Shield Weight	Reactor Weight Increment ++
I-1-A*	0	0	0	0	II-3-A	1375	0	1375	1480
I-1-B	0	488	488	467	II-3-B	1375	488	1863	1964
I-1-C	0	975	975	933	II-3-C+	1375	975	2351	2452
I-1-D	0	1950	1950	1866	II-3-D	1375	1950	2839	3430
I-2-A	664	0	664	757	II-4-A	3025	0	3025	3294
I-2-B	664	488	1173	1224	II-4-B	3025	488	3507	3779
I-2-C	664	975	1662	1690	II-4-C	3025	975	3996	4267
I-2-D	664	1950	2634	2625	II-4-D	3025	1950	4975	5245
I-3-A	1370	0	1368	1515	III-2-A	892	0	892	906
I-3-B	1370	488	1857	1981	III-2-B	892	488	1380	1395
I-3-C+	1370	975	2345	2448	III-2-C	892	975	1868	1882
I-3-D	1370	1950	3320	3381	III-2-D	892	1950	2844	2858
I-4-A	2740	0	2740	3038	III-3-A	1785	0	1785	1812
I-4-B	2740	488	3228	3496	III-3-B	1785	488	2273	2300
I-4-C	2740	975	3715	3961	III-3-C+	1785	975	2760	2788
I-4-D	2740	1950	4690	4896	III-3-D	1785	1950	3737	3764
II-2-A**					III-4-A	3568	0	3568	3624
II-2-B**					III-4-B	3568	488	4037	4114
II-2-C**					III-4-C	3568	975	4524	4601
II-2-D**					III-4-D	3568	1950	5500	5577

*The case number designation indicates the exact nature of the shield configuration as follows:

The first symbol (Roman numeral I, II, or III) indicates the location of the shield, i. e.,

I = Central shield below support plate

II = Central shield combined with support plate

III = Central shield above support plate

The second symbol (Arabic number 1, 2, 3, or 4) indicates the thickness of the central shield.

1 = No central shield

2 = 1/2 Reference shield

3 = Reference shield (mass thickness of 43.4 g/cm^2)

4 ~ 2 x the reference shield

A = No peripheral shield

B = Light peripheral shield

C = Medium peripheral shield

D = Heavy peripheral shield

**II-2 Not mechanically possible

+ Base case for each shield location

++ Includes reactor structural weight
increment

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TABLE 3

COMPARISON OF SECONDARY GAMMA SOURCE STRENGTHS
FOR THREE SHIELD CONFIGURATIONS

Source Strength Ratio

$$\frac{\text{Shield Source (Top Shield Configuration)}}{\text{Shield Source (Shield Below Support Plate)}} = 0.172$$

$$\frac{\text{Support Plate Source (Top Shield Configuration)}}{\text{Shield Source (Shield Below Support Plate)}} = 19.1$$

$$\frac{\text{Homogenized Shield Support Plate Source}}{\text{Shield Source (Shield Below Support Plate)}} = 0.95$$

$$\frac{\text{Heterogeneous Shield Support Plate Source}}{\text{Homogeneous (Shield Support Plate Source)}} = 1.01$$

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TABLE 4

ABSOLUTE SOURCE STRENGTHS FOR THREE SHIELD CONFIGURATIONS

<u>Configuration No.</u>	<u>Description</u>	<u>Shield Source</u>	<u>Support Plate Source</u>
1	Shield Below Support Plate	1.79(19) Mev/sec	2.02(18) Mev/sec
2	Top Shield Configuration	3.09(18) Mev/sec	3.85(19) Mev/sec
3	Combined Shield-Support Plate (Heterogeneous)	1.72(19) Mev/sec	
4	Combined Shield-Support Plate (Homogeneous)	1.70(19) Mev/sec	

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TABLE 5

HEATING IN A SINGLE MODULE PROPELLANT TANK FOR
VARIOUS SHIELD CONFIGURATIONS

Heating Rates-KW											
<u>Case</u>	<u>Gamma</u>	<u>Neutron</u>	<u>Total</u>	<u>Case</u>	<u>Gamma</u>	<u>Neutron</u>	<u>Total</u>	<u>Case</u>	<u>Gamma</u>	<u>Neutron</u>	<u>Total</u>
I-1-A	1043	157	1200	} →	Peripheral shield only for all 0.0 central shields						
I-1-B	976	143	1119								
I-1-C	947	131	1078								
I-1-D	877	115	992								
I-2-A	465	117	582	II-2-A	762	150	912	III-2-A	698	82	780
I-2-B	412	99	511	II-2-B	640	163	803	III-2-B	645	71	716
I-2-C	370	86	456	II-2-C	580	148	728	III-2-C	602	64	666
I-2-D	320	68	388	II-2-D	560	148	708	III-2-D		59	
I-3-A	360	80	440	II-3-A	354	56	409	III-3-A	469	51	520
I-3-B	317	64	381	II-3-B	284	52	446	III-3-B	540	42	472
I-3-C+	263	54	317	II-3-C+	236	41	277	III-3-C+	411	37	448
I-3-D	220	41	261	II-3-D	204	33	237	III-3-D	376	33	409
I-4-A	300	47	347	II-4-A	261	36	297	III-4-A	257	22	279
I-4-B	220	33	253	II-4-B	193	29	222	III-4-B	216	16	232
I-4-C	160	22	182	II-4-C	155	20	175	III-4-C	212	10	222
I-4-D	140	11	151	II-4-D	125	13	138	III-4-D	256	9	202

+ Base case for each shield location

TABLE 6

HEATING IN CENTRAL PROPELLANT TANK OF A THREE MODULE CLUSTER
FOR VARIOUS SHIELD CONFIGURATIONS

Case	Total Heating Rate KW	Case	Total Heating Rate KW	Case	Total Heating Rate
I-1-A	2667				
I-1-B	2478				
I-1-C	2307	(Same as I-1 -)		(Same as I-1 -)	
I-1-D	2127				
I-2-A	1726	II-2-A	2087	III-2-A	2045
I-2-B	1459	II-2-B	1846	III-2-B	1816
I-2-C		II-2-C	1656	III-2-C	1603
I-2-D	1212	II-2-D	1560	III-2-D	1296
I-3-A	1541	II-3-A	1528	III-3-A	1649
I-3-B	1277	II-3-B	1248	III-3-B	1455
I-3-C+	1110	II-3-C+	1093	III-3-C+	1350
I-3-D	1051	II-3-D	982	III-3-D	1280
I-4-A	1373	II-4-A		III-4-A	1280
I-4-B	1120	II-4-B	1101	III-4-B	1177
I-4-C	983	II-4-C	996	III-4-C	1056
I-4-D	910	II-4-D	866	III-4-D	974

+ Base case for each configuration

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TABLE 7

HEATING IN THE OUTBOARD PROPELLANT TANK OF A THREE MODULE
CLUSTER* FOR VARIOUS SHIELD CONFIGURATIONS

<u>Case</u>	<u>Heating Rate --KW</u> <u>Total</u>
I-1-A	1934
I-1-B	1799
I-1-C	1692
I-1-D	1560
I-2-A	1152
I-2-B	984
I-2-C	799
I-2-D	
I-3-A	990
I-3-B	824
I-3-C+	709
I-3-D	655
I-4-A	850
I-4-B	682
I-4-C	590
I-4-D	533

*Heating from one adjacent + central reactor; far reactor, contributing 2-5%⁽⁴⁾, was neglected.

+ Base case for Configuration I

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CONFIGURATION	DESCRIPTION
1	SHIELD BELOW SUPPORT PLATE MODEL
2	TOP SHIELD MODEL
3	HETEROGENEOUS MODEL OF COMBINED SHIELD-SUPPORT PLATE
4	HOMOGENEOUS MODEL OF COMBINED SHIELD-SUPPORT PLATE

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Figure 1. Geometrical Models for 2-D Transport Cell Study of NR-1 Shield Configurations

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Figure 2. Basic Configuration, Shield Below Support Plate

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612176-3B

Figure 3. Basic Configuration, Combined Shield-Support Plate

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Figure 4. Basic Configuration, Shield Above Support Plate

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Figure 5. Average Axial Gamma Source Distributions, 2-D Transport Cell Study, Combined Shield-Support Plate (Configurations 3 and 4)

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Figure 6. Average Axial Gamma Source Distributions, 2-D Transport Cell Study, Shield Below Support Plate (Configuration 1)

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Figure 7. Average Axial Gamma Source Distributions, 2-D Transport Cell Study, Shield Above Support Plate (Configuration 2)

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Figure 8. NR-1 Shield Location and Thickness Study, Shield Below Support Plate Configuration--Case I-1-A

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Figure 9. NR-1 Shield Location and Thickness Study, Shield Below Support Plate Configuration, (Polar Traverses at 30 ft from the Core Center)--Case I-1-A

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Figure 10. NR-1 Shield Location and Thickness Study, Shield Below Support Plate Configuration, (Polar Traverses at 30 ft from the Core Center)--Case I-1-C

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Figure 11. NR-1 Shield Location and Thickness Study, Shield Below Support Plate Configuration, (Polar Traverses at 30 ft from the Core Center)--Case I-1-D

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Figure 12. NR-1 Shield Location and Thickness Study, Shield Below Support Plate Configuration, (Polar Traverses at 30 ft from the Core Center)--Case I-2-A

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Figure 13. NR-1 Shield Location and Thickness Study, Shield Below Support Plate Configuration, (Polar Traverses at 30 ft from the Core Center)--Case I-2-B

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Figure 14. NR-1 Shield Location and Thickness Study, Shield Below Support Plate Configuration, (Polar Traverses at 30 ft from the Core Center)--Case I-2-C

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Figure 15. NR-1 Shield Location and Thickness Study, Shield Below Support Plate Configuration, (Polar Traverses at 30 ft from the Core Center)--Case I-2-D

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Figure 16. NR-1 Shield Location and Thickness Study, Shield Below Support Plate Configuration, (Polar Traverses at 30 ft from the Core Center)--Case I-3-A

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Figure 17. NR-1 Shield Location and Thickness Study, Shield Below Support Plate Configuration, (Polar Traverses at 30 ft from the Core Center)--Case I-3-B

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Figure 18. NR-1 Shield Location and Thickness Study, Shield Below Support Plate Configuration, (Polar Traverses at 30 ft from the Core Center)--Case 1-3-C

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Figure 19. NR-1 Shield Location and Thickness Study, Shield Below Support Plate Configuration, (Polar Traverses at 30 ft from the Core Center)--Case I-3-D

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Figure 20. NR-1 Shield Location and Thickness Study, Shield Below Support Plate Configuration, (Polar Traverses at 30 ft from the Core Center)--Case I-4-A

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Figure 21. NR-1 Shield Location and Thickness Study, Shield Below Support Plate Configuration, (Polar Traverses at 30 ft from the Core Center)--Case I-4-B

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Figure 22. NR-1 Shield Location and Thickness Study, Shield Below Support Plate Configuration, (Polar Traverses at 30 ft from the Core Center)--Case I-4-C

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Figure 23. NR-1 Shield Location and Thickness Study, Shield Below Support Plate Configuration, (Polar Traverses at 30 ft from the Core Center)--Case I-4-D

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Figure 24. NR-1 Shield Location and Thickness Study, Shield Below Support Plate Configuration, (Polar Traverses at 30 ft from the Core Center)--Case II-2-A

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Figure 25. NR-1 Shield Location and Thickness Study, Combined Shield-Support Plate Configuration, (Polar Traverses at 30 ft from the Core Center)--Case II-3-A

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Figure 26. NR-1 Shield Location and Thickness Study, Combined Shield-Support Plate Configuration, (Polar Traverses at 30 ft from the Core Center)---Case II-4-A

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Figure 27. NR-1 Shield Location and Thickness Study, Combined Shield-Support Plate Configuration, (Polar Traverses at 30 ft from the Core Center)--Case II-2-B

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Figure 28. NR-1 Shield Location and Thickness Study, Combined Shield-Support Plate Configuration, (Polar Traverses at 30 ft from the Core Center)--Case II-2-C

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Figure 29. NR-1 Shield Location and Thickness Study, Combined Shield-Support Plate Configuration, (Polar Traverses at 30 ft from the Core Center)--Case II-2-D

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Figure 30. NR-1 Shield Location and Thickness Study, Combined Shield-Support Plate Configuration, (Polar Traverses at 30 ft from the Core Center)--Case II-3-B

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Figure 31. NR-1 Shield Location and Thickness Study, Combined Shield-Support Plate Configuration, (Polar Traverses at 30 ft from the Core Center)--Case II-3-C

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Figure 32. NR-1 Shield Location and Thickness Study, Combined Shield-Support Plate Configuration, (Polar Traverses at 30 ft from the Core Center)--Case II-3-D

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Figure 33. NR-1 Shield Location and Thickness Study, Combined Shield-Support Plate Configuration, (Polar Traverses at 30 ft from the Core Center)--Case II-4-B

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Figure 34. NR-1 Shield Location and Thickness Study, Combined Shield-Support Plate Configuration, (Polar Traverses at 30 ft from the Core Center)--Case II-4-C

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Figure 35. NR-1 Shield Location and Thickness Study, Combined Shield-Support Plate Configuration, (Polar Traverses at 30 ft from the Core Center)--Case II-4-D

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Figure 36. NR-1 Shield Location and Thickness Study, Top Shield Configuration, (Polar Traverses at 30 ft from the Core Center)--Case III-2-A

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Figure 37. NR-1 Shield Location and Thickness Study, Top Shield Configuration, (Polar Traverses at 30 ft from the Core Center)--Case III-2-B

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Figure 38. NR-1 Shield Location and Thickness Study, Top Shield Configuration, (Polar Traverses at 30 ft from the Core Center)--Case III-2-C

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Figure 39. NR-1 Shield Location and Thickness Study, Top Shield Configuration, (Polar Traverses at 30 ft from the Core Center)--Case III-2-D

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Figure 40. NR-1 Shield Location and Thickness Study, Top Shield Configuration, (Polar Traverses at 30 ft from the Core Center)--Case III-3-A

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Figure 41. NR-1 Shield Location and Thickness Study, Top Shield Configuration, (Polar Traverses at 30 ft from the Core Center)--Case III-3-B

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Figure 42. NR-1 Shield Location and Thickness Study, Top Shield Configuration, (Polar Traverses at 30 ft from the Core Center)--Case III-3-C

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Figure 43. NR-1 Shield Location and Thickness Study, Top Shield Configuration, (Polar Traverses at 30 ft from the Core Center)--Case III-3-D

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Figure 44. NR-1 Shield Location and Thickness Study, Top Shield Configuration, (Polar Traverses at 30 ft from the Core Center)--Case III-4-A

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Figure 45. NR-1 Shield Location and Thickness Study, Top Shield Configuration, (Polar Traverses at 30 ft from the Core Center)--Case III-4-B

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Figure 46. NR-1 Shield Location and Thickness Study, Top Shield Configuration, (Polar Traverses at 30 ft from the Core Center)--Case III-4-C

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Figure 47. NR-1 Shield Location and Thickness Study, Top Shield Configuration, (Polar Traverses at 30 ft from the Core Center)--Case III-4-D

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Figure 48. Incident Nuclear Heating Rate in a Single-Module Propellant Tank vs Reactor Weight Increment (Shield Above Support Plate)

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Figure 49. Incident Nuclear Heating Rate in a Single-Module Propellant Tank vs Reactor Weight Increment

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Figure 50. Incident Nuclear Heating Rate in a Single-Module Propellant Tank vs Reactor Weight Increment (Shield Below Support Plate)

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Figure 51. Incident Nuclear Heating Rate in the Central Tank of a 3-Module Cluster vs Reactor Weight Increment (Shield Combined with Support Plate)

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Figure 52. Incident Nuclear Heating Rate in the Central Tank of a 3-Module Cluster vs Reactor Weight Increment

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Figure 53. Incident Nuclear Heating Rate in the Central Tank of a 3-Module Cluster vs Reactor Weight Increment (Shield Below Support Plate)

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Figure 54. Incident Nuclear Heating Rate in the Outboard Tank of a 3-Module Cluster vs Reactor Weight Increment (Shield Below Support Plate)

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Figure 55. Incident Nuclear Heating Rate in a Single-Module Propellant Tank
(Minimum Reactor Weight Increment).

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Figure 56. Incident Nuclear Heating Rate in the Central Tank of a 3-Module Cluster
(Minimum Reactor Weight Increment)

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Figure 57. Incident Nuclear Heating Rate Shield Below Support Plate
(Minimum Reactor Weight Increment)

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Figure 58. 5000 MW NR-1, Gamma Dose Rate from Several Reactor Regions, No Shield

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Figure 59. 5000 MW NR-1, Gamma Dose Rate from Several Reactor Regions, Central Shield Only (1370 lbs)

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Figure 60. 5000 MW NR-1, Gamma Dose Rate from Several Reactor Regions, Central and Peripheral Shields (1370 + 975 lbs)

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APPENDIX A

GAMMA RADIATION LEVELS FROM SEVERAL REACTOR COMPONENTS

The breakdown of major contributors to the gamma radiation levels at 30 feet as a function of polar angle as given in Figures 58 through 60, show that major portions of the shielded propellant heat comes from the core, reflector and pressure vessel. Because the vessel wall is outside the radius of the shield, its radiation contribution is not attenuated by the flight shield inside the reactor vessel. With the shield below the support plate (configuration 1-3-C), the Inconel vessel is responsible for over 25 percent and 12 percent of the propellant gamma heating in a central and off-axis module, respectively (Figure 60).

These data are presented to show which reactor source regions and polar angles are affected by the shield.

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