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A one-dimensional shield optimization program based on the method of discrete ordinates has been developed and is used to determine material thicknesses used in asymmetric 4π shields for space power reactors. The two-dimensional discrete ordinates program DOT is used to check the design and the information generated in the DOT calculation is used as a guide in shaping the shield which may be considered a first step in two-dimensional shield optimization.

Introduction

The design of space reactor shields based on minimum weight for a specified set of dose constraints is important for obvious reasons. A one-dimensional shield optimization program, ASOP (ref. 1), has been developed and is used in conjunction with the two-dimensional discrete ordinates program, DOT (ref. 2), for the design of such shields. The next section describes briefly the ASOP optimization technique and the last section discusses the process of combining the results of two or more ASOP calculations in a 4π shield design and the significant weight savings which have been obtained using results of DOT calculations of the 4π shield.

The ASOP Technique

Most methods available for shield design or optimization based on minimum weight and specified dose constraints require analytic functions to describe the radiation transport through the shield and use complex mathematical methods to effect the weight optimization. To adequately describe the effects of spectral shifts in transition regions near interfaces and the production of secondary gamma rays the analytic function must be quite complex. Typically coefficients must be determined for each of the several sources of neutron and gamma radiation. These coefficients are usually derived from many separate transport calculations and must, or should, be reevaluated for each significant change in shield configuration. It was felt that a better, more general approach would be to include the transport calculations directly in the optimization process and, therefore, calculate precisely the radiation transport in the shield for each change in configuration.

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Recent advances in technique have caused the discrete ordinates method to become widely accepted as a tool for performing deep penetration or shield--ing calculations. Two developments in particular made the method attractive for a shield optimization program where repetitive calculations of both neutron and gamma-ray transport are required. First the technique of space-dependent scaling (ref. 3) has significantly accelerated the convergence of the inner iterations or flux calculation, and second, the development of combined neutron and gamma-ray multigroup cross section sets (ref. 4) has made simultaneous neutron-gamma-ray calculations routine.

The optimization technique is relatively simple. If one considers the design of a shield composed of layers of different materials, the derivative of the dose at some external point with respect to the shield weight may be determined at each material interface. If the dose-weight derivatives are different at two or more boundaries, it is possible to move those boundaries such that the dose remains constant and the net shield weight decreases. If all dose-weight derivatives are equal this process is not possible and the shield weight is at least at a relative minimum. It is this condition of everywhere equal dose-weight derivatives which forms the basis of the ASOP technique.

Equations (1) and (2) describe the local approximations used in the ASOP program. First, for small perturbations the logarithm of the dose is approximated as a linear function of each material boundary position, r_i ,

$$\ln D = \sum_i A_i r_i + B \quad (1)$$

Second, the dose-weight derivative at each boundary is approximated as a linear function of the position of that boundary.

$$(\Delta D / \Delta W)_i = E_i r_i + F_i \quad (2)$$

In order to determine these coefficients for each ASOP iteration an automated series of ANISN (ref. 5) calculations is performed including the initial configuration and two displacements of each movable shield boundary. The set of $n+1$ equations (3) may then be solved for a new set of boundary positions, r_1 through r_n . The solution attempts to maintain the dose at some design level, D^d , and also produce a configuration in which all the dose-weight derivatives are equal to λ , which is the $(n+1)^{th}$ unknown. The superscript zero denotes conditions of the initial configuration.

$$\begin{aligned}
 A_1 r_1 + A_2 r_2 + \dots + A_n r_n &= \ln(D^d/D^0) + \sum_i A_i r_i^0 \\
 E_1 r_1 &-\lambda = -F_1 \\
 E_2 r_2 &-\lambda = -F_2 \\
 &\vdots \\
 E_n r_n &-\lambda = -F_n
 \end{aligned}
 \quad (3)$$

Since the new boundary positions may involve perturbations for which the approximations in Equations (1) and (2) are not accurate, the entire process is repeated with the new r_i 's as the initial configuration. Convergence of both the dose and dose-weight derivatives is usually obtained after three to five such cycles of calculation.

Asymmetric Shield Design

4π shields for space power reactors are typically asymmetric because in the interest of conserving shield weight there are relatively large differences in the crew dose requirements and in the dose requirements outside the crew quarters which allow docking maneuvers or other extra-vehicular activities. If mission requirements such as power, dose constraints, and system configuration are well defined, an ASOP calculation may be performed for each of the separate dose constraints and the resulting material thicknesses combined, with some intuition, in a three-dimensional shield. The symmetry of the shield usually permits a detailed calculation with DOT in two-dimensional R-Z geometry. In general, however, mission requirements are not well defined and a set of survey calculations is performed with ASOP covering a wide range of dose rate to power level ratios. Figure 1 shows the results of such a survey for a two-cycle, tungsten-lithium hydride crew shield. Material

thickness is plotted versus the dose rate to power level ratio for a crew-reactor separation distance of one hundred feet. With curves of this type for each separate anticipated dose constraint, it is possible to compute weights for a variety of shield configurations as a function of power level, dose constraints, crew-reactor separation distance, size of crew quarters, etc. Variation of shield weight may then be considered in determining the final system configuration.

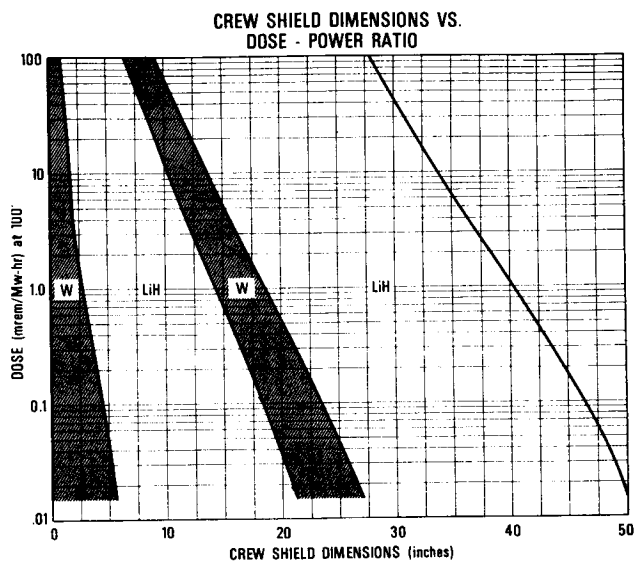


FIGURE 1.- Crew Shield Dimensions vs. Dose-Power Ratio.

The relative merits of any shield designed from several one-dimensional calculations are determined from a DOT calculation of the complete shield as mentioned previously. The DOT calculations of two specific shields will be discussed. Figures 2 and 3 show respectively neutron and gamma-ray isodose contours obtained from a DOT calculation of a tungsten-lithium hydride shield. The reactor assembly -- in the rectangular region centered at $r = 0$ and $z = 0$ -- is the zirconium hydride reference reactor similar in design to the SNAP-8. The relatively thin bands in the thickest portion of the shield are tungsten and the remainder of the shield is lithium hydride. The reactor power is 600 kWt and the dose constraints on a 100-ft radius sphere are 6 mrem/hr within the 60° cone angle of the thick portion of the shield and 100 rem/hr elsewhere. The material thicknesses were determined from ASOP calculations and the absence of tungsten

around the side and top of the reactor is due to the relatively high 100 rem/hr dose constraint. The DOT calculation indicated that the shield met or exceeded the dose constraints.

In general the isodose contours are plotted for each factor of ten decrease in dose through the shield but it is the shape of the contour, rather than the magnitude, which is important in this discussion. It should be noted that the sporadic shape of the contours near the shield surface is due primarily to mesh effects in the calculation since diagonal and curved lines must be represented by a series of rectangular steps. This effect is most pronounced when the dose gradients are very flat causing increased uncertainty in the location of the isodose lines. It appeared obvious from figure 2 that the lithium hydride at the bottom of the core could be trimmed to conform to the last neutron isodose contour without sacrificing the dose constraint within the cone angle. Because there is relatively little attenuation of gamma rays in lithium hydride the same reasoning seemed appropriate with respect to the last gamma-ray isodose contour completely contained in the last tungsten layer.

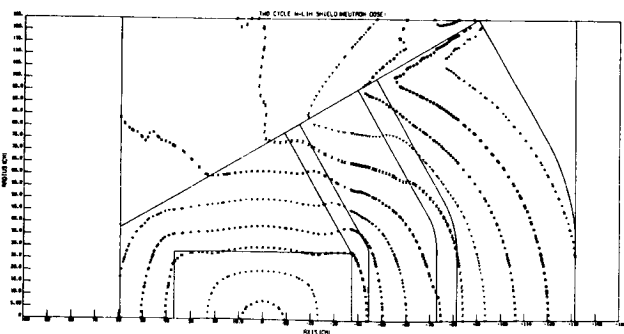


FIGURE 2.-Asymmetric Shield Configuration with a 60-deg Cone Angle - Neutron Isodose Contours.

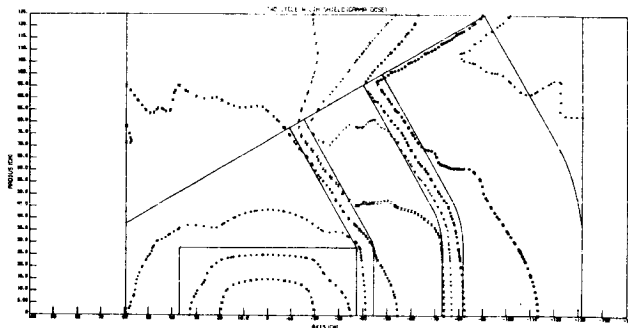


FIGURE 3.-Asymmetric Shield Configuration with a 60-deg Cone Angle - Gamma-Ray Isodose Contours.

The trimmed configuration and the resulting isodose contours are shown in figures 4 and 5. While the doses on the 100-ft sphere were slightly higher the original dose constraints were still satisfied. The shield weight was reduced from 28,000 lbs to 19,000 lbs primarily because the outer tungsten layer accounts for a significant portion of the total shield weight.

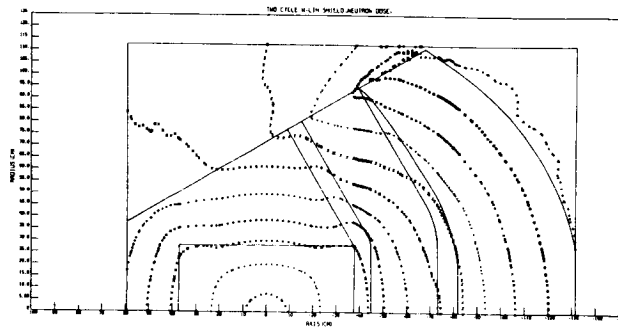


FIGURE 4.-Trimmed Asymmetric Shield Configuration with a 60-deg Cone Angle - Neutron Isodose Contours.

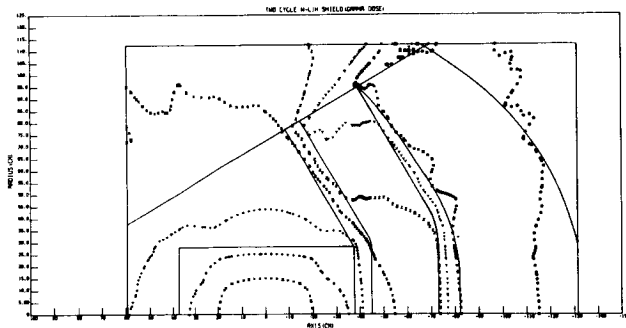


FIGURE 5.-Trimmed Asymmetric Shield Configuration with a 60-deg Cone Angle - Gamma-Ray Isodose Contours.

The second example of an asymmetric 4π shield is shown in figures 6 and 7. The reactor in this case is a small, fast spectrum core, reflected by niobium and cooled by heat pipes dispersed in the uranium nitride fuel matrix (ref. 6). The reactor power is 450 kWt. The dose constraints are 3 mrem/hr within the 90° cone angle and 300 mrem/hr elsewhere, all on a 100-ft radius sphere. The major portion of the shield is a three-cycle tungsten-lithium hydride design. Because of the high temperature of the heat pipes they could not be allowed to penetrate a lithium hydride shield. That portion of the shield at the top of the core surrounding the heat pipes was designed by ASOP from considerations of total thickness rather than minimum weight and consists of an iron-B₄C mixture followed by a BeO-B₄C mixture. The portion of the shield between the heat pipe region and the 90° cone was reduced to a two-cycle tungsten-lithium hydride configuration by ASOP because of the higher dose constraint and the fact that the inner boundaries of the tungsten layers were constrained to the positions determined for the 3 mrem/hr shield in order to avoid discontinuities.

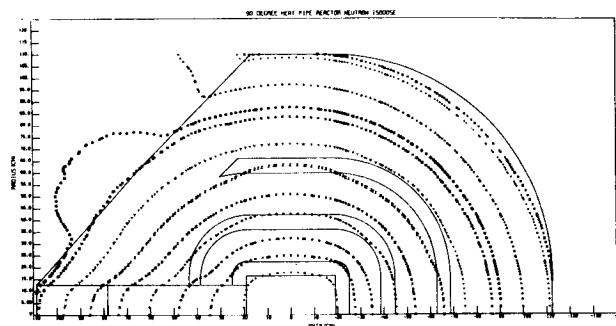


FIGURE 6.-Asymmetric Shield Configuration with a 90-deg Cone Angle - Neutron Isodose Contours.

The DOT calculation showed that the configuration did meet the design dose constraints. The isodose contours did not indicate obvious trimming of any significance however. This is attributed to the fact that the large cone angle and the wrap-around design within that cone angle cause the heaviest portion of the shield to approximate a hemisphere for which the one-dimensional ASOP calculation was quite adequate. Both the outer lithium hydride boundary and the outer tungsten boundary were trimmed slightly in the curved portion and because of the apparent direction of the gamma-ray streaming in the outer lithium hydride along the side of the core, the outer tungsten was trimmed in the side region. The resulting shield weight decreased from 28,000 lb to 25,000 lb and a DOT calculation confirmed that the design dose constraints were satisfied.

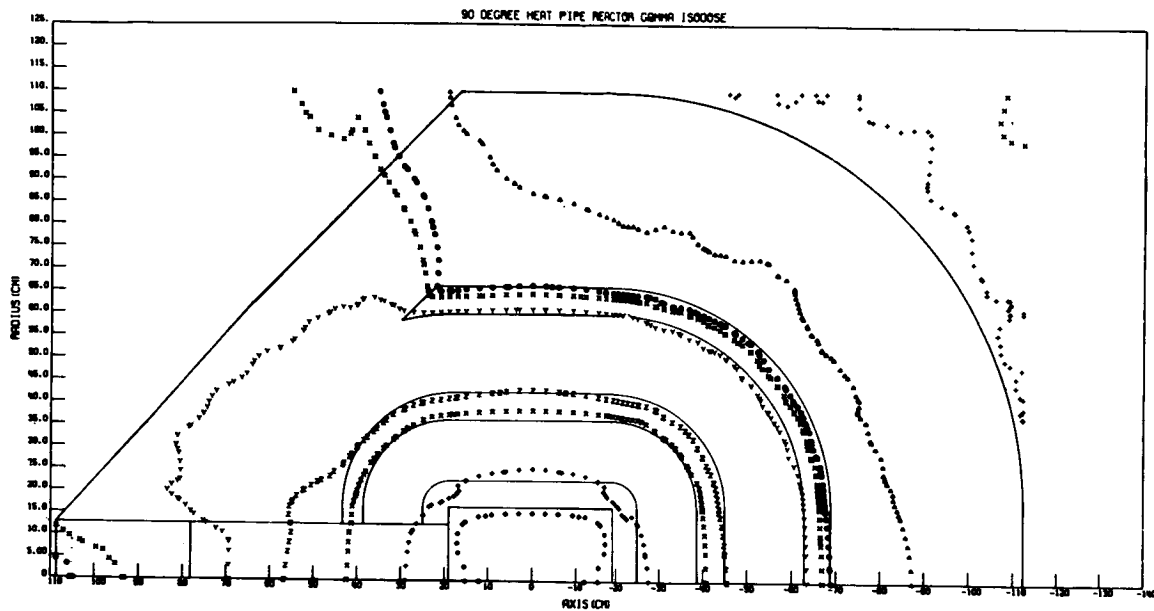


FIGURE 7.-Asymmetric Shield Configuration with a 90-deg Cone Angle - Gamma-Ray Isodose Contours.

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