NASA TECHNICAL MEMORANDUM

NASA TM X-67937

NASA TM X-67937

EFFECT OF ANGULAR QUADRATURE ON RESULTS OF TWO-DIMENSIONAL SPACE POWER REACTOR SHIELD CALCULATIONS

by D. J. Connolley and G. P. Lahti
Lewis Research Center
Cleveland, Ohio

TECHNICAL PAPER proposed for presentation at
American Nuclear Society Winter Meeting
Miami Beach, Florida, October 17-21, 1971

EFFECT OF ANGULAR QUADRATURE ON RESULTS OF TWO-DIMENSIONAL SPACE POWER REACTOR SHIELD CALCULATIONS

by D. J. Connolley and G. P. Lahti

Lewis Research Center
National Aeronautics and Space Administration
Cleveland, Ohio

E-6615

ABSTRACT

A study has been made of the effect of angular quadrature on the results of two-dimensional transport calculations made to evaluate radiation environment in the vicinity of a shielded space power reactor. The application considered here is for a manned space-station; crew shielding must be provided within a 25° cone angle. The asymetric shield layout is evaluated using the two-dimensional transport code DOT. Within the shield, an S_6 angular quadrature yields satisfactory results. For regions where the ray effect may occur it is not apparent that an S_{10} quadrature is adequate. Anomalies in results due to (1) transport of particles in a void and (2) necessary geometric approximations were observed.

INTRODUCTION

Radiation shields presently considered for space power nuclear reactors generally are asymmetric. That is, the shielding in some solid angle containing a crew compartment is much thicker than that required in other directions. Two-dimensional (or three-dimensional) transport methods are necessary to design and evaluate such shields.

The discrete ordinates Sn transport codes are commonly used for shield calculations. The two-dimensional codes, however, require extensive computer time. The computer time required to run a two-dimensional problem is directly proportional to the number of space points, energy groups, and discrete angles specified for the problem. (The running time is weakly proportional to the order of scattering approximation.) The code user has to make some compromise in the selection of these parameters. But the effect of these on the overall accuracy of the solution is not adequately known.

Mynatt et al. (Ref. 1) explored the problem of the Sn parameters (scattering order and angular quadrature) for the case of fast neutron transport in water using the one-dimensional transport code ANISN (Ref. 2) and compared the results with both moments method results and experimental data. The purpose of this report is to attempt to show the effect of angular quadrature on the radiation field within and outside of a two-dimensional space power reactor-shield assembly and to establish a reasonable angular quadrature order for use in 2-D design calculations which will minimize computation time but not sacrifice accuracy. The geometry chosen for this study is that of a prototype-shield design. The system utilizes a ZrH reactor and shield designed to allow a dose rate of 6 mrem/hr at a 200 feet diameter crew dose plane 200 feet distant from the shield and 10 rem/hr at 200 feet distant elsewhere.

Particular emphasis is placed upon the effect of angular quadrature on the two-dimensional transport solution. However, some additional anomalies that developed in the application of the codes to the particular chosen configuration (although not necessarily unique to it) are discussed.

GEOMETRY OF TEST PROBLEM

The shield geometry selected as a vehicle for this test problem is shown in Fig. 1a. The layout is typical of designs presently considered for space station applications of a 125 KWth beryllium-reflected zirconium hydride reactor system. The reactor-reflector assembly is surrounded by a refractory metal (tungsten) containment shell-thermal shield-gamma shield followed by a layer of lithium hydride neutron shielding. The crew is within a 25° half-angle cone and at a distance of 200 feet from the reactor center. Additional shielding layers provided for the crew in this direction are shown in Fig 1a. The goal of this design was to meet a dose rate of 6 mrem/hr at 200 feet within the 25° cone (crew dose) and 10 rem/hr 200 feet distant elsewhere. The layout shown in Fig. 1a is a first estimate of a shield design generated from a one-dimensional parametric study and optimization. No attempt was made to tailor the shield to match the dose constraints and thus minimize weight.

TRANSPORT CODES AND PROCEDURES USED

The discrete ordinates Sn code DOT (Refs. 2 and 3) was used to calculate radiation transport throughout the shield; a 41-group coupled neutron-gamma cross-section set was used. The MAP code (Ref. 4) utilizing the surface angular fluxes was used to transport the radiation to points 200 feet distant.

An outline of the R-Z cylindrical geometry mockup of this reactor shield mockup is shown in Fig. 1b. This R-Z geometry is required by the transport code. The overlay of the 72-axial mesh intervals and 42-radial mesh intervals used in the present calculations results in the conical section of the shield being approximated by a series of steps as shown in the figure. Also the Sn transport calculation is carried out through the void region to the outer boundary marked on Fig. 1b.

Calculations were made for symmetric angular quadrature of S_4 to S_{10} (16 to 70 discrete angles) for a scattering approximation of P_2. The scalar fluxes and moments calculated for one case were used as input for the next, thus minimizing total computer time. All cases were run to approximately the same convergence criteria.

RESULTS AND DISCUSSION

The criteria used for comparing the results of the study are neutron and gamma ray dose rates. These are presented for positions on the centerlines of the reactor-shield system, on the external surface of the shield, and on a dose surface at a radius of 200 feet. Although the integral quantity dose rate was selected as the criteria for simplicity, the trends illustrated apply equally well for other quantities of interest such as heating rates and neutron and gamma ray fluxes. The results are presented in Figs. 2 through 6.

Dose Rates Within the Reactor-Shield Assembly

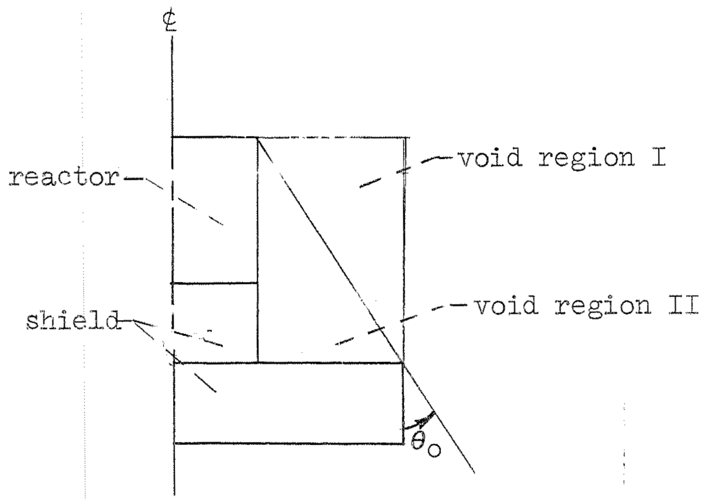
Results of this study showing the effects within the assembly are presented in Figs. 2 through 5. Shown in Fig. 2 are the neutron and gamma dose rates along the centerline of the system for P_2 scattering and S_4 to S_{10} angular quadrature. Maximum differences occur at the outer surface of the shield. The results calculated with lower order quadrature are lower than those calculated with higher order. Differences in neutron dose rate are at most 20 percent. This result is in substantial agreement with Mynatt (Ref. 1), a conclusion not surprising since on the axis of the system one would expect reasonable agreement between one- and two-dimensional transport solutions. Differences in gamma dose are at most 40 percent. The S_6 gamma results are within 10 percent of the S_8 results; the S_8 gamma results are virtually the same as the S_{10} results.

Presented on Fig. 3 are the neutron and gamma dose rates along the midplane of the assembly for P_2 scattering and S_4 to S_{10} angular quadrature. Again differences are less than 20 percent.

The neutron and gamma dose rates along the bottom surface of the thick shield are presented on Fig. 4. Again results are shown for P_2 scattering and S_4 to S_{10} angular quadrature. The results are similar to those discussed above. However, serious discrepancies (of up to a factor of 5 difference) are apparent near the outer corner of the shield.

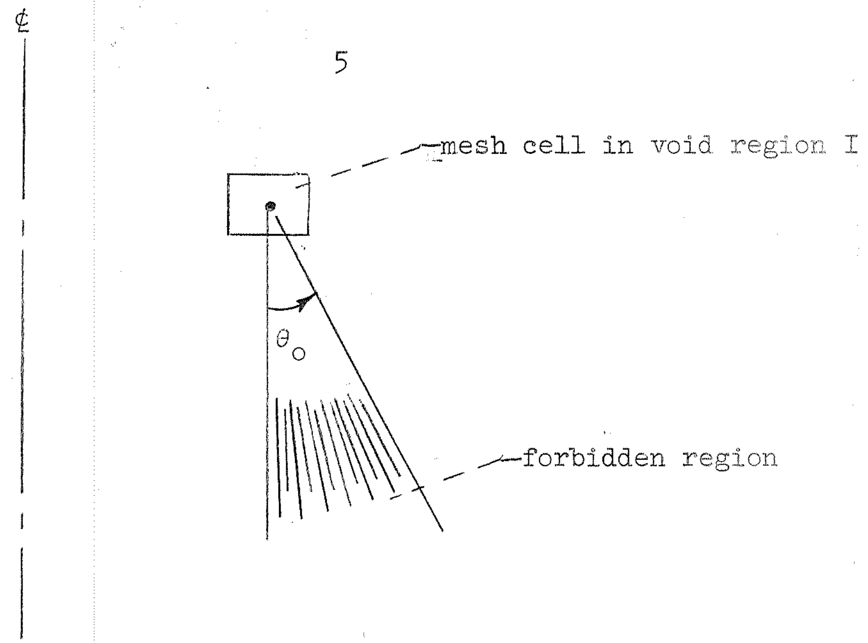
The differences are due to the so-called "ray-effect" (Ref. 5) in the discrete-ordinates equations as well as the stepped R-Z cylindrical mockup of the outer edge of the conical shield. The dose rate in the vicinity of the corner of the shield is, in this setup, dominated by radiation streaming through the side shield, then through the void where ray effects appear, and finally through a thin section of shielding. In reality, the lower corner of the conical shield should not "see" the surface of the shielding on the side of the reactor. However, because of the discrete R-Z stepped cylindrical geometry mockup of the cone, the spurious upturn at the edge of the shield occurs. The magnitude of this upturn is further perturbed by the ray effect which depends on the quadrature.

Another anomaly involving the convection of particles through the void regions that are present in two-dimensional transport codes also appears here and affects the fluxes in the vicinity of the corner of the shield. That anomaly may be described using sketch (a) below:



Sketch (a)

This sketch shows a simplified reactor-shield geometry similar to the problem presently considered. The void region is separated into two regions and called void region I and void region II. Because of the geometry, mesh cells in void region I should have a region in which certain angular fluxes are zero. This region is shown in sketch (b).



Sketch (b)

The angular flux at any discrete angle θ between 0 and θ_0 as shown in the above sketch must be zero if the mesh cell is in void region I. However, because of negative extrapolations of the flux and subsequent fixup procedures in DOT, nonzero angular fluxes in this region persist and may propagate to the corners of the shield in the present geometry. Some of this effect is also taking place in the present problem. The nonphysical fluxes in the boundaries then result in incorrect MAP-transport calculations to a distant field point. This effect is discussed in the next section.

Finally, Fig. 5 shows the dose rates along a line at a radius of 117 centimeters for all ordinates between the midplane of the reactor and bottom of the thick shield. Results are shown for S_4-S_{10} scattering. Here, rather large fluctuations are apparent. These are due to the ray effect since for most positions shown, discrete angular radiation is transported from the surface of lithium hydride surrounding the reactor assembly (radius of 46 cm) through a 70 centimeter thick void region. The data is presented here to alert 2-D Sn code users to inadvertent uncertainties encountered in interpreting transport calculations for configurations such as this. All one can say regarding the curves of Fig. 5 is that the higher the S order, the fewer the spurious fluctuations in the curve; one can only conjecture as to the true values of the dose rates at this extreme boundary of the two-dimensional problem.

Dose Rates at Points Distant from the Reactor-Shield Assembly

Radiation dose rates at detector points 200 feet from the reactor center were calculated using the MAP code. This code determines the contribution to a distant detector from each surface area element of a discrete ordinates problem. The converged angular fluxes are known for each surface area element and discrete angle at the termination of a DOT calculation. Given a set of detector coordinates, the MAP code determines the discrete angle closest to the line connecting the center of the area element and the detector point, and assumes this to be the angular flux (per unit solid angle) heading in the direction of the detector. This is the principal assumption of the code. Using standard formulae, the contribution to the detector is determined for each area element seen by the detector and summed to obtain a total dose rate. Thus MAP-calculated results should also show the effects of discrete angular quadrature.

Shown in Fig. 6 are the MAP-calculated total (neutron plus gamma) dose rates for detectors at a distance of 200 feet from the reactor center and at several angles with the reactor axis. Calculations were made from DOT results obtained with S_4, S_6, S_8, and S_{10} angular quadrature. The effects of the discrete angle approximation are apparent; the higher the number of angles (the closer any one discrete angle is to the detector) the better resolved is the dose rate versus angle curve. Large differences are apparent at positions where the angle nearest the area-detector line changes abruptly from one discrete angle to the next. the 0° centerline position is poorly predicted because of lack of a specific angle pointing in that direction; this is also true for the 90° position. At intermediate positions, results oscillate. In spite of the wide variations observed in Fig. 5, the results in Fig. 6 for angles between 50° and 120° do not show unreasonable agreement. This is probably because of averaging out variations in the complete surface integration.

The foregoing local variations are unique to the specific method utilized in the MAP code. If one used a smoothing of the discrete surface angular fluxes the oscillations in the Sn results would probably be negligible.

The other anomaly, mentioned before, propagates itself in the MAP calculation in that at certain distant detectore dose points (within the 25° angle position), nonphysical dose contributions are made from void regions to the detectors from the side surfaces of the reactor.

CONCLUDING REMARKS

From these results it appears that an S_6 angular quadrature is adequate for predicting results within a scattering medium such as along the centerline or midplane of an assembly such as described here. For regions where the ray effect may appear, it is not apparent that even an S_{10} quadrature is adequate. Although some remedies have been proposed to cure the ray effect (Ref. 6), the best method seems to be to simply increase the number of angles in the quadrature. Thus the selection of angular quadrature should really be dependent on where in the problem one needs an accurate answer. For parametric studies one could use S_4 quadrature with appreciable time savings followed by higher order calculations for a final configuration.

REFERENCES

1. F. R. MYNATT, N. M. GREEN and W. W. ENGLE, JR., "On the Application of Discrete-Ordinates Transport Theory to Deep-Penetration Fast-Neutron-Dose Calculations in Water, Trans. Am. Nucl. Soc. 9, 366-367 (1966).

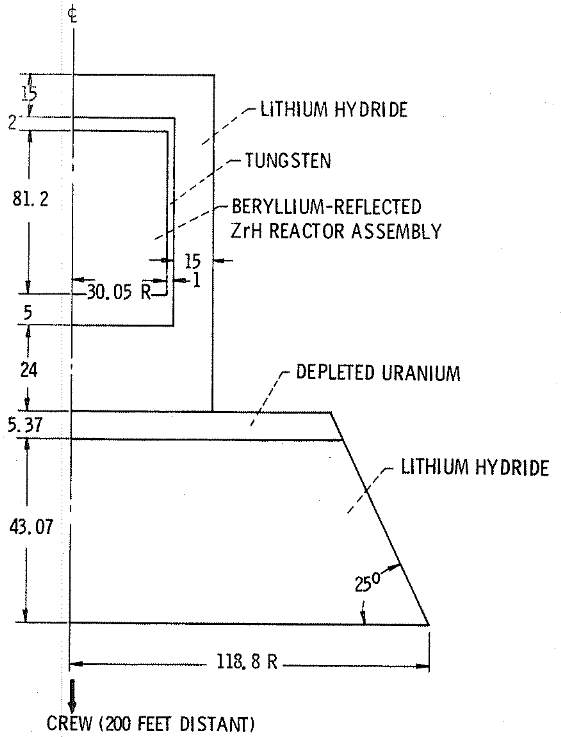
2. F. R. MYNATT, "A User's Manual for DOT: A Two-Dimensional Discrete Ordinates Transport Code with Anisotropic Scattering," K-1694, Union Carbide Corp., (1967).

3. R. G. SOLTESZ and R. K. DISNEY, "User's Manual for the DOT-IIW Discrete Ordinates Transport Computer Code," WANL-TME-1892, Westinghouse Astro-Nuclear Laboratory, (1969).

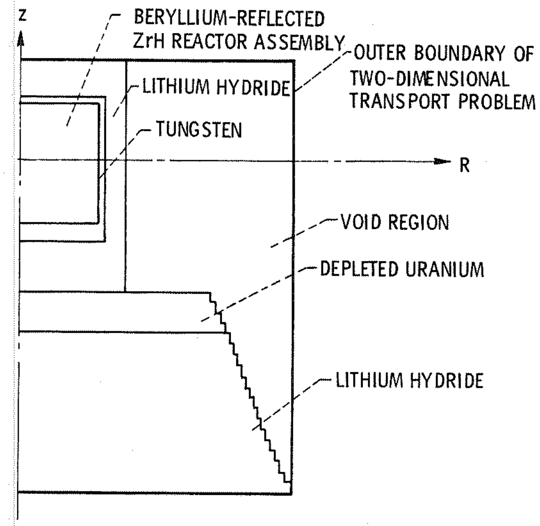
4. R. K. DISNEY, R. G. SOLTESZ, J. JEDRUCH and S. L. ZEIGLER, "Code Description and User's Manual for the MAP Radiation Transport Computer Code," WANL-TME-2706, Westinghouse Astronuclear Laboratory, (1970).

5. K. D. LATHROP, "Ray Effects in Discrete Ordinates Equations," Nucl. Sci Eng. 32, 357-369 (1968).

6. K. D. LATHROP, "Remedies for Ray Effects," Nucl. Sci. Eng. 45, 255-268 (1971).



(a) REACTOR-SHIELD GEOMETRY. ALL DIMENSIONS SHOWN ARE IN CENTIMETERS.



(b) R-Z MOCK-UP OF REACTOR-SHIELD GEOMETRY FOR 2-DIMENSIONAL TRANSPORT CALCULATIONS.

Figure 1

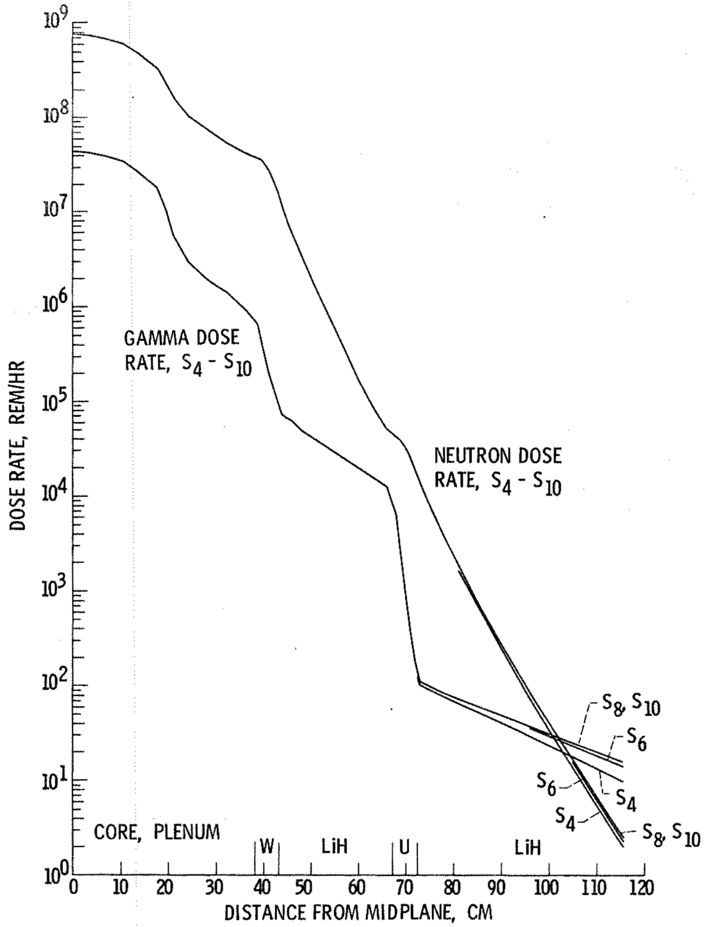


Figure 2. - Dose rates along reactor, shield centerline. Calculations are for P_2 scattering, various angular quadratures denoted by n of Sn.

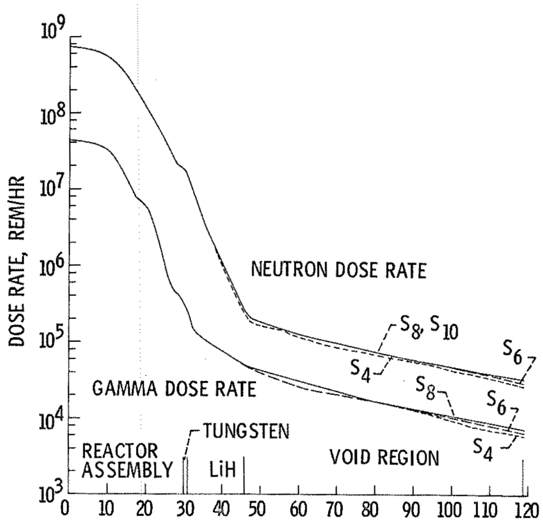


Figure 3. - Dose rates along midplane of shield. Calculations are for P_2 scattering and various orders of angular quadrature denoted by n of Sn.

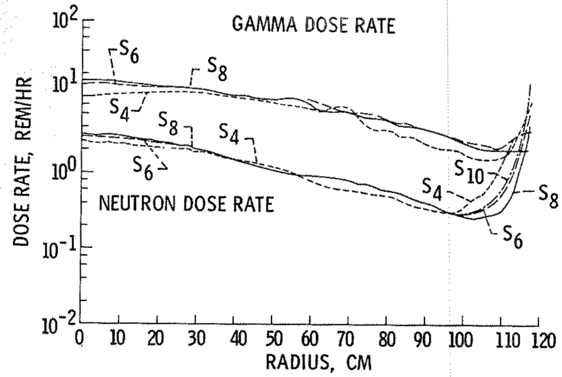


Figure 4. - Dose rates along bottom surface of shield. Calculations are for P_2 scattering and various orders of angular quadrature denoted by n of Sn.

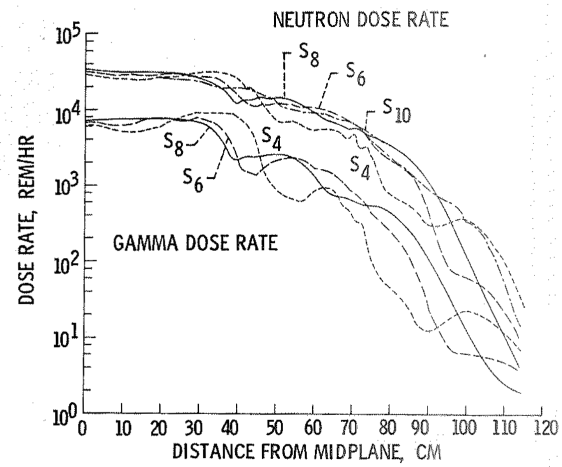


Figure 5. - Dose rates at radius 117 centimeter (near outer radial boundary of transport problem). Calculation are for P_2 scattering and various orders of angular quadrature denoted by n of Sn.

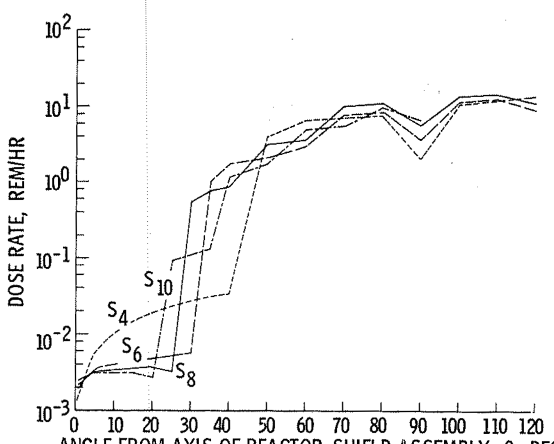


Figure 6. - Total dose rate 200 feet distant from reactor center. Straight line segments connect data points to guide the eye. Data is based on DOT calculations made with S_4 to S_{10} angular quadrature.