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Y. Gohar and S. Yang

Argonne National Laboratory
Fusion Power Program
9700 South Cass Avenue
Argonne, IL 60439

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SKYSHINE STUDY FOR NEXT GENERATION OF FUSION DEVICES

Y. Gohar and S. Yang
Argonne National Laboratory

ABSTRACT

A shielding analysis for next generation of fusion devices (ETR/INTOR) was performed to study the dose equivalent outside the reactor building during operation including the contribution from neutrons and photons scattered back by collisions with air nuclei (skyshine component). Two different three-dimensional geometrical models for a tokamak fusion reactor based on INTOR design parameters were developed for this study. In the first geometrical model, the reactor geometry and the spatial distribution of the deuterium-tritium neutron source were simplified for a parametric survey. The second geometrical model employed an explicit representation of the toroidal geometry of the reactor chamber and the spatial distribution of the neutron source. The MCNP general Monte Carlo code for neutron and photon transport was used to perform all the calculations. The energy distribution of the neutron source was used explicitly in the calculations with ENDF/B-V data. The dose equivalent results were analyzed as a function of the concrete roof thickness of the reactor building and the location outside the reactor building.

INTRODUCTION

The shield system of a fusion reactor consists of two parts, the different materials around the vacuum chamber and the concrete walls of the reactor building. The first part of the shield has to reduce the neutron and photon leakage intensities from the outer shield surface. This reduction ensures several design criteria: a) the different reactor components are protected from radiation damage and excessive nuclear heating, b) the neutron reaction rates in the reactor components which produce undesirable radioactive isotopes are reduced, and c) the workers are permitted in the reactor hall one day after shutdown. The second part of the shield has to protect the workers and the public from radiation exposure during the reactor operation. This part of the shield is the subject of this paper.

The International Commission on Radiological Protection recommendations and the U.S. Federal Regulations[1] limit the occupational exposure to 5 rem/y with a maximum of 3 rem/quarter. The occupation exposure based on regular working hours is 2.5 mrem/h. However, the current practice in the nuclear industry, the exposure policy of the U.S. Department of Energy (DOE), and the national Laboratories' guidelines are to reduce radiation exposure as low as reasonably achievable. Specifically, DOE order 5980.1, Chapter XI states: "Exposure rates in work areas should be reduced as low as reasonably achievably by proper facility design layout. Design efforts to consider are: occupancy time, source terms, spacing, processes, equipment, and shielding. On-site personnel exposure level less than one-fifth of the permissible dose equivalent limits, prescribed in this chapter should be used as a design objective". This guideline limits on-site workers to <1 rem/y (0.5 mrem/h).

The analysis of this paper is concerned with the total dose equivalent outside the reactor building during operation to satisfy the 0.5 mrem/h design criterion. A parametric study was performed to define the dose equivalent outside the reactor building as a function of the roof thickness including the contribution from neutrons and photons-scattered back by collision with air nuclei (skyshine). A simple three dimensional model was employed to carry out this analysis. The materials and the dimensions used in the model are based on the INTOR shielding analyses given in Refs. 2-5. Another elaborate model was developed to study the impact on the dose equivalent results from the simplified assumptions used in the previous model and the use of a small amount of boron carbide and lead at the outer surface of the reactor shield. The MCNP general Monte Carlo code[6] for neutron and photon transport was used to perform all the calculations. Three variance reduction schemes were employed for the calculations. These are splitting, Russian roulette, and weight cutoff with Russian roulette. The energy distribution of the neutron source was used explicitly in the calculations with a nuclear library based on ENDF/B-V data.

CALCULATIONAL MODELS

In the simple calculational model, the deuterium tritium neutron source is presented by an isotropic point source. The energy spectrum n(E) of the neutron source is described by a Gaussion distribution:

$$n(E) \; \alpha \; \exp \left[- \left(\frac{E-b}{a}\right)^2\right] \quad ,$$

where a = 0.3359 MeV and b = 14.057 MeV. The reactor geometry is presented by a hollow sphere to simulate the vacuum chamber and the shield materials. A 1.3 m of steel shield is used to provide the adequate protection for the reactor components and permit the workers to access the reactor hall one day after shutdown. The steel shield consists of 90% Fe-14Mn-2Ni-2Cr steel alloy (Fe1422) and 10% water by volume. The reactor building is presented by a vertical cylinder of ordinary concrete. The radius and the height of the inner cylinder are 20 and 30 m, respectively. The wall thickness of the reactor building is 1.8 m. Three roof thicknesses are included in the analysis: 0.8, 1.0, and 1.2 m. The dose equivalent values are evaluated as a function of the distance from the reactor wall at the neutron source level. The 1.8 m wall thickness was chosen to reduce the dose equivalent to 0.5 mrem/h during operation based on the one-dimensional analysis of Ref. 3.

The second geometrical model replaces the spherical representation of the reactor by a torus of 5.1 m major radius. The torus has a rectangular cross section and a 1.3 m steel shield. The inner dimensions of the rectangular are 2.8 and 4.24 m in the horizontal and vertical directions. The plasma has a 1.2 m minor radius and 1.6 elongation factor. A scrape-off layer of 0.2 m is included around the plasma. In this model, the neutron source has uniform distribution over the plasma volume. The reactor building has a 1.0 m thick roof. Ordinary concrete is the building material for both models.

DOSE EQUIVALENT ANALYSIS

The first geometrical model was used to calculate the dose equivalent outside the reactor building without skyshine contribution. This was accomplished by replacing the air above the reactor building by vacuum. The purpose of this calculation was to confirm the adequacy of the 1.3 m of steel shield and the 1.8 m of concrete to reduce the dose equivalent to about 0.5 mrem/h during reactor operation. The reactor fusion power is 620 MW (2.2×10^{20} fusion neutrons per second) based on the INTOR design parameters.[2] The dose equivalent results from this calculation is shown in Table 1 as a function of the distance from the reactor wall. The maximum value of the dose equivalent is 0.64 ± 0.11 mrem/h.

TABLE 1.
Dose Equivalent Results as a Function of the Distance from the Reactor Wall without Skyshine Contribution

Distance Relative to the Reactor Wall (m)	Dose Equivalent (mrem/h)	Fraction Standard Deviation
0.10	0.64	0.18
0.70	0.51	0.16
1.70	0.43	0.14
3.70	0.41	0.12
4.70	0.39	0.11
15.20	0.36	0.18

The dose equivalent including the skyshine contribution was calculated as a function of the roof thickness. The results are shown in Fig. 1 for three roof thicknesses. For the roof thickness of 0.8 m, the skyshine contribution is about 90% of the total dose at 0.7 m from the building. In fact the skyshine contribution of the total dose increases slowly as the distance from the reactor building increases. At 1.0 and 1.2 m roof thicknesses the skyshine contributions are about 72 and 32%, respectively. These results show the importance of the skyshine contribution to the total dose equivalent outside the reactor building. It also indicates that the roof thickness should be greater than 1.0 m to satisfy the exposure criterion during the reactor operation.

The second geometrical model was used to define the impact of the geometry simplification on the results. A 1.0 m roof thickness is used with the torus geometry and the uniform neutron source distribution in the plasma volume. Figure 2 shows the results from the simple and the elaborate geometrical models as a function of the distance from the reactor building. These results show that the simple geometrical model over estimates the dose equivalent by a factor of 4 to 8 depending on the distance from the reactor building. Also, the impact of including B_4C and lead in the last 10 cm of the steel shield was investigated. A 5 cm layer of a boron carbide shield (60%

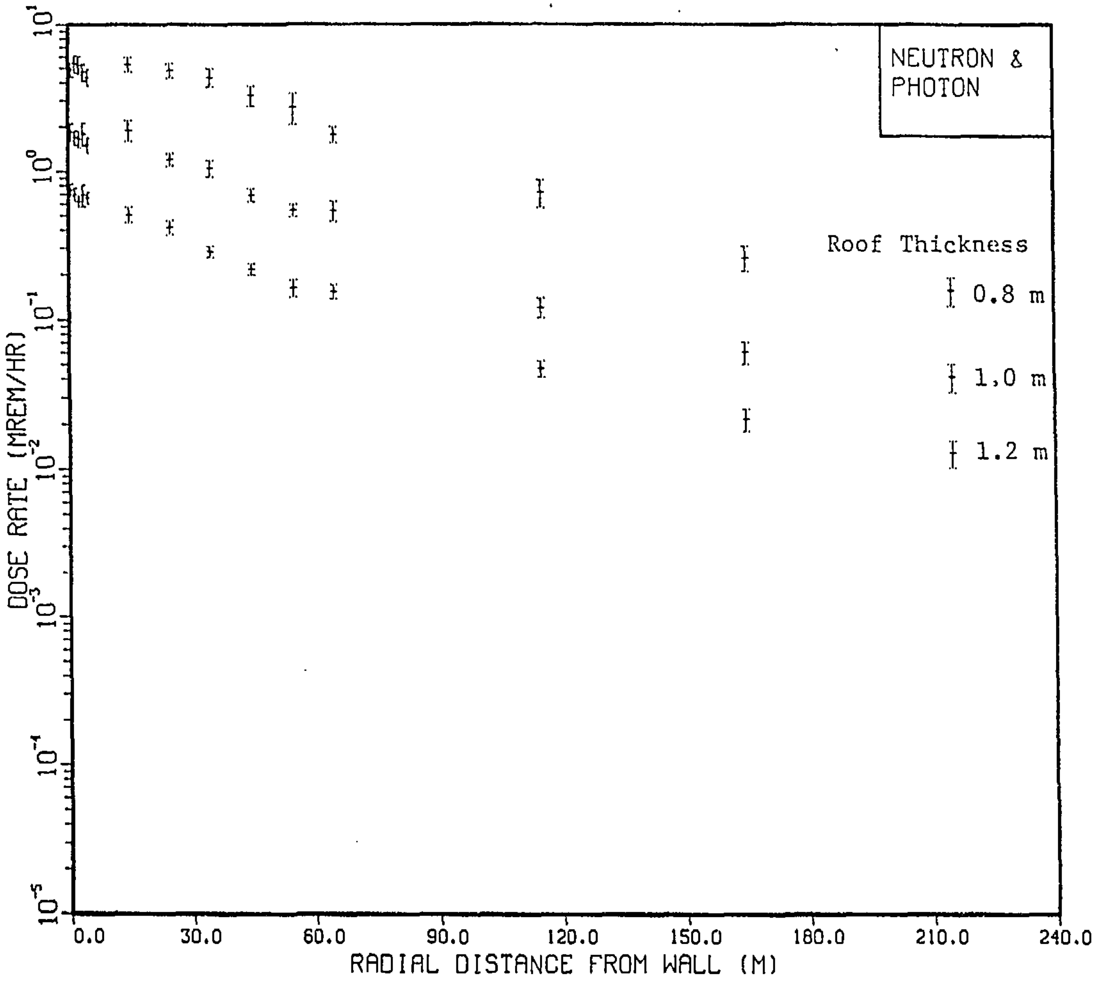

Figure 1
Total dose equivalent as a function of the radial distance from the reactor building for different roof thicknesses.

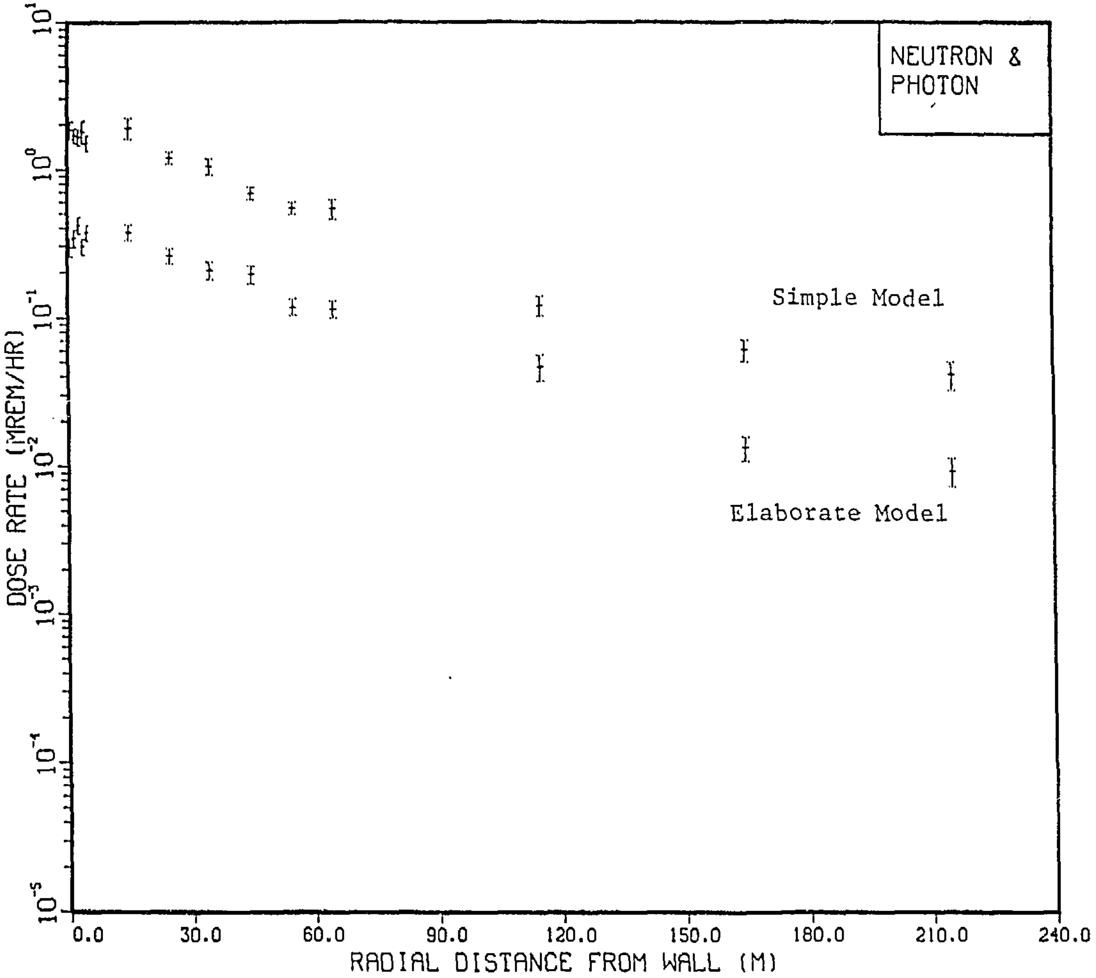

Figure 2
Total dose equivalent as a function of the radial distance from the reactor building from two different geometrical models.

B_4C with a 0.7 density factor, 20% Fe1422, and 20% H_2O) is employed at the back of the reactor shield to reduce the activation in the reactor components. Another 5 cm of lead is used as a gamma-ray attenuator at the outermost surfaces of the reactor shield, so that the dose equivalent in the reactor building is reduced after shutdown. The dose equivalent results is only increased by about 10% when the two layers are included in the calculations.

CONCLUSIONS

The dose equivalent analysis for the ordinary concrete fusion reactor building shows that a 1.0 m thick roof and a 1.8 m thick wall reduce the maximum dose equivalent value outside the reactor building to 0.44 to 0.06 mrem/h during operation for fusion reactors designed to satisfy the 2.5 mrem/h dose equivalent one day after shutdown criterion inside the reactor hall. The skyshine contribution is about 72% of the total dose for this configuration. The use of a simplified geometrical model over-estimates the dose equivalent by a factor of four to eight the actual value. The dose equivalent outside the reactor building is not very sensitive to the use of boron carbide and lead at the outer surfaces of the reactor shield.

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