Study on neutron and photon shielding properties of various concretes using MCNP code

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Abstract. The neutron and photon shielding properties of four types of concrete are studied by simulation with MCNP5 code. The photon dose transmission factors with photon energy between 0.1MeV to 20MeV, and the neutron dose transmission factors with neutron energy between thermal neutron to 15MeV are plotted. The result shows that all the properties strongly depend on the particle type, energy, as well as the material density and atomic composition. The secondary photon dose equivalent together with the ratio between secondary photon dose equivalent and neutron dose equivalent is worked out and their variations with the incident neutron energy of various concretes are also plotted. It shows that the secondary photon dose equivalent must be considered especially when the incident neutron energy is low. The results of this paper can provide some reference for future use of concretes and other shielding materials.

1. Introduction
Radiation shielding is crucial for environmental protection in all areas of nuclear energy utilization, such as reactors, medical cyclotrons, industrial radiation inspections. Concrete is considered to be one of the most excellent shielding materials, which is relatively inexpensive and can be cast into various shapes easily [1]. It has great properties for the shielding of both photons and neutrons because of its high content of light and heavy elements. Accurate neutron and photon shielding properties of concretes are of great significance for its engineering applications and academic research. In recent years, the photon attenuation coefficients [2-4] and neutron shielding properties [5,6] of various types of concrete have been studied.

MCNP is a general-purpose Monte Carlo N–Particle code that can be used for neutron, photon, electron, or coupled neutron/photon/electron transport. This code can be used to simulate the neutron and photon shielding properties of various shielding materials.

The aim of this paper is to determine the neutron and photon shielding properties of four types of concrete by the MCNP code and consequently provide some reference for the use of this concrete as shielding materials.

2. Materials and methods

2.1. Material specification for concretes
In this study, four types of concrete are studied [7]. The specific compositions and density of each concrete samples are presented in Table 1. The former three types contain oxygen and silicon or oxygen and barium as dominant elements, while iron is the predominant element in the last type of
concrete. The percentages by weight of each types of concrete are introduced to the MCNP code using the material card.

Table 1. Percentage of atomic composition for four types of concrete and their densities

| Element   | Ordinary | Barite | Serpentine | Steel-magnetite |
|-----------|----------|--------|------------|-----------------|
|           | 2.3g∙cm⁻³ | 3.35g∙cm⁻³ | 2.6g∙cm⁻³ | 5.1g∙cm⁻³       |
| Hydrogen  | 2.21     | 0.36   | 7.2        | 0.51            |
| Carbon    | 0.25     | –      | 0.15       | –               |
| Oxygen    | 57.75    | 31.18  | 55.6       | 15.7            |
| Sodium    | 1.52     | –      | –          | –               |
| Magnesium | 0.13     | 0.11   | 10.2       | 0.58            |
| Aluminum  | 2.1      | 0.42   | 2.5        | 0.66            |
| Silicon   | 30.56    | 1.04   | 17.55      | 2.68            |
| Phosphorus| –        | –      | –          | 0.08            |
| Sulphur   | –        | 10.78  | –          | 0.06            |
| Potassium | 1.08     | –      | 0.08       | –               |
| Calcium   | 4.39     | 5.02   | 5.64       | 3.95            |
| Manganese | –        | –      | –          | 0.07            |
| Iron      | 0.7      | 4.75   | 1.08       | 75.73           |
| Barium    | –        | 46.34  | –          | –               |

2.2. Geometry system of concrete samples

MCNP code version 5 is used for the simulation. The geometry arrangement of MCNP simulation model is shown in Fig 1. Its source is a monodirectional plane source which is in the direction of the positive normal to the shielding surface. The particle type and energy will be changed according to the simulation needs. The length and width of the concrete samples are both 100cm while the thickness is 50cm. The detector cell is 80cm far from the sample center and of 10cm radius. Sample and detector cell are defined by MCNP surface and cell card.

![Fig.1. Geometry arrangement of MCNP simulation model](image)

2.3. Tally definition

Tally card F4 as well as dose energy (DEn) card and dose function (DFn) card was used to record the personal dose equivalent. Depending on the particle type and energy, the simulation histories as well
as the variance reduction technique including geometry splitting, weight window and exponential transform will change to ensure that all the simulation data passes all 10 statistical checks and the relative error is less than 1%.

2.4. Photon and neutron ambient dose equivalent, dose transmission factor
The ambient dose equivalent \( H^*(d) \) is associated with the measured personal dose equivalent \( H_p(d) \). For strongly penetrating radiation, a depth of 10mm is employed. The relationship is as follows:

\[
H_p(d) = \int_0^\infty \Phi(E) \cdot H^*(d, E) \quad (1)
\]

Where \( H_p(d) \) is the personal dose equivalent, \( \Phi(E) \) is the particle fluence and \( H^*(d) \) is the ambient dose equivalent. Here we choose \( d = 10 \text{mm} \), the \( H^*(10) \) of photon and neutron corresponds to different energy have been shown in Table 2 and Table 3.

Table 2. Photon ambient dose equivalent corresponds to different energy

| Energy/MeV | \( H(10) \)/pSv cm\(^2\) |
|------------|--------------------------|
| 0.01       | 0.061                    |
| 0.015      | 0.83                     |
| 0.02       | 1.05                     |
| 0.03       | 0.81                     |
| 0.04       | 0.64                     |
| 0.05       | 0.55                     |
| 0.06       | 0.51                     |
| 0.08       | 0.53                     |
| 0.1        | 0.61                     |

Table 3. Neutron ambient dose equivalent corresponds to different energy

| Energy/MeV | \( H(10) \)/pSv cm\(^2\) |
|------------|--------------------------|
| 1.00E-09   | 6.6                      |
| 1.00E-08   | 9                        |
| 2.53E-08   | 10.6                     |
| 1.00E-07   | 12.9                     |
| 2.00E-07   | 13.5                     |
| 5.00E-07   | 13.6                     |
| 1.00E-06   | 13.3                     |
| 2.00E-06   | 12.9                     |
| 5.00E-06   | 12                       |
| 1.00E-05   | 11.3                     |
| 2.00E-05   | 10.6                     |
| 5.00E-05   | 9.9                      |
| 1.00E-04   | 9.4                      |
| 2.00E-04   | 8.9                      |

The dose transmission factor which can express the shielding properties can be defined as:

\[
DTF = \frac{H_p}{H_{p0}} \quad (2)
\]

Where \( H_{p0} \) (pSv) is the photon or neutron personal dose equivalent in front of the sample and \( H_p \) (pSv) is the value behind the sample. The smaller the \( DTF \), the better the shielding effect is.

3. Results and discussion

3.1. Photon dose transmission factor
Fig. 2 Variation of photon dose transmission factor of concretes versus incident photon energy

The variation of photon dose transmission factor of four types of concrete versus incident photon energy range from 0.1MeV to 20MeV is shown in Fig 2. It shows that the DTFs of all samples increase with the photon energy increasing. The maximum value is about 9 orders of magnitude higher than the minimum value. The dose transmission factor increases rapidly with the increase of the photon energy in the low energy region, whereas slowly in the high energy region. At the same energy point the order of photon dose transmission factor is as followed: ordinary concrete>serpentine concrete>barite concrete>steel-magnetite concrete. This order is contrary to their density.

3.2. Neutron dose transmission factor

Fig 3 shows the variation of neutron dose transmission factor of four types of concrete versus incident neutron energy that range from thermal neutron to 15MeV. It is observed that the neutron dose transmission factor increases versus the incident neutron energy but is not monotonically which is similar to their ambient dose equivalent. The neutron dose transmission factor of steel-magnetite concrete is much smaller than that of the other three samples because of its high density when the incident neutron energy is below 0.01MeV. Except the steel-magnetite concrete, the order of neutron dose transmission factor of the other three samples at the same energy point is as followed: barite concrete>ordinary concrete>serpentine concrete, which is contrary to their percentage of element hydrogen.
Secondary photons will be produced by inelastic scattering, capture or other nuclear reaction when neutron transmit to the concrete. Therefore, the secondary photon dose equivalent must be considered when the incident particle is neutron. Fig 4 shows the variation of unit secondary photon dose equivalent versus incident neutron energy. It can be seen that the maximum secondary photon dose equivalent of barite concrete and steel-magnetite concrete is about 2 orders of magnitude higher than the minimum value, and that of the other two samples is 1 order of magnitude higher. The ratio between secondary photon dose equivalent and neutron dose equivalent is shown in Fig 5. It is presented that the neutron dose equivalent of barite concrete is higher than the secondary photon dose equivalent over the entire neutron energy range. While the ratio of ordinary and serpentine concrete is almost 1 when the neutron energy is below 0.001 MeV, and then the neutron dose equivalent is higher than the secondary photon dose equivalent. The secondary photon dose equivalent of steel-magnetite concrete is higher than the neutron dose equivalent and decreases rapidly with the increase of the neutron energy in the low energy region, and until the neutron energy exceeds 0.001 MeV the neutron dose equivalent is higher than the secondary photon dose equivalent.
4. Conclusion

In this study, the photon and neutron dose transmission factor as well as the secondary photons of four types of concrete are simulated by MCNP code. It can be concluded that the neutron and photon shielding properties of any type of concrete depend strongly on the particle type, energy, as well as the material density and atomic composition. In order to select an appropriate concrete as shielding material, all these parameters should be considered thoroughly. For photon shielding, steel-magnetite concrete is the best shielding material among the four samples. For neutron shielding, the secondary photon dose equivalent must be considered as well especially when the neutron energy is low. The results of this paper can provide some reference for the future use of the four types of concrete, and it also provide a simulation way based on MCNP to obtain the neutron and photon shielding properties of other shielding materials.

References

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