Designing Neutron Shield Material for D-T Neutron Generator

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Abstract. If hydrogen-rich material is used to shield the 14 MeV neutrons produced by D-T neutron generator whose neutron yield is $10^8$ n/s, its thickness must be more than 74 cm to make dose of neutron radiation less than 0.025 mSv/h. For decrease the thickness, two layers material composed of boron-polyethylene and copper used as 14 MeV neutron shielding material. The calculation result shows that the minimum thickness of the two layers material is 52 cm, in which the thicknesses of copper and boron-polyethylene are 38 cm and 14 cm and the boron concentration is 1.00%.

Keywords: radiation dose; 14 MeV neutron; two layers material; D-T neutron generator

1. Introduction
Because of the feature of movable, compact, cost-efficient, and no radiation once being turned off, D-T neutron generator is the best NR (Neutron radiography) neutron source, NIPGA (Neutron Induced Prompt Gamma-ray Analysis) and BNCT (Boron Neutron Capture Therapy) [1-3]. The neutrons from D-T neutron generator spread in 4π direction which cannot be focused due to its electrical neutrality, with its moving course changed only by a collision. The neutron’s average energy is about 14 MeV, which is harmful to human body. In order to reduce the radiation around equipment, design of a 14 MeV neutron shield is needed. Although water, PE (polyethylene), paraffin and other hydrogen-rich materials are usually used as neutron shield materials [4] they are not ideal for these higher energy neutrons of 14MeV. Given the nature of neutron shield, this Paper uses MCNP program to design shield for D-T neutron generator achieving better results than simply hydrogen-rich materials [5-7].

2. Hydrogen-Rich Materials
Following an elastic collision with a target nucleus, neutrons lose their energy by $2A/(A+1)^2E_0$ (A is the mass-number of the nucleus, $E_0$ is the initial energy of the neutron). In the 14 MeV neutron shield referred to in this paper, the energies of neutrons are reduced to thermal energies by $[n, n]$ and $[n, n \gamma]$, and then the thermal neutrons are absorbed by $[n, \gamma]$. When comparing the results of such hydrogen-rich materials as H$_2$O, polyethylene(PE), paraffin wax, polypropylene(PP) and organic glass used as 14 MeV neutrons shielding materials [8], it is hard to have accurate answer because more factors need consideration, e.g., the mass-number of the nucleus and the cross sections of $[n, n]$, $[n, n \gamma]$, and $[n, \gamma]$. Thus in this paper, the shield results of these materials are simulated by MCNP code. The maximum annual radiation dose of operators allowed is 0.05Sv. Assume a operator is on duty for 2000 hours per year, so the maximum hourly radiation dose allowed is 0.025mSv [9]. Based on this standard, the minimum hydrogen-rich material shield thickness ($d_{th}$) needed in order to shield the neutrons when the yield of D-T neutron generator is $10^8$ n/s are shown in table 1 below.
**Table 1.** Varying Thickness of Hydrogen-rich Materials and the Corresponding Neutron Radiation Dose.

| $d_{H-rich}$ / cm | Neutron Radiation Dose / (mSv/h) |
|------------------|---------------------------------|
|                  | PE     | Water | Paraffin | PP | OG   |
| 10               | 140.427| 152.070| 144.040  | 145.113| 148.567|
| 20               | 20.466 | 24.508 | 21.935  | 22.369| 23.799|
| 30               | 4.678  | 6.272 | 5.270   | 5.448| 5.994|
| 40               | 1.263  | 1.899 | 1.499   | 1.571| 1.779|
| 50               | 0.371  | 0.627 | 0.465   | 0.494| 0.574|
| 60               | 0.115  | 0.217 | 0.152   | 0.163| 0.194|
| 70               | 0.036  | 0.078 | 0.051   | 0.056| 0.068|
| 71               | 0.033  | 0.070 | 0.046   | 0.050| 0.061|
| 72               | 0.029  | 0.063 | 0.041   | 0.045| 0.055|
| 73               | 0.026  | 0.057 | 0.037   | 0.041| 0.050|
| 74               | 0.023  | 0.052 | 0.033   | 0.037| 0.045|
| 75               | 0.021  | 0.047 | 0.030   | 0.033| 0.040|
| 76               | 0.019  | 0.042 | 0.027   | 0.030| 0.036|
| 77               | 0.017  | 0.038 | 0.024   | 0.027| 0.033|
| 78               | 0.015  | 0.035 | 0.022   | 0.024| 0.030|
| 79               | 0.013  | 0.031 | 0.020   | 0.022| 0.027|
| 80               | 0.012  | 0.029 | 0.018   | 0.020| 0.024|
| 81               | 0.011  | 0.026 | 0.016   | 0.018| 0.022|
| 82               | 0.010  | 0.023 | 0.014   | 0.016| 0.020|
| 83               | 0.009  | 0.021 | 0.013   | 0.014| 0.018|
| 84               | 0.008  | 0.019 | 0.012   | 0.013| 0.016|
| 85               | 0.007  | 0.017 | 0.010   | 0.012| 0.014|

From table 1 we can obtain: The best effect is PE in shielding 14 MeV neutrons, as PE needs to be just 74 cm thick when the yield of the D-T neutron generator is $10^8$ n/s, where the actual neutron radiation dose is lower than the maximum hourly radiation dose allowed for operators.

2. Two Layers Material Composed of Metal and PE

Once 14 MeV neutrons collide with dense metal, the energy of most scattered neutrons are lower than 3 MeV, with the spike of their energy spectrum being about 2 MeV, which is the range where hydrogen moderates best. Therefore, Dense metal can be used to neutralize 14 MeV neutrons before using a hydrogen-rich material for shielding [10].

Cu, W, Pb, Fe, Ag, Cd, Mn, Ti and Ni are commonly high-density metals. To select appropriate metals for shielding 14 MeV neutrons, metal thickness ($d_{metal}$) is changed in this paper while the overall thickness of shield remains 74 cm. The results of simulation are shown as table 2.
Table 2. Varying Thickness of two layers Materials and the Corresponding Neutron Radiation Dose.

| $d_{\text{metal}}$ /cm | Neutron Radiation Dose /mSv/h | Cu  | W   | Pb   | Fe   | Ag   | Cd   | Mn   | Ti   | Ni   |
|-------------------------|-------------------------------|-----|-----|------|------|------|------|------|------|------|
| 0                       | 0.0232                        | 0.0232 | 0.0232 | 0.0232 | 0.0232 | 0.0232 | 0.0232 | 0.0232 | 0.0232 | 0.0232 |
| 10                      | 0.0125                        | 0.0107 | 0.0208 | 0.0151 | 0.0166 | 0.0189 | 0.0153 | 0.0252 | 0.0125 |         |
| 15                      | 0.0088                        | 0.0071 | 0.0194 | 0.0119 | 0.0128 | 0.0169 | 0.0124 | 0.0259 | 0.0089 |         |
| 20                      | 0.0063                        | 0.0044 | 0.0178 | 0.0093 | 0.0111 | 0.0147 | 0.0098 | 0.0267 | 0.0063 |         |
| 25                      | 0.0044                        | 0.0028 | 0.0162 | 0.0073 | 0.0079 | 0.0129 | 0.0078 | 0.0272 | 0.0043 |         |
| 30                      | 0.0031                        | 0.0017 | 0.0148 | 0.0054 | 0.0071 | 0.0111 | 0.0061 | 0.0279 | 0.0030 |         |
| 35                      | 0.0021                        | 0.0010 | 0.0132 | 0.0043 | 0.0048 | 0.0096 | 0.0048 | 0.0285 | 0.0021 |         |
| 40                      | 0.0014                        | 0.0007 | 0.0119 | 0.0033 | 0.0045 | 0.0082 | 0.0038 | 0.0290 | 0.0014 |         |
| 45                      | 0.0010                        | 0.0004 | 0.0110 | 0.0025 | 0.0028 | 0.0070 | 0.0029 | 0.0293 | 0.0010 |         |
| 50                      | 0.0007                        | 0.0002 | 0.0106 | 0.0020 | 0.0027 | 0.0059 | 0.0024 | 0.0298 | 0.0007 |         |
| 55                      | 0.0006                        | 0.0001 | 0.0121 | 0.0021 | 0.0016 | 0.0051 | 0.0023 | 0.0309 | 0.0009 |         |
| 60                      | 0.0007                        | 0.0001 | 0.0226 | 0.0044 | 0.0017 | 0.0047 | 0.0036 | 0.0357 | 0.0025 |         |
| 65                      | 0.0017                        | 0.0001 | 0.0777 | 0.0178 | 0.0111 | 0.0054 | 0.0111 | 0.0622 | 0.0134 |         |
| 70                      | 0.0062                        | 0.0002 | 0.4438 | 0.1198 | 0.0018 | 0.0126 | 0.0480 | 0.2689 | 0.1070 |         |
| 72                      | 0.0132                        | 0.0003 | 1.0392 | 0.3222 | 0.0018 | 0.0286 | 0.1165 | 0.6620 | 0.2805 |         |
| 74                      | 0.0396                        | 0.0009 | 2.8147 | 1.0595 | 0.0056 | 0.1040 | 0.4604 | 1.8362 | 0.6795 |         |

From Table 2 we can obtain:

1. The best effect in shielding 14MeV neutron is two layers material composed of metal and PE. Where metal thickness varies between 0-74 cm, a minimum radiation dose exists after neutrons are shielded, i.e., either any kind of metal or PE alone cannot have the best result.

2. Among two layers materials composed of metal and PE, the best effect in shielding 14 MeV neutrons is the composition of tungsten and PE.

3. The composition of copper and PE performs second only to that of PE and tungsten.

3. Two Layers Material Composed of Tungsten and PE

As mentioned above, if only shielding result is considered, the two layers material composed of tungsten and PE is no doubt the best to shield 14 MeV neutrons, which is why we first look at this two layers material here. Set 0.025 mSv, the aforementioned maximum hourly radiation dose allowed for an operator, as standard, the minimum thickness of the two layers material is calculated by MCNP code when the D-T neutron generator’s yield is $10^8$ n/s.

In the following calculation, $d$ represents shield thickness, which is the sum of tungsten thickness ($d_W$) and PE thickness ($d_{CH2}$):

1. $d$ was increased from 2 cm to 74 cm in steps of 1 cm;
2. Every time $d$ changes, $d_W$ increases from 1 cm up to ($d$-1)cm in steps of 1 cm, and $d_{CH2}$ is ($d$-$d_W$)cm;
3. Calculating neutron radiation dose of each combinations when the D-T neutron generator’s yield is $10^8$ n/s;
4. Selecting the minimum $d$ among the combination where the neutron radiation dose is less than 0.025mSv.

Due to the space limit, only some of the data are given in figure 1 below.
As is shown in figure 1, the minimum thickness of the composition is about 47 cm, 38 cm of which is of tungsten thickness. In this case, 8755 kg of tungsten would be needed surrounding the D-T neutron generator which would cost more than $27 million. Therefore, the two layers material composed of tungsten and PE is not the most economical.

4. Two Layers Material Composed of Copper and PE
Considering that copper costs less than $ 8 per kilogram and that the two layers material composed of copper and PE performs next only to the composition of tungsten and PE in shielding 14 MeV neutrons, the research of the composition of copper and PE is also carried out. Again, in the following calculation, \( d \) represents shield thickness, which is the sum of copper thickness \( (d_{Cu}) \) and PE thickness \( (d_{CH2}) \):

1. \( d \) was increased from 2 cm to 74 cm in steps of 1 cm;
2. Every time \( d \) changes, \( d_{Cu} \) increases from 1 cm up to \((d-1)\) cm in steps of 1 cm, and \( d_{CH2} \) is \((d-d_{Cu})\) cm;
3. Calculating neutron radiation dose of each combinations when the D-T neutron generator’s yield is \(10^8\) n/s;
4. Selecting the minimum \( d \) among the combination where the neutron radiation dose is less than 0.025 mSv.

Due to the space limit, only some of the data are given in figure 2 below.

As is shown in figure 2, the minimum thickness of the composition of copper and PE is 52 cm, only 5 cm thicker than that of the composition of tungsten and PE, but they cost less than $33,000,
which is financially feasible and why the two layers material composed of copper and PE is adopted in this Paper.

5. Two Layers Material Composed of Copper and PE Containing Boron

Boron has large capture cross section for thermal neutrons. In order to reduce the thermal neutrons contribution to the radiation dose, Mixed PE in Boron. When polyethylene (PE) is 14 cm thick and copper is 38 cm thick, the neutron radiation dose varies with boron concentration, as is shown in figure 3.

![Figure 3. Neutron radiation dose changes with varying concentration of boron.](image)

It can be seen in figure 3 that, when the thickness of copper and PE is maintained at 38 cm and 14 cm respectively, the neutron radiation dose decreases markedly as the boron concentration within PE increases. Once the boron concentration, however, exceeds 1.00%, the dose of neutron radiation decreases little. Therefore, in practice, it is suggested that 1.00% of boron be added in to PE.

6. Conclusions

The above research in this paper can lead to the following conclusions:

1) Among common hydrogen-rich materials, PE is the best when it comes to shielding neutrons. As we know, the element with the smallest relative atomic mass is hydrogen while PE is the material with the highest hydrogen concentration per unit volume. The fast neutron inelastic scattering cross section of carbon \((425\text{mb})\) and the above factors are considered, PE has best effect among single materials in shielding neutrons, which is authenticated by the simulation result.

2) In shielding 14 MeV neutrons, two layers materials composed of PE and high-density metal are better than PE. Once 14 MeV neutrons collide with high-density metal, the average energy of the scattered neutrons is about 2 MeV which is the range where hydrogen moderates best. Therefore the best effect in shielding 14MeV neutrons is the combination of PE and high-density metal.

3) After taking into consideration factors such as density, fast neutron inelastic scattering cross section, thermal neutron absorption cross section and cost, the two layers material composed of copper and PE is the ideal material for shielding 14 MeV neutrons.

4) When the D-T neutron generator’s yield is \(10^8\text{n/s}\), the dose of neutron radiation can be made less than 0.025mSv after 14 MeV neutrons are shielded by the two layers material composed of 38cm-thick copper and 14cm-thick PE containing 1.00% of boron. In practice, the thicknesses of copper and PE and the concentration of boron can be designed based on the D-T neutron generator yield and/or the maximum neutron radiation dose allowed for operators.
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