Shielding performance test of irradiation monitor tube transport container

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Abstract. This paper focuses on the transport container of irradiation monitoring tube about test technology of the γ radiation shielding performance. Through simulation calculation and test measurement, the external radiation level of irradiation monitor tube transport container is obtained. The experimental results are compared with the calculated results, and the position deviation of the radioactive source in the container is analysed. The results show that it is feasible to use the radioactive source with small activity to test the shielding performance, and improve the shielding performance detection technology of long cylindrical transport container.

1. Introduction

The irradiation monitoring tube is composed of base metals sample from reactor pressure vessel materials, weld and heat affected zone sample, connecting tube assembly and grab assembly. It is placed in the reactor inner ring cavity and is a device to monitor the irradiation effect of reactor pressure vessel. In order to monitor the radiation effect of reactor pressure vessel materials, a certain number of irradiation monitoring tubes are installed in the reactor to obtain the radiation environment data of reactor pressure vessel, the degree of radiation embrittlement and development trend of materials. These data are used to evaluate the integrity of the reactor pressure vessel and revise the reactor operation parameters to prevent brittle fracture of the pressure vessel, so as to ensure the safe operation of the reactor.

Since the irradiation monitoring tube is irradiated by continuous neutrons, it has strong radioactivity. After being removed from the reactor pressure vessel of the nuclear power plant, it is necessary to use the transport container to send it to the hot cell for relevant testing. To ensure that the container can withstand possible transport accidents during transportation, the shielding performance verification of the container shall be carried out according to the requirements of Regulations for the Safe Transport of Radioactive Material [1], which requires that the radiation level on the surface of the container shall not be greater than 2 mSv·h⁻¹, and at 1m shall not be greater than 0.1 mSv·h⁻¹.

This paper focuses on the transport container of irradiation monitoring tube about test technology of the γ radiation shielding performance. Through simulation calculation and test measurement, the external radiation level of irradiation monitor tube transport container is obtained. The test and calculation results are compared, and the position deviation of radioactive source in the container is analyzed. The results show that it is feasible to use the radioactive source with small activity to test the shielding performance, and improve the shielding performance detection technology of long cylindrical transport container.
2. Structure of transport container
The transport container of neutron irradiation monitoring tube is composed of outer package box, shielding container and container support. The shielding container of irradiation monitoring tube is a cylindrical structure, with a total mass of about 4 t. The shielding container of irradiation monitoring tube is composed of container body, upper end plug, lower end plug and lifting lug. The main body of the shielding container is composed of an inner shell, a lead shielding layer, an outer shell, an upper end plug and a lower end plug. The upper end plug and the lower end plug are used to fix and clamp irradiation monitoring tubes with different lengths. The structure of irradiation monitoring tube shielding container is shown in Figure 1.

3. Source term
3.1. Source items to be loaded
When designing the transport container of irradiation monitoring tube, considering the application scope of the container. Based on the current mainstream reactor types in China, the maximum source term is designed, and the selection principles of calculation parameters are as follows: 1) The maximum neutron fluence of each reactor type shall be selected for the pressure vessel; 2) The maximum volume of monitoring tube shall be selected in each reactor type; 3) The irradiation time of the monitoring tube is the shortest value of the irradiation time under the maximum neutron fluence; 4) The impurity nuclide composition takes the upper limit value; 5) The nuclide content of the detector in the irradiation monitoring tube is the maximum; 6) The source term of irradiation supervision tube is 24 cycles of irradiation and 7 days cooling out of reactor.

This project is supported by Super Monte Carlo Program for Nuclear and Radiation Simulation, named SuperMC, which is developed by Institute of Nuclear Energy Safety Technology, Chinese Academy of Science/the FDS Team. SuperMC is a general, intelligent, accurate and precise simulation software system for the nuclear design and safety evaluation of nuclear system [2, 3]. It is used to calculate according to 17 energy groups. The total maximum γ source strength of irradiation monitoring tube is 9.36×10^{11} n·s\(^{-1}\), and the results are shown in Table 1.

Table 1. The γ source strength of irradiation monitoring tube.

| Upper energy limit (MeV) | strength | Upper energy limit (MeV) | strength |
|--------------------------|----------|--------------------------|----------|
| 0.015                    | 1.01×10^{11} | 0.575                    | 2.60×10^{10} |
| 0.025                    | 5.68×10^{9}   | 0.85                     | 3.37×10^{11} |
| 0.0375                   | 3.10×10^{9}   | 1.25                     | 4.30×10^{10} |
| 0.0575                   | 3.71×10^{9}   | 1.75                     | 4.13×10^{9}  |
| 0.085                    | 1.85×10^{9}   | 2.25                     | 4.54×10^{8}  |
| 0.125                    | 1.51×10^{9}   | 2.75                     | 7.77×10^{5}  |
| 0.225                    | 1.69×10^{9}   | 3.50                     | 1.28×10^{2}  |
| 0.375                    | 1.96×10^{10}  | 5.00                     | 1.33       |
3.2. Source term for test
The $^{60}$Co radioactive source used in this test is produced by Chengdu Gaotong Isotope Co., Ltd., and the activity during the test is $2.4 \times 10^{12}$ Bq.

4. Radiation level calculation
The calculation of radiation level is also used SuperMC.

4.1. Dose conversion coefficients
The flux dose rate conversion adopts the data given in Appendix B of Dose Conversion Coefficients for Use in Radiological Protection Against Photon External Radiation (GBZ/T 144-2002), and uses the conversion coefficient of photon fluence-ambient dose equivalent $H^*(10)$ of different energy for conversion. It is also consistent with the data given by ICRP Publication No. 74 [4]. The parameters and Gamma energy spectra of nuclides are quoted from the ENDF/B-VII.1 database of the international nuclear data center.

4.2. Shielding calculation model
The main structure is composed of steel-lead-steel, in which the thickness of inner and outer steel layer is both 10 mm and lead shielding layer is 150 mm, and the main parameters of materials are shown in Table 2. The self-shielding effect of neutron monitoring tube is not considered. Considering that the maximum radiation level of the container appears in the center of the side, the plugs at both ends of the container are simplified according to the shielding function without considering the operating accessories such as bolts and lifting lugs. The irradiation neutron monitor tube is simplified and treated as a long rod radiation source without self-shielding, with a length of about 2 m and a diameter of about 5 cm.

| Materials       | Density (g·cm$^{-3}$) | isotope | Mass fraction (%) |
|-----------------|-----------------------|---------|------------------|
| stainless steel | 7.92                  | Fe      | 69.5             |
|                 |                       | Cr      | 19.0             |
|                 |                       | Ni      | 9.5              |
|                 |                       | Mn      | 2.0              |
| Lead            | 11.34                 | Pb      | 100              |

4.3. Results

4.3.1. Design source term. According to the calculation of design source term, the maximum radiation level on the container surface and 1 m from the surface can be obtained. The calculated results are shown in Table 3. The table shows that the maximum radiation level on the surface of the container is 22.1 $\mu$Sv·h$^{-1}$, and the maximum radiation level at 1 m is 3.0 $\mu$Sv·h$^{-1}$.

| Position          | Radiation level ($\mu$Sv·h$^{-1}$) |
|-------------------|-----------------------------------|
| The side of the container | 22.1                              |
| The end face of container    | 1.11                              |

Table 2. Main parameters of materials.

Table 3. Calculation results of maximum radiation level outside the container.
4.3.2. Test source term. It is assumed that the $^{60}$Co point source is in the middle of the container cavity. The radiation levels on the side surface of the container and at a distance of 1 m are calculated respectively, and the points at different distances from the radiation source along the axial direction are calculated. The results are shown in Figure 2. The maximum radiation level at the surface is 1691.5 $\mu$Sv·h$^{-1}$ and 56.2 $\mu$Sv·h$^{-1}$ at 1 m, which decreases with the increase of radiation source distance. As the axial distance increases, the thickness of the shielding layer between the calculation point and the source point increases rapidly, so that the radiation on the surface decreases rapidly. Since the growth rate of the shielding layer between the calculation point and the source point is less than that of the surface, when the axial distance is greater than 60 cm, the radiation level of 1 m is greater than that of the surface.

![Figure 2](image1.png)

**Figure 2.** Variation of radiation level on the side of the container with the distance of radiation source.

5. Shielding performance test

Because of the symmetry of the container body, it is considered to preset the radioactive source position on the half side of the container. Place the $^{60}$Co radioactive source in the preset position in turn (1#~3#, see Figure 3), in which the 1# point is 50 cm away from the upper end plug, the 2# point is 85 cm and the 3# point is 120 cm.

![Figure 3](image2.png)

**Figure 3.** Diagram of radioactive source placement position.

As shown in Figure 4, the measuring zone of the container is divided into 24 equal parts at an equal interval of 10 cm along the axial direction, which are J1 ~ J24 areas respectively from the upper end plug end (J1 from the upper end plug).
5.1. Equipment
The dose rates on the surface of the container, over the surface and at the distance of 1 m from the surface were measured with a FHZ612-10 long rod x, γ Dose rate probe (GM counter, Thermo Fisher Scientific Inc., America), which has a measuring range from 0.5 µSv·h\(^{-1}\) to 10 Sv·h\(^{-1}\), two energy compensation GM tubes, calibration factor of 0.98, and uncertainty of 5% (K=2) [5].

5.2. Results and analysis

5.2.1. Radiation level of side surface of container. The maximum measured value of surface radiation level is about 1130~1460 µSv·h\(^{-1}\), the radiation level decreases rapidly with the increase of axial distance, and the approximate trend is consistent with the calculated results, see Figure 5. Due to the distance deviation introduced by the placement attitude of the instrument, the sensitive volume size of the detector of the gamma dose rate instrument, the accurate positioning of the radioactive source in the container, etc., the distance deviation between the radioactive source and the measuring point is large, especially at several points with large radiation level, resulting in extremely poor stability and repeatability of the measured value of radiation level. In practice, the above situation cannot be effectively avoided, so it is not suitable to be used as shielding test.

5.2.2. A Radiation level 1m from the side of the container. When the radiation source is placed at points 1#, 2# and 3#, the maximum radiation level measured at 1m on the container surface is 48.9 ~ 42.7 µSv·h\(^{-1}\), and decreases with the increase of axial distance, as shown in Figure 6. The deviation of each measured value is within the measurement uncertainty range of the instrument, and the measured value
has good comparability with the calculated result. The surface measurement error factors described above lead to the deviation of the distance between the radiation source and the measuring point, which has little impact on the measurement of the point at 1m. However, because the instrument uses $^{137}\text{Cs}$ for calibration, and the measured radiation field is actually composed of $^{60}\text{Co}$ and its Compton effect formed through the shielding layer, there is a deviation between the measured value and the calculated value, but the deviation is within $\pm 20\%$ of the allowable range of the instrument.

Because the self-shielding effect of the radiation source is not considered in the simulation analysis and calculation, the calculation result of the radiation level is slightly higher than the measured value in the competitive distance from the radiation source.

![Figure 6](image-url)

**Figure 6.** Variation of the measuring radiation level with axial distance at 1 m.

6. Conclusions
This paper introduces a shielding performance test method for radioactive material transport container by using low activity radioactive source. In this paper, the shielding performance of the transport container of irradiated neutron monitor tube is tested. By using Monte Carlo software, the radiation level on the surface and 1m loading $^{60}\text{Co}$ radiation source is simulated and compared with the measurement results of the container radiation level. The results show that:

1. In the design of the irradiation monitor tube container, in order to expand the application scope of it, the maximum source term of the irradiation monitor tube is calculated by referring to the current mainstream reactor types in China. The total maximum $\gamma$ source strength of irradiation monitoring tube is $9.36 \times 10^{11}$ n·s$^{-1}$.

2. For surface radiation level, the deviation of the distance between the radiation source and the measuring point is caused by the sensitive volume size of the detector of the instrument, the placement attitude of the instrument during measurement, the inaccuracy of the central position of the radiation source, the size of the radiation source itself, etc. As a result, there is a large deviation between the measured value and the calculated value, and between the measured values is also large, so it is impossible to evaluate the relevant test results.

3. For 1 m, the deviation between the measured values of each point is within the measurement uncertainty of the instrument. The measured values and the calculated results have good comparability. The conclusion that the maximum radiation level on the surface of the irradiation monitoring tube transport container is 22.1 µSv·h$^{-1}$ and at 1m is 3.0 µSv·h$^{-1}$ is credible.

4. In order to further improve the accuracy, the G(E) function method can be considered to obtain the radiation level through energy spectrum measurement.
References

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