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ARTICLE

Novel monolayer shields of a neutron powder diffractometer SPICA at BL09 of J-PARC

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A new neutron powder diffractometer, SPICA, at the ninth beamline has been constructed for the study of materials under special environments at J-PARC. We have made shielding design for SPICA with the Monte Carlo transport code system, PHITS, considering shield optimization to reduce amount of shields and to simplify shield configuration. At the first time, a reference design of the optimized multilayer shield was made using conventional shielding materials such as iron, concrete, polyethylene and boric acid resin. Then, novel monolayer shield design has been performed to give equivalent or lower radiation dose rates than those of the reference design by using the new neutron shielding concrete which contains colemanite and peridotite used as a aggregate of concrete. Overall shield thickness saving was also attained in the main shields for the neutron scattering room.

Keywords: high-energy proton accelerator; neutron diffractometer; shielding design; neutron beam line; Monte Carlo; dose distributions; J-PARC; neutron-shield concrete; shield optimization

1. Introduction

Recently, we have constructed the time-of-flight (TOF) neutron powder diffractometer SPICA [1], which is used for special environment measurements, for battery research etc., using an intense pulsed neutron beam at the ninth beamline (BL09) in the Materials and Life Science Facility (MLF) of the Japan Proton Accelerator Research Complex (J-PARC). In order to precisely measure the atom location or the change of the atomic configuration, SPICA was designed to have the high resolution and high intensity. The BL09 beamline was selected because it viewed the decoupled-poisoned moderator. Moreover, high resolution is expected by adopting the second longest flight path of 52 m from the moderator to the sample position in the neutron spectrometers of MLF. Therefore, the experimental building of SPICA was built outside the MLF building as like the super high resolution powder diffractometer (SHRPD) at BL08 of which flight path was about 100 m. High intensity is obtained by the straight configuration of the beam line and neutron guide tube of elliptical shape in two dimensions. The preliminary simulation of the neutron guide showed that the elliptic guide has an excellent performance over a wide range of wavelengths, in particular at short wavelength. SPICA consists of three large neutron-detector banks where the length from sample to detector is 2 m.

Large radiation shields for the long neutron beam-line and the large neutron scattering room should be designed to reduce radiation dose rates outside the shields and neutron background in the detector banks by considering high intensity neutron beam. Such large shields must increase construction cost of SPICA. On the other hand, we have developed the neutron shielding concrete [2] (hereafter abbreviated to “NS concrete”) composed of colemanite and peridotote used as an aggregate. The NS concrete has already been applied to the main shields of the Versatile High Intensity Total Diffractometer, NOVA [2], and Small Angle Neutron Spectrometer, TAIKAN [3] of the J-PARC. However, neutron beamline shield was not included in the application. In the present work, the NS concrete was applied for the first time to neutron beam line shield as well as main shield for the neutron scattering room. In this paper, design of the SPICA shield is described, emphasizing the shield optimization to realize novel monolayer shields composed of NS concrete.

2. Neutron shielding concrete (NS concrete)

Concrete is usually used for neutron shielding, since it can easily form any shape and has moderate neutron-

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shielding performance. Although it is inexpensive, massive thickness is required. Thus, development of the inexpensive concrete having better shielding performance and the same mechanical properties as ordinary concrete was a long-time dream. Boron carbide is a good neutron absorber and often used as a constituent of concrete. But the cost of its shield has risen steeply because boron carbide is very expensive.

On the other hand, boron and hydrogen atoms are contained in natural rock, and it is better to use natural rock as aggregate of concrete from the viewpoints of cost and demand for construction. Colemanite is an example of the natural rock that contains boron. However, most of past works to develop the colemanite concrete reported that a hardening delay occurred. The reason is that the colemanite slightly dissolves in water and does not have uniform mechanical strength. The authors found [4] through the Monte Carlo neutron transport calculations that a few tens par cent of colemanite was enough to give a good shielding performance. Such small amount of colemanite used as a coarse aggregate with portland cement resulted in forming a hard mass [2]. Serpentinite that was hydrogen-rich was used for concrete in the past, and the most familiar example is the pedestal concrete shield on the reactor vessel in the fast breeder demonstration reactor Monju [5], but we adopted similar hydrogen-rich but harmless periotite instead of serpentinite which was a raw material for a harmful asbestos.

Finally, the NS concrete has been developed with colemanite, peridotite, and ordinary Portland cement by controlling the content of the colemanite up to around 15 wt% of the concrete composition aiming at improved shielding performance and production of the concrete. The density of neutron shield concrete is the same as that of ordinary concrete.

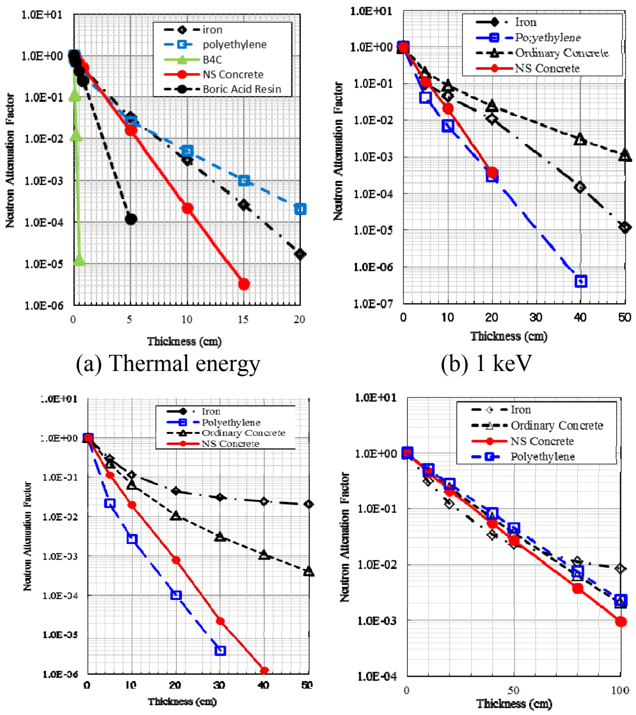
Basic shielding property of NS concrete and other shielding materials used for the shields of neutron spectrometers was calculated with the particle transport code MCNP5 [6] and the JENDL-3.2-base library. **Table 1** shows the atomic composition of the NS concrete. The calculated results are shown at various incident neutron energies as a function of shield thickness in **Figure 1**. In general, the NS concrete occupies the second position concerning neutron shielding transmission except for thermal energy that B_4C and boric acid resin are superior to the NS concrete. Since he NS concrete absorbs neutrons well, secondary gamma-rays are quite lower in the NS concrete than in iron, polyethylene and ordinary concrete.

Table 1. Atomic compositions of the NS concrete.

(unit: atoms/barn*cm)

H	B10	B11	O	Na
2.28E-02	2.80E-04	1.14E-03	4.18E-02	2.99E-05
Mg	Al	Si	P	S+Cl
9.04E-03	6.03E-04	6.92E-03	1.87E-05	5.87E-05
K	Ca	Ti	Mn	Fe
2.81E-05	2.84E-03	1.99E-05	1.87E-05	9.18E-04

As for mechanical properties, compressive strength test showed that the strength increase behavior of the NS concrete after placing concrete slightly delayed but became the same as that of ordinary concrete after 13 weeks. The drying shrinkage and carbonation tests proved that the NS concrete was better.



(a) Thermal energy (b) 1 keV

(c) 100 keV (d) 20 MeV

Figure 1. Comparison of neutron transmission.

3. Shielding designs of SPICA

SPICA is a large neutron spectrometer. Its flight path from moderator to a sample position is 52 m. Central axis of the neutron beam line was located at 1773 mm height. SPICA has three detector banks that are the backward detector bank, the multipurpose detector bank and the forward (small angle) detector bank. The distance from the sample to detectors is about 2 m for all banks. Thus, the scattering room was taken to be large: approximately 9 m long, 6 m wide and 3.5 m high. Radiation shield design for SPICA has been performed by using the PHITS code [7], employing the source biasing technique and taking into account of scattering-effects by super-mirror neutron-guide tubes of elliptical shape in two dimensions. Designs were carried out by two steps: designs aiming at optimized multilayer shields using conventional shielding materials and advanced design of novel monolayer shields using NS concrete. Shield thickness was determined so as to satisfy the design criterion of radiation dose rates both outside of the biological shield and at the boundary of the radiation controlled area. Outside the MLF building, the latter condition become influent, since the controlled area where only radiation worker was permitted to approach was set to be narrower in the MLF building.

3.1. Design of optimized multilayer shields

Initially, we considered multilayer shields composed of conventional shielding materials of iron, ordinary concrete, polyethylene and boric acid resin which were generally used for neutron-spectrometer shields.

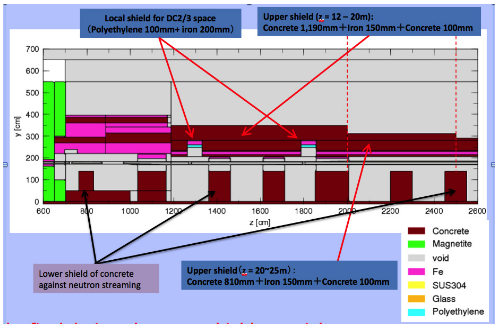


Figure 2. Vertical view of the configuration of the neutron beamline shield for distance from the moderator, Z, between 6 m and 26 m.

Initially, 100 mm thick polyethylene was used as the most inner shield, followed by 200 mm thick iron and 460 mm thick ordinary concrete in the beam-line shield surrounding the void space of 600 mm wide and 2060 mm high behind the front shield up to Z=46 m , because of large neutron streaming through the beamline. Next, the concrete blocks partially carrying a saddle-shaped iron shield were set under the guide tube between guide-tube supporters. They were found to effectively reduce so much neutron streaming that polyethylene was substituted with ordinary concrete except for the local spaces for disk choppers. Multilayer shields composed of concrete and iron form a shape of reverse “U” letter and was limited above 1400 mm height in order to reduce construction cost. Below 1400 mm, ordinary concrete was used as the beamline side shield. **Figure 2** shows the vertical view of a part of the beamline shield along the neutron beamline. Thickness of the upper concrete shield changes stepwise from 1,190 mm to 460 mm with a distance from the moderator.

Calculated neutron dose rates outside of the shields are below 1 μSv/hr, as shown in **Figure 3**.

Shield designs for the neutron scattering room were made to reduce radiation dose rates outside the shields and the neutron background in the detector bank. Main shield was determined to be multilayer composed of 5,000 mm or 6,000 mm thick concrete and an inner liner of 50 mm thick boric acid resin, as shown in **Figure 4**.

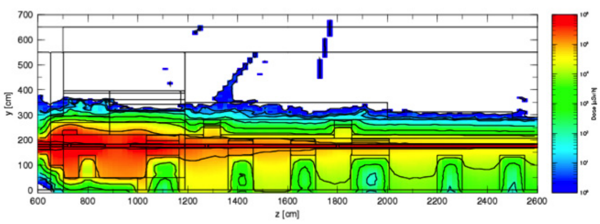


Figure 3. Neutron dose rate distributions along the center vertical plain in the neutron beamline shields.

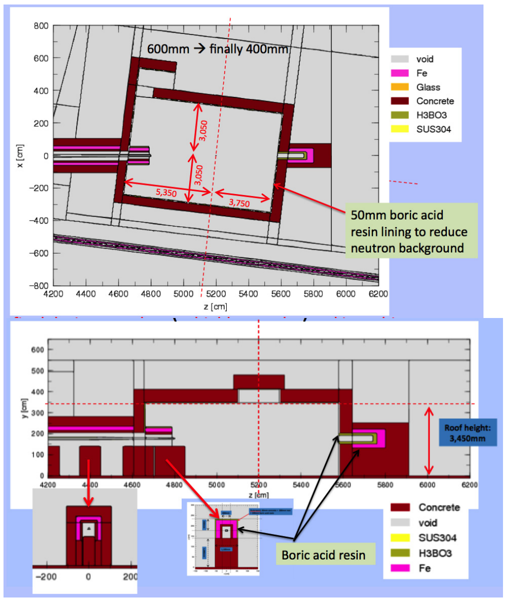


Figure 4. Configuration of neutron beam line shields and main shields for the neutron scattering room.

Special care was paid to the neutron beamline shield up to Z= 48.5 m to take narrower void area of 400 mm wide and 573 mm high and multilayer shield of concrete, iron and boric acid resin above 1400 mm high ordinary concrete shield in order to reduce background neutrons in the room. Their thicknesses were determined to be 100 mm concrete, 200 mm iron and 50 mm boric acid.

Beam dump was composed of 100 mm thick boric acid resin, 200 mm thick iron and 300 mm thick concrete surrounding 300 mm x 300 mm beam hole in perpendicular direction, and 200 mm thick resin, 400 mm iron and 1,100 mm concrete behind the beam hole. Depth of the beam hole was about 1,650 mm.

3.2. Advanced design of novel monolayer shields

Large multilayer shields seemed to be fairly expensive. Further design to change the multilayer shields into novel monolayer shields was made by using NS concrete so as to ascertain that radiation dose rates become lower than those of multilayer shields. In the neutron beamline shields, all shielding materials were substituted with NS concrete except for the lower concrete blocks to be located to reduce neutron streaming. Thus, volume size of the shields was unchanged. Main shields for the neutron scattering room were modified into thinner NS concrete shield by removing the boric acid resin lining and resulted that the room became extended. The shield at the entrance was also slimmed from 600 mm concrete and 50 mm boric acid resin lining to 400 mm NS concrete, since we reduced the incident neutrons to the entrance tunnel due to lowering its roof height from 3.45m to 2.96m in addition to shield exchange. Hatched door on the roof was also done from 600 mm concrete and 50 mm boric acid resin lining to 550 mm NS concrete.

Backward shield of the beam dump was also reduced by 200 mm by using @Eponite [8] which was mixture

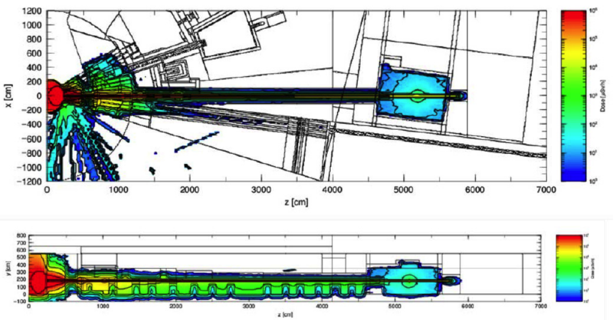


Figure 5. Calculated radiation dose rate distributions.

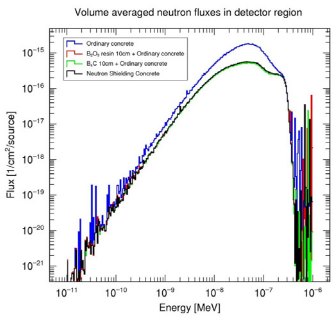


Figure 6. Comparison of neutron spectra in detector bank.

of boron carbide with a phenol-based resin instead of boric acid resin.

Finally, radiation dose rates were calculated for the region including neighboring beamlines BL08 and BL10. Calculated results are shown in **Figure 5**. Calculated radiation dose rates satisfy the design criterion and seem to have some kind of margins around the neutron beamline shields. Neutron spectra in the detector bank also calculated to clarify that the present monolayer shield reduce background neutrons as much as boric acid resin. The calculated results are shown in **Figure 6**. The NS concrete exhibits the same spectrum as the 10 cm boric acid resin and 10 cm B_4C lining on concrete.

The shield simplification mentioned above by the NS concrete is understandable considering good performance of the NS concrete in the whole energies as shown in Figure 1. The shield simplification to the concrete bring construction cost saving. It also enables us to built-and-disassemble the shields quite easily and hence reduce construction cost.

4. Concluding remarks

SPICA is a large neutron powder diffractometer constructed for the study of materials under special environments at J-PARC. In the present work, design of novel monolayer shields to such large spectrometer has been completed. The following is the summary:

It has been found that our NS concrete has a good shielding performance in the whole neutron energy range from thermal to a couple of tens MeV. As a result, NS concrete has realized thinner novel monolayer shields for long NBL and large scattering room of a neutron powder diffractometer SPICA of J-PARC.

Further shield optimization than substitution of materials will enable us to additively reduce shield thickness. The shield simplification to the concrete also enables us to built-and-disassemble the shields quite easily and hence reduce construction cost. Other merit of the neutron shield concrete is to reduce a neutron-induced activities, since it effectively diminish thermal neutrons. The NS concrete will be also applicable to fusion reactors.

In last, SPICA shields have been already constructed in December 2011 and are contributing to the SPICA operation.

Acknowledgements

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