Discussion on radiation shielding materials for slit space between accelerator buildings

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Abstract

For the new construction of an accelerator building adjacent to an existing facility, it is necessary to give careful consideration with reference to two regulations; the building and radiation codes. For the slit space between the accelerator buildings in case of using of the two facilities as one, two kinds of investigation were conducted on the development of shielding flexible materials and on the evaluation of neutron dose attenuation through elemental data on several types of concrete in the radiation shielding calculations. A new flexible shielding material was tested for several aspects, and the radiation shielding calculation for application of the material was carried out to confirm the performance. As a result, a urethane-based material was selected and applied as designed. Another calculation of neutron dose attenuation for the slit space between the buildings was conducted for thirteen different types of concrete for shielding. This investigation emphasized that proper concrete data should be used for the radiation shielding calculation, while the hydrogen content and the density of the concrete were dominant for neutron attenuation.

Keywords: accelerator radiation shield, concrete for shield, Monte Carlo, dose attenuation

§1. Introduction

Concrete is one of the main materials used for constructing buildings, infrastructure, and facilities, which are a major part of human public activities. These materials are also typically used in reactor and accelerator facilities for shielding.

The construction of an accelerator facility requires at least two aspects of regulation; building and radiation. The building code provides the shape and soundness as the container of the building, including structural and aseismic excellence. On the other hand, radiation protection is, of course, very important for the facility. In particular, the above two aspects should be considered very carefully in the case of using the two facilities as one.

There are two accelerators located at Kyushu University; one Fixed-Field Alternating Gradient accelerator (FFAG) and one tandem accelerator. The building for the FFAG was constructed in 2008 [1], and that for the tandem accelerator in 2014. Since the newer building was constructed as a separate structure away from the FFAG building with a joint radiation controlled area, special consideration was required to construct the newer building with sufficient space between the two buildings.

§2. Flexible radiation shielding material for accelerator buildings

A new type of flexible shielding material was applied to the narrow space of 8 cm in width between the two accelerator buildings (the existing building and the newly constructed one) for neutron shield. The main requirements of this shielding material were flexibility, shielding performance, and durability.

2.1 Requirements of the material

Four kinds of performance for the material fitted to the slit space between buildings were required, such as building structural aspect, radiation shielding aspect, material aspect and construction aspect. Flexibility was necessary to absorb the displacement of the buildings in case of an earthquake, in order to avoid damage caused by the two buildings crashing together when their shaking cycles differed. For the radiation shielding aspect, neutron shielding performance was assumed as the main issue for the material, while the cranked shaping concrete wall would be good for shielding against gamma ray. The narrow-slit space for the material fitted between buildings was outside of the building and mostly shaded. Because the performance should be maintained throughout a certain period despite several problems posed by the weather, reasonable durability was necessary. Another important factor in selecting the material was construction-related performance, such as workability, ease of manufacture, and reasonable cost.

2.2 Durability test for the material

Fifteen candidate material samples (silicon rubber, water sealant, special epoxy, urethane polymer, polyethylene and mortal slate) were gathered at the location so as to be reasonably available once supply was confirmed within the construction schedule. Upon receiving the above samples, we started to test certain aspects of the durability performance, assuming a settled condition for the actual construction.

The outlines for the results [2] of the tests were as follows;

1) A comparison of the before and after tests showed no shrinking and no mass change for any samples.
2) Three samples had changed in size (a reduction of more than 15 % due to the curing) after an accelerated weather-proof test and heat resistance test.
3) Besides the above, a few samples changed in colour after tests, but the changes did not affect the performance.

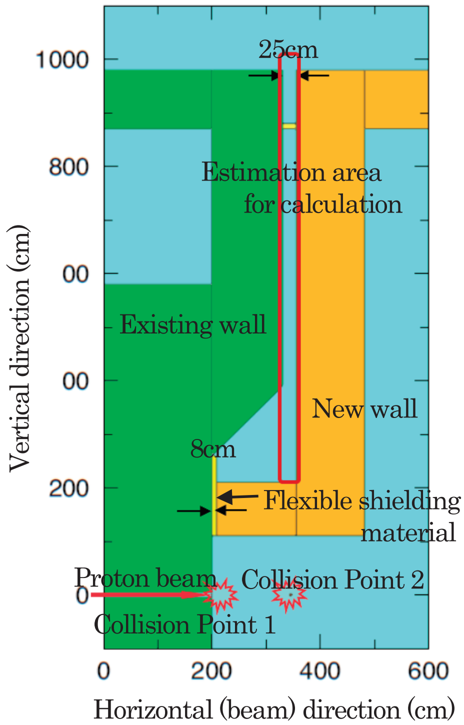

Figure 1 Calculation model for the two buildings.

Further investigation was conducted for other conditions such as flexibilty, stability, workablity, shield performance to select the material to apply to the space.

We had developed normal urethane into a new type of flexible shielding material in workablity and manufacturability.

The shape of the material was set as a block (230 mm x 350 mm x 80 mm) from the point of view of construction. More than 1000 blocks were manufactured at the construction site, and applied to spaces of 80 mm and 250 mm space.

2.3 Calculation for the adaptation of the material

After the material durability tests, estimation of the performance of the urethane-based flexible shielding material was conducted using Monte Carlo code, PHITS 2.96[3]. Figure 1 shows the calculation geometry for this investigation. Because the border space between the two buildings was a very complicated shape and around 10 m in height, we used R-Z cylindrical geometry with the vertical direction of the building for the radial (R) direction and with the horizontal direction for the Z axis, to achieve a reasonably small statistical error. The green portion on the left indicates the existing building with the FFAG (typically a 150 MeV proton beam) and the right orange portion indicates the new building. The model for the calculation was focused on the vertical attenuation of the dose generated by the proton beam to the virtual iron set around the border of the two buildings.

The proton beam was transported from the existing building through the beam hole in the existing wall, which was on the centre line of the calculation geometry (vertical direction = 0 cm in Figure 1) with 150 MeV. The virtual iron target was set on the line at Z = 200 cm, which was assumed right after the existing wall and right below the narrow slit fitted by the flexible shielding material (Collision Point 1, referred a CP1 in figures). In another case, the calculation was conducted with the iron target set at Z = 327.5 cm on the centre line under the border space of the two buildings (Collision Point 2, referred to a CP2 in the figures). Several estimations were conducted for the outdoor border space, for which there is a 25-cm width to the celling of the first floor of the new building, which is 8 m high.

Table 1 shows the material elemental data for the calculation. For the new building, chemical analyses were conducted for 18 samples from constructed concrete, which are recorded as FH02[4] in the table. Another piece of concrete data in the table, shown as AV03[4] assumed the typical concrete shielding data discussed in the Atomic Energy Society of Japan. The elemental data for the flexible shielding material were calculated according to the chemical equation listed in the material safety data sheet.

Table 1 Elemental data of materials for the calculation

	Element													w%	Density
Material	H	C	O	Na	Mg	Al	Si	S	K	Ca	Ti	Fe	N	Cl	g/cm^{-3}
Av03	0.6	0.6	48.6	1.7	1.3	5.7	26.2	0.1	1.9	10.0	0.3	3.0			2.26
FH02	0.5	5.1	48.8	0.7	0.5	2.7	16.0	0.0	1.1	23.7	0.1	0.6			2.27
SFM	9.8	72.5	16.0				0.1						1.2	0.4	1.00

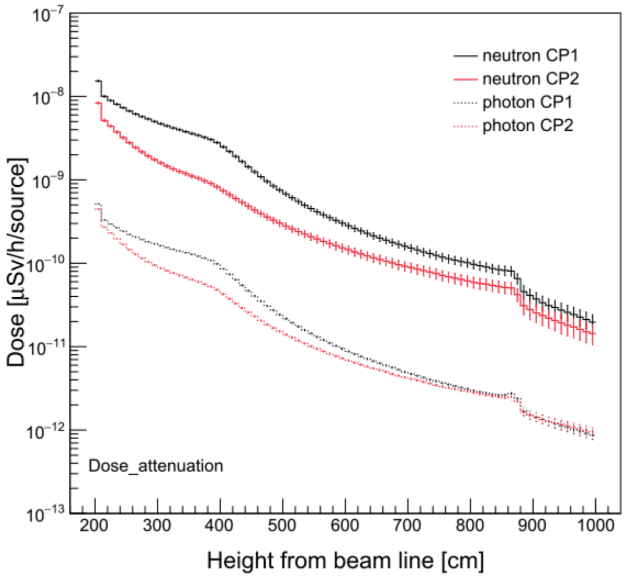

Figure 2. Calculated dose attenuation in the border area

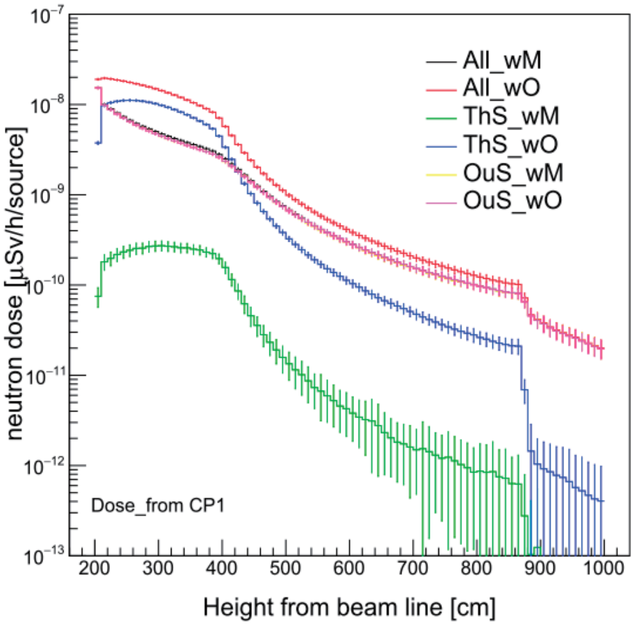

Figure 3. Comparison of neutron dose attenuation for the installation of the flexible shielding material originated proton-iron reaction at CP1.

The area for the calculation was the 25-cm border space between the two buildings which is outlined in red in Figure 1. T-Track tallies were set in the area for the neutron and photon spectrum and the dose with dose conversion factors [5].

The new urethane-based flexible shielding material was installed at the slit area between the two buildings, which was 8 cm in width and 150 cm in length from the bottom of the concrete slab for the new building through the slit to 50 cm upon the surface of the concrete.

Figure 2 indicates the calculated dose attenuation of photon and neutron for the border space between the buildings, from proton-iron collision at CP1 and CP2, respectively. The dose for neutron from CP1 (indicated with a solid black line) is the highest among the four curves, and the orders describe the doses for neutron from CP2, for photon from CP1, and photon from CP2. Since the doses for the neutron are 100 times higher than those for photon for all calculated heights, further estimation was conducted for neutron attenuation for CP1 only.

The case with the materials installed in the 8-cm slit and the case without the materials were compared. Four different calculations with/without the installation of the material were conducted. The indexes in the figure for the calculation conditions refer to the installation of the flexible shielding material as “wM” in the last two characters and to the case not using the material (set air in this case) as “wO” in following figures.

In the calculation, the paths of the neutron transportation were also estimated using the counter feature in PHITS code. The curves with a “ThS” index in the first three characters show the calculated dose for the neutron which were transported through the 8-cm slit, while the other curves with an “OuS” index show those for the neutron which were transported out of the slit for whole the life in the calculation. The curve with a “ThS_wM” index refers to the calculation in the case with the installation of the flexible shielding material for the neutron transported through the slit, for example.

Figures 3 shows a comparison of neutron dose attenuation between cases with and without the flexible shielding material installed, with neutron occurring due to proton-iron collision at CP1. This figure indicates that the neutron dose decreased to less than half, and that the neutron dose through the slit significantly decreased to less than 1/20 with the material installed at a high of 390 cm from the beam line with a proton-iron reaction originating at CP1. As the quantity of the neutron dose with “All_wO” was less than that with “All_wM”, the installation was clearly effective in reducing the radiation dose in this case.

§3. Comparison of the dose attenuation for the slit space on different concrete

In shielding design for new buildings, existing published concrete data are used for calculation. These data, however, might not have been chosen reasonably. Therefore, the influence on the differences between these concrete data is estimated in this session.

3.1 Concrete data for the calculation

The calculation geometry and the Monte Carlo code for the investigation were the same as in Session 2 (Figure 1 and PHITS2.96). Elemental data were gathered on thirteen types of concrete to be used in calculating for the dose attenuation.

Table 2 summarizes the elemental data for thirteen types of concrete, namely ANL5800 type 1 (referring ANL501), ANL5800 type 2a (ANL502a)[6], ANL6443 type 2b (ANL602b)[7], composition of CONCRTE PORTLAND in NIST (NIST98)[8], NBS type03 (NBS03), NBS type 04 (NBS04), Los Alamos National Laboratory concrete (LANL), Oak Ridge National Laboratory concrete (ORNL) Hanford Dry concrete (HFDd)[9], JAERI-M-6928 type 1 (JAERI1), JAERI-M-6928 type 2 (JAERI2)[10], F02SD, and Standard concrete 2017 (STD17)[11]. Data for the first eleven were provided by national organizations in the USA, and the next two by JAERI. The data for F02SD was chemically analyzed data with existing concrete samples in this building. STD17 was defined through a discussion on the standardization of concrete elements for radiation shield in Japan.

These elemental values for each density were used as concrete in the calculation for both the existing and new walls in Figure 1. The dose attenuation curves for the 25-cm slit (referred to as “estimation area” in the figures) were calculated using the proton reaction at CP1. The flexible shielding material described in Section 2 was not applied to the narrow, 8-cm slit in this calculation.

3.2 Result of the calculation

Figure 4 shows the calculated neutron dose attenuation curves for the 25-cm slit space with the elemental data for the different types of concrete listed in Table 2, as well as originating proton iron reaction at CP1 in Figure 1. The thirteen curves were divided into three groups by attenuation rates (“High”, “Medium” and “Low”). The “High” group contains ANL502a, NIST98, NBS03, and F02SD, while the “Low” group contains ANL501, HFDd and STD17, and the “Medium” group contains the others. These categorizes also come from the weight percentage of hydrogen given in Table 2. The figures and the table indicate that the neutron dose attenuation for the slit space is influenced by the hydrogen content of the surrounding concrete.

Figure 5 shows the other calculations of neutron

Table 2. Elemental data of materials for the calculation

Name	Element												w%	Density
	H	C	O	Na	Mg	Al	Si	P	S	K	Ca	Ti	Mn	Fe	g/cm^{-3}
ANL501	0.21	5.58	49.3	0.00	0.21	0.51	18.8	0.00	0.08	0.00	24.9	0.00	0.00	0.31	2.33
ANL502a	1.00	0.10	53.0	1.60	0.22	3.39	33.7	0.00	0.00	1.30	4.34	0.00	0.00	1.39	2.30
ANL602b	0.52	0.10	51.3	1.67	0.23	3.55	35.2	0.00	0.00	1.36	4.55	0.00	0.00	1.46	2.20
NIST 98	1.00	0.10	52.9	1.60	0.20	3.39	33.7	0.00	0.00	1.30	4.40	0.00	0.00	1.40	2.30
NBS03	0.85	5.01	47.3	0.00	2.42	3.61	14.5	0.00	0.30	0.17	24.69	0.00	0.00	1.10	2.35
NBS04	0.56	0.00	49.8	1.71	0.26	4.57	31.5	0.00	0.13	1.92	8.29	0.00	0.00	1.24	2.35
LANL	0.45	0.00	51.3	1.53	0.00	3.56	36.0	0.00	0.00	0.00	5.79	0.00	0.00	1.38	2.25
ORNL	0.62	17.52	41.0	0.03	3.26	1.08	3.4	0.00	0.00	0.11	32.1	0.00	0.00	0.78	2.30
HFDd	0.40	0.00	48.2	0.22	1.41	6.94	27.8	0.00	0.00	1.30	8.02	0.00	0.00	5.75	2.18
JAERI1	0.42	0.00	50.7	0.00	0.12	0.45	38.6	0.00	0.07	0.00	6.87	0.00	0.00	2.74	2.30
JAERI2	0.48	0.27	49.6	1.10	0.95	5.61	29.9	0.00	0.16	0.80	8.25	0.17	0.25	2.55	2.43
F02SD	0.88	5.10	50.1	0.63	0.51	2.63	14.4	0.03	0.00	1.07	24.0	0.08	0.02	0.57	2.32
STD17	0.34	1.23	47.4	1.64	1.12	5.42	24.5	0.04	0.13	1.86	13.1	0.26	0.04	2.91	2.10

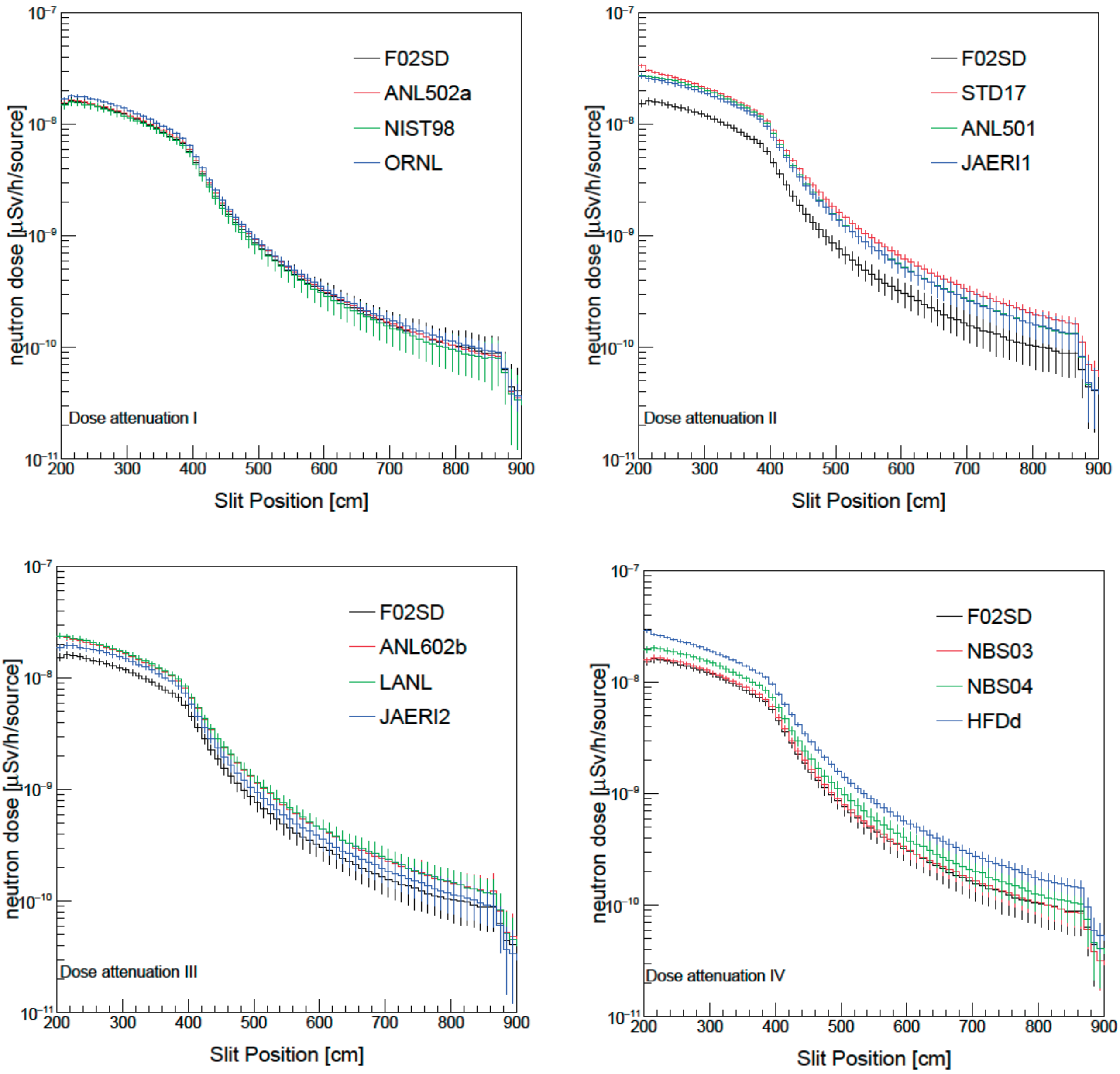

Figure 4. Comparison of neutron dose attenuation for the slit space on different types of concrete with the proton-iron reaction originating at CP1.

dose attenuation for the proton iron reaction originating in the slit at CP2 with those originating at CP1 for "High" group and "Low" group. The dose attenuation for CP2 are almost all smaller than those for CP1, and it is indicated that the "Low" group (ANL501a and STD17) would have a different attenuation due to its density because of the attenuation paths.

Therefore, the investigation of neutron dose attenuation for the slit space with the elemental data of different concrete was conducted with the hydrogen content and density as the key indexes of the attenuation. It is also important to choose proper data from among the variety of published concrete elemental data in order to estimate the dose attenuation accurately.

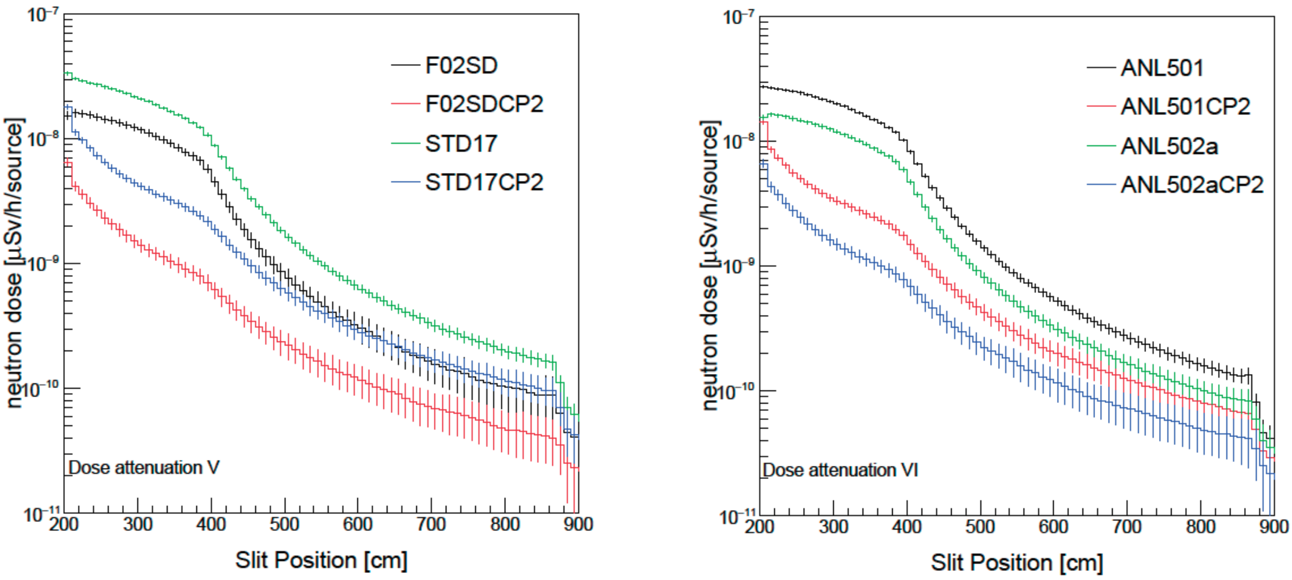

Figure 5. Comparison of neutron dose attenuation for the slit space with different types of concrete at CP1 and CP2.

§4. Conclusion

In the case of new construction as a separate, adjacent building, two investigations were conducted. For the narrow-slit space (8 cm in width between buildings), a new type of flexible shielding material was developed with consideration for the specifications of the required performance for the four aspects (structural, radiation shielding, material, and construction). After several durability tests and radiation shielding calculations, a urethane based material was selected and applied as designed.

Elemental composite data on thirteen types of concrete for radiation shield calculation were gathered to compare the dose attenuation for the slit space between the two buildings. The calculation results for the neutron dose indicate that the hydrogen content and density of concrete were important for the attenuation. It was also important to choose reasonable concrete data to properly estimate the radiation shield because of the wide variation in hydrogen contents and density in data published in the past.

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Short comment

Accelerator facilities are one of the targets of application for the Low-Activation technology. In addition, investigation of elemental composite for concrete is also important in estimating dose attenuation properly.