Investigation into activation of accelerators at various synchrotron radiation facilities in Japan

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ABSTRACT
To establish systematic guidelines for accelerator decommissioning, a large-scale activation survey was conducted at representative synchrotron radiation facilities in Japan. The neutron flux during accelerator operation was measured with various dosimeters. A Monte Carlo simulation was conducted for some facilities to verify the actual neutron distribution and their spectra. Beam loss points, reflected as high-dose-rate areas, were identified by a whole-beamline survey with a survey meter, and the generated radionuclides and their activity were determined with a lanthanum bromide (LaBr3) scintillation spectrometer. In all facilities, the activation level was quite low. Whole-beamline tunnels made of concrete were not activated, and no radionuclides were detected except for natural nuclides. In addition, almost all beam-line components were either not or minimally activated. Although the acceleration energy is very high for radiation synchrotron facilities, the generation of radioactive waste would be very low.

1. Introduction

Accelerators of electrons, protons, and various charged particles are widely used in science, engineering, and medical fields, and have played a significant role in the development of human society. However, one drawback of an accelerator is that the activation of beamline components and surrounding materials, which is attributed to beam loss, has become a significant concern regarding waste management. Activated areas of accelerator facilities must be thoroughly decontaminated, treated as radioactive waste, and strictly regulated when decommissioning the accelerator. Generally, magnets and beamline components consisting of metallic materials and buildings consisting of concrete occupy the most volume and mass in an accelerator facility. In some cases, decontamination work may incur significant time and economic costs, and it significantly depends on the quality and quantity of the induced activities. In particular, long-lived nuclides such as 60Co (half-life: 5.27 y [1]) and 152Eu (half-life: 13.5 y [1]) must be treated for a prolonged time. Therefore, the site, type, and activity of radionuclides generated in the beamline and the building should be clarified properly at each facility before it is decommissioned [2–9].

In Japan, there are over 1000 accelerator facilities from small to large scale. Based on their useful lifetimes, many of them will require renovation or decommissioning in the near future. However, guidelines for decommissioning have not been prepared, except in small-scale medical-purpose accelerator facilities. As the activation level and generated radionuclides depend on the acceleration energy and current in each facility, systematic studies are required to comprehend the activation of the entire accelerator facility. To establish a reasonable procedure for decommissioning of an accelerator facility, we have investigated various types of facilities, such as synchrotrons, cyclotrons, and electrostatic accelerators [10,11]. Herein, we focused on synchrotron radiation facilities in Japan, and a systematic activation survey for typical facilities was conducted. Whole beamlines were scanned with a survey meter and a scintillation-type γ-ray spectrometer after accelerator operation. Beam loss points, reflected as high-dose-rate areas, were identified, and the generated radionuclides were determined. The neutron flux during accelerator operation was determined using various dosimeters. For some facilities, a Monte Carlo simulation was conducted to verify the spatial neutron distribution and their spectra. In this paper, the current activation

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conditions for each facility are compared, and the future activation conditions are predicted from the series of measurement results.

2. Target facilities

The five accelerators shown in Table 1 were selected as representatives for the activation survey. These accelerators differ not only in maximum energy, but also in the type of pre-accelerator used to the storage ring. The Super Photon Ring – 8 GeV (SPring-8), Photon Factory (PF), and Ultra-Violet Synchrotron Orbital Radiation (UVSOR) facilities operate in both storage and top-up modes, whereas the Hiroshima Synchrotron Radiation Center (HiSOR) and the Synchrotron Radiation Center (SR Center) operate only in storage mode.

SPring-8 [12] is the largest synchrotron radiation facility in Japan, with the highest acceleration energy of 8 GeV. In this facility, the electron beam is accelerated to 1 GeV by the linear accelerator, then sent to the booster synchrotron where it is further accelerated to 8 GeV, and finally sent to the main storage ring. PF [13–15] is located at the High Energy Accelerator Research Organization (KEK). A 2.5-GeV electron beam from the linear accelerator enters the main storage ring. The linear accelerator is excluded from the survey target in this study because, unlike the accelerators of other facilities, it is not used exclusively for beam injection into synchrotron radiation storage rings. UVSOR [16] is located at the Institute for Molecular Science. In this facility, the electron beam is accelerated to 15 MeV by the linear accelerator and sent to the booster synchrotron, where it is further accelerated to 750 MeV. Finally, it is sent to the main storage ring. HiSOR [17,18] is located at Hiroshima University. In this facility, the electron beam is accelerated up to 150 MeV by the microtron and then sent to the main storage ring, where it is accelerated to 700 MeV. The SR Center [19], which has a very similar structure to HiSOR, is located at Ritsumeikan University. In this facility, the electron beam is accelerated up to 150 MeV by the microtron and sent to the main storage ring, where it is accelerated to 575 MeV. HiSOR and the SR Center are relatively more compact than the other facilities.

The numbers of average stored electrons (normalized by the storage ring perimeter) in the main ring are also summarized in Table 1. Regardless of the difference in geometrical scales and acceleration energies, all accelerators show similar values for the average stored electrons.

3. Activation survey methodology

3.1. Magnets and metallic components on the beamline

The investigation of activated metallic materials in the beamline, such as beam-pipes, magnets, profile monitors, and gate-valves, was performed by contact dose-rate measurement to rapidly distinguish the activated area, and γ-ray spectrometry to identify the generated radionuclides. Ordinary, a survey meter was used for the dose-rate measurement, and a Ge semiconductor detector or a lanthanum bromide (LaBr₃) scintillation detector were used for γ-ray spectrometry. The residual radionuclides depend on the period from the end of the accelerator operation. Thus, mainly short-lived nuclides can be evaluated when the survey is conducted immediately after the operation, whereas long-lived nuclides can be evaluated when sufficient time will be elapsed from the last operation. However, since all target facilities are in use for synchrotron radiation experiments by various users throughout the year, we had limited opportunities and periods for the activation surveys. Figure 1 summarizes the survey date for each facility, and the accelerator operation periods are depicted as the solid arrow line.

The purpose of the beamline survey is to clarify the location, type, and activity of the radionuclides generated in the accelerator facility. The amount of radioactive waste generated at the time of decommissioning and sufficient cooling period for attenuating residual activity can be estimated. At the beginning of the beamline survey, we scanned the contact dose-rate on an entire beamline using a sodium iodide (NaI) scintillation survey meter (Hitachi, TCS-171) to reveal the activated area at a relatively high dose. Simultaneously, γ-ray spectrometry at high-dose

| Table 1. Synchrotron radiation facilities investigated in this study. |
|---------------------------------|-------------|-------------|-------------|-------------|-----------|
| Facility                        | SPring-8    | PF          | UVSOR       | HiSOR       | SR Center |
| Foundation year                 | 1996        | 1982        | 1993        | 1996        | 1996      |
| Energy (GeV)                    | 8           | 2.5         | 0.75        | 0.7         | 0.575     |
| Type                            | L–B–MR      | L–MR        | L–B–MR      | MR          | MR        |
| Operation mode                  | Storage/Top-up | Storage/Top-up | Storage/Top-up | Storage       | Storage     |
| Annual operation period (days)  | 230         | 160         | 250         | 210         | 180       |
| Perimeter of the storage ring (m) | 1436       | 187         | 13            | 22          | 3.14      |
| Average stored electrons (m⁻¹)  | 2.08 × 10⁸  | 9.37 × 10⁸  | 6.25 × 10⁸  | 2.06 × 10⁸  | 1.6 × 10¹⁰ |

L: Linear accelerator (linac)
B: Booster synchrotron
MR: Main ring (storage ring)
areas was performed with a LaBr₃ scintillation spectrometer (Mirion, InSpector1000), and the generated nuclides were identified.

### 3.2. Concrete building

The activation of a concrete building is difficult to evaluate directly because the contact dose-rate is weaker than the beamline components, and the spatial distribution of the activated area is broad. Normally, the activation of the concrete wall and floor can be estimated from the ambient neutron flux [20,21]. As summarized in Figure 1, we performed an ambient neutron flux evaluation experiment using dosimeters (solid track detectors (CR-39) [22] and thermoluminescent dosimeters (TLD) [23]) and a pair of gold foils as the activation detector [20,21]. One of the gold foil pairs was covered with 1 mm-thickness of cadmium plates. TLD was covered with 0.5 mm-thickness cadmium plate. These were installed at the principal point where the highest neutron dose in the entire facility was expected, depicted as a filled colored dot in Figures 2–6, and mapped thermal and epithermal neutron flux. The installation periods for each facility are depicted as blue bars in Figure 1. As the activation level of each radiation synchrotron facility is not expected to be strong, we basically used solid track detectors suitable for low neutron doses. Gold foils are suitable for high neutron flux fields and were therefore adopted where strong activation was expected. After the dosimeters were set, the accelerator was operated for between 1 week and 1 month, after which the dosimeters were withdrawn and analyzed.

There is another evaluation method for ambient neutron flux. We have developed an in situ measurement method using a Ge detector combined with a thick radiation shield [24]. This method estimates the ambient neutron flux around the concrete floor by using the activity value of ²⁴Na generated by the thermal neutron capture reaction of ²³Na(n,γ)²⁴Na. In parallel with the beamline survey, we performed γ-ray spectrometry of the concrete floor using the above method. Essentially, this method regards the concrete floor as a large activation detector, such as a gold foil.

In PF alone, a destructive analysis by core sampling method was conducted to precisely determine the activation level and depth distribution of induced activity. A core drill was used to take concrete samples of 15 cm length from the walls at a total of five points, with an additional 50 cm length taken from a point on the floor. The sampling points are shown in Figure 3. The samples were sliced every 2 cm from the surface, ground to a 100 μm mesh particle size using a ball mill, and then analyzed with a Ge detector after being packed into a U8-type plastic container. The sample amount was 70 g each, and the measurement time was 10,000 s. In addition, β-emitting nuclides (³H and ¹⁴C) in concrete sample were extracted by heating, collected the water vapor with a cold trap, and collected the CO₂ with monoethanolamine, then quantified by a liquid scintillation counter [25,26].

### 4. Results

#### 4.1. Survey results of each facility

**4.1.1. Spring-8**

The beamline survey was conducted 1 h after the operation stopped. As shown in Figure 7, a total of 50 high-dose-rate points over 0.2 μSv·h⁻¹ on the beamline are found, whereas almost all beamline components are indistinguishable from background. Four principal activated areas show dose rates over 1 μSv·h⁻¹: at the end of the linear accelerator, the injection point of the booster synchrotron, the ejection point from the booster synchrotron and transfer beamline, and the injection point of the main ring. The maximum value of the net contact dose rate of the beamline component was 10 μSv·h⁻¹, at the transfer beamline from the booster synchrotron. The principal
Figure 2. Overview of SPring-8 and all points of dosimeter installation. Dosimeters SP-108 ~ 116 and SP-120 ~ 128 were installed in a $3 \times 3$ arrangement on the coaxial of the branch photon beamline.

Figure 3. Overview of PF and all points of dosimeter installation. Some dosimeters were installed on the maintenance corridor beneath the accelerator tunnel (labeled as 'UG').
activated areas on the beamline were measured with a LaBr₃ detector, and the following typical nuclides generated by the photonuclear reaction were detected: $^{44m}$Sc (half-life: 58.6 h [1]), $^{46}$Sc (half-life: 83.8 d [1]), $^{48}$V (half-life: 15.97 d [1]), $^{51}$Cr (half-life: 27.7 d [1]), $^{52}$Mn (half-life: 5.59 d [1]), $^{54}$Mn (half-life: 312 d [1]), $^{56}$Co (half-life: 77.2 d [1]), $^{57}$Co (half-life: 272 d [1]), $^{58}$Co (half-life: 70.9 d [1]), and $^{57}$Ni (half-life: 35.6 h [1]), as shown as an example in Figure S1. In particular, $^{54}$Mn and $^{57}$Ni were detected in many activated areas.

The ambient neutron flux determined by the CR-39 ranged between orders of magnitude of $10^{-1}$ and $10^2$ cm⁻²·s⁻¹ across the entire facility. The maximum value of ambient neutron flux was $1.9 \times 10^2$ cm⁻²·s⁻¹ at the injection point of the booster synchrotron. The results of the in situ concrete floor measurements using a Ge detector were almost consistent with those using the CR-39.

4.1.2. PF

The beamline survey was conducted 0.5 h after the operation stopped. As shown in Figure 8, a total of 20 high-dose-rate points over 0.2 μSv·h⁻¹ on the beamline are found, whereas, similar to SPring-8, the activated level of PF is also quite low, and the net contact dose rate values of almost all beamline components are comparable with the background level. In particular, the transport line from the linear accelerator and the injection point of the main ring had relatively high dose rates. The maximum value of the net contact dose rate of the beamline component was 5 μSv·h⁻¹ at the middle part of the transport line. Similar to the γ-ray spectroscopy results of SPring-8, $^{48}$V, $^{51}$Cr, $^{52}$Mn, $^{54}$Mn, $^{56}$Co, $^{57}$Co, and $^{57}$Ni were detected.

The ambient neutron flux determined by the CR-39 and the other dosimeters ranged between orders of magnitude of $10^{-2}$ and $10^2$ cm⁻²·s⁻¹.
across the entire facility. The maximum value of ambient neutron flux was $5.4 \times 10^2$ cm$^{-2}$s$^{-1}$ at the injection point of the main ring. The TLDs could not determine the neutron flux because the relative dose of γ-rays was too high. In addition, no radio-nuclides apart from natural nuclides were detected from the core concrete samples.

4.1.3. UVSOR

The beamline survey was conducted 2 days after the operation stopped. As shown in Figure 9, a total of 15 high-dose-rate points over 0.2 μSv·h$^{-1}$ on the beamline are found. Similar to SPring-8 and PF, the contact dose rate values were comparable with the background level for most beamline components. In particular, the ejection point from the booster ring, which consists of the kicker magnet, and the upstream side of the transport line from the booster synchrotron had relatively high dose rates. The maximum value of the net contact dose rate of the beamline components was 5 μSv·h$^{-1}$ at the kicker magnet. Similar to the γ-ray spectrometry results of SPring-8 and PF, $^{48}$V, $^{51}$Cr, $^{52}$Mn, $^{54}$Mn, $^{56}$Co, $^{57}$Co, and $^{57}$Ni were detected.

The ambient neutron flux determined by the CR-39 and the other dosimeters ranged between orders of magnitude of $10^0$ and $10^3$ cm$^{-2}$·s$^{-1}$ across the entire facility. The maximum value of the

Figure 6. Overview of the SR Center and all points of dosimeter installation.

Figure 7. Activation survey results of SPring-8: principal activation points on the beamline are depicted as filled squares, and ambient neutron flux is depicted as shaded circles.
Figure 8. Activation survey results of PF: principal activation points on the beamline are depicted as filled squares, and ambient neutron flux is depicted as shaded circles.

Figure 9. Activation survey results of UVSOR: principal activation points on the beamline are depicted as filled squares, and ambient neutron flux is depicted as shaded circles.

Figure 10. Activation survey results of HiSOR: principal activation points on the beamline are depicted as filled squares, and ambient neutron flux is depicted as shaded circles.
ambient neutron flux was $2.0 \times 10^3 \text{ cm}^{-2}\text{s}^{-1}$ at the surface of the kicker magnet. The neutron flux could not be determined at some points, because the number of tracks on the dosimeters was too crowded to count them accurately.

### 4.1.4. HiSOR

The beamline survey was conducted 20 min after the operation stopped. Although six high-dose-rate points over 0.2 μSv·h$^{-1}$ are found on the beamline, as shown in Figure 10, their activation level is very low; even in the strongest activated area, the contact dose rate is only 0.41 μSv·h$^{-1}$. From these points, $^{54}\text{Mn}$ and $^{57}\text{Ni}$ were detected, but their activity was very low.

The neutron flux was also very low, ranging between the orders of magnitude of $10^{-1}$ and $10^1 \text{ cm}^{-2}\text{s}^{-1}$ across the entire facility. The maximum value of the ambient neutron flux was $2.0 \times 10^1 \text{ cm}^{-2}\text{s}^{-1}$ at the injection point to the main ring.

### 4.1.5. SR-Center

The beamline survey was conducted as soon as the operation stopped. The result was summarized in Figure 11. No activation was observed in this facility. The contact dose rate measurement did not exceed the background level at any point. The neutron flux was also very low, ranging between the orders of magnitude of $10^{-1}$ and $10^1 \text{ cm}^{-2}\text{s}^{-1}$ throughout the facility, except at a few points. The maximum value of the ambient neutron flux was $2.0 \times 10^3 \text{ cm}^{-2}\text{s}^{-1}$ on the surface of the main ring inside the yoke. This high flux was due to the special geometry, in which generated neutrons accumulated in a very narrow space.

### 5. Discussion

#### 5.1. Location of the activation points on the beamline and the generated nuclides on there

Activation of the yoke and coil of the magnet was not observed, but it was revealed that stainless steel components such as the beam pipe and vacuum chambers were activated. In the case of a synchrotron radiation facility, the activated area would be limited in all facilities. The contact dose rate on the almost-beamline components did not exceed the background level.

The detected radioactive nuclides from the beamline were almost the same across all facilities, regardless of the acceleration energy. This result reflects the giant resonance of the photonuclear reaction [27−29]. From the cross-section of the photonuclear reaction and the concentration of the constituent atoms in the 304-grade stainless steel, the production of radionuclides was roughly estimated. The 10 most prominent nuclides, $^{57}\text{Ni}$, $^{51}\text{Cr}$, $^{56}\text{Co}$, $^{52}\text{Mn}$, $^{55}\text{Fe}$ (half-life: 2.74 y [1]), $^{58}\text{Co}$, $^{57}\text{Co}$, $^{54}\text{Mn}$, $^{48}\text{V}$, and $^{44}\text{Sc}$, occupy more than 99% of the total content. This estimation is considered to be consistent with the beamline survey results. The photon energy emitted from $^{55}\text{Fe}$ is too low to be detected by the detector for the γ-rays employed in this study.

#### 5.2. Relation between generated nuclides and dose rate

If the dose rate can be associated with the results of γ-ray spectrometry, useful information such as nuclides and radioactivity can be easily obtained using a survey meter which can provide the dose rate value of the measurement object rapidly. Assuming a disk-shaped stainless steel plate with a diameter of 10 mm and a thickness of 1 mm, the activities of $^{44}\text{Sc}$, $^{48}\text{V}$, $^{51}\text{Cr}$, $^{52}\text{Mn}$, $^{54}\text{Mn}$, $^{56}\text{Co}$, $^{57}\text{Co}$, and $^{57}\text{Ni}$ were estimated from the γ-ray spectrum obtained with the LaBr$_3$ detector. The detection efficiency of γ-rays was calculated using ISOCS [30,31]. The activities were corrected to the values at the start of the beamline survey. The relation between the displayed dose rate value on the survey meter ($D$) and the activity of radionuclides included in the target material ($A$) can be described by Equation (1), using the 1 cm dose equivalent rate constant ($I$) [32] and the factor with respect to the shielding condition ($F$) [33] for each nuclide. The term $d$ is the distance between the survey meter and the target.

$$D = \frac{A \cdot I \cdot F}{d^2}$$

**Figure 11.** Activation survey results of the SR Center: ambient neutron flux is depicted as shaded circles.
Figure 12. Summarizes the contribution ratios from detected radionuclides to the dose rate measurement results at each facility. Two nuclides, $^{54}$Mn, which has the longest life, and $^{57}$Ni, which has the shortest, account for a large portion of the total. However, their ratios are not constant and have no correlation with the magnitude of the dose rate. Therefore, unless γ-ray spectrometry is performed, the species of generated nuclides and their activities cannot be determined. However, there was a good correlation between the sum of the contribution ratios (apparent activity) of all nuclides and the dose rate, as shown in Figure S2. This result implies that only the eight detected nuclides contributed to the dose; i.e. no other nuclides will be generated. Except for $^{54}$Mn, they will attenuate within a year, due to their short life, and the correlation between the activity of $^{54}$Mn and the dose rate will become stronger over time.

5.3. Prediction of accumulated activities in the concrete material

In all facilities, the thermal neutron flux on the concrete walls and floor ranged between orders of magnitude of $10^0$ and $10^2$ cm$^{-2}$s$^{-1}$. Generating neutrons accompanied by accelerator operations will be apparent as accumulated radionuclides in the concrete material. We simulated the future accumulated activities of $^{60}$Co and $^{152}$Eu which remain for a prolonged period in concrete. Assuming an average accelerator lifetime of 30 years, the measurement results of thermal neutron flux and annual typical operation period for each facility, the concentrations of natural cobalt and europium in concrete [34,35], and neutron capture cross-sections of $^{59}$Co and $^{151}$Eu [36] were employed. The detailed procedure is described elsewhere [24]. Applying the maximum neutron flux on the concrete material for each facility, the accumulated activities of $^{60}$Co + $^{152}$Eu after 30 years was deduced as follows: 0.00097 Bq·g$^{-1}$ for SPring-8, 0.00055 Bq·g$^{-1}$ for PF, 0.0011 Bq·g$^{-1}$ for UVSOR, 0.000064 Bq·g$^{-1}$ for HiSOR, and 0.00014 Bq·g$^{-1}$ for the SR Center. These values are much lower than the clearance level of $^{60}$Co and $^{152}$Eu, 0.1 Bq·g$^{-1}$. The core sampling result of the PF also corresponds to this; no radioactive nuclides were detected except for natural nuclides.

Confirmation by a Monte Carlo code (PHITS3.02 [37], D-CHAIN-SP [38]) was also conducted for the SPring-8, PF, and UVSOR facilities. The region shown in Figure S3 is reflected in the calculation system, assuming a 100% electron beam loss along a 1-mm-thick iron pipe. The radionuclides generated in concrete after 30 years of typical operating conditions were also estimated. The concrete density and its constituent elements were obtained from the database [33,34,39]. From the calculation results, generated thermal neutrons spread uniformly in all three facilities (Fig. S3). The calculated neutron flux overestimates the measured value at concrete floor; the ratio of the calculation to measurement (C/M) is 6.71 for SPring-8 (SP-045), and C/M is 15.3 for PF (PF-010). On the other hand, the result of UVSOR slightly underestimates the measured value at the concrete floor; C/M is 0.40 (UV-008). Although it is difficult to determine accurately the beam loss amount, location, and distribution, due to bremsstrahlung, even a simplified calculation model could reproduce the approximate result was found. We predicted the accumulated activities of 30 years later, employing a typical electron beam current and the annual number of operating days for each facility. Figure 13 shows the ten most prominent nuclides generated in the concrete material, in terms of their ratios to clearance level. The sum of the ratio of each activity value to clearance level (Σ(D/C)) for calculated nuclides are respectively 0.0825 for Spring-8, 0.0385
induced activities are generally similar to those used this study. In addition, the method for determining the activity of difficult-to-measure radionuclides, such as $^{55}$Fe and $^{63}$Ni, of taking the ratio to a proxy nuclide has been adopted in these decommissioning processes. We expect this methodology could be applied to the decommissioning of synchrotron radiation facilities and other large accelerator facilities in Japan.

In many synchrotron radiation facilities worldwide, experimental areas are transitioning to administration as non-radiation-controlled areas [44]. However, at present, all synchrotron radiation facilities in Japan designate experimental areas as radiation-controlled areas, which require complicated procedures for users. From the results of this study, regarding the two facilities HiSOR and the SR Center, no dose increase occurred during operation, except when the electron beam was incident on the storage ring. In addition, the residual radioactivity was extremely low. In these facilities, it is worth considering the removal of the radiation-controlled area enforced in the experimental hall, with the exception of the beam injection period.

The study in this paper was conducted as a part of the ‘Clearance of materials from the decommissioning of accelerator facilities’ research program, with support from the Nuclear Regulation Authority (NRA) Japan. The aim of this program is the establishment of a reasonable and effective decommissioning process for accelerator facilities. Our studies will be implemented to the complete or partial administration of actual accelerator decommissioning after the NRA has authorized our final report.

7. Conclusion
A systematic study of accelerator activation was conducted for typical synchrotron radiation facilities in Japan, including the largest, SPring-8 (8 GeV), and the smallest, the SR Center (575 MeV). A series of surveys were conducted on metallic beamline components and concrete buildings. The contact dose rates of all beamline components were scanned with a NaI survey meter, and no radiation above the background level was detected in most areas; i.e. they were not activated. From the high-dose areas on the beamline, we detected various radionuclides generated by photonuclear reactions, such as $^{54}$Mn and $^{57}$Ni, by y-ray spectrometry with a LaBr$_3$ detector. Almost all the detected nuclides have short half-lives (below 1 year); therefore, their activity will decrease rapidly within several years.

The activation of concrete walls and floors was evaluated by measuring the ambient neutron flux on the principal places in each facility using various dosimeters. In all facilities, the thermal neutron flux

for PF, and 0.0162 for UVORS. It was found, induced activities in the concrete beamline tunnels of the radiation synchrotron facilities would be sufficiently low compared by the clearance level, considering typical operation.

6. Implementation of this study to actual decommissioning administration
Many synchrotron radiation facilities are Class 4, considered to have the highest risk of activation by IAEA standards [40], because of their high acceleration energies. However, their activation is not significant and it is expected that activation will not become serious in the future.

In the United States and Europe, some large-scale accelerator facilities had been decommissioned [41–43]. Steps such as zoning that distinguishes between activated and non-activated areas and an identification of the type and intensity of

Figure 13. Estimation result for the accumulated activities of ten most prominent nuclides generated in the concrete material of SPring-8, PF, and UVORS, after 30 years’ operation.
on the concrete walls and floor ranged between orders of magnitude of $10^4$ and $10^2 \text{cm}^{-2}\cdot\text{s}^{-1}$, and this value corresponded to $10^{-5}$ and $10^{-3} \text{Bq}\cdot\text{g}^{-1}$ as the accumulated activities of $^{60}\text{Co}$ and $^{152}\text{Eu}$ at 30 years later. These values are much lower than the clearance level of $^{60}\text{Co}$ and $^{152}\text{Eu}$, which is $0.1 \text{Bq}\cdot\text{g}^{-1}$. In addition, no radionuclides except for natural nuclides were detected from the core concrete sampling analysis in the PF. This indicates that, as long as normal operation is performed, no concrete material in a radiation synchrotron facility should be radioactive, and it should be possible to treat it as normal waste with no cooling period.

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No potential conflict of interest was reported by the author(s).

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