Shielding Aspects of Accelerators, Targets and Irradiation Facilities – SATIF-8

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Radiation shielding design for the J-PARC project

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Abstract

The J-PARC (Japan Proton Accelerator Research Complex) project is in progress, aiming at studies on the latest basic science and the advancing nuclear technology. In the project, the high-energy proton accelerator complex of the world highest intensity is under construction. Because of its very high beam power and its energy as well as the large-scale accelerator complex, we have encountered some difficult radiation problems in the radiation safety design. In order to overcome the problems on the shielding design for J-PARC, a calculation system with both simplified and detailed methods is used for the shielding design of J-PARC. This paper reviews the current status of the radiation shielding design for J-PARC by using the calculation system.
Introduction

Aiming at studies on basic sciences and the advancing nuclear technologies, the J-PARC (Japan Proton Accelerator Research Complex) project is being conducted under collaboration between High Energy Accelerator Research Organisation (KEK) and Japan Atomic Energy Agency (JAEA). J-PARC is composed of three accelerator facilities: a 600-MeV linac (LINAC), and 3 GeV rapid cycle synchrotron (3GeVCRS) and 50 GeV synchrotron (50GeVMR), and four experimental facilities: Material and Life Science Facility (MLF), Nuclear and Particle Physics Facility (NP), Nuclear Transmutation Experiment Facility and Neutrino Facility (ν), as shown in Figure 1. The high-energy proton accelerator complex with the world's highest intensity, 3 GeV beam of 1 MW maximum power, is under construction [1-3].

From the viewpoint of radiation shielding, the large-scale accelerator complex with high beam intensity and energy causes many difficult radiation problems in shielding design. Characteristics of J-PARC are: i) high beam power (up to 1 MW); ii) high beam energy (up to 50 GeV); iii) large-scale accelerator complex (3.6 km in length). Radiation problems come from: i) widely distributed radiation source; ii) thick shield; iii) many ducts and so on. On the other hand, shielding methods with high accuracy were strongly required for a detailed design study. In order to overcome the radiation problems, a calculation system with both simplified and detailed methods are applied for shielding design and safety analyses with estimating the accuracy of the methods by using experimental benchmark analyses [4-6]. This paper describes the current status of the radiation shielding design for J-PARC by using the combination method.

Shielding design criteria

In Japan, “Laws concerning Prevention of Radiation Hazards due to Radioisotopes, etc.” is main law for accelerator facilities. In the law, exposure limit for workers is 50 mSv/y and 100 mSv/Sy based on ICRP 1990 recommendation. Under the limitation dose limits for each area are regulated as tabulated in Table 1. As the design criteria of shielding design for the J-PARC facility, half of the regulation for inside the site and one twentieth for site boundary were adopted by considering the safety factor of two and following the customs of other large accelerator facilities in Japan. For gaseous and liquid wastes, regulations on concentration and total amount by government and local government were adopted as the criteria. These wastes are managed by using confinement systems so as to keep the regulations. Activated air generated in rooms of the facilities will be controlled by a confinement system in rooms with negative pressure and a buffer region having monitoring system during operation, and released after waiting decay-out of nuclei with short life after operation and removing 7Be with HEPA filter in ventilation equipment. (Figure 2) As for activation in cooling system, the coolant is used in closed cycle during operation and released after monitoring the activity, mainly tritium, in disposal tanks.

Shielding design conditions

It is difficult to exactly estimate primary beam-loss conditions in accelerator devices except for beam dumps and targets. In the shielding design of J-PARC, it is assumed that the average beam loss is less than 1 W/m at almost all part of the beam line of the accelerators so as to permit the hands-on maintenance, based on the experience and estimation at various high energy accelerator facilities [7-9].

Proposed beam operation times are 5 500 hours for LINAC and 3GeVCRS, 5 000 hours for 50 GeV MR and MLF, and 4 000 hours for NP and ν. About 10 campaigns of three-week continuous operation and one-week maintenance are expected with two-month long maintenance in a year.

Shielding methods

Because the beam loss assumption has a large uncertainty, exact calculations for the shielding design with detailed methods make little sense. Considering the large uncertainty in source term estimation, we basically employ semi-empirical formulas and/or simplified methods for almost of the design. However, it is difficult to apply the simplified methods for the design calculations at the target, the beam dump and the injection and extraction points of the accelerator, because the geometries are
complicated and the large beam losses are expected. Although usually very time consuming, some
detailed methods must be applied for the design calculations there. Thus, a calculation system with
both simplified and detailed methods is used for the shielding design of J-PARC [6].

As for the simplified methods, for bulk-shielding calculations by specifying the beam-loss rates
and the beam energy for the calculations at almost all parts of the accelerator, the Tesch’s formula [10]
for a proton energy of below 1 GeV and the Moyer model [11] above 1 GeV are used. For labyrinths of
access ways and ducts in facilities, simple empirical formulas of Nakamura and Uwamino [12] and a
simplified duct streaming code, DUCT-III [13,14] are applied. In order to estimate the dose due to
radiation at the site boundary, Stapleton’s formula [15] is applied for all skyshine sources. A PC-based
calculation system composed of simplified formulae for bulk shield and the empirical formula for
neutron skyshine, named SSCAT [16], is used for comprehensive radiation safety estimation of whole
facilities in J-PARC.

In detailed methods, a calculation system combined with various codes is used, as shown in
Figure 3 [5]. In this system, several Monte-Carlo codes PHITS [17], MARS14 [18] and MCNPX [19], are
used for high-energy particle transport calculation, making full use of the characteristics of each code.
The PHITS code is a multi-purpose particle and heavy ion transport Monte Carlo code based on the
NMTG/JAM code [20]. The combined system of the PHITS and DCHAIN-SP 2001 [21] codes is used to
design a spallation neutron target system in J-PARC, because the code system can easily estimate the
evolution of induced radioactivity and nuclear heating in the spallation target and radiation damage of
the target structure. The MCNPX code is famous and widely used for the designs, because the code
has various kinds of estimators and variance reduction techniques. The MARS code can calculate the
radiation flux and dose in a rather short time, compared with other Monte-Carlo codes. The MARS
code can easily connect with the STRUCT code [22] calculating proton beam tracing in accelerators
and the ANSYS code for calculating heat transfer. The MCNP-4 code [23] with a nuclear data set,
JENDL-3.3 [24], is applied for low-energy neutrons up to 20 MeV and photons. The DCHAIN-SP 2001
code with mainly the FENDL-Dosimetry file [25] is used for induced radioactivity and dose estimations
due to residual nuclei in the machine components and the wall of the accelerator room.

Benchmarking

In order to study the accuracy of the methods and make clear the differences among the results by
the methods, some benchmark analyses on thick target neutron yield, beam dump, bulk shielding,
streaming and skyshine were carried out. As an example of benchmarking, comparisons of the
calculated dose-equivalent due to skyshine radiation among the Stapleton’s formula, the SHINE-III [25]
and NMTG/JAM codes are presented in Figure 4. It has been shown that the calculations are in very
good agreement with each other from the point of very near to the source region up to a distance of
2 000 m for neutrons generated by 600 MeV and 3 GeV proton beams [5].

Shielding designs

In shielding design for J-PARC, numerous calculations have been done for estimation of shielding
thickness on bulk shields, effective dose rate due to radiation streaming on ducts and access paths,
effective dose rate due to skyshine at site boundary and activities in air, water and structural
materials such as wall, target and accelerator devices. Calculated results on nuclear heating and
radiation damage are applied for mechanical and thermo-hydraulic design of a mercury target and
estimation of life time of target vessel. In this chapter, some typical examples are presented from
some facilities in J-PARC.

Figure 5 shows the dose distribution due to beam loss at the 30-degree beam dump in linac tunnel.
In the calculation proton beam of 190 MeV and 100 W irradiates the beam dump embedded in the
concrete wall of LINAC tunnel. By using the calculated results, the size of the beam dump itself and
thickness of the concrete wall around the beam dump were designed. The calculated neutron flux was
used for estimation of effective dose rate at the ground surface. The neutron and proton fluxes were
used for estimation of activities in air of the accelerator room and in water of coolant used for accelerator
devices, and the estimated activities applied to design the ventilation system and cooling system.
Effective dose rate distribution along a duct at 3GeVRS is shown in Figure 6, which is the calculated result by the PHITS code due to the average beam loss of 1 W/m at quadruple magnets of 3GeVRS. It is presented in the figure that the generated radiation attenuates of about 5, order of magnitude in the two-bend duct, but a thin concrete shield was required to be below the design criteria.

Dose distribution due to beam loss at air in a duct in front of a fast beam dump of 7 kW for 50GeVMR was calculated by the MARS code. In the calculation an effect of air in the beam duct was examined and it was presented that the high power beam of 7 kW required an additional shield in case that the duct was filled by air as shown in Figure 7.

Many items were calculated in design of MLF [13]. For the mercury target design, neutron yield from the target was calculated and moderator performance was estimated. For shielding, effective dose around the target and residual activities in the target were estimated. Nuclear heat distribution was calculated for structural design on cooling system. Radiation damage of the target vessel irradiated by the proton beam was estimated and the maintenance scenario was planned. Figure 8 shows the distribution of nuclear heat on horizontal plane around a mercury target calculated by the PHITS code as an example of estimations. In the calculation the target for a neutron spallation source is irradiated by proton beams of 3 GeV and 1 MW. Nuclear heat above about 0.1 W/cc/MW is generated at the proton beam window and the mercury target, and a few amount of nuclear heat in the shields around the target is observed. The distribution of the nuclear heat was used as the design parameter of the cooling system of the beam window, target and shields.

Summary

J-PARC is a large-scale experimental facility consisting mainly of a high-intensity, high-energy proton accelerator of top world class. Thus, shielding design for J-PARC must be prudent, concerning radiation safety aspect more than for the existing accelerator facilities. In order to secure safety, attaining economical rationality, the shielding design and safety evaluations are performed by a combined method of the simplified and sophisticated methods with reliable data. Safety factor of two was applied for the shielding design based on experimental benchmarking. As the first step of a safety review, we obtained an approval for use of linac. Safety review will be done for approval in use of other facilities: 3GeVRS, 50GeVMR, MLF, NP and v, in the near future.

References


Table 1: Radiation dose limit in the Japan regulation

<table>
<thead>
<tr>
<th>Area</th>
<th>Radiation dose limits</th>
</tr>
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<tbody>
<tr>
<td>Controlled area</td>
<td>1 mSv/1week</td>
</tr>
<tr>
<td>Boundary of controlled area</td>
<td>1.3 mSv/3months</td>
</tr>
<tr>
<td>Site boundary</td>
<td>250 μSv/3months</td>
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</tbody>
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Figure 1: Bird's eye view of planned J-PARC facilities

Figure 2: Conceptual view of air confinement system for J-PARC
Figure 3: Calculation flow of radiation and activity for J-PARC [5]

Radiation
- High-energy particle flux
  - PHITS, MCNPX, MARS
    (En>20MeV, Ei>1MeV
    i=p, pion, meson)
- Neutron source for
  low energy calculation

Activity
- Neutron flux
- Particle flux
  2nd γ-ray
- Nuclear decay
  data set

Residual nuclei

Nuclear decay
DCHAIN-SP 2001

γ-ray from
residual nuclei

γ-ray transport
QAD-CGQP2, MCNP

Low-energy particle flux
- MCNP
  (En<20MeV, 2nd-γ-ray)
- Neutron transport
  X'sect for
  low energy

Air, Water

Devices

Dose
- Site boundary
- In site
- Controlled area

Residual Activity

Dose due to
residual nuclei

Figure 4: Comparison of the skyshine dose as a function of the distance from the source among Stapleton's equation, the SHINE-III code and the NMTC-MCNP code [5]
Figure 5: Dose distribution due to beam loss at 30-degree beam dump in LINAC tunnel

Figure 6: Effective dose rate distribution in a duct due to the average beam loss of 1W/m at quadruple magnets at 3GeV RCS
Figure 7: Dose distribution due to beam loss at air in a duct in front of a fast beam dump of 7 kW for 50 GeV MR calculated by the MARS code

a) Geometry

b) Dose distribution

Figure 8: Distribution of nuclear heat on horizontal plane around a mercury target calculated by the PHITS code

Horizontal plane $Y = -2.500 \sim 2.500$