BENCHMARK CALCULATION FOR THE J-PARC SHIELDING DESIGN

H. Nakashima, Y. Nakane, F. Masukawa, N. Matsuda, Y. Iwamoto and T. Shibata
Japan Atomic Energy Agency
Tokai, Naka, Ibaraki, 319-1195 Japan
e-mail: nakashima.hiroshi@jaea.go.jp

N. Nakao*, T. Suzuki and H. Hirayama
High Energy Accelerator Research Organization
Oho, Tsukuba, Ibaraki 305-0801 Japan

The J-PARC (Japan Proton Accelerator Research Complex) project is now in progress. In order to establish a reasonable shielding design for J-PARC, shielding calculation methods with high accuracy were strongly required and benchmarking of the methods was carried out. This paper reviews the benchmark calculation for the detailed calculation methods used in the J-PARC shielding design.

I. INTRODUCTION

High Intensity Proton Accelerator Project promoted jointly by Japan Atomic Energy Agency (JAEA) and High Energy Accelerator Research Organization (KEK), named as J-PARC (Japan Proton Accelerator Research Complex) is under construction. The accelerator complex of J-PARC consists of three accelerators: 400 MeV Linac, 3 GeV rapid cycle synchrotron (RCS) and 50 GeV synchrotron, and four major experimental facilities: Material & Life Science Facility, Hadron Experimental Facility, Nuclear Transmutation Experimental Facility and Neutrino Facility as shown in Fig.1. Various secondary particles produced by high energy proton beam are used for a variety of sciences such as material and life science by muons and neutrons, and nuclear and particle

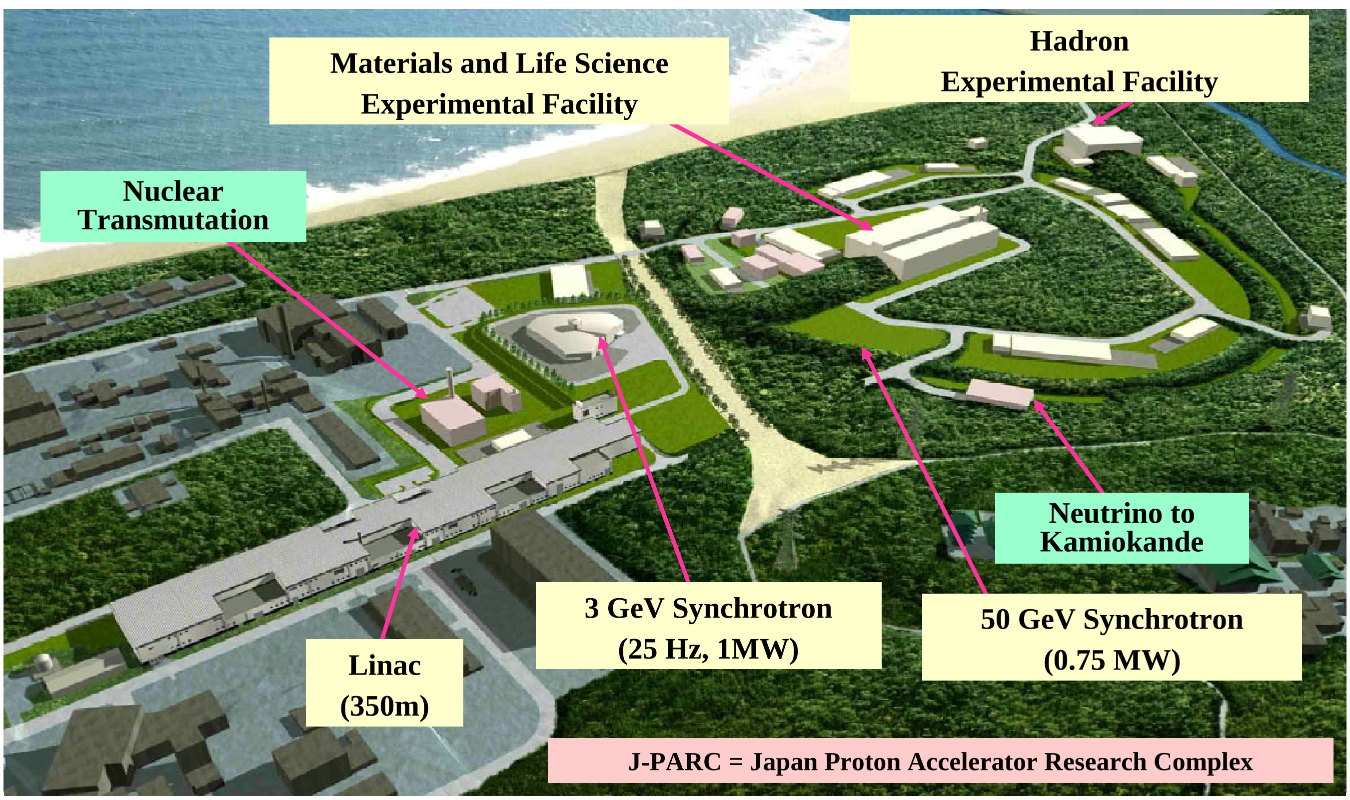

Fig. 1. Bird's eye view of planned J-PARC facilities.[2]

*Present Address: Fermi National Accelerator Laboratory physics including neutrino as well as accelerator driven nuclear transmutation technology.[1, 2, 3]

From the viewpoint of radiation shielding design, the characteristics of J-PARC are summarized as high beam power of 1 MW, high beam energy up to 50 GeV and large-scale accelerator complex. For the shielding design, shielding design methods with high accuracy were strongly required. A calculation system with both simplified and detailed methods is used for shielding design and safety analyses for licensing.[4, 5, 6, 7] In order to estimate the accuracy of the calculation system, a various benchmark calculation was carried out. This paper reviews benchmark calculations for the detailed shielding calculation methods.

II. CALCULATION METHODS

The calculation flow used in the shielding design for the J-PARC is shown in Fig. 2.[5]

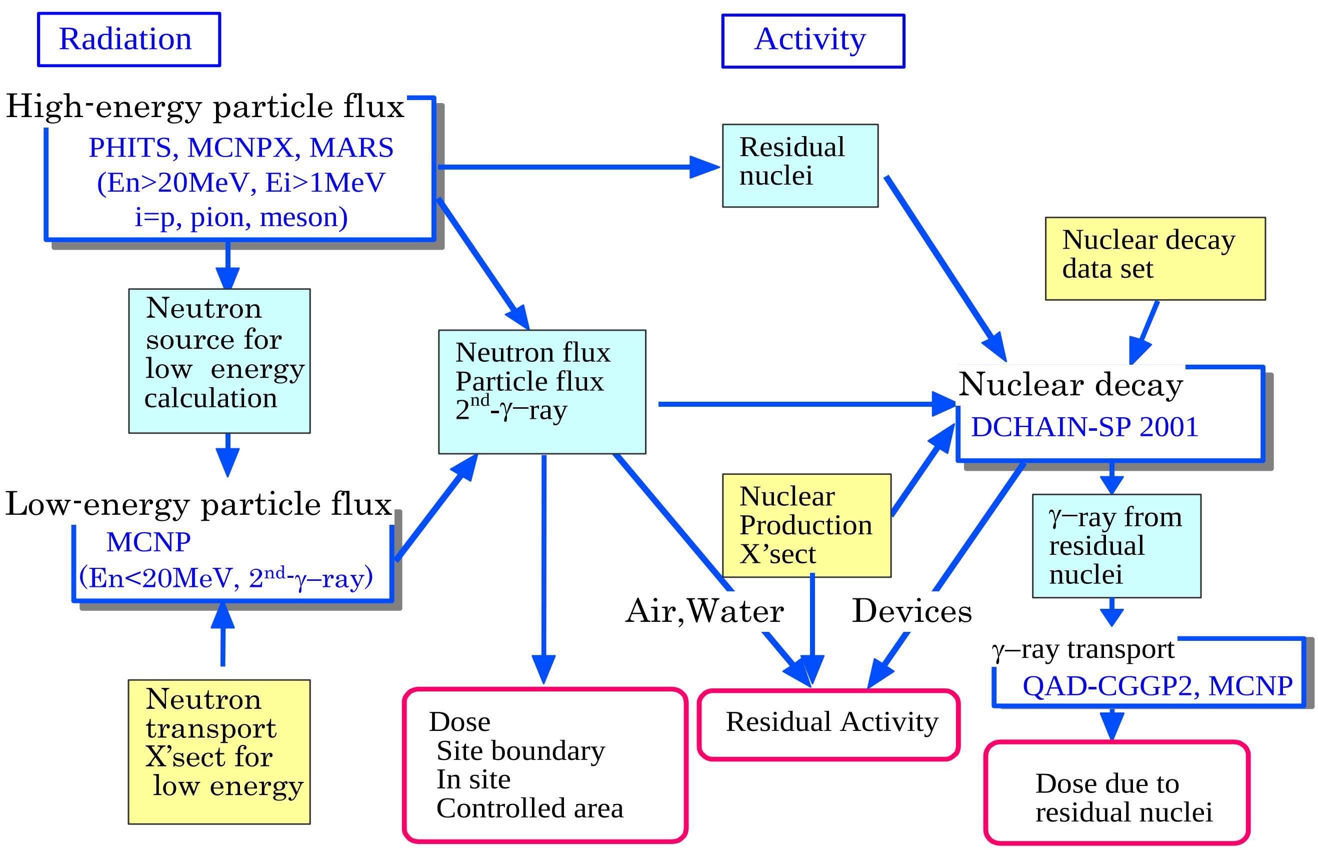

Fig. 2. Calculation flow of radiation and activity used in the J-PARC shielding design[5].

In this system, several Monte-Carlo codes: PHITS[8], MARS14[9] and MCNPX[10], are used for high-energy particle transport calculation, which have unique characteristics for shielding design. These code are a multi-purpose particle and heavy ion transport Monte-Carlo codes. The PHITS code is based on the NMTC/JAM code[11], and developed under collaboration among RIST, JAEA and so on. PHITS is used to design a spallation neutron target system at J-PARC[12], because the code is easily connected with the DCHAIN-SP 2001[13] codes and the system can be used to estimate the evolution of induced radioactivity and nuclear heating in the spallation target and radiation damage of the target structure. The MCNPX code is widely used for the designs of high and medium energy accelerator facilities as well, because the code has various kinds of estimators and valiance reduction techniques. The MARS code uses CEM03 module below 3 GeV, and MCNP cross-section library[16] below 14 MeV. It is especially refined for very high energies and transport in accelerator structure. The MARS code was used for collimation and shielding calculations of RCS[14, 15], using the beam-loss distribution simulated by the multi-turn tracking code, STRUCT[17], and shielding calculation of the neutrino beam line with 50-GeV protons,. The MCNP-4 code[16] with a nuclear data set, JENDL-3.3[18], is applied for low-energy neutrons up to 20 MeV and photons. The DCHAIN-SP 2001 code with mainly the FENDL-Dosimetry file[19] is used to calculate induced radioactivity and dose estimations due to residual nuclei in the machine components and the wall of the accelerator room. The JENDL-HE file[20] was also used to estimate the residual activity of light nuclei in air in accelerator room and cooling water for accelerator devices and beam dumps, because the accuracy of the calculation system of the PHITS and DCHAIN-SP 2001 codes is less reliable for estimating the radioactivity produced from light nuclei, compared with intermediate and heavy nuclei.

III. BENCHMARKING

The simplified methods are usually tailored so as to overestimate the doses inside and around the facilities in order to keep safety, based on experiments and experience, while detailed methods should be validated with benchmarking, because the codes based on the physical models have some ambiguities and sometimes underestimate particle fluxes and doses. In order to study the accuracy of the methods and make clear the differences among the results by the methods, some benchmark analyses on beam dump, bulk shielding, streaming and activation were carried out,. In this chapter some examples of the benchmarking are presented.

III.A. Beam Dump

A series of experiments on a mercury spallation target using high-peak-power GeV proton-beam from the Alternating Gradient Synchrotron (AGS) of Brookhaven National Laboratory (BNL) was analyzed as a beam dump problem.[21, 22, 23] In the experiment, a mercury target was bombarded with 1.6-, 12- and 24-GeV-protons, and neutron spatial and energy distribution along the target was measured as shown in Fig. 3. In the experiments, various kinds of activation detectors, such as In, Bi and so on, were used to cover wide neutron energy region.

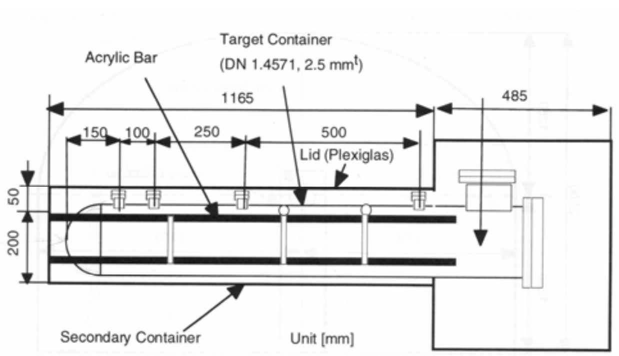

Fig. 3 Cross-sectional view of the mercury target irradiated by proton beams at BNL/AGS.[21]

Figure 4 shows measured spatial distributions of the rate of the ^{209}Bi(n, 4n)^{206}Bi reaction (threshold energy: E_{th} 22.6 MeV) due to neutrons generated in the mercury target by incident protons of 1.6, 12 and 24 GeV,

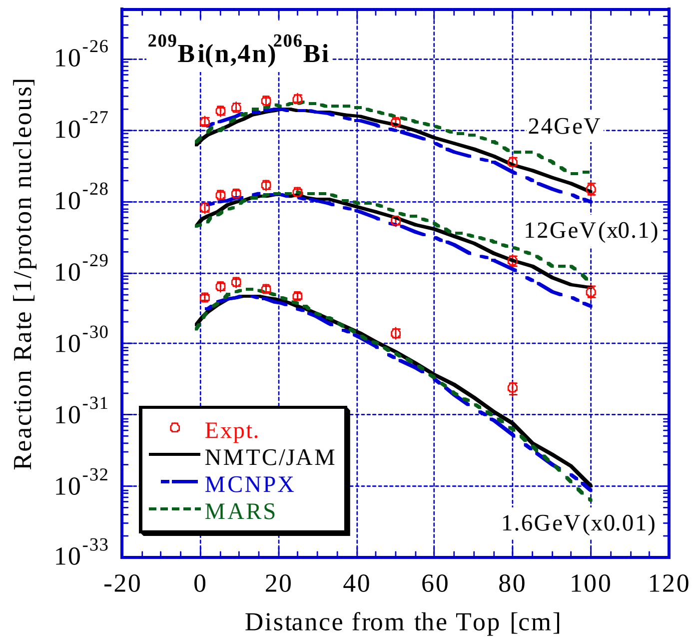

Fig. 4 Comparisons on distributions of ^{209}Bi(n, 4n)^{206}Bi reaction rates parallel to the axis of the mercury target among calculations and measurement at BNL/AGS.[25]

compared with calculations by the NMTC/JAM code with free and in-medium cross section options and by the MCNPX code as an example of benchmarking.[23] In the NMTC/JAM code, the parametrized in-medium NN cross sections similar to those of Cugnon[24] can be employed instead of the free cross sections to calculate the mean free path and collision probability of nucleon in a target nucleus divided some regions as an alternative option for the intranuclear cascade calculation.[11] All calculations are in good agreement with the measurements as a whole. The calculations of NMTC/JAM with the in-medium cross section (In medium) underestimate the measurement at 1.6 GeV and at positions less than 40 cm from the front of the target at 12 and 24 GeV by a factor of 2. The NMTC/JAM calculations with the free cross section (Free) underestimate all measurements. The NMTC/JAM (In medium) calculation is larger and closer to the measurements than the NMTC/JAM (Free) calculations within a factor of 2. The MCNPX calculation at 1.6 GeV gives almost the same result as the NMTC/JAM (In medium) calculation, while the shape of the distributions at 12 and 24 GeV given by the MCNPX code are different from those by the NMTC/JAM code within a factor of 2. Resultantly it is concluded that accuracy of the codes for calculation on beam dump was estimated to be within a factor of 2. Most of calculation results with the MARS code are in good agreement with the experimental ones within a factor of 2, while the MARS results slightly give underestimation in the region up to 20 cm from the top of the target and overestimation in the region above 40 cm.[23, 25]

III.B. Bulk Shielding

A shielding experiment carried out using steel and concrete shields set around the mercury target at AGS/BNL[22, 23] was analyzed as a bulk shielding problem. Figure 5 shows the arrangement of lateral and forward shields made of steel of 3.3 m thick and ordinary concrete of 5.0 m.

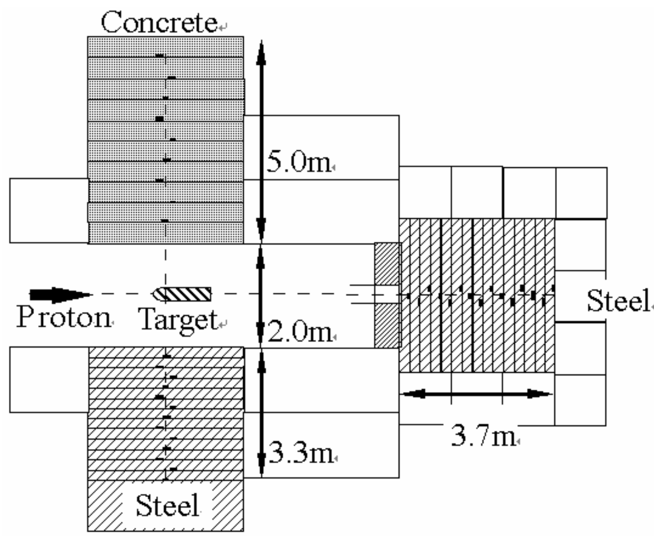

Fig. 5 Horizontal cross sectional view of shield arrangement for shielding experiment at BNL/AGS.[22, 23]

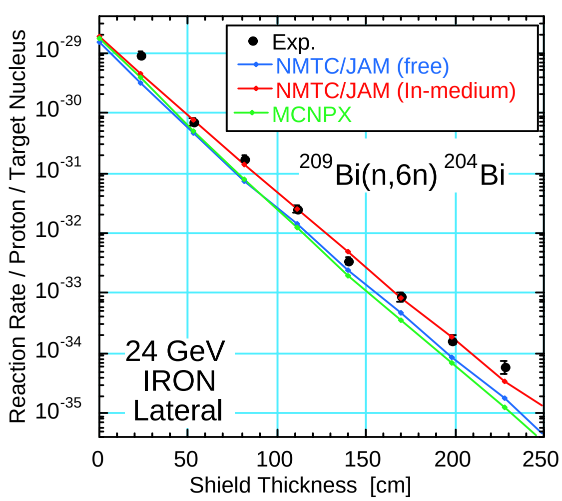

Fig. 6 Comparisons on distributions of ^{209}Bi(n, 6n)^{204}Bi reaction rates in iron shield among calculations and measurement at BNL/AGS.[6, 23]

Measured spatial distribution of neutron reaction rates of the ^{209}Bi(n, 6n)^{204}Bi reaction (E_{th}: 38.0 MeV) inside the steel shield is compared with the NMTC/JAM (Free) and (In-medium) calculations and the MCNPX calculations at 24 GeV protons in Fig. 6 as an example. The NMTC/JAM (In-medium) calculation agrees very well with the measurement almost at all positions. The NMTC/JAM (Free) and MCNPX calculations show the same tendency of neutron attenuation and agree with the measurement within a factor of 2, although the calculations yield slightly lower values than the measurement.[23]

III.C. Streaming

A streaming experiment carried out with two types of the large concrete-lined tunnels at the synchrotron beam line of the NIMROD accelerator facility[26] was analyzed as a streaming problem.[27] Tunnels were constructed as a part of the normal extracted beam blockhouse at right angles to the direction of the beam, as shown in Fig. 7. The secondary particles were generated at a cupper target of 10 mm in diameter and 50 mm in thickness bombarding 7-GeV protons. The relative attenuations of the reaction rates along the centerline in the straight and bent tunnels were measured by using various activation detectors.

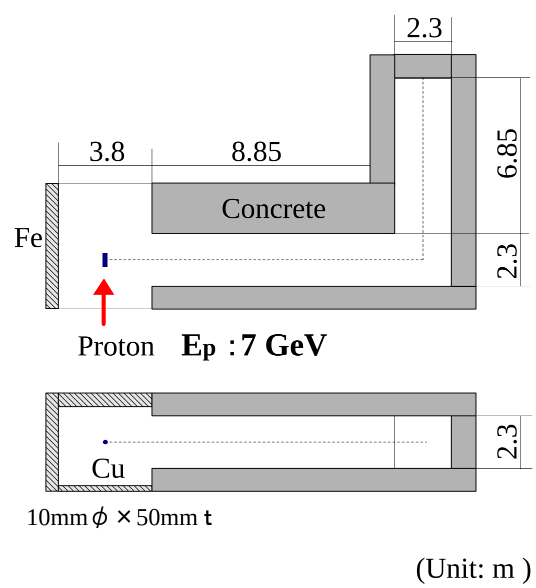

Fig. 7 Cross-sectional views of the bend tunnel at NIMROD.[26, 27]

An example of the results of the experimental analysis is shown in Fig. 8. The attenuation curves of the calculated induced radioactivity of the ^{12}C(n, 2n)^{11}C reaction are compared with measurements along the centerline in the straight and bend tunnels, in which the calculations were normalized by the measurement at the entrance of the tunnel. Calculations by the Monte Carlo codes reproduce the measurements within a factor of 2 at all regions. In order to confirm the accuracy of the simplified method used in the shielding design of J-PARC as a reference, the results of the DUCT-III code[28, 29] is also shown in Fig. 8. The DUCT-III code is based on Shin's formula[30] with an albedo matrix made by the NMTC/JAM code. The calculation by DUCT-III is in good agreement with the measurements in the first leg, although they slightly overestimate them by a factor of 2 in the second leg.[27]

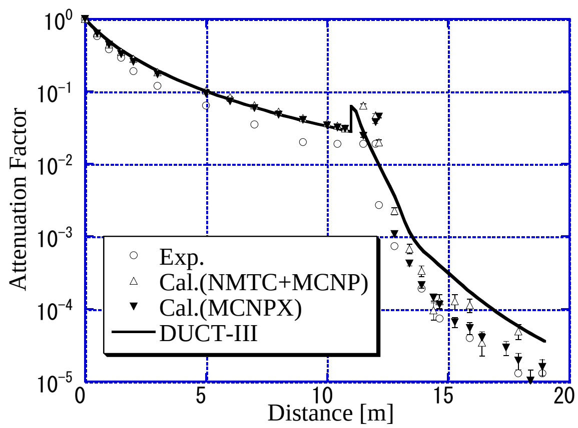

Fig. 8 Attenuation curves of the induced radioactivity for the $^{12}C(n, 2n)$ reaction in the bent tunnel at NIMROD.[27]

III.D. Activation[22]

An experiment on induced radioactivities and residual nuclei distributions of mercury carried out at AGS/BNL[31] was analyzed, in order to estimate the precision of activation calculation code systems of the NMTC/JAM, MCNP4A and DCHAIN-SP codes. In the experiment, samples were irradiated by the secondary particles generated in the target bombarded with the primary protons, by putting the sample at the side of the target as shown in the insert of Fig. 9. An example of the results of residual nuclides: ^{206}Bi, ^{205}Bi, ^{204}Bi and ^{203}Pb, generated from a ^{209}Bi sample in case of the incident energy at 1.6 GeV, is shown in Fig. 9. Both experiments and calculations are in good agreement within a factor of 2.

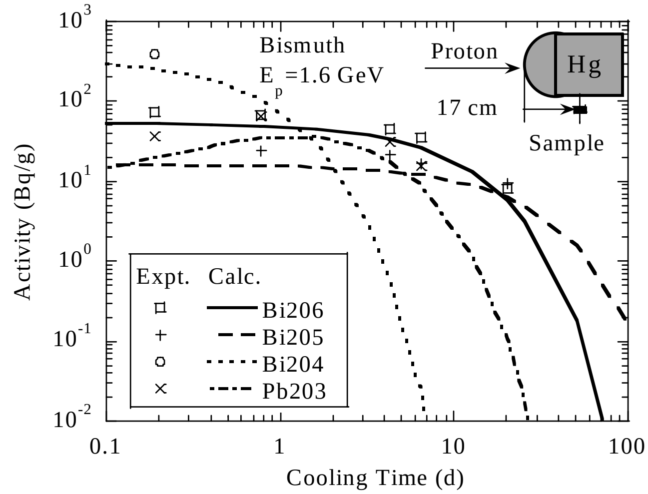

Fig. 9 Measured time evolution of the radioactivities of radial nuclides in a ^{209}Bi sample at 1.6 GeV protons. Calculations with the NMTC/JAM, MCNP4A and DCHAIN-SP codes are also shown for comparison.[22]

IV. SUMMARY

In order to overcome many problems on the shielding design for J-PARC, various shielding design methods were applied with estimating the accuracy of the shielding design method by experimental benchmark analyses. Based on the benchmarking, it was concluded that the safety factor should be 2 for the shielding calculation with the detailed methods. By using the shielding design methods, the shielding design was performed and the facilities are under construction. Now LINAC is in normal operation and the beam commissioning of the 3GeV synchrotron will be started in this fall.

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