Radiation Safety Considerations for the TPS Accelerators

R.J. Sheu, J. Liu, and J.P. Wang

National Synchrotron Radiation Research Center, 101 Hsin-Ann Road, Hsinchu Science Park, Hsinchu 30076, TAIWAN

Abstract

This study investigates the characteristics of prompt radiation field and some issues of induced activities due to the operation of the Taiwan Photon Source (TPS). Starting from assumed beam loss scenarios and using the FLUKA Monte Carlo simulations, energy spectra and dose distributions of the prompt radiation field for its shielding design were studied. Radiation environment around the penetrations on shielding walls were also taken into account. As to the impact of induced radioactivity, we also used the FLUKA to evaluate the residual activities, remanent dose rates, and their time behaviors for various target materials and cooling times based on conservative irradiation conditions. The paper summarizes the present status of the radiation safety evaluation for the TPS accelerators.

1. Introduction

The Taiwan Photon Source (TPS) in National Synchrotron Radiation Research Center (NSRRC) will be a 3 GeV light source with a circumference of 518.4 m and operating fully at 400 mA in top-up mode, aiming to provide synchrotron light with extremely high brilliance and low emittance of less than 2 nm-rad [1]. It is now approaching its final design and will start civil construction by the end of this year. In addition to its main body of a 3-GeV electron storage ring, the accelerator complex includes a 150-MeV LINAC and a large 3-GeV concentric booster. Significant amount of radiation will be produced due to the loss of such high-energy electrons and result in radiation safety concerns. Generally, four kinds of radiation sources originating from the operation of a synchrotron accelerator should be considered – bremsstrahlung, neutrons, induced activation and synchrotron light. The former three forms of radiation sources result from interactions between lost electrons and accelerator components or walls. Electrons of greater energies interact with matter and cause an electromagnetic cascade [2]. The resultant copious bremsstrahlung photons with a broad energy spectrum tend to be forward-peaked and are the primary target for shielding design. Neutrons are produced by photonuclear interactions from high-energy gamma rays; although neutrons are much fewer and lack a strong directional dependence. Shielding against them is also an important part of the shielding design due to their strong penetration of matter. Induced activation can be found in accelerator components when exposed to highly intense radiation. The susceptibility to activation is dependent on the energy and power of the incoming radiation as well as target material. As to the radiation protection against synchrotron radiation, due to the complex combination of synchrotron source, beamline configuration and optical design, shielding design will be conducted separately according to the distinct characteristic of each beamline and will not included in this paper.

The design objective of radiation safety system is to minimize the hazards arising from these sources. Fig.1 is a portion of the TPS layout showing the main accelerator components and its bulk shielding configuration [1]. Its basic structure consists of a ratchet style shielding for the outer wall of the storage ring and shielded labyrinths in the inner shielding wall for mainly personnel access. The 150-MeV LINAC will be housed in an independent room with 1 m thick concrete shielding. Both the storage ring and concentric booster will be installed in a shared tunnel made of 1 m thick concrete walls and removable roof. The shielding in the injection area and ratchet end walls will be at least 1.2 m thick concrete. This study aims to evaluate the general characteristics of prompt radiation field outside the bulk shielding and radiation streaming through some penetrations, as well as possible impact from induced radioactivities due to the TPS operation.

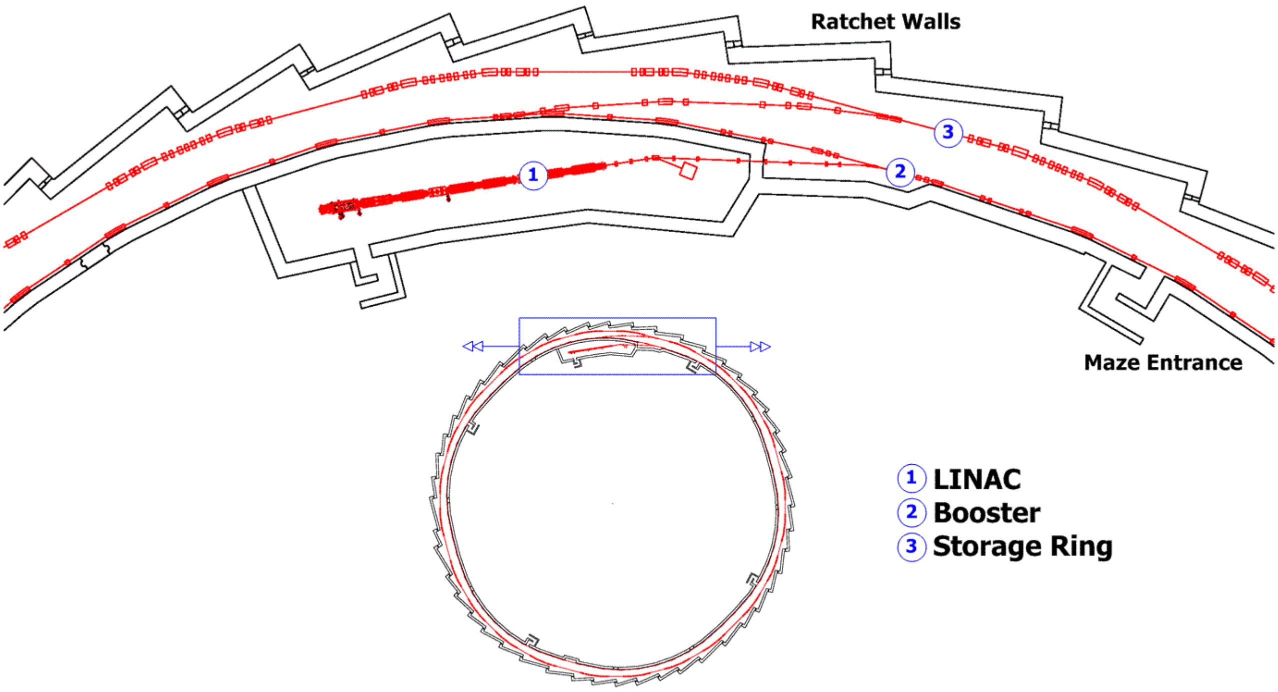


Fig.1 - A schematic layout of the main accelerator components and shielding design of the TPS.

2. Materials and Methods

2.1. Design Dose Limits and Beam Loss Analysis

In Taiwan, the Atomic Energy Council has established dose limits as basic guidelines for radiation protection. For radiation workers, the annual effective dose should not exceed 50 mSv and the accumulated dose should not exceed 100 mSv for five consecutive years. In addition, the dose limit for both non-radiation workers and the general public off site is 1 mSv per year. To comply with ALARA principle and recommendations from similar facilities, we have decided to accept a more challenging dose limits for the TPS of 1 mSv/y for all staff and users who are working 2000 hours a year and an environmental dose of 0.5 mSv/y at site boundaries for operating 6000 hours a year. These design limits guide shielding requirements and the design of radiation safety program and systems.

Beam loss analysis is crucial for the shielding design of an accelerator facility. All electrons generated from the gun filament, accelerated by the LINAC and booster, transferred by transport lines, and finally injected into the storage ring are eventually lost somewhere along the orbit. To facilitate the evaluation of possible beam losses, we have logically divided the electron trajectory into the following accelerator sections: GUN → LINAC → LTB → Booster → BTS → Storage Ring, where LTB is the transport section from LINAC to booster, and BTS is referring to that from booster to storage ring. Based on the design specifications of TPS and through operation experience with the existing Taiwan Light Source (TLS), our accelerator physicists have determined a relatively conservative assumption about the beam transfer efficiencies between these accelerator sections as shown in Fig. 2. The overall beam transfer efficiency from LINAC to storage ring is about 48% and 73% from booster to storage ring. Our assumed numbers are slightly more conservative than those of the SLS [3], which is the first light source featuring a concentric booster design and full-time top-up operation. This comparison is reasonable and instructive since we have adopted the same concept of accelerator design. The max LINAC output is about 2.25 W and the minimum lifetime for 400 mA stored beam is 7 hours. It is clear that this is not a worse-case beam loss; this is an assumed beam loss scenario under normal operating conditions. Based on this reference beam loss, we also have defined a more conservative operation envelope to ensure the safety envelope, i.e. the design limits, will not be exceeded.

Under normal operating conditions, total electron loss rates occurring in the shared tunnel were estimated to be about 2.43×10^{10} and 1.71×10^{8} electrons per second during beam injection and storage periods, respectively. To estimate the total number of electron losses per year, we have conservatively assumed 6000 hours of operation in 300 days. For each daily operation of the TPS, the storage ring is started by a fresh injection to its maximum current, immediately followed by 20 hours of top-up operation, and finally terminated by dumping the beam. Then, annual summation of electron losses due to the operation of TPS has been estimated to be 7.71×10^{15} electrons per year. To specify the operational boundary conditions, we have defined envelope conditions for abnormal operation by increasing the maximal electron loss rate at each stage to five times the quota under normal condition [1].

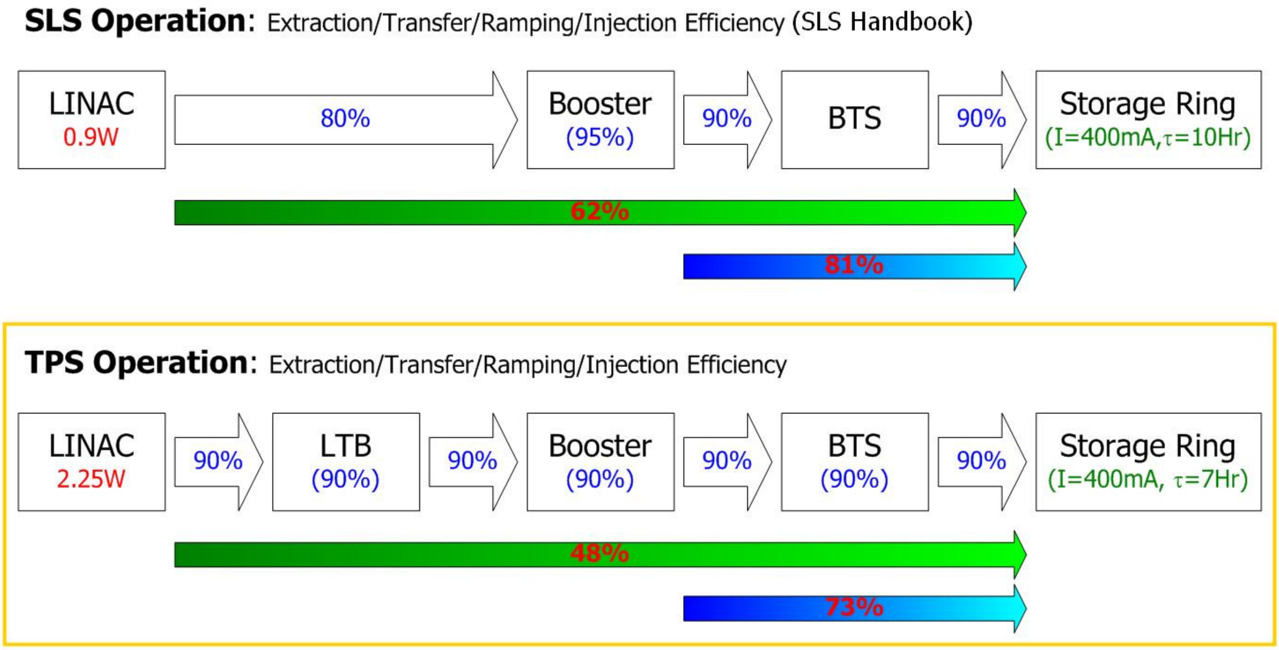


Fig.2 - Comparison of beam transfer efficiencies between main accelerator components of the SLS and TPS.

2.2. Calculation Methods

In this study, two extreme beam loss cases are assumed to bound the possible beam loss scenarios occurring in the shared tunnel, i.e. all electrons are lost at one point or they are lost uniformly along the electron orbit [4]. A high-energy electron accelerator is a very complex device containing many components. For point and uniform beam loss models, the geometries of the TPS accelerators and shared tunnel have been greatly simplified to facilitate the simulation. The point beam loss model is the worst case of beam loss for radiation protection in accelerators. Comparing with the worst case of point beam loss, we consider uniform beam loss around the booster or storage ring should be more realistic for long-term dose evaluation since most of the hot spots could be easily compensated by local shielding arrangement. When the TPS LINAC operates in stand-alone mode, all accelerated electrons from the output of the last section have to be absorbed by a dedicated beam dump. Our beam dump is the same design as that in the NSLS-II [5] which is a three-layer cylinder with an iron target inside and wrapped with 15 cm thick lead and 20 cm thick polyethylene in both lateral and forward direction. We have used the FLUKA Monte Carlo code [6] to simulate the high-energy electron induced electromagnetic cascade and the subsequent photonuclear reactions to calculate the energy spectra and dose distributions of those secondary particles, including gamma rays, neutrons and muons. FLUKA is not only a particle transport and interaction Monte Carlo code but also, with recent development, an integrated code for the buildup and decay of produced radioisotopes. Calculations of induced radioactivities and their time evolution as well as tracking of emitted radiation from unstable residual nuclei can be performed together and on-line with radiation transport.

3. Results and Discussion

3.1. Prompt Radiation

Energy spectra and dose distributions of the prompt radiation field outside the bulk shielding of the TPS have been investigated using the FLUKA Monte Carlo simulations. First of all, for a 2.25 W LINAC beam power during stand-alone operation, dose rates outside the independent LINAC room should be within the range between 0.1 and 83 μSv/h in forward directions and between 1.1 and 14 μSv/h in lateral directions. The minimal and maximal bounds of the dose ranges are estimated by considering the scenarios of how and where the beam is lost during LINAC operation: electrons impinge on our well-shielded beam dump or electrons unexpectedly hit a target without any local shielding. Regarding the possible dose rates outside the shared tunnel due to the operation of booster and/or storage ring, proper modeling of the beam loss in the TPS tunnel is the first step and of most importance to dose estimation. Energy spectra of secondary particles outside the bulk shielding reveal that, because of thick concrete shielding, the dose contributions from photon and neutron components outside the lateral wall of the TPS tunnel are roughly comparable. Muon contribution is negligible. For an event of full beam loss, the estimated doses outside the lateral shielding wall are about 12 and 0.2 μSv per event for point and uniform loss scenarios, respectively. During the beam injection period, the maximal dose rates in the experimental hall have been estimated to be about 128 and 3.4 μSv/h corresponding to point and uniform beam losses. On the other hand, during the beam storage period, the maximal dose rates of decay loss will be about 1.7 and 0.02 μSv/h corresponding to point and uniform beam losses. As stated in Section 2.2, those dose rates corresponding to the uniform beam loss model or with local shielding are considered to be more realistic in the long term. Taking into account reasonable use and occupancy factors, these estimated dose rates enhance our confidence in achieving the design dose limit of 1 mSv/y for staff and users working 2000 hours in the TPS.

According to the conservative estimates of annual beam loss and calculated dose distribution, annual dose assessment as a function of distance can be derived and the results are shown in Fig. 3. Two distances shown in Fig. 3 are of particular interest, i.e. 2 m and 43.8 m, corresponding to the locations near the surface of outer shielding wall and at the nearest site boundary of the TPS, respectively. Under normal operation conditions, the maximal annual dose in the experimental hall of TPS is estimated to be 0.44 mSv/y and the total dose at the nearest site boundary is only about 14 μSv/y. For the worst operation case before interlock system to intervene, i.e. our operation envelope, the maximal annual dose in the experimental hall may increase to 2.2 mSv/y and the total dose at the nearest site boundary will then be roughly 70 μSv/y. The possible doses at the nearest site boundary due to the TPS operation are apparently far below the environmental dose limit of 0.5 mSv/y, i.e. 500 μSv/y. On the other hand, the maximal dose of 2.2 mSv/y in the experimental hall is obtained based on the condition of 6000-h operation; therefore the expected personnel dose for 2000-h working time should be less than 0.73 mSv/y and that is also within our design limit of 1 mSv/y. The dose assessment confirms that the present shielding and interlock design should be able to provide enough protection for ensuring the safety envelope of TPS operation including normal and abnormal conditions.

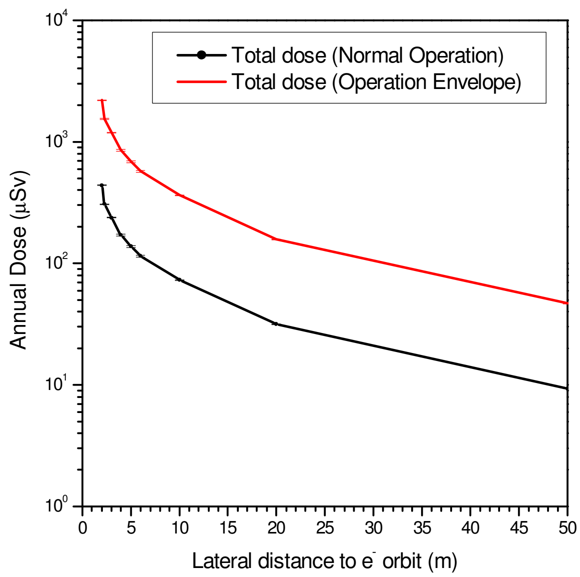


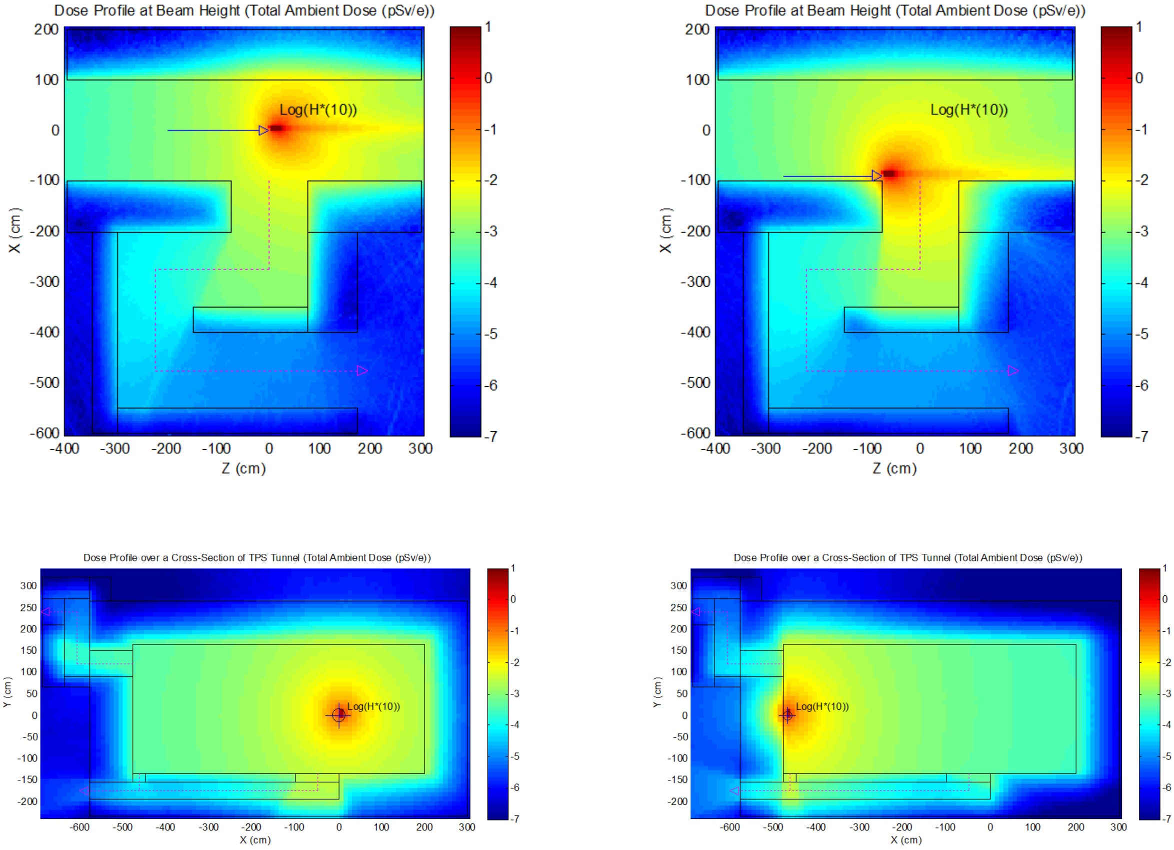
Fig.3 - Annual dose assessment for the TPS operation.

3.2. Radiation through Penetrations

Based on the assumed beam loss scenarios, the above results indicate that our bulk shielding arrangement for the TPS accelerators should be highly practicable to achieve its annual dose limit. However, in reality, no practical accelerator shielding can be constructed perfectly intact without penetrations for the access of personnel and supporting utilities. Compared to the relatively thick shielding walls, radiation streaming through those penetrations should be more carefully evaluated because they undermine the integrity of bulk shielding. In this section, we consider three kinds of penetrations around the inner shielding walls of the TPS including labyrinths for personnel entrance, air-conditioning ducts and underground trenches. For more detailed layout and dimensions please refer to our design handbook [1]. We carried out the FLUKA Monte Carlo simulations to investigate the design in detail and to understand the radiation field around those penetrations. To justify the maze design, we need to compare the doses outside those penetrations with a reference value, which has been reasonably chosen to be the dose outside an intact shielding wall.

First, according to the layout of the TPS shielding as shown in Fig. 1, a total of five maze entrances have been allocated along the inner shielding walls of the TPS mainly for personnel access, four standard-sized mazes for the long shared tunnel and a small one for the independent LINAC room. They are all typical four-legged maze design. Figs. 4(a) and 4(b) show the calculated dose distributions around the maze, the total dose at the maze exit is about 90% of the reference value for a storage ring beam loss scenario and meets our design goal without question. When considering a booster beam loss occurred near the maze mouth, the total dose at the maze exit increases to about 40% higher than that of the reference. This modest increase does not pose serious concern for radiation safety in practical situations and should be acceptable since our machine physicists do not expect significant full-energy beam losses in those regions during booster operation. Energy spectrum scoring also indicates that thermal neutrons resulting from multiple scatterings and streaming through the maze are the most evident portion of dose contribution at the maze exit.

In addition to the maze entrances, there are also 24 ducts on the upper part of inner shielding walls for air-conditioning piping and 96 underground trenches for the connection between accelerators and supporting utilities. Figs. 4(c) and 4(d) show the predicted radiation environment around the TPS tunnel with respect to the beam losses occurred in the storage ring and booster, respectively. The shielding design for the air duct appears to be acceptable since, in both cases, the doses at the duct outlet and its neighborhood are all comparable to or well below the reference dose outside the shielding. The calculated dose at the duct outlet for a storage ring beam loss is about 80% of the reference value and further drops to only 10% of the reference value for a booster beam loss. In contrast, the trench arrangement is not ideal in terms of radiation safety. The dose at the exit of the trench for a storage ring beam loss is then 70% higher than the reference dose and, more severely, the dose at trench exit for a booster beam loss is much higher than the reference by an order of magnitude. As to the dose contribution, no matter the air ducts or underground trenches, the neutron component is always the dominant one to the total dose at the exits similar to that of the above personnel mazes. To further reduce the dose, radiation protection in the neighborhood of the trench exits will be enhanced by local shielding after all necessary cable and piping are settled down. In fact, all the exits of the air ducts and trenches of the TPS tunnel will be located inside 24 nearby rooms called the Control Interface Area (CIA). All the CIA rooms locating along the inner shielding walls of the TPS tunnel will be radiation control area with limited access to authorized staff. Taking into account the shielding enhancement and limited occupancy factor, we are confident to make sure our design dose limit in these CIAs will be met even with all these penetrations on the TPS bulk shielding.



(a) (b)

(c) (d)

Fig.4 - Dose distributions around TPS penetrations including personnel maze, air-conditioning ducts and underground trenches for the storage ring and booster beam losses.

3.3. Induced Radioactivity

Radioactivity may be induced in various accelerator components and its surroundings when irradiated by a high-energy electron beam directly or exposed to the secondary radiation fields. At the TPS facility, the potential materials to be activated are aluminum, iron, copper, tungsten, and lead. In addition, the concrete shielding housing the accelerator, the air and cooling water inside the tunnel may also become activated due to high-energy bremsstrahlung and its subsequent neutron interactions. They present an additional hazard that needs to be carefully analyzed and managed. Our estimations of induced radioactivity and remanent dose rates in these materials are based on the direct FLUKA calculations. When it is available, the FLUKA-calculated results are compared with those listed in the well-known IAEA-188 report [2] for verification and validation. Two extreme irradiation conditions for the TPS operation are assumed to investigate the possible impact. One case (case 1) is a long-term continuous irradiation by an average low-power beam loss of 7.71×10^{15} electrons per year (~0.12W) and the other case (case 2) is a short irradiation period by an intense full injection power of 4.48×10^{10} electrons per second (~21.5W). The first condition corresponds to the irradiation situation of a 20-year operation during TPS lifetime and the second condition intends to simulate a possible irradiation event of a 1-hour beam loss during injection difficulty. This section briefly presents the results of our activation analyses; the TPS design handbook can be consulted for details [1].

Using the FLUKA Monte Carlo calculation, we can obtain the production rates of all radionuclides in an irradiated material. Depending on many factors, the production rates are quite different from isotope to isotope. Having the production rate and half-life of each isotope, FLUKA can further predict the time behaviour of each isotope during beam irradiation and after shutdown. Radioactivity builds up during the accelerator operation. When operations stop, there is a rapid decay of short-lived isotopes. After that, only median- and long-lived isotopes remain. The time evolution of residual radionuclides strongly depends on the irradiation profile. Figs. 5(a) and 5(b) show the time evolution of the maximal specific activities inside various targets for the case (1) and (2) irradiation conditions respectively. For case (1) 20-year operation, some long-lived radionuclides have the opportunity to build up and play an important role after the shutdown of machine. For case (2) 1-hour high-power irradiation, the maximal residual activities in targets are obviously higher than those in case (1), but they decay quickly after shutdown since only short-lived radionuclides are dominantly produced and accumulated. It is evident that, among these materials, aluminum is the most preferred and tungsten is more susceptible to activation. Lead and copper are roughly the same degree of susceptibility to be activated.

Electrons, positrons, X-rays or gamma rays emitted from the decay of radionuclides result in remnant dose around an activated component. They may pose a possible radiation hazard to the workers nearby during a maintenance period after machine shutdown. Figs. 5(c) and 5(d) show the decay of the residual dose rates at 1m away from various targets for the same case (1) and (2) irradiations respectively. As expected, the initial residual doses for the case (2) irradiation are much higher than those for the case (1), but concurrently they undergo a much faster decay due to the dominance of short half-lived isotopes in this case. Since most radionuclides are produced in a certain depth below the surface of the target. Due to the self-shielding effect of target material, the remnant dose rates in either case is not very high and should only have moderate impact on the staff working nearby during a maintenance period.

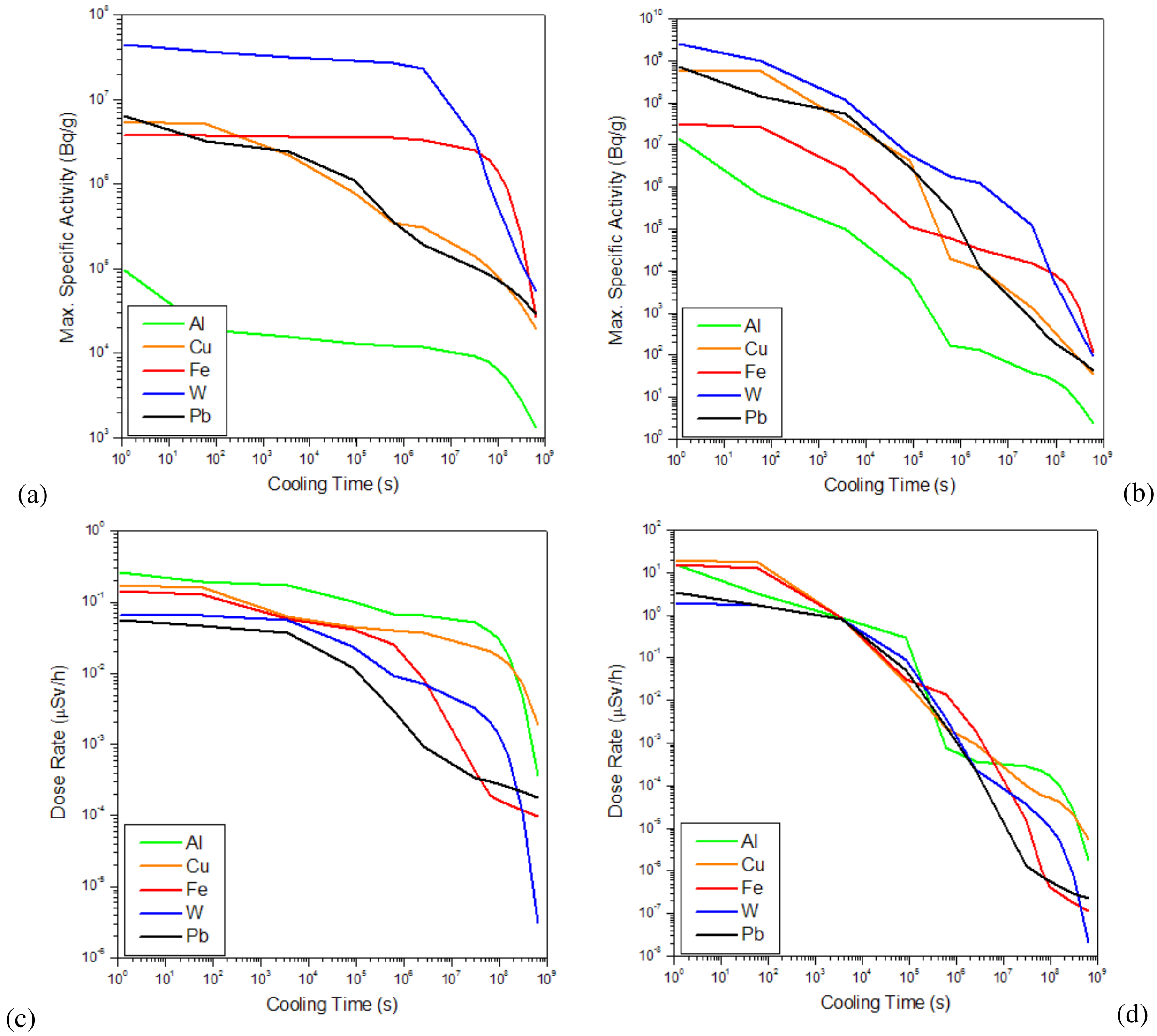


Fig.5 - Time evolution of the maximal specific activities inside various targets and the remanent dose rates at 1m away from targets for Case (1) and (2) irradiations respectively.

Although the potential for activation in bulk shielding should be limited at an electron accelerator, since most of the beam energy is absorbed by components such as magnets, absorbers or local shielding. It is deemed desirable to evaluate the degree of activation of the concrete shielding wall and to determine whether it is a radioactive waste or not. Following the same methodology, we have performed a residual activity zoning study for a concrete silo where an iron target is located inside and bombarded by 3-GeV electron beam. Our results indicate that the massive concrete block used in bulk shielding can be treated as a general waste without further storage for cooling [1]. Considering the impact of possible environmental release, the activation of air and cooling water in the accelerator tunnel should be evaluated cautiously. Taking into account the material compositions, reaction cross sections, and the half-lives of the radionuclides produced, it is seen that ^{13}N and ^{15}O produced by the $^{14}N(\gamma,n)^{13}N$ and $^{16}O(\gamma,n)^{15}O$ reactions in air and water are the radioisotopes of most importance [2]. Based on the current estimates, even considering the maximal injection power loss (~21.5W) in the tunnel, the possible concentrations of ^{13}N and ^{15}O in the air and cooling water inside the tunnel are well below the AEC exemption limit of 100 Bq/g for these two radionuclides.

4. Concluding Remarks

Prompt radiation fields and induced radioactivity due to the operations of TPS accelerators have been investigated using the FLUKA Monte Carlo simulations. Based on conservative and representative beam loss scenarios, radiation levels outside the bulk shielding and radiation streaming through penetrations on shielding walls were evaluated. The results demonstrate that the basic shielding design of the TPS is highly feasible and the 1 mSv/y design dose limit for staff and users should be practicably achievable. Meanwhile, the environmental dose at the nearest site boundary is also far below the regulatory requirement with comfortable margin. In addition to prompt radiation hazards, the design and operation of the TPS accelerators also requires a careful assessment and planning for the radioactivity induced around the facility. Our calculated results lead to the conclusion that the TPS is a fairly low electron consumption synchrotron light source; therefore radioactivities induced in accelerator components and surrounding concrete walls are rather moderate and manageable; and possible activation of air and cooling water and their environmental releases should be negligible.

References

[1] NSRRC, “Taiwan Photon Source (TPS) Design Handbook”, National Synchrotron Radiation Research Center, January 2009.

[2] W.P. Swanson, “Radiological Safety Aspects of the Operation of Electron Linear Accelerators”, Technical Report Series No. 188, International Atomic Energy Agency (1979).

[3] SLS, “Safety Report about the Swiss Light Source”, SLS Handbook, Chapter 9, Paul Scherrer Institute (1997).

[4] R.J. Sheu, J. Liu, J.P. Wang, K.K. Lin, G.H. Luo, “Characteristic of prompt radiation field and shielding design for Taiwan Photon Source”, ICRS-11/RPSD-2008, Pine Mountain, GA, USA, Apr. 13-18, 2008.

[5] BNL, “Preliminary Design Report of National Synchrotron Light Source II”, Brookhaven National Laboratory (2007).

[6] A. Ferrari, P.R. Sala, A. Fassò, J. Ranft, “FLUKA: a Multi-particle Transport Code”, CERN 2005-10, INFN/TC_05/11, SLAC-R-773 (2005).