An Analysis of Radiation Penetration through the U-Shaped Cast Concrete Joints of Concrete Shielding in the Multipurpose Gamma Irradiator of BATAN

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Abstract. An analysis of radiation penetration through the U-shaped joints of cast concrete shielding in BATAN’s multipurpose gamma irradiator has been carried out. The analysis has been performed by calculating the radiation penetration through the U-shaped joints of the concrete shielding using MCNP computer code. The U-shaped joints were a new design in massive concrete construction in Indonesia and, in its actual application, it is joined by a bonding agent. In the MCNP simulation model, eight detectors were located close to the observed irradiation room walls of the concrete shielding. The simulation results indicated that the radiation levels outside the concrete shielding was less than the permissible limit of 2.5 μSv/h so that the workers could safely access electrical room, control room, water treatment facility and outside irradiation room. The radiation penetration decreased as the density of material increased.

Keywords: radiation penetration, cast concrete joints, multipurpose gamma irradiator.

1. Introduction

The National Nuclear Energy Agency of Indonesia (BATAN) has a multipurpose gamma irradiator. It is a panoramic type, IAEA category IV irradiator whose radiation source, Cobalt-60 (Co-60), is stored in a pool filled by demineralized water when not in use [1][2]. In the irradiation room, the Co-60 source is lifted by a pneumatic system to the irradiation position. It is then lowered by gravity to the storage pool after the completion of irradiation process. The gamma irradiator is loaded with a 300-kCi Co-60 source and is designed to accommodate a radiation source with a maximum activity of up to 2 MCi.

BATAN’s multipurpose gamma irradiator, or henceforth referred to simply as “the irradiator” or “the multipurpose gamma irradiator” for brevity, has been designed to be very safe following the requirements of the IAEA Basic Safety Standards. The facility should keep the individual dose, the number of people exposed, and the probability of incurring exposures as low as reasonably achievable and below permissible dose limits [3][4]. Therefore, the use of appropriate radiation shielding that
encircles the irradiation room should be optimized to diminish direct radiation exposures toward workers and members of the public to the most effective levels [5].

Based on the Chairman of BAPETEN Regulation No. 11/Ka-BAPETEN/VI-99, the radiation shielding for irradiation facilities must be designed sufficiently thick to shield against radiation exposures of up to one and a half times the maximum source activity [6]. The implementation of the Regulation to the irradiator means that its radiation shielding should be able to protect against radiation exposures from source activities of up to 3 MCi, so the radiation shielding can reach 2 m in thickness [2].

The appropriate shielding material should be chosen to protect and ensure the safety of the workers and members of the public from radiation exposures. The radiation shielding construction must consider the seismic load [6], economic value of the material used, and building construction capacity. Concrete, earth fill, steel, lead, and iron may be used as radiation shielding in irradiation facility [5][6]. Among the materials mentioned above, concrete is frequently used as material for constructing radiation shields [5].

The radiation shielding of the multipurpose gamma irradiator should have a thickness of 2 m, which means that the construction requires concrete casting procedure and must be undertaken in several steps due to the large volume of the concrete needed. Since the construction of the radiation shielding must be undertaken in several steps, the shielding wall has joints. This cast concrete joints could be a problem in the future since it may lead to structural failure [7] and radiation penetration if the joints are filled with lower-density materials. The existence of the joints in the cast concrete enables the possibility that radiation could penetrate the horizontal planes of the joints up to a certain depth. Therefore, concrete shielding without joints is safer for the workers.

The work on the radiation penetration of the concrete shielding has been performed by Ardiyati, Rozali, and Damayanti in 2016 [8]. They analyzed the possible radiation penetration through the joints of the cast concrete shielding of the multipurpose gamma irradiator at BATAN. In the work, several detectors were simulated to be placed close to the observed area of the concrete shielding. Models of the cast concrete joints of the concrete shielding were formed from U-shaped cast concrete joints. The simulated cases were the one where there were no gaps between the joints and where a 0.2-mm thick air-filled gap was present. They reported that the concrete shielding construction was safe for both cases since the radiation exposures were below the permissible limit of 2.5 μSv/h.

In this current work, we analyzed the radiation penetration in the U-shaped cast concrete joints of concrete shielding in the multipurpose gamma irradiator. The objective of this analysis was to ascertain that the radiation exposure passing through the concrete shielding to the environment would not exceed the maximum permissible limit. The work was performed by measuring the radiation penetration on the cast concrete joints that were filled with bonding agent when the Co-60 source was on irradiation position and comparing it with the radiation penetration on the cast concrete shielding without joints and with joints filled with air.

2. Theory
The concrete shielding of the multipurpose gamma irradiator had to be designed very thick compared to ordinary walls so that be able to stop the radiation from a source with activity of up to 2 M Ci. For use as a radiation shield, concrete must have a minimum density of 2400 kg/m³ [6] and capable of receiving pressures of up to 210.9 kg/cm² [6]. Moreover, the maximum permissible limit for radiation exposures on the outer walls of the building that are not supervised is 2.5 μSv/h [6].

In the concrete casting with large volumes, the casting process cannot be undertaken continuously from bottom to top, and should be undertaken in two steps instead. Joining old and new concrete requires joints because the construction of concrete shielding wall as a monolithic unit cannot be done in one placement of concrete [7]. The construction joints that were used in this concrete shielding wall can serve as stress relief [9]. The construction joints usually use bonding agent to compound the old and new concrete. Cement grout or polyvinyl acetate are usually used as bonding
agents. The construction joints should be made and positioned in the right place so that the structural strength is not reduced [10].

An analysis of radiation penetration can be performed using deterministic methods and Monte Carlo methods (probabilistic methods). Deterministic methods compute the transport equation for the average particle behavior [11]. The calculation using deterministic methods is much simpler; however, it needs nuclear material data that is difficult to obtain. Monte Carlo methods calculate individual particles and record the information of some aspects (tally) of their average behavior [11]. These methods need large calculation resources to simulate every movement and interaction of particles with matter.

Monte Carlo N-Particle Transport Code (MCNP) is a stochastic computer simulation program that randomly traces an appropriate number of particles to obtain particle transport equation with seven-dimensional phase space of time, position, direction, and energy [12]. To execute MCNP, system geometry, material and cross sections, particle source, and particle tally must be defined as inputs. The geometry was represented in the X, Y, and Z coordinates where, in this work, the X and Y coordinates were defined relative to the midpoint of the source storage pool and the Z coordinate was relative to the surface of the irradiation room floor. Material definitions include material number, material composition, and cross section compilations. Tallying is used for scoring the quantity of interest [12]. There are various tally type, i.e., F1 (surface current), F2 (average surface flux), F4 (average flux in a cell), FMESH4 (track-length tally over 3D mesh), F5a (flux at a point or ring), FIP5 (pin-hole flux image), FIR5 (planar radiograph flux image), FIC5 (cylindrical radiograph flux image), F6 (energy deposition), F7 (fission energy deposition in a cell), and F8 (pulse height distribution in a cell). The most commonly used tallies are F1, F2, F4, and F5 [12].

3. Methodology
The analysis in this work was performed by placing several detectors close to the observed irradiation room walls of the concrete shielding. This method was to examine the radiation penetration through the U-shaped cast concrete joints of the concrete shielding of the multipurpose gamma irradiator. It started with the modeling of the measurable factors needed for MCNP simulation. The simulation itself was performed by measuring the radiation penetration on the cast concrete joints filled with bonding agent when the Co-60 sources was on irradiation position and compared it with the radiation penetration on the cast concrete shielding without joints and with joints filled with air.

In the current work, the joints were filled with a bonding agent. System geometry, material, and particle source were defined as inputs to the program. The information related with concrete shielding, construction joints, detectors, and source were modeled for the geometry inputs and material definitions.

The Co-60 sources in the irradiator were cylindrical and arranged inside source pencils. The source pencils were to be placed in source modules that contained 40 source pencils each. The facility has four source modules and three source racks that are arranged side by side. In total, the multipurpose gamma irradiator has 480 source pencils that are distributed into the three source racks.

The calculation modeling in the MCNP was made conservative by ignoring source racks and irradiated product racks construction. The only material in the irradiation room that was modeled for the MCNP calculation was the 480 source pencils with equally-distributed activity in each pencil. The source pencils were modeled as having a length of 43.7 cm and diameter of 0.7 cm. They were encapsulated in AISI 304 stainless steel containers with 45.1 cm length, diameter of 1.1 cm, and density of 7897.68 kg/m³. The density of the Co-60 source was 8900 kg/m³.

Co-60 was set to have a maximum activity of 2 MCi since the radiation shielding must be designed to safely block the radiation from up to 3 MCi. Therefore, the maximum activity for the calculation modeling was 3 MCi. The maximum permissible limit for radiation exposures on the outer walls of the building was 2.5 μSv/h.

The radiation shielding of the multipurpose gamma irradiator was made from concrete. In the simulation, its geometry was defined as the actual size of the concrete shielding of the multipurpose
gamma irradiator. Its wall thickness was varied between 150 cm to 200 cm and represented in the X, Y and Z coordinates. The concrete and air densities were 2320 kg/m$^3$ and 1.294 kg/m$^3$, respectively.

The structure of the concrete shielding had to be made strong enough to withstand with all conditions including earthquakes. Therefore, the construction joints of the concrete shielding were made U-shaped since it was a new design in the concrete construction in Indonesia. The U-shaped cast concrete joints were also used for limiting direct gamma ray penetration through the gap of the cast concrete joints. The gamma rays that penetrate to the horizontal planes of the joints will be stopped by the concrete in the middle and outer part of the cast concrete joints.

To connect the old and new concrete structure, the facility used a bonding agent. The bonding agent is mainly composed of polyvinyl acetate and has density of 1100 kg/m$^3$. In the MCNP modeling, the height of the joints was set to 2 mm that made the simulation easier for both bonding agent-filled and air-filled joints. The detail of the joints was based on the research presented in [8] and can be seen in Figure 1.

![Figure 1](image1.png)

**Figure 1.** Illustration of the U-shaped cast concrete joints of the concrete shielding in the multipurpose gamma irradiator [8].

A number of detectors were placed close to the irradiation room walls of the concrete shielding. The locations of the detectors were based on the research presented in [8] and can be seen in Figure 2 below. The observed walls were chosen as they are in areas frequently accessed by the workers. The detectors’ locations were represented by their X, Y, and Z coordinates and they were modeled as spheres in the MCNP simulation.

![Figure 2](image2.png)

**Figure 2.** Location of the detectors around the irradiation room [8].
4. Results and Discussions
Based on the simulation results using MCNP, the radiation penetration on the concrete shielding can be obtained. The simulations were performed for three conditions of the concrete shielding, namely concrete shielding without joints, cast concrete joints filled with bonding agent, and cast concrete joints filled with air. It was found that the radiation levels outside the concrete shielding were less than the permissible limit of 2.5 μSv/h, as can be seen in Table 1.

Table 1. Radiation penetration results from MCNP

| No  | Detector locations          | Detector Positions in MCNP | Radiation Penetration on the concrete shielding (μSv/h) |
|-----|----------------------------|----------------------------|-------------------------------------------------------|
|     |                            | X  | Y  | Z  | Without joints | Joints filled with bonding agent | Joints filled with air |
| 1   | Workers access door        | 830| 449| 140| 3.17216E-06    | 8.51086E-05                  | 3.64966E-04            |
| 2   | Electricity room           | 781| 250| 140| 3.06209E-05    | 4.38672E-05                  | 2.09450E-04            |
| 3   | Control room               | 1021| -220| 140| 1.13869E-06    | 1.15122E-06                  | 3.04382E-05            |
| 4   | Goods access door          | 880 | -511| 140| 4.49958E-06    | 2.75530E-05                  | 5.67009E-03            |
| 5   | In front of maze           | 230 | -881| 140| 1.02415E-02    | 1.35463E-02                  | 1.40748E-01            |
| 6   | Water treatment facility   | -380| -461| 140| 2.41924E-04    | 2.60304E-04                  | 1.11635E-03            |
| 7   | Outside west wall          | -751| 100 | 140| 1.31771E-06    | 4.04498E-06                  | 1.09653E-05            |
| 8   | Outside north wall         | 0   | 711 | 140| 1.35980E-04    | 3.08053E-04                  | 1.30822E-03            |

The particle tracking figure above was generated from the MCNP modeling of the air-filled cast concrete joints. The other conditions resulted in the same particle tracking as Figure 3. From the particle tracking figure, it can be seen that the radiation particle from Co-60 could not pass through the U-shaped air-filled and bonding agent-filled cast concrete joints of the concrete shielding. It only penetrated a small portion of the inner concrete shielding wall. Therefore, from the MCNP calculation and particle tracking result in Figure 3, it could be assured that the workers could safely access control room, electricity room, water treatment facility, and the outside of the irradiator building.
Figure 4. Radiation penetration on the concrete shielding wall for each detector

Based on Table 4.1, Figure 4 graphs the radiation penetration for the three conditions of concrete shielding. It can be concluded that concrete shielding without joints resulted in least penetration, while the one with air-filled joints resulted in most, largely because of the differences in material density: the density of shielding concrete was 2320 kg/m$^3$, bonding agent 1100 kg/m$^3$ and air 1.294 kg/m$^3$. Radiation cannot penetrate as far for denser materials. However, for all the three scenarios, the concrete shielding were safe for workers to have activity outside irradiation room even when in the irradiation mode.

5. Conclusions
U-shaped cast concrete joints of concrete shielding were a new design in massive concrete construction in Indonesia and it would increase the safety level of the facility. The study simulated three conditions of the concrete shielding, namely concrete shielding without joints, cast concrete joints filled with bonding agent, and cast concrete with air-filled joints. The results of the simulations were the radiation levels outside concrete shielding were less than the permissible limit of 2.5 μSv/h.

The radiation penetration decreased as the density of material increased. The three conditions of concrete shielding is safe for workers outside the irradiation room, namely in the control room,
electricity room, water treatment facility, and outside of the irradiator, even when the irradiation is taking place.

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