

Monte Carlo dose assessment of a neutron irradiation facility with two PuBe sources

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ABSTRACT

The Neutron Irradiation Facility (NIF) utilizes neutron sources and moderating assemblies that require radiation protection assessment under various operating conditions. In this study, neutron and photon ambient dose equivalent distributions were evaluated using the Monte Carlo N-Particle (MCNP) code. Five operational configurations involving different source positions relative to the high-density polyethylene (HDPE) moderator assembly and source handling system (SHS) were simulated to characterize spatial radiation fields and support radiation zoning. Under the default condition (Configuration 1), with both neutron sources positioned within the HDPE moderator assembly, the maximum total ambient dose equivalent rate was $8.56 \mu\text{Sv/h}$, with radiation fields strongly localized near the moderator perimeter. Elevated source configurations (Configurations 2 and 3) produced higher maximum rates of 1.18×10^2 and $1.46 \times 10^2 \mu\text{Sv/h}$, respectively. For SHS configurations, Configuration 5 yielded a lower maximum ambient dose equivalent rate than Configuration 4, decreasing from 9.95 to $4.44 \mu\text{Sv/h}$. The counting room consistently exhibited low ambient dose equivalent rates, ranging from 1.82×10^{-3} to $1.81 \times 10^{-1} \mu\text{Sv/h}$. Annualized ambient dose equivalent values in Controlled Areas remained below the applicable occupational effective-dose limits of 20 mSv/y for adult workers and 6 mSv/y for student trainees aged 16–18, while supervised public-access areas outside the NIF remained below the 1 mSv/y public effective-dose limit specified in PNRI CPR Part 3 Rev. 02. These comparisons were treated as conservative screening assessments. The results demonstrate the strong dependence of radiation fields on source configuration and shielding geometry and provide a quantitative basis for radiation zoning and operational controls. Independent experimental validation is recommended for future work.

INTRODUCTION

Isotopic neutron sources (INS) have proven beneficial in various scientific applications due to their portability, stable neutron flux, and characteristically long half-lives. Unlike nuclear reactors or particle accelerators, which require massive infrastructure and complex cooling systems, INS units provide a continuous and predictable source of neutrons in a compact form factor. These sources are frequently utilized in fields such as neutron activation analysis (NAA), detector calibration, neutron metrology, and radiation research (Hassan, 2001). Within the Philippine Nuclear Research Institute (PNRI), INS has been integrated into the newly established Neutron Irradiation Facility (NIF). The NIF is a configurable moderator assembly that is made of high-density polyethylene (HDPE), which utilizes two repurposed legacy plutonium-beryllium ($^{239}\text{PuBe}$) INS. The use of HDPE is particularly significant, as its high hydrogen content serves as an effective moderator for thermalizing fast neutrons which can tailor the energy spectrum for specific experimental requirements. One of the NIF configurations is the low-dose uniform neutron irradiator system (LUNIS) that features a uniform highly thermalized volume for irradiation applications. This cavity-based geometry is neutron-dominated, with an average thermal neutron fluence rate ranging from 1.4×10^2 to $2.8 \times 10^2 \text{ cm}^{-2}\text{s}^{-1}$ (Asuncion-Astronomo et al. 2026). Another configuration is for low-flux neutron activation analysis, where the NIF assembly is setup to obtain a total neutron flux of $5.68 \times 10^3 \text{ n/cm}^2\text{-s}$, of which 51.80% is thermal neutrons (Sagana et al. 2025).

Considering the expected reconfiguration of the NIF assembly to accommodate its various operational modes, an assessment of the spatial distribution of neutron and photon dose under the different facility configurations is necessary. For a radiation facility like the NIF, a comprehensive dose assessment that includes shielding assessments and radiation zoning is essential to ensure operational safety. Characterizing the spatial dose distribution verifies that facility utilization complies with the safety standards established by regulatory bodies. Hence, this study aims to characterize and compare the neutron and photon dose distributions for five

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KEYWORDS

Radiation protection; isotropic neutron source; Monte Carlo calculation; dose assessment

operational configurations of a dual Pu–Be source irradiation facility. Furthermore, the study aim to develop recommended radiation zoning and safety measures based on the evaluated dose distributions to ensure the safe operation of the NIF.

Five configurations representing different operational conditions with potential radiation exposure were evaluated. Computational assessments were performed using the Monte Carlo N-Particle transport code (MCNP5 v1.6), a Monte Carlo radiation transport code that is widely used for modeling complex particle transport phenomena and estimating dose rates at specific points of interest. The study provides essential inputs for the radiation safety assessment and optimization of operational procedures in the facility. The findings from this study will serve as a technical

reference for the radiation protection program and will support the safe and efficient operation of the NIF.

MATERIALS AND METHODS

Facility Layout

The NIF, the source handling system (SHS), and the associated source maneuvering mechanisms are housed in an underground laboratory facility at the PNRI reactor building. The laboratory facility has an adjacent shielded counting room designed as a dedicated workspace for researchers and students. The map of the simulated NIF, and the specific locations of the thirty (30) cell detectors used is shown in Figure 1.

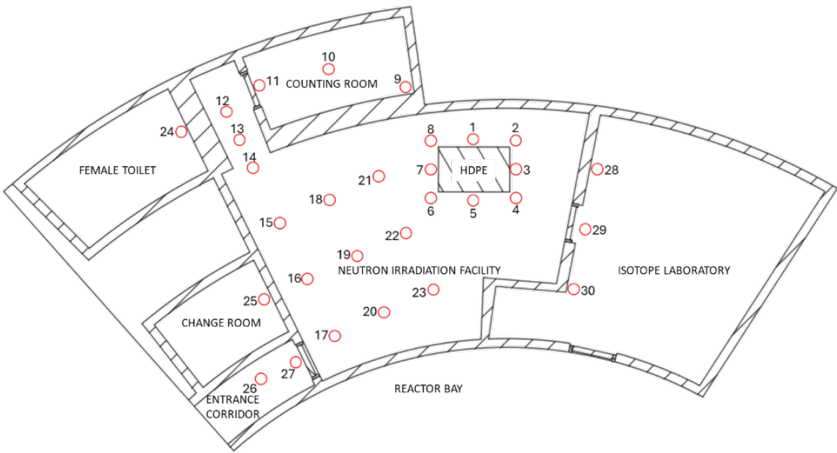


Figure 1: Neutron Irradiation Facility

Isotopic Neutron Source Characteristics

The ²³⁹PuBe radionuclides utilized in this study are (α, n) isotopic sources composed of an intermetallic compound formed from a mixture of an actinide oxide and a light element. In these sources, ²³⁹Pu isotopes undergo alpha decay, where the resulting α-particles interact with ⁹Be nuclei to produce free neutrons via the ⁹Be(α, n)¹²C reaction (Söderström et al, 2021). As these sources are legacy assets from the early operations of the Philippine Research Reactor-1 (PRR-1), historical technical documentation was initially limited. Recent characterization by Asuncion-Astronomo et al. (2024) verified the source strengths and identified the optimal configurations currently implemented in the NIF. For the Monte Carlo N-Particle (MCNP) simulations, two Pu–Be neutron sources were modeled, each with an activity of 2 Ci and a neutron emission rate of 3.6 x 10⁶ n/s. This configuration was adopted to provide a conservative estimate of the radiation dose. The physical and radiological parameters are summarized in Table 1, as established in the design study for a two-source uniform thermal irradiator (Asuncion-Astronomo et al., 2026).

Table 1: Neutron source information

²³⁹ PuBe	
Reference Date*	01 Jan 1965
Activity**	7.40 x 10 ⁹ Bq (2 Ci)
Source Strength	3.6 x 10 ⁶ n/s
Half life	24,110 years
Dimension of the active element***	Length: 4.140 cm Diameter: 1.681 cm
Dimension of SS capsule***	Length: 5.505 cm Diameter: 2.591 cm
Spectrum Reference	Sources4C (Wilson et al, 2009)

* Reference date is unknown; its effects is considered negligible because of very long half-life of the nuclide

** Source strength of each source
*** Dimensions as declared in the MCNP simulation.

HDPE Moderator Assembly and Source Handling System (SHS)

The HDPE moderator assembly features external dimensions of 188 × 118 × 104 cm³, with an internal irradiation cavity of 140 × 70 × 70 cm³ (Figure 2). The two neutron sources are encased in aluminum tubes and positioned vertically at opposing ends of the moderator. The assembly is modular, consisting of seven interchangeable HDPE slabs (each 20 × 70 × 24 cm³). In the default configuration, the sources are fixed within the central ports of Slab 1 and Slab 7. The HDPE therefore performs three simultaneous roles: storage, moderation, and biological shielding.

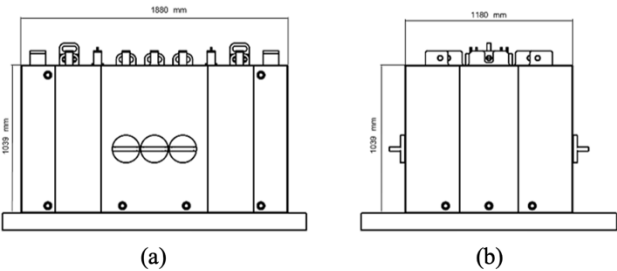


Figure 2: HDPE Moderator Assembly: (a) Front view and (b) Side view

In addition to the HDPE assembly, the facility utilizes a source handling system (SHS), which served as the storage and shielding unit for the ²³⁹PuBe sources during maintenance and whenever the NIF is used for alternative neutron sources. The SHS consists of a cylindrical SS-304 stainless steel tank (height: 80 cm, diameter: 70 cm, thickness: 0.32 cm) filled with water to a height of 75 cm to provide neutron moderation and biological shielding (Figure 3). The system includes two horizontal ports for irradiation activities, which are secured with polyethylene plugs when not in use.

Sources are navigated via vertical ports to the intersection point of the horizontal channels to maximize the available neutron flux.

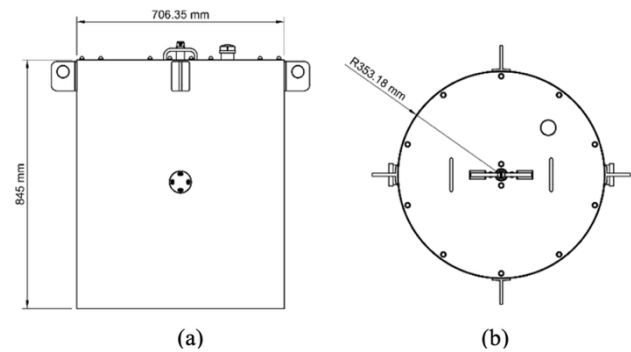


Figure 3: Source Handling System: (a) Front View and (b) Top View

Table 2: Operational Configurations

Configuration No.	Description	Purpose
1	Default	Normal operation of NIF for neutron activation analysis (NAA)
2	70 cm Above HDPE Assembly	Transferring of neutron sources
3	70 cm Above HDPE Assembly, Grouped	Transferring of neutron sources
4	Individual Placement in Holders	Storage of neutron sources while the HDPE assembly is occupied by other sources
5	Centered within SHS	Storage of neutron sources while the HDPE assembly is occupied by other sources

These configurations were selected because they represent operational conditions associated with potential radiation safety risks. Configuration 1 correspond to the default operation where both the neutron sources are within the HDPE Assembly while Configurations 4 and 5 correspond to conditions in which both neutron sources are positioned within the SHS. All represent the standard operating conditions of the facility during irradiation procedures. Configurations 2 and 3 were specifically evaluated to establish radiation safety protocols and two-dimensional dose distribution profiles during the transfer of neutron sources between moderator systems.

Monte Carlo Simulation

Simulations were performed using the Monte Carlo N-Particle transport code, MCNP5 Version 1.6 (Los Alamos National Laboratory, USA), and executed on an ultrafast computing system equipped with an AMD Ryzen Threadripper 2990WX processor (Advanced Micro Devices, Santa Clara, California, USA). The system features 18 processing cores and 36 threads, supported by 32 GB of RAM. The assessment employed coupled neutron–photon transport mode (MODE N P) to account for both primary neutron emissions and secondary gamma radiation generated through neutron capture and inelastic scattering processes. A total of 1×10^8 neutron histories were simulated to obtain relative errors below acceptable limits for all tallies of interest. The neutron sources were modeled according to the specifications presented in Table 1, while the material compositions are summarized in Table 3. The ENDF/B-VII.1 nuclear data library with corresponding $S(\alpha, \beta)$ thermal scattering data were utilized for all transport calculations. The neutron source strength was incorporated directly into the MCNP tally definitions using a normalization factor of 3.6×10^6 n/s corresponding to the 2-Ci PuBe source. These flux values

Source Configuration

This study evaluated the neutron and photon flux distributions across five distinct geometric configurations as described in Table 2.

were subsequently converted into ambient dose equivalent rates, expressed in microsieverts per hour ($\mu\text{Sv}\cdot\text{h}^{-1}$), using the ICRP-74 flux-to-dose conversion coefficients. Primary photons emitted directly by the PuBe source, such as the characteristic 4.44 MeV line, were excluded from the source definition given the conservative assumptions applied to both 2-Ci Pu-Be sources.

The radiation field was characterized using mesh tallies (FMESH) to generate two-dimensional neutron and photon flux distributions throughout the facility. The spatial neutron and photon dose distributions were calculated using rectangular FMESH tallies in the XY, XZ, and YZ planes. For the XY plane, meshes covering $1160 \times 1050 \times 10$ cm were subdivided into $580 \times 525 \times 1$ intervals, corresponding to a spatial resolution of $2 \times 2 \times 10$ cm. Analogous meshes covering $1160 \times 10 \times 650$ cm and $10 \times 1050 \times 650$ cm were used for the XZ and YZ planes, respectively, with spatial resolutions of $2 \times 10 \times 2$ cm and $10 \times 2 \times 2$ cm. Each mesh element represented a volume of 40 cm^3 .

To simulate the dose distributions at specific locations, thirty cell detectors (F4 tallies) were strategically positioned within the facility model as indicated in Figure 1, particularly in high-occupancy areas where personnel and students are most likely to operate. Each spherical cell detector had a radius of 15 cm, corresponding to a volume of approximately $14,137 \text{ cm}^3$. Spatial visualization and qualitative interpretation of the resulting neutron and gamma-ray profiles were conducted using the MCNP Visual Editor (VisEd), for comprehensive analysis of the facility’s radiation environment.

Table 3: Material composition declared in MCNP simulation

Material	Density (g/cm ³)	Composition (Weight Fraction) ^a
²³⁹ PuBe ^b	4.35	²³⁹ Pu – 6.5027E-02; ²⁴⁰ Pu – 5.6928E-03; ²⁴¹ Pu – 7.08641E-04; ⁹ Be – 9.285714E-01
SS-304	8.00	C - 8.0000E-04, ⁵⁵ Mn -2.0000E-02, ³¹ P- 4.5000E-04, S: 6.4410E-04 Si: 1.0000E-02, Cr: 1.9002E-01, Ni: 8.9944E-02, Fe: 6.8379E-01
HDPE	0.95	H: 1.4372E-01, C: 8.5628E-01
Al-6061	2.70	Mg: 1.0000E-02, Al: 9.7200E-01, Si: 6.0000E-03, Ti: 8.8000E-04 Cr: 1.9500E-03, Mn: 8.8000E-04, Fe: 4.0900E-03, Cu: 2.7500E-03 Zn: 1.4600E-03
Concrete	2.30	H: 1.0E-02, ¹⁶ O: 5.32E-01, ²³ Na: 2.90E-02, ¹³ Al: 3.40E-02, ¹⁴ Si: 3.37E-01, Ca: 4.40E-02, Fe: 1.40E-02
Air	0.00121	C: 1.2400E-04, ¹⁴ N: 7.5232E-01, ¹⁵ N: 2.9440E-03, ¹⁶ O: 2.3178E-01 ⁴⁰ Ar: 1.2827E-02
Water	0.9982	H: 1.11894E-01, ¹⁶ O: 8.88106E-01

^a Reference for Material Composition is from (McConn et al., 2011)^b Composition is based on (Tate and Coffinberry, 1958)

RESULTS AND DISCUSSION

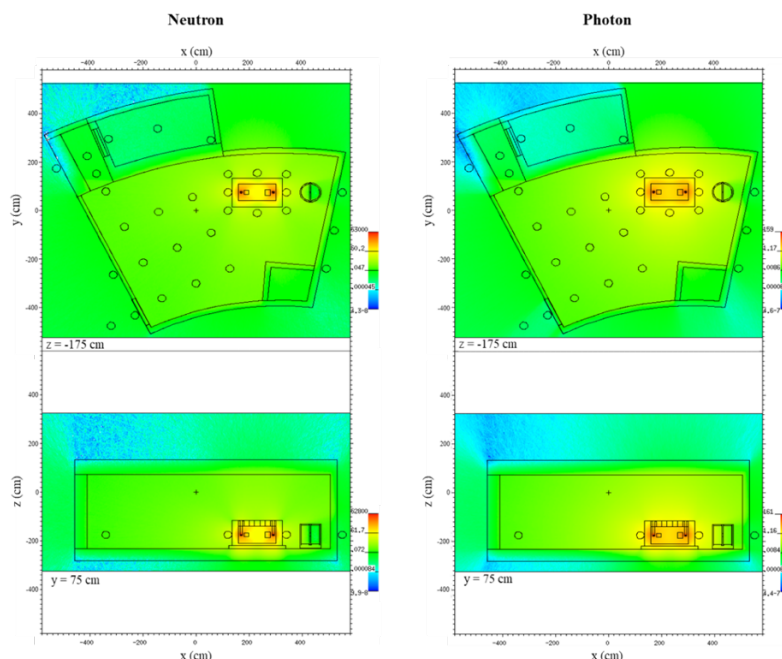
Sources inside the moderator assembly

The first simulation was performed with both neutron sources inside the moderator assembly and no additional shielding present in the irradiation room. This configuration represents the default condition of the facility. Figure 4 shows that neutron ambient dose equivalent rate dominates photon ambient dose equivalent rate by approximately two orders of magnitude throughout the room. Doses are strongly localized near the moderator assembly, with the highest values occurring adjacent to the neutron source.

Beyond the immediate perimeter of the moderator assembly, neutron dose decreases rapidly, confirming that the hydrogenous moderator efficiently attenuates fast neutrons and limits leakage. The neutron dose becomes nearly uniform at distances of approximately 1 m away from the moderator assembly, while photon dose reaches similar uniformity at approximately 2 m. This indicates that once sufficient moderation and scattering occur, the radiation field loses strong spatial gradients within the room volume.

In the horizontal (x–y) plane, the neutron ambient dose distribution shows that the counting room registers the lowest dose within the facility due to the thickness of the shielding wall. Areas outside the NIF exhibit a nearly uniform profile below <0.04 µSv/h. The isotope laboratory shows slightly higher dose relative to other external areas due to its shorter distance from the neutron sources.

In the vertical (x–z) plane, the region above the ceiling directly over the moderator assembly shows no significant radiation risk, confirming effective attenuation of upward-directed neutron leakage. A slight increase in neutron ambient dose is observed near the ceiling surface, which is attributed to surface-induced scattering and room-return effects from the concrete boundary, rather than direct neutron streaming from the sources. In contrast, a slight elevation in neutron and photon doses is observed in the lower region of the moderator assembly. This is primarily attributed to the reduced thickness of the base of the moderator, combined with the floor-induced scattering contributions.

**Figure 4:** Spatial distributions of ambient dose equivalent rates for default configuration.

Elevated source positioning outside the moderator and SHS

These configurations represent special, short-duration handling procedures during which the neutron sources are temporarily

unmoderated and unshielded while being transferred within the facility. This typically occurs when moving the sources into the SHS, when access to the HDPE cavity is required, or when another neutron source occupies the moderator assembly.

With the sources raised 70 cm above the HDPE, the shielding and moderation normally provided by the polyethylene are removed. The ambient dose maps Figure 5 and Figure 6 show that both neutron and photon dose rates increase by more than one order of magnitude relative to the default configuration. The radiation field expands across the room due to direct fast-neutron streaming prior to any significant moderation.

A spatial behavior emerges in both configurations. Beyond approximately 2 m from the neutron sources, the neutron dose becomes nearly uniform throughout the room. The photon dose reaches similar uniformity at roughly the same distance, indicating that once sufficient scattering and capture occur in room structures, the field loses strong spatial gradients.

Due to the strong attenuation and moderating properties of the HDPE, the neutron dose in its immediate vicinity increases even when the sources are positioned outside the assembly. This behavior highlights the role of neutron capture and inelastic

scattering in hydrogenous material: the HDPE acts as an efficient scattering and absorption region that redistributes the unmoderated neutron field and contributes significantly to the room-return effect. As a result, scattered neutrons and photons originating from interactions with the HDPE add to the overall dose distribution inside the facility. For the same reasons, the neutron dose inside the cavity of the moderator assembly becomes comparable to regions located more than 2 m away from the sources. This is attributed to the shielding effect of the upper HDPE thickness.

When the sources are positioned above the SHS, a noticeable dose pattern forms on the top surface of the SHS. This pattern reflects the interaction of the neutron field with the SHS, whose moderating medium is water. Figure 6 indicates localized moderation and scattering within the water-filled system, producing non-uniform dose distribution.

Comparing the two arrangements, separated sources in Configuration 2 result in a wider geometric spreading of the radiation field, leading to more distributed dose patterns throughout the room. In contrast, grouped sources in Configuration 3 produce stronger localized dose buildup due to the superposition of fluxes.

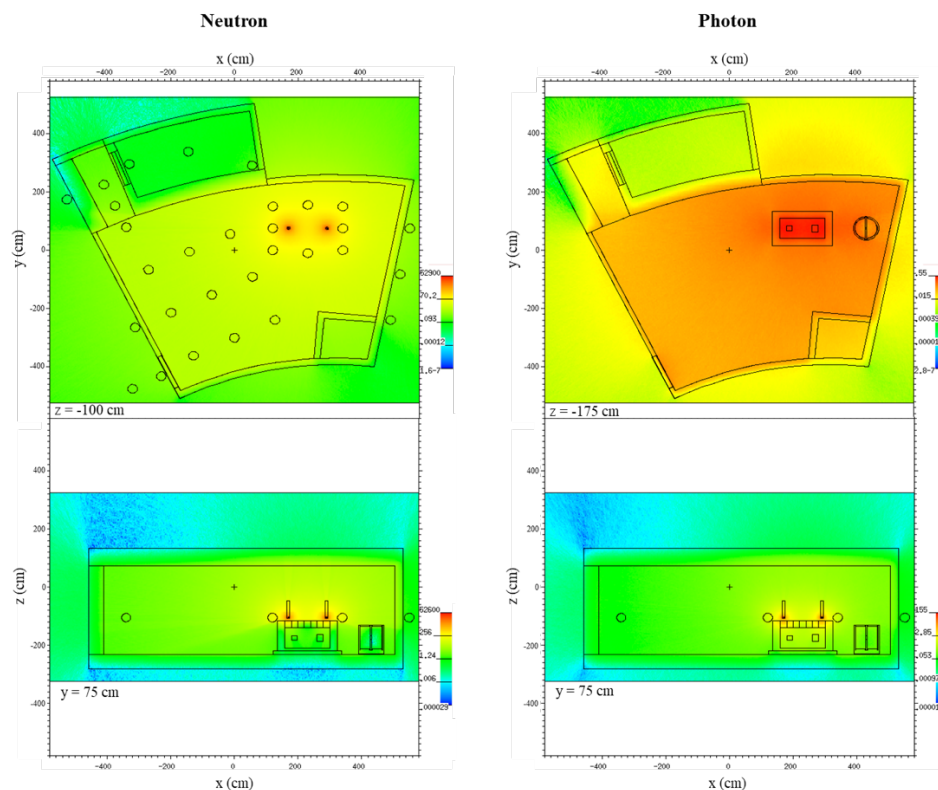


Figure 5: Spatial distribution of ambient dose equivalent rates for Configuration 2, with the neutron sources positioned 70 cm above the HDPE assembly (separated arrangement).

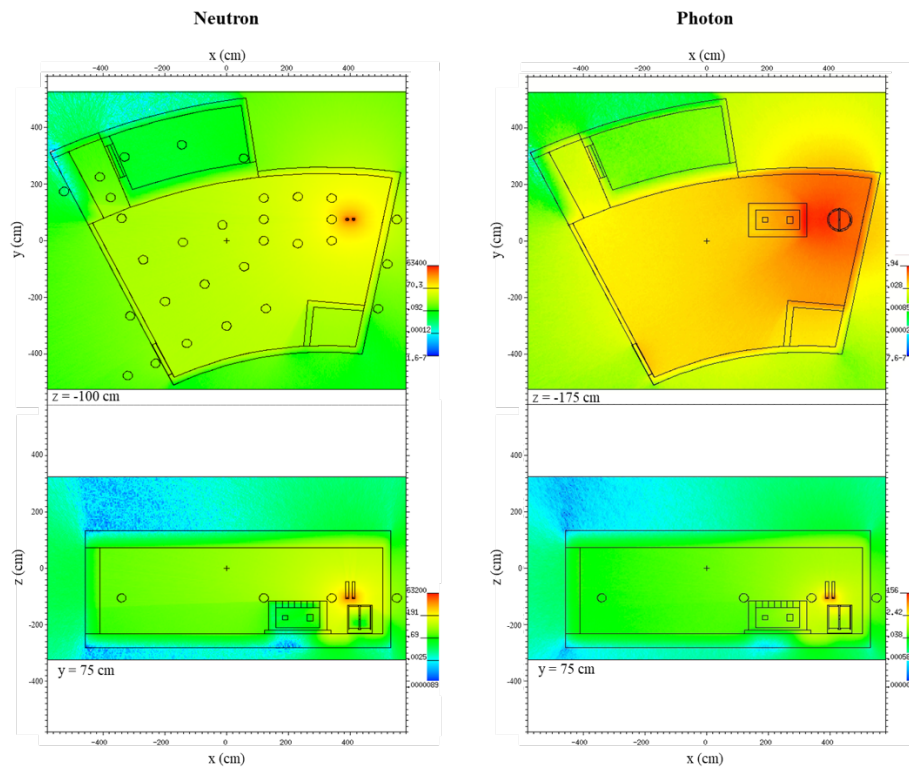


Figure 6: Spatial distribution of ambient dose equivalent rates for elevated neutron source Configuration 3 with sources positioned 70 cm above the HDPE assembly (grouped arrangement).

Sources inside the Source Handling System

When the neutron sources are placed inside the SHS, the geometry reintroduces both moderation and shielding effects. Configuration 5 yields a lower total ambient dose equivalent rate than Configuration 4, demonstrating that source positioning within the SHS measurably affects the external dose distribution. Centering the sources enhances self-shielding and increases the probability of neutron interactions within the SHS structure.

The placement of the SHS at the far end of the irradiation room also provides an additional radiological benefit. The HDPE assembly contributes further attenuation of the emerging neutron field and influences room-return scattering, thereby reducing the overall dose spread within the facility. This configuration highlights a favorable geometric coupling between the SHS and HDPE assemblies, which together improve dose mitigation across the NIF.

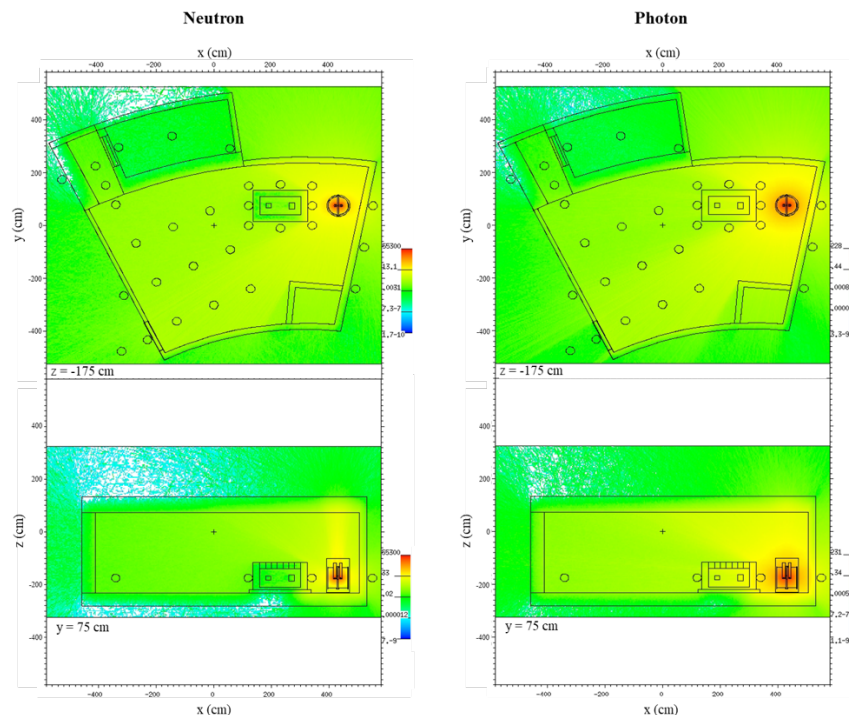


Figure 7: Spatial distributions of ambient dose equivalent rate for source handling system Configuration 4 with sources placed in individual holders within the SHS.

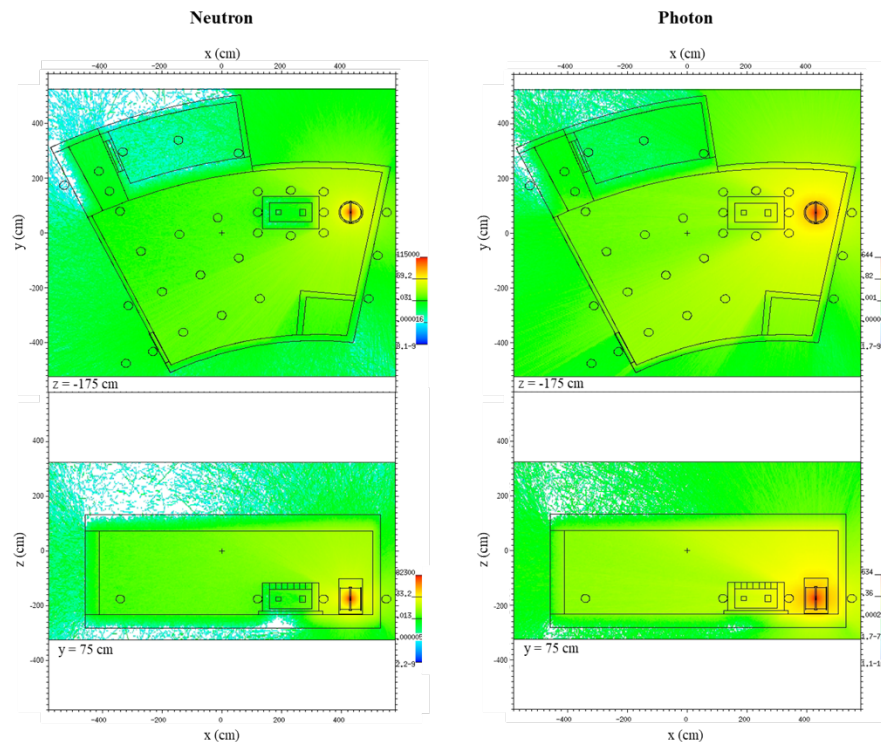


Figure 8: Spatial distributions of ambient dose equivalent rate for source handling system Configuration 5 with sources positioned at the center of the SHS.

Radiation zoning in NIF

Radiation zoning within the NIF is established based on the spatial distributions of ambient dose equivalent rate obtained from simulations of the different source configurations summarized in Table 4. Most cell tallies exhibit relative errors below 1.03×10^{-2} . The maximum relative uncertainties were observed in regions farthest from the neutron source due to lower neutron history, specifically inside the counting room (1.42×10^{-1}) and the female

rest room (7.38×10^{-1}). While these relative error values describe Monte Carlo sampling precision, radiological compliance and facility safety are evaluated strictly by comparing the resulting ambient dose equivalent magnitudes against PNRI regulatory limits. These radiation field maps provide the basis for defining operational zones, administrative controls, and worst-case exposure scenarios.

Table 4: Dose mapping for different source configurations in the NIF.

Table 1. Dose mapping for different cells being studied in the area													
Area		Cell Detector	Maximum Total Dose Rate and Percentage Change Relative to the Reference Configuration										Maximum Relative Error
			Configuration 1,		Configuration 2		Configuration 3		Configuration 4		Configuration 5		
			μSv/h	μSv/h	%	μSv/h	%	μSv/h	%	μSv/h	%		
Inside NIF	HDPE perimeter	3	8.56	1.18×10^2	1284	1.46×10^2	1609	9.95	16	4.44	-48	1.03×10^{-2}	
	Counting room	9	5.54×10^{-3}	1.81×10^{-1}	3164	5.90×10^{-2}	965	2.80×10^{-3}	-50	1.82×10^{-3}	-67	1.42×10^{-1}	
	Corridor to counting room	14	1.45×10^{-1}	3.38	2233	2.07	1327	7.81×10^{-2}	-46	3.50×10^{-2}	-76	5.06×10^{-2}	
	Working area	a	7.30×10^{-1}	1.41×10^1	1833	6.66	812	4.60×10^{-1}	-37	2.51×10^{-1}	-66	3.77×10^{-2}	
Outside NIF	Female toilet	24	3.20×10^{-4}	9.24×10^{-3}	2791	5.08×10^{-3}	1490	8.05×10^{-5}	-75	4.14×10^{-5}	-87	7.38×10^{-1}	
	Change room	25	2.37×10^{-2}	8.04×10^{-1}	3298	5.77×10^{-1}	2339	1.60×10^{-2}	-32	9.99×10^{-3}	-58	8.56×10^{-2}	
	Entrance corridor	27	1.87×10^{-2}	8.03×10^{-1}	4207	6.83×10^{-1}	3560	4.39×10^{-2}	135	2.22×10^{-2}	19	6.99×10^{-2}	
	Isotope laboratory	b	3.52×10^{-2}	1.39	3860	5.63	15894	1.05	2881	4.76×10^{-1}	1253	1.33×10^{-2}	

^aConfiguration 1 and 2: detector 21; Configuration 3: detector 22; Configuration 4 and 5: detector 23.

^bConfiguration 1: detector 29; Configuration 2 - 5: detector 28.

The reported dose rate for each monitored area is based on the representative detector cell exhibiting the maximum calculated

ambient dose equivalent rate within that location. As a result, the detector cell number may differ among configurations without

indicating a change in the physical location being evaluated. Configuration 1 represents the default operational condition of the facility. In this arrangement, radiation fields are strongly localized around the HDPE assembly, with a maximum total ambient dose rate of 8.56 $\mu\text{Sv/h}$. The field attenuates rapidly in all directions, resulting in negligible dose contributions to surrounding occupied areas. Elevated ambient dose rates occur primarily during transient source transfers due to the removal of shielding and direct exposure to unmoderated neutron emission. Detector 3, positioned at the HDPE moderator perimeter, corresponding to a distance of approximately 1 meter across all source configurations, recorded a maximum ambient dose rate of $1.46 \times 10^2 \mu\text{Sv/h}$ corresponding to Configuration 3. In contrast, Configuration 2 in which the neutron sources were elevated and positioned above the moderating assembly, produced ambient dose rates of $1.18 \times 10^2 \mu\text{Sv/h}$. For SHS configurations, Configuration 5 produced lower total ambient dose rates than Configuration 4, reducing the maximum dose rate from 9.95 $\mu\text{Sv/h}$ to 4.44 $\mu\text{Sv/h}$. This behavior demonstrates the influence of source positioning and self-shielding effects on overall dose reduction within the system. Minimum ambient dose equivalent rates below $1.81 \times 10^{-1} \mu\text{Sv/h}$ are consistently observed in the counting room across all configurations.

Outside the NIF, the isotope laboratory records the highest dose rates among adjacent areas due to its proximity to the neutron

sources. Configurations 2 and 3 represent the worst-case radiation exposure scenarios in the facility and are therefore used to define time limits, handling procedures, and radiation protection controls during source transfer operations.

The representative detector cell assigned to evaluate the maximum dose within the working area and the isotope laboratory varies across configurations. This shift occurs because changing the primary location of the neutron source alters the spatial distribution of room-return scatter, causing the maximum dose rate within those areas to relocate.

The radiation zoning scheme for the NIF and its surrounding areas during operations is summarized in Table 5, aligned with the work-area classification system applied in the PNRI reactor facility. Crucially, area categorization is determined principally by potential access to radioactive or nuclear materials and operational scope, rather than radiation dose magnitude alone. The NIF and isotope laboratory are designated as a Controlled Area due to their proximity and potential access to radioactive materials, subjecting personnel in this space to occupational exposure limits rather than public criteria. All simulated dose rates in Table 4 remain below the allowable upper thresholds for each zone category.

Table 5: Radiation zoning of NIF and adjacent structures.

Area	Access to radioactive/nuclear material	Expected normal exposure, $\mu\text{Sv/h}$	Classification of area
Inside NIF, Isotope laboratory	Close or easy access	< 200	Controlled area
Female toilet, Change room, Entrance corridor	With identified access point	< 1	Supervised area
-	No access	Background level	General access area

Table 6 summarizes the projected annual ambient dose equivalent rate across the default operational mode (Configuration 1), transient source-transfer operations (Configurations 2 and 3), and secondary storage modes in the Source Handling System (Configurations 4 and 5). In accordance with national regulations (PNRI 2021), the occupational dose limit for adult radiation workers is 20 mSv/year, averaged over five consecutive years, with a maximum of 50 mSv in any single year. Young trainees or students aged 16 to 18 years are subject to a limit of 6 mSv/year, while the dose limit for members of the public is 1 mSv/year.

For radiation-protection assessment, the calculated ambient dose equivalent rates were annualized based on the assumed annual occupancy time. The resulting annual ambient dose equivalent values were compared with the effective dose limit specified in CPR Part 3. Since the MCNP calculations provide ambient dose equivalent rates rather than organ-specific doses required for direct determination of effective dose, this comparison was used as a conservative screening assessment rather than as a direct evaluation of effective dose.

Inside the NIF, source transfer yields a theoretical maximum dose of $3.80 \times 10 \text{ mSv/year}$ near the HDPE perimeter under Configuration 3, assuming 260 h/year of exposure. This dose is approximately twice the allowable occupational dose limit for adult workers. This theoretical value represents an unmitigated projection of the transient source-transfer condition and highlights the need for the administrative controls discussed in the following section to limit personnel exposure during source-transfer operations. The projected dose in the working area is 3.67

mSv/year. Under default and alternative source-storage operations, the projected annual doses near the HDPE perimeter are 2.22 and 2.59 mSv/year, respectively, both of which satisfy the dose limits for adult workers (20 mSv/year) and students/trainees (6 mSv/year), while the rest of the other areas maintain exceptionally low dose levels well below the occupational and public dose limits.

Outside the NIF perimeter, the highest transient dose rate occurs in the adjacent isotope laboratory during Configuration 3, reaching a projected annual value of 1.46 mSv/year. Under default and alternative source storage operations, the annual dose in the isotope laboratory is only 9.15×10^{-3} and $2.73 \times 10^{-1} \text{ mSv/year}$, respectively, satisfying occupational dose limits. Annual exposures in surrounding spaces—including the female toilet, change room, and entrance corridor—remain below $1.14 \times 10^{-2} \text{ mSv/year}$ (and below $2.09 \times 10^{-1} \text{ mSv/year}$ under maximum transient conditions), consistently adhering to the 1 mSv/year public dose limit.

Table 6: Radiation dose* determined for workers in NIF.

Area		Default Configuration 1	Transient configuration		SHS configuration	
		Dose, mSv	Configuration with maximum yearly dose	Dose, mSv	Configuration with maximum yearly dose	Dose, mSv
Inside NIF	HDPE perimeter	2.22	3	3.80×10	4	2.59
	Counting room	1.44×10^{-3}	2	4.70×10^{-2}	4	7.28×10^{-4}
	Corridor to counting room	3.76×10^{-2}	2	8.78×10^{-1}	4	2.03×10^{-2}
	Working area	1.90×10^{-1}	2	3.67	4	1.20×10^{-1}
Outside NIF	Female toilet	8.31×10^{-5}	2	2.40×10^{-3}	4	2.09×10^{-5}
	Change room	6.15×10^{-3}	2	2.09×10^{-1}	4	4.15×10^{-3}
	Entrance corridor	4.85×10^{-3}	2	2.09×10^{-1}	4	1.14×10^{-2}
	Isotope laboratory	9.15×10^{-3}	3	1.46	4	2.73×10^{-1}

*Dose calculated assuming exposure of 1 hour per workday over 52 weeks per year.

Recommended administrative controls

Based on Tables 5 and 6, the following administrative protocols are recommended to ensure robust radiation protection and maintain personnel doses well below regulatory limits.

Workers should maintain a minimum distance of 1 meter from the HDPE assembly during all source-related activities to provide an added safety margin against localized dose gradients near the moderator surface. For non-routine transient source maneuvering (Configurations 2 and 3), operational time should be capped at a maximum of 30 minutes per operation. While standard source transfers typically take only 10 to 15 minutes and is not done regularly, this 30-minute cap comfortably accommodates unexpected procedural delays.

Additionally, these transient operations should be strictly restricted to trained PNRI personnel using a dedicated 1-meter handling tool designed to eliminate direct hand contact and maintain a safe working distance. Apprentices should be restricted to the working area only and should not participate in transient source-transfer operations.

Finally, visitors and members of the public should be permitted access to Controlled Areas only during default (Configuration 1) and secondary SHS (Configurations 4 and 5) storage modes, restricted to the working area, corridor, and counting room. Access to Supervised Areas outside the facility boundary, such as the female toilet, change room, and entrance corridor, may be granted to official visitors, provided that they remain under continuous supervision.

CONCLUSION

The dose assessment in the Neutron Irradiation Facility (NIF) was performed using the MCNP code to generate neutron and gamma dose distributions. This study evaluated five operational configurations to characterize and compare neutron and photon dose distributions for radiation safety considerations and to support the development of radiation zoning and protective measures based on the obtained results.

The simulated results were able to characterize the spatial distribution of neutron and photon ambient dose equivalent rates across all evaluated configurations. Configuration 1, representing the default operational condition, exhibited strong dose localization near the HDPE moderator assembly with a maximum total ambient dose equivalent rate of $8.56 \mu\text{Sv/h}$, while the field became increasingly uniform beyond 1 – 2 m. The HDPE moderator assembly reduced the neutron flux and contributed to lower gamma dose levels in working areas, where the maximum total ambient dose rate decreased to $7.30 \times 10^{-1} \mu\text{Sv/h}$. In contrast, Configurations 2 and 3, in which the neutron sources were elevated and positioned outside the moderating assembly, produced higher dose rates of $1.18 \times 10^2 \mu\text{Sv/h}$ and $1.46 \times 10^2 \mu\text{Sv/h}$, respectively, at the HDPE perimeter due to the removal of shielding and direct exposure to unmoderated neutron emission. For Source Handling System (SHS) configurations, Configuration 5 produced lower total ambient dose rates than Configuration 4, reducing the maximum dose rate from $9.95 \mu\text{Sv/h}$ to $4.44 \mu\text{Sv/h}$. This behavior demonstrates the influence of source positioning and self-shielding effects on overall dose reduction within the system.

Dose mapping for identified facility locations was also evaluated. Under Configuration 1, the total dose rate decreased from $8.56 \mu\text{Sv/h}$ at the HDPE perimeter to $5.54 \times 10^{-3} \mu\text{Sv/h}$ in the counting room, indicating attenuation within shielded areas. Similarly, locations outside the NIF, such as the female toilet and entrance corridor, exhibited low dose rates of $3.20 \times 10^{-4} \mu\text{Sv/h}$ and $1.87 \times 10^{-2} \mu\text{Sv/h}$, respectively. Across all evaluated configurations, the counting room consistently exhibited total dose rates below $1.81 \times 10^{-1} \mu\text{Sv/h}$. Furthermore, the simulated annual ambient dose equivalent rates in controlled areas remained below the occupational exposure limits (20 mSv/y for adult workers and 6 mSv/y for student trainees aged 16–18) during default and secondary SHS storage modes, while all supervised public access areas outside the NIF remained below the public exposure limit of 1 mSv/y in accordance with PNRI CPR Part 3 Rev. 02.

The highest dose conditions were observed in Configurations 2 and 3, corresponding to non-routine source transfer operations that require enhanced procedural controls and minimized personnel involvement. The simulated dose distributions were also used to determine recommended radiation zoning, access restrictions, and

appropriate administrative controls that may be implemented to maintain safe facility operation.

The study demonstrated the dependence of neutron and photon dose distributions on source configuration and shielding geometry within the NIF. The generated dose maps provide a quantitative basis for improving radiation protection strategies, operational controls, and radiation zoning within the facility. Future work should include comparison of the present MCNP results with actual dose monitoring measurements, as well as benchmarking against alternative Monte Carlo codes such as PHITS.

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CONFLICT OF INTEREST

The authors declare that there is no conflict of interest.

USE OF AI

The authors declare that artificial intelligence (AI) tools were used solely to assist in the refinement of language, grammar, readability, and overall clarity of the manuscript. AI-assisted tools were also utilized to support the organization and summarization of content. All scientific concepts, experimental design, data analysis, interpretations, and conclusions presented in this work were independently developed, reviewed, and verified by the authors. The authors assume full responsibility for the accuracy, integrity, and originality of the manuscript. No AI tools were used to generate, fabricate, alter, or manipulate research data, figures, experimental results, or scientific findings.

CONTRIBUTIONS OF INDIVIDUAL AUTHORS

J.M.C. Sion: Writing – original draft, data processing and analysis, writing – review and editing; **R.F. Menor Jr.:** Writing – review and editing, data analysis; **R.M.M. Dela Cruz:** Writing – review and editing, data acquisition; **A.A. Astronomo:** Conceptualization, data acquisition and analysis, supervision.

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