Engineering and Technology Journal e-ISSN: 2456-3358

Volume 10 Issue 07 July-2025, Page No.- 5769-5775

DOI: 10.47191/etj/v10i07.25, I.F. – 8.482

Structural Design of Nuclear Shelters Using the Computer Program CADRE

Al-Maliki Salam J. Bash[1], Al-Maliki Mohammed S[2]

[1]Al-Iraqia University, College of Engineering

[2]Middle Technical University, college of health and medical technologies

ABSTRACT: In the design of nuclear shelters, numerous critical factors must be taken into account, including engineering considerations (architectural and civil), site selection, prevailing meteorological conditions, the extent of burial, air circulation systems, supplies, and the thicknesses of walls, among others. The findings of this study advocate for the construction of nuclear shelters below ground level to achieve maximal protective efficacy. An underground shelter effectively mitigates the impact of overpressure on the roof slab and completely eliminates the effects of dynamic pressure. Additionally, this approach reduces radiation exposure, which not only simplifies the overall design process but also lowers material costs in comparison to shelters that are partially or entirely above ground. To assess the shielding performance of various materials, two distinct types of concrete were evaluated through the use of the CADRE computational program. In parallel, the BMIX program was employed to calculate critical parameters required for the radiation shielding analysis. This integrated methodology enabled the determination of the optimal thicknesses of walls needed to attenuate the dose of radioactivity from a small scale nuclear burst (about 1000 distant away from point zero) to an acceptable level of 2 mrem/h for the individuals inside the shelter.

KEYWORDS: Radiation attenuation, CADRE, Shielding, Nuclear shelter

I. INTRODUCTION

The primary functions of a nuclear shelter are to withstand overpressure and dynamic pressure (wind forces), and reduce the impact of radiation exposure. Since Alpha (α) and Beta (β) particles have limited penetration capabilities, the shielding focus must first addresses the Gamma (γ)-rays and neutrons, while for fallout, the primary radiation of concern is γ-rays [1]. The attenuation of γ-rays is determined by the material's mass per unit area. Low-density materials require greater thickness to achieve the same level of attenuation as higher-density materials. Both theoretical models and empirical data have led to the introduction of the concept of "$10^{th.}$ value thickness, TVT" a parameter used to assess the shielding effectiveness of a material against γ-rays of a specific energy. The TVT refers to the thickness of a given material that reduces the radiation dose (or dose rate) to one-tenth of its original value (Table 1).

Neutron attenuation involves multiple stages. Initially, high-energy neutrons must be moderated to a lower, intermediate energy range, which requires the use of materials capable of inelastic scattering, such as those containing Barium or Iron. Subsequently, these moderately fast neutrons must be further slowed to thermal energies through elastic scattering with materials having a low atomic mass [2].

Table 1. The specifications of common materials against the fallout and initial radiation [3]

Substance	Density (kg/m^3)	TVT	
		Initial radiation (cm)	Fallout (cm)
Concrete	2305	45.70	30.50
Water	1000	94.0	66.0
Steel	7850	13.50	9.40
Wood	545	177.80	122.0
Earth	1600	66.0	45.70

Water is highly effective for radiation shielding because its two basic elements have low atomic weights that make it important for the absorbtion of slow neutrons. Additionally, it's important to include materials that can block γ-rays to prevent them from escaping after neutron capture processes. When selecting materials for radiation shielding, several critical factors must be considered: high density to ensure efficient attenuation of γ-radiation while minimizing the material thickness, uniformity in density and composition across the material to maintain consistent shielding performance, and an adequate concentration of hydrogen (typically provided by water chemically bound in the material) to effectively thermalize neutrons [4]. The material should also demonstrate resistance to degradation from radiation exposure, the content of heavy components enables for both fast neutrons moderation and the absorbtion of secondary γ-radiation that is produced during neutron interactions, and structural integrity to support the shelter framework, as shielding is often incorporated into the overall load-bearing structure. Furthermore, the material must be joint-free to prevent potential radiation leakage and exhibit high fire resistance, ensuring a low combustion rate and the capacity to self-extinguish once removing the heat source. Shielding materials are typically divided into three sets based on each primary utility. These aformentioned materials are most commonly utilised to block γ-rays and to moderate the fast neutrons; in the range of 1 MeV, through inelastic collisions. Materials like Carbon, Iron, stainless steel nd steel, fit into this set. Lead and its alloys are also commonly used in nuclear reactor shielding because of their high density and ease of fabrication. These materials are especially effective at blocking γ-rays in the range of 2 MeV, with the required mass of lead to reduce radiation being roughly the same as that of iron.

The effectiveness of hydrogen-rich materials in shielding neutrons depends on their hydrogen content, which can be measured as the number of hydrogen atoms per unit volume. Water, because of its high hydrogen content and low cost, is considered one of the most effective materials for neutron shielding. However, it has some drawbacks, such as poor γ-ray attenuation, a low boiling temperature at atmospheric pressure, and vulnerability to breakdown due to radioactivity. Despite these limitations, water is still useful for heat dissipation via radiation absorbtion [5].

Concrete is another highly recommended material because of its strength, affordability, and adaptability for both monolithic and block construction. With a 2.3 Mg/m^3 density of the ordinary concrete that generally contains about 7-8% water by weight when cured, hence the fast neutrons thermal macroscopic cross-section in concrete is about 8.5 m^{-1}, as compared to that of water; about 10 m^{-1}. However, concrete is much more effective than water in attenuating γ-rays, essentially because of the heavy element contents like calcium and silicon, which make up about 50% by weight of the material [1]. In addition to shielding from initial radiation, protection from fallout radiation is a critical consideration for shelters. Fallout radiation contributes to the total dose received by people inside the shelter. It is assumed that fallout will cover all the horizontal planes uniformly, and the emitted radiation from fallout is considered at 1.12 hours after the burst. The fallout γ-ray energy generally falls within the range between 0.2 and 3.0 MeV [5]. Several possible interactions between γ-rays and the shielding barrier are considered in areas protected from fallout radiation. The γ-ray may pass with no interaction through the wall; direct transmission, The γ-ray and an electron in the material may interact and lose all its energy and being immersed, and the γ-ray may undergo Compton scattering, where it interacts with an electron, loses part of its energy, and produces lower-energy photons that scatter in different directions. The third interaction may occur either in the material itself or in the surrounding air. Radiation from the Compton effect in the barrier is referred to as scattered radiation, while radiation scattered in the air is known as skyshine radiation[6].

For a simple above-ground shelter, imagine a rectangular structure situated on a flat, infinite plane. The shelter would have a uniform mass thickness and no openings. The floor is at ground level, with radioactive fallout particles spread uniformly across the ground surface and the roof of the shelter. The radiation reaching a detector located 1 meter above the shelter floor (representing the average human body height) is shown in Fig. 1.

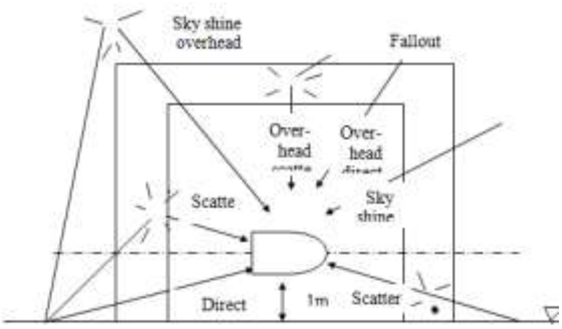

Fig. 1. The common sources of radiation for a nuclear shelter

The fallout shielding calculation is determined by geometric and barrier shielding approaches. The geometric shielding evaluates the directional response to different sources of radiation and the under study area's shape impact, via the law of inverse square. The conclusion is quantified by the fraction of solid angle (w) of that area; a unit-radius solid angle subtended area, divided by the area of a unit-radius hemisphere. For the shelter described by Fig. (2), the ratio of eccentricity and the altitude ratio are utilised in calculating the barrier shielding that represnts the attenuation of incident radiation by a dense barrier, with its effectiveness depending on the barrier's mass thickness. The structure factor of protection (pf) shown in Fig. (2) is composed of contributions from both the walls (Cg) and roof (Co). These factors are influenced by the geometry of the shelter and the characteristics of the shielding material, as expressed by the formula [7];

$$pf = \frac{1}{Co + Cg} \qquad 1$$

The overhead contribution pertains to the radiation that passes through the underside of the roof barrier, as shown in Fig. (3), and reaches the detector. This contribution is divided into three components [4]; Direct overhead radiation, Surface overhead radiation, and Skyshine radiation from above.

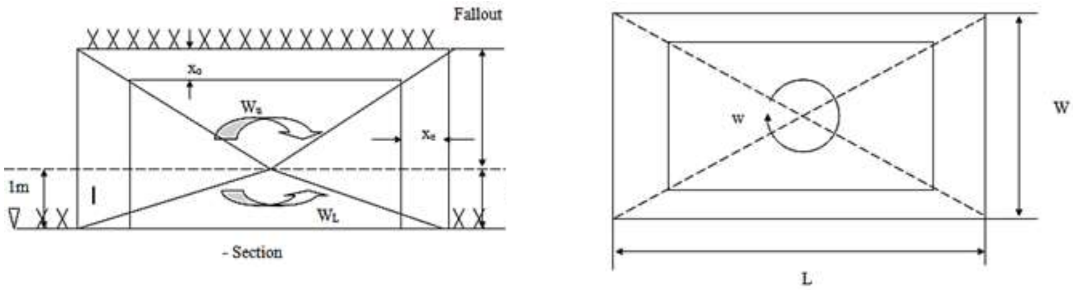

Fig.2 A typical shelter (plane and section views)

It is important to note that no matter the location of the shelter’s roof is to the ground level, Co remains as the dominant radiation source. This contribution is critical in determining the protection factor for the structure. The through-walls radiation that reaches the detector originates from the contaminated surface fallout particles. The total radiation from this source is referred to as the ground contribution

.

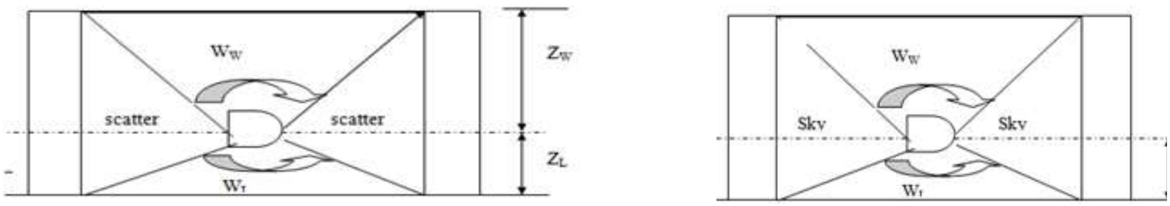

Fig. 3 components of the ground contribution.

The scenarios depicted in Fig. (4) are commonly encountered in the design and construction of shelters. In scenario (a), all principles associated with fallout shielding are applied in the conventional manner. The floor in scenario (b) is located beneath the ground, but the detector plane remains higher than the contaminated surface. This configuration increases the fraction of solid angle and reduces the direct radiation effect. Although theoretical contributions through the buried wall section and earth exist, especially due to sources that are directly contiguous to the structure, such contributions are commonly insignificant as compared to the other sources and hence can be disregarded. In scenario (c), the plane of detector and the ground surface coincide, effectively eliminating both direct and scattered radiation from the segment of lower wall. The structure in scenario (d) is furtherly buried, resulting in a reduction of contributions from the sky shine and scattered radiation of the upper wall part. The configuration is more complex, as partial solid angle fractions must be considered for the region above the detector. However, the geometric factor for the ground contribution (Cg) can still be expressed in a straightforward manner, as outlined below [8]:

$$C_{g=}\ Gf_a\,.(W_w - W_u)(1 - S_d) + E.Sf_w\,.Gf_s\,.(W_w - W_u)$$
2

Where;

Gf_a: skyshine radiation geometric factor (above the detector`s plane).

Gf_s: scattered radiation geometric factor (above or below the detector`s plane).

Sf_w: scattering fraction (the dispersed portion of the total radiation within the walls).

E: the configuration factor.

$$E = (e + 1)/\sqrt{e^2 + 1} \qquad 3$$

The complete wall in scenario (e) is buried, hence the sole radiation originates from the sources overhead. Further submergence, like in scenario (f), would cause an increase in the overhead mass thickness due to the additional earth coverage, thereby enhancing the shielding effect.

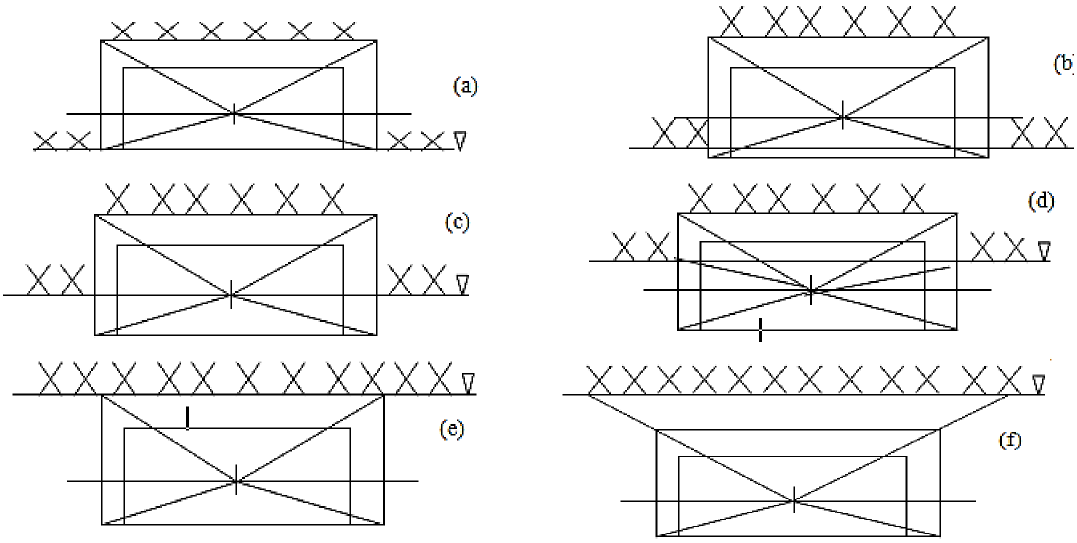

Fig. 4 Effect of burying structure on detector response

The calculation of fast neutron flux φ, is based on the expression;

$$\varphi = S_v^n \left(E_2 (b_1) - E_2 (b_1 + b_2)\right)/2\sum R \qquad 5$$

Where:

S_v^n : the volumetric strength of fast neutron (neutron/cm ^{3} s)

$$b_1 = \sum_{i=1}^{n} . \sum_R^i Z_i \qquad 6$$

$$b_2 = 2.\sum R . \sum R_c \qquad 7$$

Z_i : The width of i^{th} layer (cm).

$\Sigma R_{(i):}$ The removal X- section for neutron fission in i^{th} layer (1/cm).

ΣR: The source material average removal X-section for neutron fission (1/cm).

R_c: The radius (cm).

E_2 (b_1), E_2(b_1+b_2): The 2^{nd}. order function of exponential integral.

This paper primarily addresses radiation protection, considering both the immediate effects of the nuclear explosion and the subsequent fallout.

II. RESEARCH ELABORATIONS

CADRE is one of the most commonly utilized computer programs for shielding nuclear reactors (a simplified flowchart of CADRE is presented in Fig. (5)). The program calculates the necessary thickness of a multilayer shield to reduce the dose rate from the radiation source (nuclear reactor core) to a target dose rate at the exterior surface (the reactor's outer wall) [9].

Since the explosion energy disperses spherically in all directions, the fraction of energy that reaches the shelter is:

$$S_x = (A_s . S . e^{-\mu x})/(4\pi . x^2) \qquad 4$$

Where:

S_x: Strength of source at distance (x cm) from point zero (power/cm^3 s).

x: The distance between the shelter and source (cm).

μ: The air coefficient of attenuation (cm $^{-1}$).

A_s: The surface area of source (cm^2).

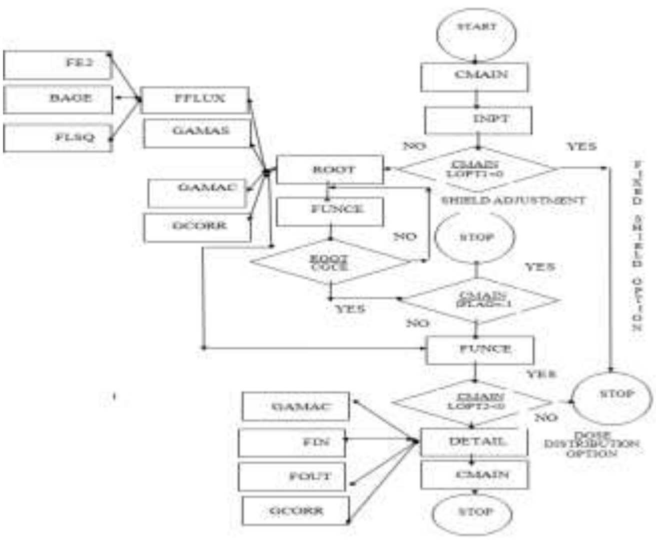

Fig.7 Flow Diagrame of Program CADRE

The attenuation coefficient is derived for each energy group by multiplying by the material density (ρ).

The Program BMIX facilitates the calculation of build-up factors (B) for multilayer and finite shielding arrangements. This program handles the aforementioned complications based on the Goldstein's method that applies a linear reliance of B and the attenuating thickness (∝r). The BMIX program calculates an average α-coefficient that is applied in the calculations of the multi-layer shielding slab [10].

III. RESULTS AND FINDINGS

The objective in this case is to decide the shielding thickness of a shelter wall required to control the radiation dose rate originating from a nuclear burst; approximately 1000 m distant, to an acceptable level on the inner space. To accomplish this, the CADRE program requires modification to reverse the radiation direction (from outward to inward). Several input parameters for the CADRE program are specified in Table (2).

The thermal factor of build-up; B_{th} is calculated as follows;

$$B_{th} = e^{\Sigma_R^2 \tau - h} / \Sigma_a (1 - (\Sigma_R L)^2) \quad 8$$

Where:

τ: Fermi age parameter (cm^2).

h: correction constant.

$\sum_a$: macroscopic cross section for neutron absorbtion (cm^{-1})

L: diffusion length of neutrons in the medium (cm).

.

The primary γ -flux is obtained finally, to determine the dose rate, hence the total dose rate is gained thru all dose rates summing. The linear attenuation coefficient is determined as follows;

$$\mu/\rho = \sum_i W_i \cdot \mu_i/\rho_i \quad 9$$

where:

ρ : Material density (g/ cm^3)

W_i : The mixture`s i_{th} constituent (weight proportion).

Table 2 Input parameters for program CADRE.

Energy band (Kev)	primary γ-rays Conversion factors (cm^2/s to mrem/h)	number of primary γ-rays per fission	
		U_{235}	Concrete
500	94 E -6	8.40	1.0
2000	299 E -5	3.30	1.0
4000	477 E -5	4.00	1.0
6000	631 E -5	4.60	1.0

Additional data, such as the removal cross-sections, ∑R, are averaged across all energy groups for the shielding materials. These values can be computed for all used concrete types based on the specific properties. Table (3) provides the compositions of the understudy concrete types; Portland and Baryte, along with each component`s corresponding ∑R for [11].

Table 3 The Composition and specifications of the understudy types of concrete

Portland concrete				
Constituent	Atomic Weight	concrete density kg / m^3	Neutron attenuation	
			∑R/ρ (m^2/kg)	∑ R (m^{-1})
Al	26.97	33.00	3.01E-03	1.00E-05
C	12.01	76.10	5.00E-03	3.80E-05
Ca	40.08	771.20	2.40E-03	1.85E-04
Fe	55.85	18.30	2.00E-03	4.00E-06
H	1	25.00	6.02E-02	1.50E-04
K	39.1	7.90	2.45E-03	2.00E-06
Mg	24	42.60	3.20E-03	1.40E-05
Na	23	11.60	3.30E-03	4.00E-06
O	16	1103.00	4.10E-03	4.52E-04
Si	28.06	281.50	2.95E-03	8.30E-05
Aggregate		2370.00		9.42E-04
Barytes concrete				

Constituent	Atomic Weight	concrete density kg / m^3	Neutron attenuation	
			$\sum R/\rho$ (m^2/kg)	$\sum R$ (m^{-1})
Al	26.97	20.00	3.01E-03	6.00E-06
Ba	137.36	1470.00	1.24E-03	1.82E-04
Ca	40.08	159.00	2.40E-03	3.80E-05
Fe	55.85	307.00	2.00E-03	6.10E-05
H	1	15.00	6.02E-02	9.00E-05
Mg	24.32	13.00	3.20E-03	4.00E-06
Mn	54.93	3.00	1.24E-03	1.00E-06
Na	23	5.00	3.30E-03	2.00E-06
O	16	1090.00	4.10E-03	4.47E-04
S	32.07	348.00	2.75E-03	9.60E-05
Si	28.06	61.00	2.95E-03	1.80E-05
Aggregate		3491.00		1.82E-04

Substituting table (3) values in equation (9), the corresponding coefficients of attenuation are calculated and presented in table (4)

Table 4 The calculated coefficients of attenuation for the tested energy groups.

Energy (Mev)	μ (1/cm)		
	Type of concrete		U_{235}
	Portland	Barytes	
0	0.236	0.2312	0.0046
0.5	0.216	0.1989	0.176
2	0.12	0.1121	0.048
4	0.081	0.0788	0.044
5	0.1938	0.1876	0.0469
6	0.245	0.2129	0.0455
8	0.184	0.1799	0.0479

The final determined thickness values for each concrete type are presented in table (5).

Table 5 The program CADRE calculated material thicknesses

Type of concrete	Thickness (cm)
Barytes	259.52
Portland	262.58

IV. CONCLUSIONS

The key conclusions of this study emphasize that the most effective location for a nuclear shelter is below ground level. Constructing a shelter underground provides superior protection against the harmful effects of a nuclear detonation. The earth’s mass offers substantial attenuation of radiation, particularly gamma rays and neutrons, which significantly reduces the risk of exposure. Additionally, the surrounding soil absorbs a considerable portion of the overpressure and blast waves, making subterranean shelters the most reliable and efficient option for safeguarding occupants during a nuclear event. In terms of structural integrity, a wall thickness of 259.52 cm composed of Barytes concrete or 262.58 cm of Portland concrete would be sufficient to reduce the received dose of radiation from a 20 KT nuclear burst to acceptable levels within the shelter. These specified wall thicknesses effectively attenuate the radiation emitted by the explosion, ensuring that the internal radiation levels fall within safe thresholds for human exposure. Barytes concrete, with its higher density and enhanced shielding properties, offers superior performance compared to other materials. However, Portland concrete, though slightly less effective, still provides adequate protection. This underscores the critical importance of selecting the appropriate shielding material and thickness to ensure the safety of shelter occupants and minimize potential health risks from radiation.

Furthermore, the CADRE program emerges as a highly efficient, flexible, and precise tool for determining the required shielding thickness in various nuclear scenarios, whether the radiation source is internal (e.g., a reactor) or external (e.g., from a nuclear explosion or other sources). CADRE offers significant versatility in calculating the shielding thickness required for different configurations. By leveraging advanced computational methods, the program evaluates parameters such as material composition, structural geometry, and radiation energy spectra, providing an accurate and rapid solution for shelter design. This capability streamlines the design process, enabling the creation of effective protective structures that comply with the necessary radiation shielding standards.

REFERENCES

1. Kupka T. Nuclear Magnetic Resonance. The Royal Society of Chemistry, 2020, vol. 46, pp. 1-33.
2. Shultis, John & Faw, Richard. Radiation shielding technology. Health physics. 2005,vol. 88, pp. 587-612. 10.1097/01.HP.0000148615.73825.b1.
3. Venkata Subramanian, Dhandapani & Haridas, Adish & Kumar, Sunil & Arul, John & Puthiyavinayagam, Pillai. Neutron attenuation studies with borated polyethylene slabs containing 30% natural boron and its comparison with hydrogenous materials. Indian Journal of Pure and Applied Physics. 2018, vol. 56, pp. 583-586.
4. Abdulrazaq, Ahmad & Joseph, Emmanuel & Ibrahim, Nura. Investigation of Borated Polyethylene as a Neutron Shielding Material using Monte Carlo Simulation Code. Journal of Science Research and Reviews. 2024, vol. 1, pp. 6-15. 10.70882/josrar.2024.v1i1.1.
5. Mirji, Rajeshwari & Lobo, Blaise. Conference: National Conference on ‘Advances in VLSI and Microelectronics”, P. C. Jabin Science College, Huballi, Karnataka, India. 2017, vol. JABINTRONICS, pp. 96-100.
6. El-Fiki, S., El Kameercy, S. U., El Nashar, D. E., Abou-Leila, M. A., El-Mansy, M .K., Ahmad, M. Influence of the Bismuth content on the mechanical andgamma ray attenuation properties of silicon rubber composites. International journalof advanced research. *Radiation shielding materials: A brief review on methods*. 2015, vol. 3, 6 pp. 1035-1039.
7. Todd A Hanson. Fallout Shelter: Designing for Civil Defense in the Cold War. *A Journal of American Material Culture* . 2013, vol. 47, No. 4 pp. 299-300.
8. Rahman, Md. Motiur & Rabby, Md Fajle & Ahmed, Rubel & Akter, Mahmuda & Habib, AKM. Radiotherapy Bunker Shielding Calculations and Recommendations for Structural Design for High Energy Photon Facilities. *Journal of Radiation and Nuclear Applications*. 2023, vol. 8. Pp. 201-208. 10.18576/jrna/080302.
9. James Wood. Computational Methods in Reactor Shielding. Pergamon press. 2013. ISBN-13: 9781483148137.
10. Manoj Kumar Hansda, Shaji Mammen. 3DGShield: A new 3D gamma ray shielding code for arbitrary source and shield geometry based on point kernel technique. *Annals of Nuclear Energy*. 2021, vol. 159, 108352. doi.org/10.1016/j.anucene.2021.108352.
11. Rahman, Md. Motiur & Rabby, Md Fajle & Ahmed, Rubel & Akter, Mahmuda & Habib, AKM. Radiotherapy Bunker Shielding Calculations and Recommendations for Structural Design for High Energy Photon Facilities. Journal of Radiation and Nuclear Applications. 2023. Vol. 8, pp. 201-208. 10.18576/jrna/080302.