Shielding Outlines of a High Activity ^{241}Am-Be Multi-Source Mixed Field Irradiation Facility

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Objectives:

- Design a shield for the ^{241}Am-Be thermal irradiation facility using Several materials considering neutron and gamma radiations.
- The implemented shielding materials are:
    - paraffin, borated-paraffin, beryllium, copper, tantalum, tungsten, zinc, bismuth, and lead.

Introduction:

- Designing a proper shield is essential due to the biological effects of neutrons and gamma rays on the body and surroundings. The shielding design considers neutrons and the gamma-rays released by the ^{241}Am source and gamma rays produced via a neutron-gamma (n,c) interaction.
- Neutron shielding mostly depends on the moderation of fast neutrons to thermal energy, primarily through elastic scattering while slow and thermal neutrons have a significant likelihood of being captured. The light elements, particularly hydrogen, are the best at slowing down neutrons. Concrete, paraffin, polyethylene, and water are examples of hydrogenous materials that work well as neutron shields.
- Gamma rays are released when thermal neutrons are captured using absorbent substances like boron, cadmium, and indium. Hence, for a complete shield design, the use of an additional gamma-ray absorption substance in the outermost layer is required.

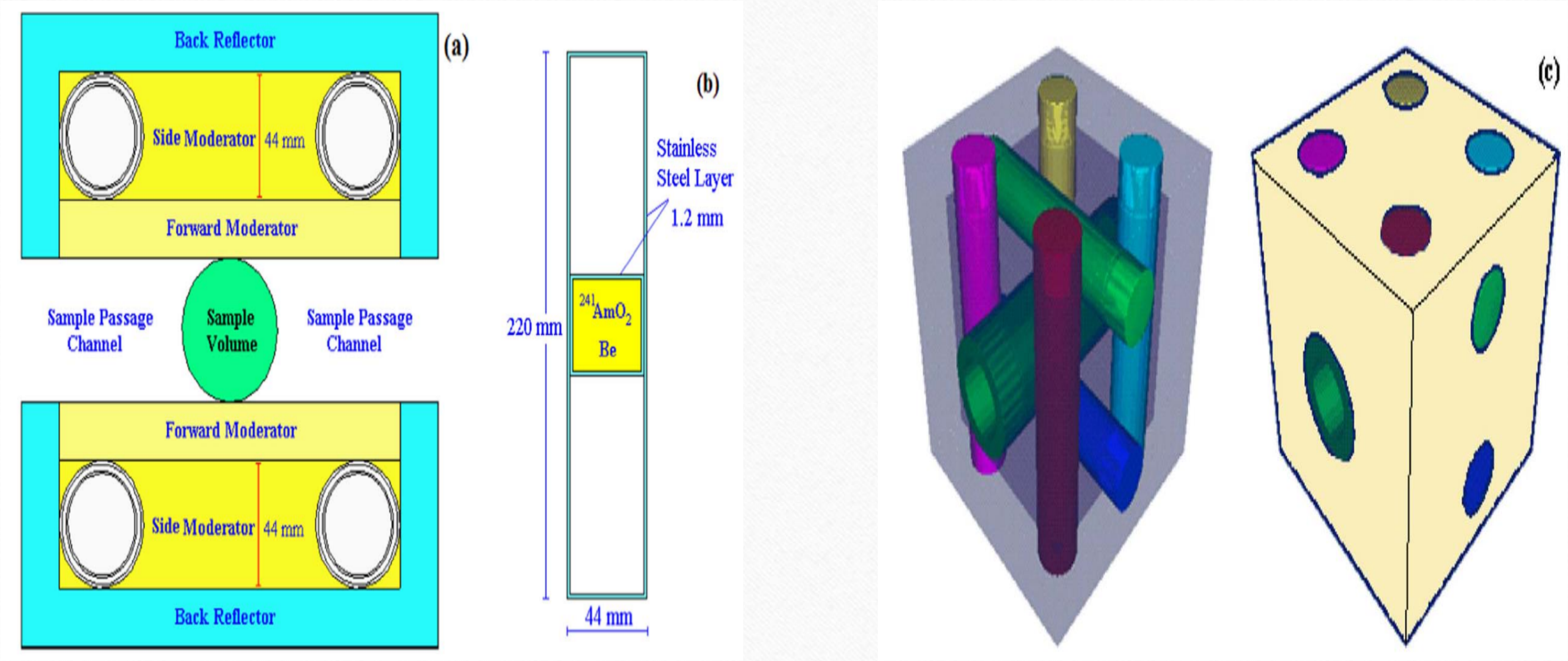
Materials and Methods:

➢ Source specifications:

- The irradiation system consists of six identical ^{241}Am-Be (α, n) sources.
- The activity is 30 Ci each and the total emission rate is 6.6E+07n/s,
- which is distributed over an energy range extending from $4.14 \times 10{-}7$ up to 11 MeV according to the ISO-8529 industry-standard spectrum **(ISO-8529, 2001)**.
- Source geometry is a cylindrical with a double encapsulation of welded stainless-steel
  - D_{out}= of 4.4 cm , L =22 cm.
  - Stainless-steel layer thickness=1.2 mm
- Source design feature is as follows;

Design features:

- The six neutron sources are arranged symmetrically around the irradiation volume to maintain the maximum possible neutron flux homogeneity at the sample volume.
- Sources’ arrangement was chosen to achieve equal moderator thickness in all directions around the sample.
- The irradiation sample was assumed to be spherical in shape with a diameter of 5 cm.
- Paraffin wax was used as a moderating and reflecting media because of its availability with low price and its ease of processing into complex shapes.
- A plastic framework is used to support the proposed structure (Fig. 1c) because it has nearly the same density and moderation properties as those of wax. Therefore, it will not affect the design geometry too much.



(a) Schematic diagram of irradiation facility model using mcnp-5 (cross-sectional view along the x-y plane), (b) Am-Be source model (cross-sectional view along the z-y plane), (c) 3D model of the proposed irradiation facility.

Monte Carlo simulation

- The MCNP-5 code tallies (F1 and FM) were used to calculate:
  - The flux distributions of neutron and photon ($p/cm^2/s$),
  - The neutron and gamma dose rate (μSv/h) at 0cm from the outer-box-surface of the ^{241}Am-Be irradiation facility,
  - Estimation the thickness of the required shielding layers to reduce the total effective dose rate for both neutron and gamma to be less than 10μSv/h.

Results Shielding design

<u>Single Layer Model</u>

				Dose Component					
Shielding Layers Description	**Shield Layer Thickness (cm)**	**Shield Layer Weight (kg)**	**Facility External Dimension[1] (cm)**	**Neutrons AmBe (μSv/h)**	**Gamma due to neutron Interactions (μSv/h)**	**Gamma ^{241}Am Decay (μSv/h)**	**Gamma ^{12}C* De-excitation (μSv/h)**	**Gamma Dose Rate[2] (μSv/h)**	**Total Dose Rate[3] (μSv/h)**
56.0cm Par.	56	1983	128.8	0.54	4.29	0.55	4.92	9.76	10.30
51.0cm B.P.	51	1638	118.8	1.16	1.49	0.78	6.30	8.57	9.73
63.0cm Be	63	5378	142.8	2.99	5.42	0.03	1.23	6.67	9.66
52.0cm Cu	52	15752	120.8	8.83	0.21	<0.01	<0.01	0.22	9.05
65.0cm Zn	65	22554	146.8	9.11	<0.01	<0.01	<0.01	0.00	9.11
39.0cm Ta	39	14140	94.8	8.70	0.07	0.02	<0.01	0.09	8.79
36.0cm W	36	13423	88.8	9.60	0.09	0.02	<0.01	0.11	9.71
Zn	60	18245		16.07	<0.01	<0.01	<0.01	<0.01	16.07
Pb	60	29003		188.45	0.03	<0.01	<0.01	0.03	188.48
Bi	60	24991		290.69	0.03	<0.01	<0.01	0.03	290.72

[1] Facility External Dimension = core dimension (16.8cm) + 2* thickness of the shielding side.

[2] Gamma Dose = neutron interaction + ^{241}Am decay + ^{12}C* de-excitation Dose.

[3] Total Dose = neutron + gamma components

Single Layer Model:

- In this shielding model we used one layer of a single material to shield against both neutron and gamma.
- For Zn, Pb, and Bi cannot reduce the dose down to the required limit within acceptable dimensions. Therefore, they could not be considered suitable mono-layered shielding materials, due to their poor neutron attenuation characteristics in spite of their good gamma attenuation properties. Table 2 confirms that idea by noticing that 60cm thickness can cut down the gamma dose to less than 0.03 μSv/h, while neutron dose cannot be reduced to less than 16.07, 188.45, and 290.69 μSv/h, respectively.

Single Layer Model:

- It should be noted that Be has lower shielding thickness in comparison with Zn, Pb, and Bi. It seems that Be (n, 2n) process is more effective than the (n, n') process of other metals for reducing the fast neutron energy. However, Be has little shielding usability due to its high cost and hazard, in addition to the legal issues connected with its handling.
- On the other hand, paraffin could reduce the dose down to its limit using 56cm thickness. It has good neutron shielding properties due to its high neutron moderating power and enough capture cross- section. However, its gamma shielding efficiency is not as good due to 2.226 MeV gamma emission following the radiative capture process, and to its poor attenuation of the high energy $^{12}C^{*}$ de-excitation gamma. This explanation is evident from table 2, where paraffin could down the neutron dose component to 0.54 μSv/h, meanwhile, the gamma dose components due to gamma emission of neutron 2^{ry} interactions (most probably 2.226 MeV) as well as the 4.4MeV $^{12}C^{*}$ de-excitation gamma, is kept around 4 μSv/h each.

Single Layer Model

- Within the same context, borated paraffin (BP) has better attenuation behavior. BP makes use of the moderation power of paraffin, in addition to the high neutron capture cross-section of ^{10}B and the emission of lower gamma energy following ^{10}B radiative capture. Hence, it results in a smaller shielding thickness of 51 cm, as the lower energy photons are associated with higher mass-attenuation coefficients. Although; Cu has a shielding ability comparable to BP, it makes use of different physical processes. It relies on its higher density (8.96 g/cm^3), gamma mass attenuation coefficient, and (n, n') process.
- Alternatively, W and Ta exhibit outstanding shielding characteristics, as a result of their high density (19.30 and 16.69 g/cm^3, respectively) and gamma attenuation coefficients related to the high atomic number (Z). In addition, they have enough inelastic scattering (n, n') cross-sections, which efficiently reduces the fast neutron energy to the intermediate range. Therefore, only thicknesses of 36 and 39 cm, respectively, are enough to attenuate the dose rate down to the 10 μSv/h limits. From the above discussion, it is clear that although the use of high-density metals can result in compact shielding design, they are not favorable in our case due to their excessive weight and high cost.

Double Layer Model

			Dose Component					
Shielding Layers Description	Shield Layer Weight (kg)	Facility External Dimension[1] (cm)	Neutrons AmBe (µSv/h)	Gamma due to neutron Interactions (µSv/h)	Gamma ^{241}Am Decay (µSv/h)	Gamma ^{12}C* De-excitation (µSv/h)	Gamma Dose Rate[2] (µSv/h)	Total Dose Rate[3] (µSv/h)
10.0cm Par. + 45.0cm B.P.	1991	126.8	0.58	3.18	0.40	4.92	8.49	9.07
20.0cm Par. + 35.0cm B.P.	1984	126.8	0.60	3.99	0.43	4.97	9.40	10.00
10.0cm Par. + 36.0cm Cu	11135	108.8	9.35	0.09	0.02	0.01	0.12	9.46
37.0cm Par. + 06.0cm Cu	3718	102.8	4.74	1.95	0.07	2.60	4.62	9.36
10.0cm Par. + 26.0cm W	12594	88.8	9.20	0.05	0.10	0.01	0.16	9.36
32.0cm Par. + 06.0cm W	5729	92.8	8.96	0.19	0.15	0.23	0.57	9.53
38.0cm Par. + 04.0cm Pb	3293	100.8	6.22	1.48	0.08	1.94	3.51	9.73

Double Layer Model:

-Aiming to improve the shielding efficiency, a double layered model has been tested. Depending on using metals for gamma attenuation, while hydrogenous materials are effective in reducing neutron energy. From the double-layers model, it is found that a thick hydrogenous-moderator layer followed by a few centimeters of the metallic layer is sufficient for shielding against both neutron and gamma radiations.

- From the table consider 10, 20, and 30 cm thicknesses on the inner paraffin layer. 20cm and 30cm layers did not result in improved shielding efficiency. In the meantime, a 10cm paraffin layer is found enough, as a reflector, to reach the saturation thermal neutron flux over the sample volume, in agreement with that suggested previously (Kotb et al. 2018). Therefore, the design procedure will be continued considering only the 10cm paraffin as the first inner layer of the layered shielding structure.

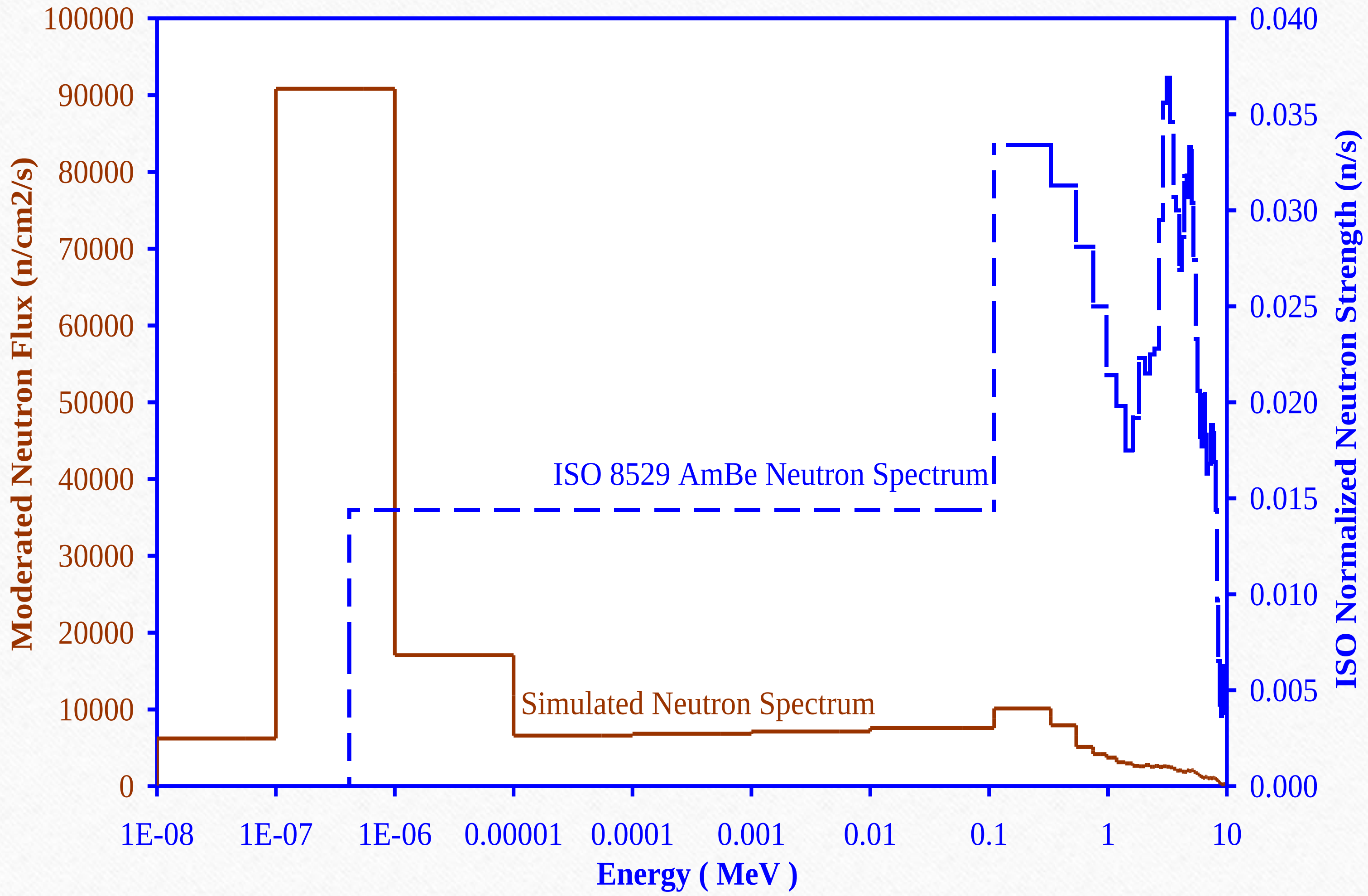
Triple-Layers Model

Shielding Layers Description	Shield Layer Weight	Facility External Dimension[1]	Neutrons AmBe (μSv/h)	Gamma Dose Rate[2] (μSv/h)	Total Dose Rate[3](μSv/h)
10.0cm Par. + 26.0cm B.P. + 06.0cm Pb	4356	100.8	7.61	1.28	8.96
10.0cm Par. + 02.5cm Pb + 31.2cm B.P.	**1342**	**104.2**	**3.87**	**6.01**	**9.87**
10.0cm Par. + 06.0cm W + 20.5cm B.P.	1919	89.8	8.14	1.82	9.96
10.0cm Par. + 06.0cm Cu + 26.0cm B.P.	1527	100.8	3.64	5.87	9.51

Triple-Layers Model

- The choice of a triple-layer model composed of a 10cm paraffin innermost layer for maximum thermal neutron reflection, thick PB for fast neutron moderation and thermal neutron absorption, followed by the outermost metallic layer for gamma absorption is the most suitable configuration.

- To reduce the shielding weight, trials to exchange the materials of middle and external layers are tested. This is because a metal middle layer has less weight than the external layer of the same thickness. Metal in that configuration will be able to shield against the gamma produced in the source as well as that induced by neutron interaction with the paraffin inner layer. However, the shielding against gamma induced by neutron interaction in the exterior BP layer will depend on the self-shielding character of that layer, providing it has sufficient thickness.



ISO-8529-1 neutron spectrum vs. Moderated neutron spectrum over the spherical sample volume for the suggested facility's final configuration

Effective dose rate (*μSv/h*) considering operators exposed positions for different external facility plans, according to ICRP-116(Assuming surface-operator distance equals 0 cm).

Position	Facility sample entrance Surface	Facility Sample exit Surface	Facility Front surface	Facility Rear surface	Facility Top surface	Facility Bottom surface
Operator Antero-Posterior	11.2	11.2	9.1	9.1	9.0	9.0
Operator Postero-Anterior	8.7	8.7	7.4	7.4	7.3	7.3
Operator Right Lateral	7.3	7.3	6.2	6.2	6.1	6.1
Operator Left Lateral	6.8	6.8	5.8	5.8	5.7	5.7

Conclusion

- The MCNP-5 code was employed to simulate the design of a multi-source neutron irradiation facility using a 30 Ci ^{241}Am-Be source. The geometrical characteristics of the suggested design were optimized.

- The most efficient choose in terms of weight was a triple-layer model with a center metal layer. The selected triple-layer shield has a 10cm paraffin layer, followed by a 2.5cm lead layer, and finally, 31.2cm of borated-paraffin layers.

Thank you