

Neutron Shielding Properties of a New High-Density Concrete

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Abstract. The neutron shielding properties of a new high-density concrete (commercially available under the name Hormirad™, developed in Spain by the company CT-RAD) have been characterized both experimentally and by Monte Carlo calculations. The shielding properties of this concrete against photons were previously studied and the material is being used to build bunkers, mazes and doors in medical accelerator facilities with good overall results. In this work, the objective was to characterize the material behaviour against neutrons, as well as to test alternative mixings including boron compounds in an effort to improve neutron shielding efficiency. With that purpose, Hormirad™ slabs of different thicknesses were exposed to an ²⁴¹Am-Be neutron source under controlled conditions in the neutron measurements laboratory of the Nuclear Engineering Department at UPM. The original mix, which includes a high fraction of magnetite, was then modified by adding different proportions of anhydrous borax (Na₂B₄O₇). In order to have a reference against common concrete used to shield medical accelerator facilities, the same experiment was repeated with ordinary (HA-25) concrete slabs. In parallel to the experiments, Monte Carlo calculations of the experiments were performed with MCNP5. The experimental results agree reasonably well with the Monte Carlo calculations. Therefore, the first and equilibrium tenth-value layers have been determined for the different types of concrete tested. The results show an advantageous behaviour of the Hormirad™ concrete, in terms of neutron attenuation against real thickness of the shielding. Borated concretes seem less practical since they did not show better neutron attenuation with respect to real thickness and their structural properties are worse. The neutron attenuation properties of Hormirad™ for typical neutron spectra in clinical LINAC accelerators rooms have been also characterized by Monte Carlo calculation.

KEYWORDS: *Neutron shielding, Accelerator shielding, High-density concrete, MCNP.*

1. Introduction

A new high-density concrete based on magnetite has been developed by a commercial Spanish company (CT-RAD) and is available under the name Hormirad™[†] [1-2]. The shielding properties of the new concrete against photons were previously studied [3] and the material is being used to build bunkers, mazes and doors in medical accelerator facilities with good overall results. The purpose of this work was to test and characterize the material behaviour as neutron shielding material. Experimental tests were performed with a ²⁴¹Am-Be neutron source under controlled conditions in the neutron measurements laboratory of the Nuclear Engineering Department at UPM. MCNP5 calculations allowed deducing the shielding properties against monoenergetic neutrons as well as for typical neutron spectra in LINACS used in radiotherapy. The basic Hormirad™ material was compared with conventional concrete as well as with new mixings including boron compounds in an effort to improve their neutron shielding efficiency.

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[†] US and European patent applications have been presented by the producer for the Hormirad™ “heavy mass for manufacturing products with a high radioprotection capacity”.

2. Materials and methods

Hormirad™ concrete is very rich in magnetite, which represents almost 90% of its weight. Based on information provided by the manufacturer and by the magnetite stone supplier, the elemental composition is indicated in Table 1 compared to typical Portland concrete. Its main characteristic is the elevated content of iron, about 60%, compared to 48% cited in the literature for magnetite concretes [4-5]. The manufacturing procedure is made carefully so that homogeneity of the resulting blocks is rather high. The resulting density is on the order of 4 g·cm⁻³. For the tests, Hormirad™ slabs of 25 cm x 25 cm and different nominal thicknesses (1, 2, 5, 10 cm) have been used in different combinations. The actual dimensions and weight were measured with calibrated instruments and the resulting density determined to be between 3.44 and 4.10 g·cm⁻³, 3.99 g·cm⁻³ on average. Thicker slabs got higher density, because the thinner need some steel mesh inside to reinforce them against breaking.

Table 1: Elemental composition (percent in weight) of Hormirad™, based on information provided by the manufacturer, compared to conventional Portland concrete (taken from [6]).

Element	Hormirad™ density: 3.44 ÷ 4.10 g·cm ⁻³	Portland concrete density: 2.30 g·cm ⁻³
Fe	60.80%	1.40%
O	31.26%	52.91%
Ca	4.36%	4.40%
Si	1.87%	33.70%
H	0.44%	1.00%
Mg	0.39%	0.20%
P	0.29%	-
Ti	0.19%	-
Al	0.17%	3.39%
K	0.06%	1.30%
Mn	0.06%	-
V	0.05%	-
C	0.04%	0.10%
S	0.01%	-
N	0.003%	-
Na	-	1.60%

The slabs were exposed to a ²⁴¹Am-Be neutron source under controlled conditions in the neutron measurements laboratory of the Nuclear Engineering Department at UPM [7]. The experimental configuration is shown in Fig. 1. A calibrated Berthold LB6411 monitor [8] was used to measure and register the ambient dose equivalent rate, $\dot{H}^*(10)$. Measuring time was typically 400 s, with data recorded every 20 s, so the used values were the average between at least 20 recorded values. For all the measurements, the distance between the source axis and the centre of the detector was fixed in 65 cm. The source and the detector are situated 3 m above the ground in a large room of 9 m x 15 m x 8 m in order to reduce the neutron room return as much as possible. This was determined by calculations [7] and with a shadow cone to be $6.35 \pm 0.10 \mu\text{Sv}\cdot\text{h}^{-1}$. This value was used to correct the measured values of $H^*(10)$, by applying equation (1), and by propagating uncertainties according to equation (2).

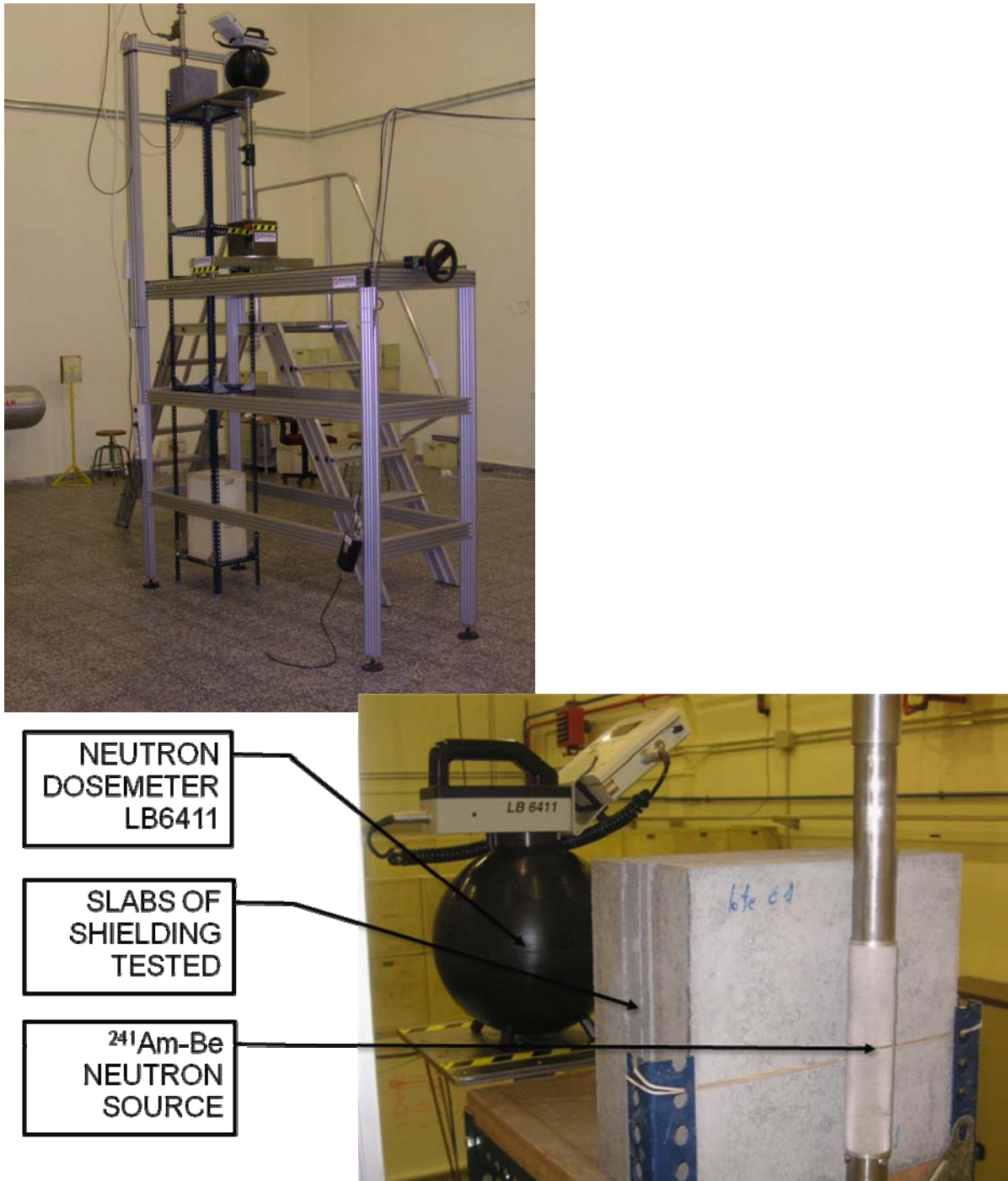
$$H^*(10)_{\text{corrected}} = H^*(10)_{\text{Total measured}} - H^*(10)_{\text{dispersed}} \quad (1)$$

$$\sigma_{H^*(10)_{\text{corrected}}} = \sqrt{\sigma_{H^*(10)_{\text{Total measured}}}^2 + \sigma_{H^*(10)_{\text{dispersed}}}^2} \quad (2)$$

Conventional concrete slabs (ref. HA-25), with measured density $2.2 \text{ g}\cdot\text{cm}^{-3}$ were also tested by the same procedure in order to have a reference to concretes usually employed in building clinical accelerator rooms.

Additionally, in an attempt to find better shielding materials against neutrons, other slabs were prepared by adding anhydrous borax ($\text{Na}_2\text{B}_4\text{O}_7$) to the magnetite concrete, with the following fractions in weight: 1.19% , 5% and 25.13% (equivalent to 5% in B).

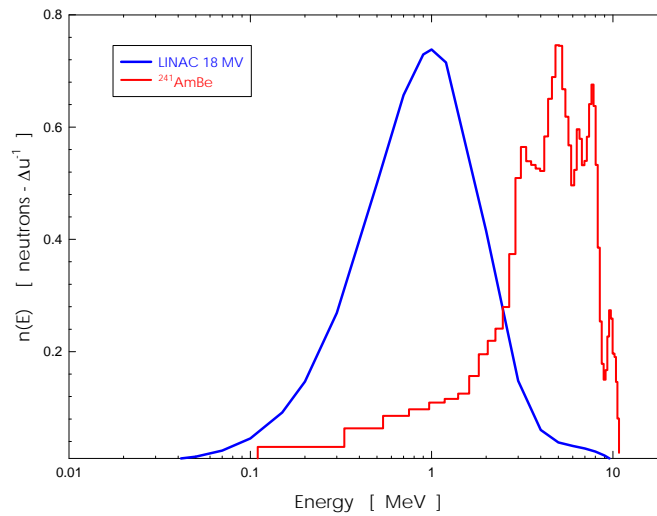
Figure 1: General and detailed view of the experimental setup. The distance between the source axis and the center of the detector is 65 cm. The source and the detector are situated 3 m above ground in a large room of 9 m x 15 m x 8 m to reduce backscattering contributions as much as possible.



MCNP5 [9-10] calculations were performed to corroborate the validity of the experimental results and the elemental composition of the material. Models of the source, the room and the experimental setup were prepared as realistic as possible, both with respect to geometry and the atomic composition of the tested materials. Variance reduction techniques assigning increasing importance to shielding layers closer to detector were applied.

Once the composition of Hormirad™ was verified, its shielding properties against point monoenergetic neutrons between 0.01 eV and 20 MeV were studied. Also, by considering typical neutrons produced by a clinical LINAC of 18 MV [11-12], and their attenuation in Hormirad™ and ordinary concrete.

Figure 2: Comparison of neutron spectra of a clinical LINAC of 18MV [11-12] and a ²⁴¹Am-Be source [13].



3. Results

3.1. Hormirad™ alone with the ²⁴¹Am-Be source

The experimental values of $\dot{H}^*(10)$ as a function of the thickness of Hormirad™ shielding can be seen in Fig. 3. In this figure, as well as in the corresponding Monte Carlo calculations, it can be observed a behavior that is not purely exponential. This is due to the influence of neutrons dispersed both in the shielding and in the air that reach the detector. This effect is usually represented by an “accumulation factor” [14] $B(\Sigma x)$, where x is the shielding thickness, Σ is the neutron attenuation coefficient that depends on the neutron energy and the shielding properties.

Both the experimental and the calculated values were adjusted by a corrected exponential function like that in equation (3). We used weighted least squares [15] using the inverse of the variance of $H^*(10)$ as weighting factor.

$$H^*(10)(x) = B(\Sigma x) \cdot H^*(10)(0) \cdot e^{-\Sigma x} \quad (3)$$

In this equation, $H^*(10)(0)$ is the ambient equivalent dose without shielding, and the accumulation factor was expressed as

$$B(\Sigma x) = 1 + \beta \Sigma x. \quad (4)$$

From the least squares adjustment the values of Σ , β , and $H^*(10)(0)$ were obtained for both the experimental and the calculated values. The values obtained are indicated in Table 2.

Figure 3: Plot of experimental values of $H^*(10)$ with regard to HormiradTM thickness with the ²⁴¹Am-Be source.

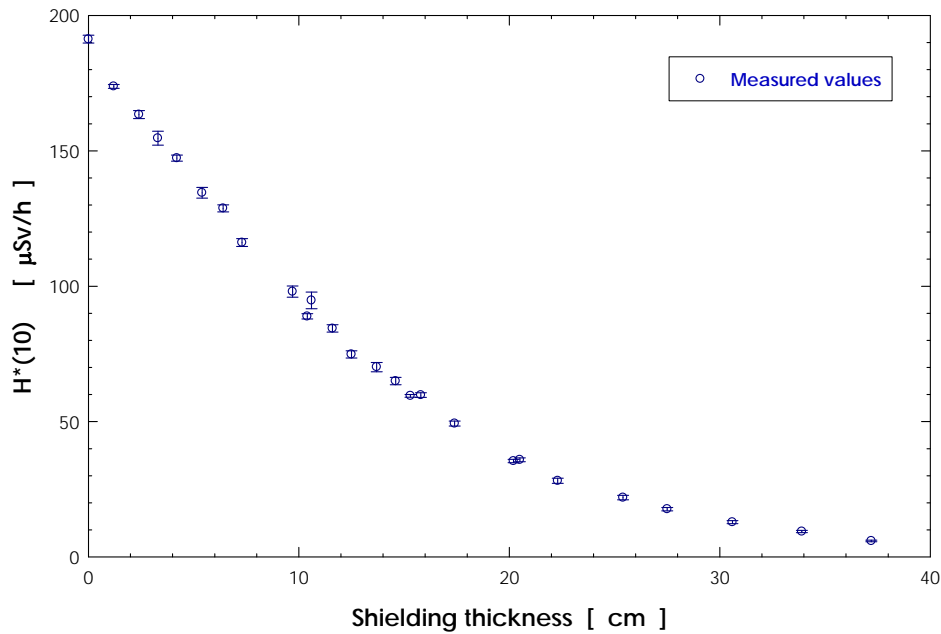


Table 2: Coefficients obtained from the adjustment of the measured and calculated values of $H^*(10)$ with the ²⁴¹Am-Be source.

Coefficient	Experimental data	Calculated data
$H^*(10)(0)$ [$\mu\text{Sv/h}$]	185.7047 ± 1.4823	194.2079 ± 2.4713
Σ [cm^{-1}]	0.1300 ± 0.0020	0.1220 ± 0.0037
β [no units]	0.6692 ± 0.05485	0.5820 ± 0.0991

In Figure 4 the measured and calculated values together with their adjustment functions are displayed. In order to verify the validity of the adjustments we applied the χ^2 statistical test. In the case of the measured data, the resulting value of χ^2 is 1.2106, while for the calculated data is 4.6066. The critical value for this problem (25 freedom degrees) with confidence level of 95% is 14.611. This means that there are no significant statistical differences between the discrete values (measured and calculated) and the respective adjustment functions.

Using the adjusted functions the values of the half-value layer (HVL), $x_{1/2}$, and the tenth-value layer (TVL), $x_{1/10}$ were estimated by using equations (5) and (6) respectively. Then, changing the right-side values in the equations by $1/4$ and $1/100$ the second HVL and TVL were obtained. All these obtained values are indicated in Table 3. As it can be seen, the most conservative values of the first layers for the HormiradTM would be $x_{1/2} = 10.23$ and $x_{1/10} = 27.81$ cm.

$$(1 + \beta \Sigma x_{1/2}) e^{-\Sigma x_{1/2}} = \frac{1}{2} \quad (7)$$

$$(1 + \beta \Sigma x_{1/10}) e^{-\Sigma x_{1/10}} = \frac{1}{10} \quad (8)$$

Figure 4: Plot of the measured and calculated data with the $^{241}\text{Am-Be}$ source together with their adjustment functions (relative ambient dose equivalent with regard to HormiradTM shielding thickness).

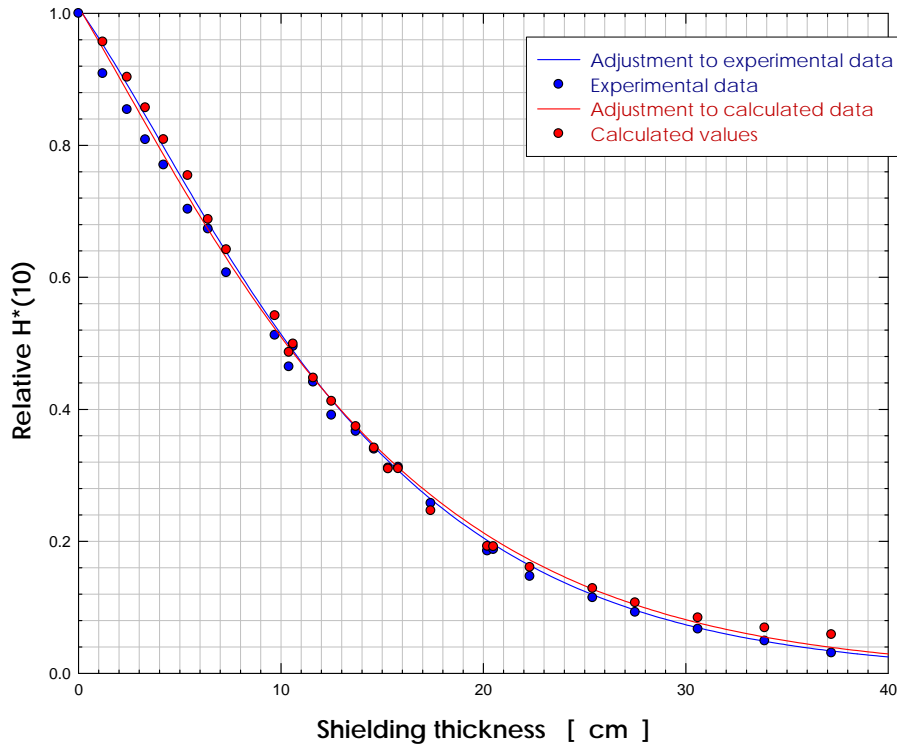


Table 3: Half-value and tenth-value layers for HormiradTM shielding of an $^{241}\text{Am-Be}$ source obtained from the adjustment functions of the measured and the calculated values.

Layer	Experimental [cm]	Calculated [cm]
First $x_{1/2}$	10.23 ± 0.16	10.12 ± 0.31
First $x_{1/10}$	27.01 ± 0.42	27.81 ± 0.85
Second $x_{1/4}$	17.88 ± 0.30	18.15 ± 0.56
Second $x_{1/100}$	48.08 ± 0.75	50.19 ± 1.53

3.2. Borated mixings

The results of adding anhydrous borax ($\text{Na}_2\text{B}_4\text{O}_7$) to the HormiradTM magnetite mixture in different percentages in weight is summarized in Table 4. The reductions obtained in the first TVL with regard to the value for the HormiradTM alone are indeed not significant. This is due to the relatively hard spectrum of the $^{241}\text{Am-Be}$ source, and to the decrease in density of the material. Moreover, these compound materials have several disadvantages that make them not good options, like the increase in cost and the poorer structural properties, especially if the fraction of borax is elevated.

Table 4: TVL obtained for $^{241}\text{Am-Be}$ neutrons with borated mixings of different characteristics.

Shielding Material	Average density	First TVL for $^{241}\text{Am-Be}$ neutrons	
		Mass thickness	Real thickness
Mixed Hormirad TM with 1,19% borax	$3,94 \text{ g/cm}^3$	1046.6 kg/cm^2	26.56 cm
Mixed Hormirad TM with 5% borax	$3,62 \text{ g/cm}^3$	959.4 kg/cm^2	26.50 cm
Mixed Hormirad TM with 25.1% borax	2.68 g/cm^3	794.0 kg/cm^2	29.64 cm

3.3. Calculations of $H^*(10)$ attenuation for point sources

The behaviour of HormiradTM shielding, quasi-infinite layers of different thicknesses, in the case of point sources has been analysed by MCNP5 calculations. The simulations considered different point monoenergetic sources of 10^{-8} , 0.1, 1, 5, 15 and 20 MeV, as well as the typical photoneutrons produced by a clinical LINAC of 18 MV and also the neutrons of an ²⁴¹Am-Be source. The results are represented graphically in Fig. 5. In this figure, we represent the normalized ambient dose equivalent ($H^*(10)$ per neutron emitted by the source) against mass-thickness of the shielding, by assuming a density of the HormiradTM of $4.1 \text{ g}\cdot\text{cm}^{-3}$. The corresponding representation in terms of linear thickness can be seen in Fig. 6.

Figure 5: Reduction of normalized $H^*(10)$ with the mass-thickness of HormiradTM for point sources of monoenergetic neutrons, compared with those of typical LINAC of 18 MV and ²⁴¹Am-Be.

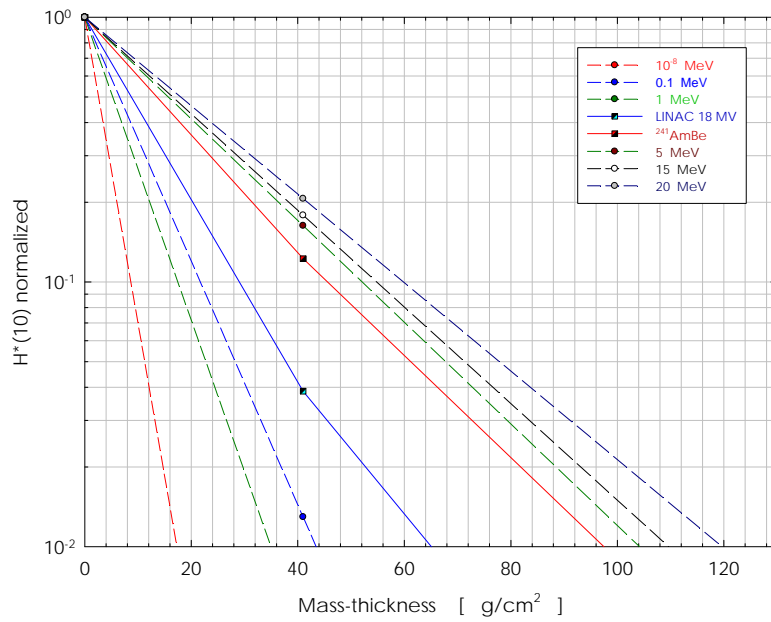
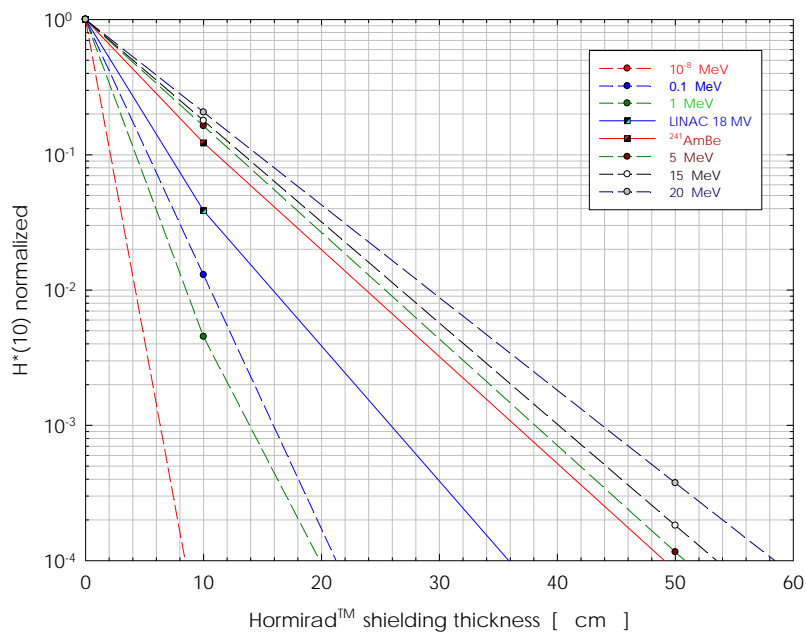


Figure 6: Reduction of normalized $H^*(10)$ with the linear thickness of HormiradTM for point sources of monoenergetic neutrons, compared with those of typical LINAC of 18 MV and ²⁴¹Am-Be.



It can be observed that the attenuation capacity for $H^*(10)$ of HormiradTM is higher for the LINAC photoneutrons than for the ²⁴¹Am-Be source. This is due to the lower average energy of the former (1.25 MeV for a LINAC of 18 MV) compared to the latter (4.16 MeV). It can also be observed how the attenuation functions would be more uniform for monoenergetic neutrons than for polyenergetic because the interactions with the shielding compounds are very dependent on the neutron energy.

3.4. Comparison of HormiradTM and ordinary Portland concrete

As a final step, measurements and MCNP5 calculations were done to compare the attenuation properties of HormiradTM against ordinary Portland concrete.

For the ²⁴¹Am-Be source of the laboratory, tests with ordinary concrete slabs (HA-25 type with density 2.2 g·cm⁻³) gave an experimental first HVL of 260 kg·m⁻² and a first TVL of 875.5 kg·m⁻², equivalent to real thicknesses of 11.8 and 39.8 cm, respectively. These values are comparable to values indicated in [5].

The results of the MCNP5 calculations for point sources of ²⁴¹Am-Be and photoneutrons of the LINAC 18 MV are summarized graphically in Fig. 7 and Fig. 8. The assumed properties of both shielding materials were those indicated in Table 1, assuming a density of 4.1 g·cm⁻³ for HormiradTM. Fig. 7 shows the attenuation of the original neutron flux while Fig. 8, as previously, is referred to the normalized $H^*(10)$.

It is obvious that the HormiradTM has better shielding properties than ordinary concrete, which are amplified as the average energy of neutrons increases.

However, it would be interesting to perform calculations for a whole radiotherapy treatment room also including the cost of the shielding material as a relevant factor to compare.

Figure 7: Attenuation of the neutron flux from point sources of ²⁴¹Am-Be and a LINAC of 18 MV in HormiradTM and Portland concrete.

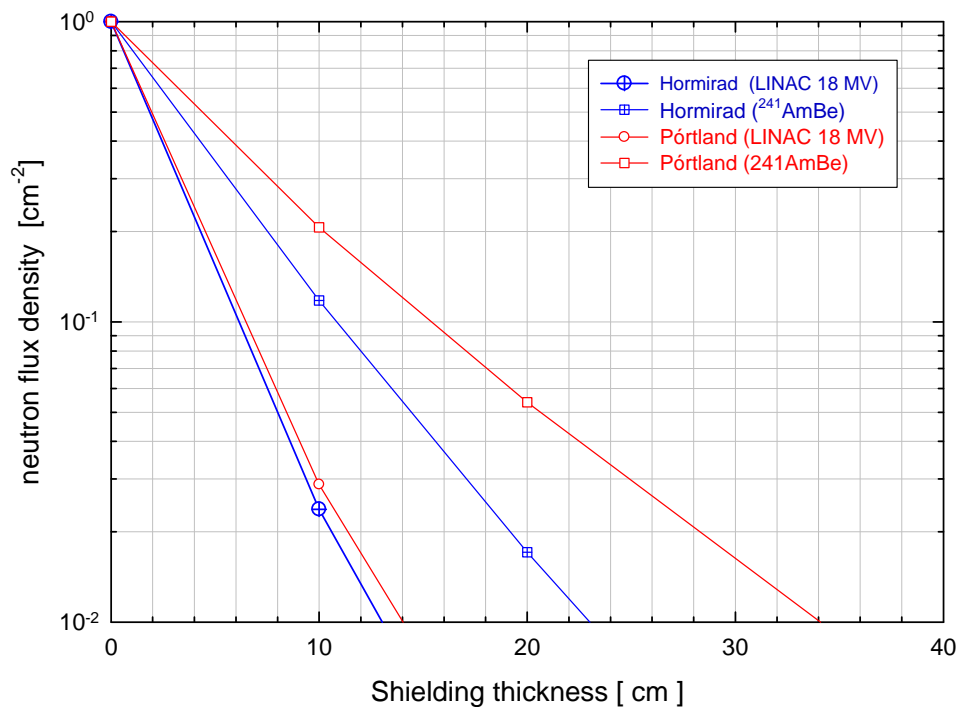
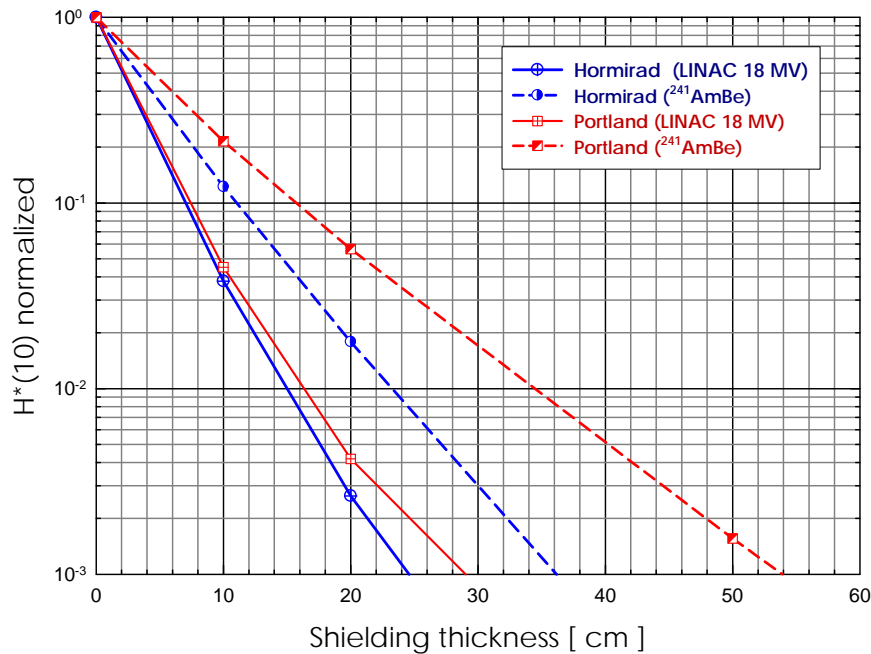


Figure 8: Attenuation of the normalized ambient dose equivalent from point sources of $^{241}\text{Am-Be}$ and a LINAC of 18 MV in HormiradTM and Portland concrete.



4. Conclusions

For $^{241}\text{Am-Be}$ neutrons, LINAC 18 MV photoneutrons and monoenergetic neutrons, the magnetite-based HormiradTM concrete has shown a clearly advantageous behaviour, when comparing neutron attenuation against mass and linear shielding thickness, with regard to ordinary concrete.

Although borated compounds with borax added show better neutron attenuation with respect to mass-thickness, the resulting reduction in density and structural properties makes them less practical.

One key factor for shielding design, the cost, has been not considered.

Other comparisons, with barites concrete or with concrete with naturally-containing boron compounds (like colemanite) could provide additional insights into the relative advantages of this new shielding material.

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