TA-3 Dosimetry and Instrumentation
Poster Session 2

NEUTRON SHIELDING PERFORMANCE OF WATER-EXTENDED POLYESTER

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ABSTRACT

A Monte Carlo study to determine the shielding features to neutrons of water-extended polyester was carried out. Materials with low atomic number are predominantly used for neutron shielding because these materials effectively attenuate neutrons, mainly through elastic and inelastic collisions. In addition to neutron attenuation properties, other desirable properties for neutron shielding materials include mechanical strength, stability, low cost, and ease of handling. During the selection of materials to design a neutron shield, prompt gamma production as well as radionuclide induced by neutron activation must be considered. In this investigation the Monte Carlo method (MCNP code) was used to evaluate the performance of a water-extended polyester shield designed for the transportation, storage, and use of a ^{252}Cf isotopic neutron source, for comparison the calculations were extended to water shielding, the bare source in vacuum and in air.

INTRODUCTION

The Nuclear Engineering Teaching Laboratory (NETL) at the University of Texas at Austin has a ^{252}Cf isotopic neutron source from Oak Ridge National Laboratory (ORNL) through the U.S. Department of Energy's Californium University Loan Program. In December 31st, *1994, the mass of the ^{252}Cf source, designated as NSD-61, was 16.42 μg, with a neutron emission rate of $2.31 \cdot 10^{6}$ s^{-1}-μg^{-1}. In this source californium is in the form of oxysulfate, $Cf_2O_2SO_4$, as the result of the thermal decomposition of the Bio-Rad 50W-X8 resin on which the californium was sorbed. The source has a double encapsulation made of standard stainless steel 304L (Van Cleve et al., 1972). The isotopic composition of the californium from which NSD-61 was made is shown in Table 1.*

Table 1.- Isotopic composition of NSD-61.

Nuclide	Atomic fraction [o/a]
Cf - 249	11.04
Cf - 250	12.10
Cf - 251	4.05
Cf - 252	72.81
Cf - 253	< 0.001
Cf - 254	< 0.00013

This neutron source was stored in a water-extended polyester shield structure originally designed and constructed to transport and store 1 mg of ^{252}Cf (Cage et al., 1971). The shield was built in 1971, and the personnel involved in the construction are no longer at NETL, hence information about the rationale of using WEP for the construction was not available. The shield had been stored outdoors for some years, and was beginning to show water/rust damage until its resurrection/restoration in 1994. To check the performance of this shield structure, a Monte Carlo calculation using MCNP 4C (Briesmeister, 2000) was conducted. In this calculation, the ambient dose equivalent (H(10)) was calculated at four points around the shield structure and compared with the H*(10) produced by the source in vacuum, air and water shielding.*

The WEP as neutron shielding

WEP resin has several features that make it a desirable neutron shield, namely:

a. *Easy to prepared*
b. *High water content*
c. *Fire resistance*

d. Mechanical strength properties between that of wood and concrete

Unsaturated polyester resins readily emulsify with water. When properly catalyzed, the emulsion cures by an exothermic chemical reaction into a hard material, similar in appearance to a fine-grained plaster. WEP consists of equal parts of styrene monomer and polyester resin combined with up to 65-70% by weight of water. The final cured emulsion has an average atomic number of 3.50 grams/gram-mol and an average mass density of 1.1 g·cm^{-3}. To compare this material with those normally utilized in neutron shield Table 2 shows the elemental concentration, in weight percent, for hydrogen, carbon, and oxygen for WEP, water and polymethyl methacrylate (Lucite). In terms of hydrogen content, WEP compares favorably to lucite and is close to water.

Table 2.- Percent in weight of WEP, Water and Lucite

Element	WEP	Water	Lucite
H	9.7	11.2	8.0
C	25.3	0.0	60.0
O	65.0	88.8	32.0

The Laboratory of the Nuclear Engineering Department of the Polytechnic University of Madrid (DIN-UPM) owns a facility for neutron dosimetry research with two isotopic sources of ^{241}Am-Be of 74 and 111 GBq. Substantial efforts have been realized to have this facility functional. Up today, this is the first and unique facility at Spain with the capability to perform neutron instrumentation calibration and to make controlled irradiation with neutron fields. (Gallego et al., 2004)

Having only ^{241}Am-Be sources the facility has several limitations; therefore a ^{252}Cf source is going to be purchased. The nuclear properties of ^{252}Cf require a specific investigation about the handling, shielding and storage conditions. WEP shielding is currently utilized at NETL of the University of Texas at Austin to store ^{252}Cf neutron sources, for this reason we have focus our study in this shielding material. Thus, the aim of this investigation is to study the shielding features of WEP and to compare it with water.

MATERIALS AND METHODS

MCNP modeling

The performance to shield neutrons of the NETL WEP shielding was studied, this is shown in Figure 1. This has some radial ports and one axial port; during this investigation ports were sealed with WEP enclosures therefore it was studied as a single piece. The WEP shield is a right cylinder, 121.9 cm diameter by 132.0 cm height. It was constructed from a 0.152 cm thick stainless steel pipe which had been welded to a 1.27 cm-thick steel base plate. A 0.635 cm thick top plate was welded to the top. Neutron shielding features were calculated using the Monte Carlo code MCNP 4C (Breismeister, 2000).

The ^{252}Cf source is doubly encapsulated in 304L stainless steel which contains carbon, manganese, phosphorous, sulfur, silicon, chromium, nickel, and iron, details of neutron source is shown in Figure 2. The $Cf_2O_2SO_4$ was modeled as a point located in the cell of the encapsulation that actually contained the ^{252}Cf source. The californium compound is pressed with an aluminum pellet, and there is a vacuum gap on the top. This gap was modeled as air-filled in the MCNP model.

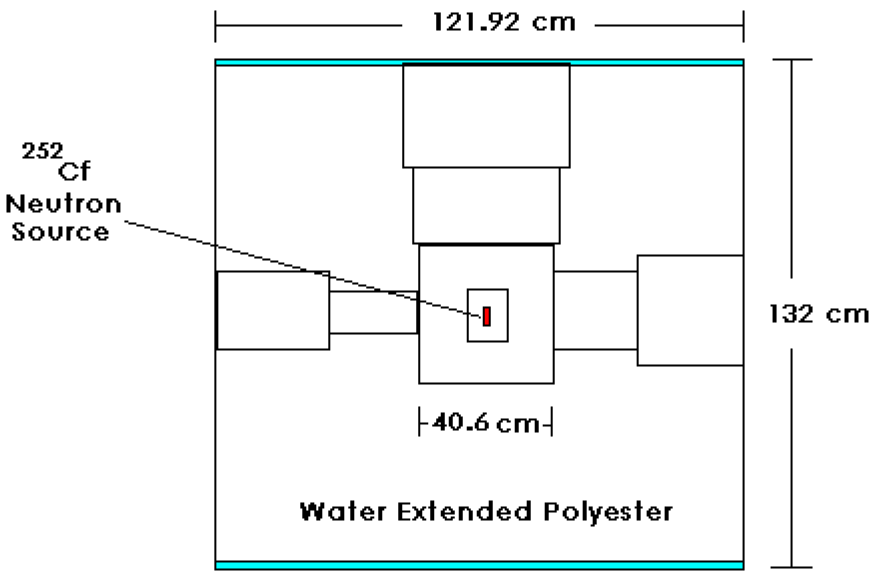

Figure 1.- Nuclear Engineering Teaching Laboratory WEP neutron shielding.

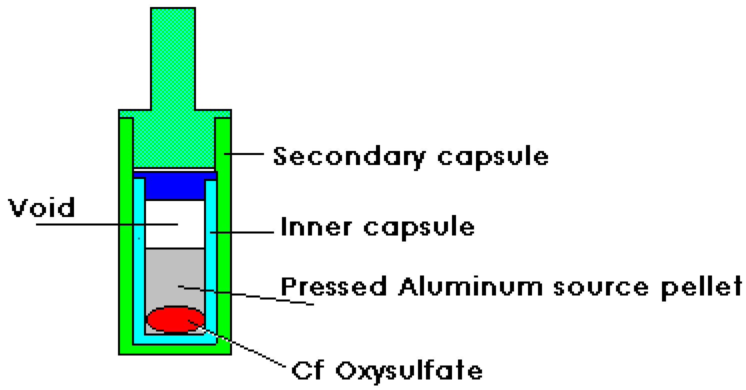

Figure 2.- Cf-252 encapsulation.

As source term the reference spectra recommended by ISO (ISO 1989) was utilized. The lethargy neutron fluence spectrum of the source term is shown in figure 3.

The WEP shield model with the ^{252}Cf neutron source are shown in figure 4. Here, points A, B, C and D are those sites where neutron spectra and H(10) were calculated.*

A cylindrical cavity filled with air was included in the model to take into account the neutron skyshine. Also a concrete base was used below the WEP shielding to include the contribution of neutron groundshine.

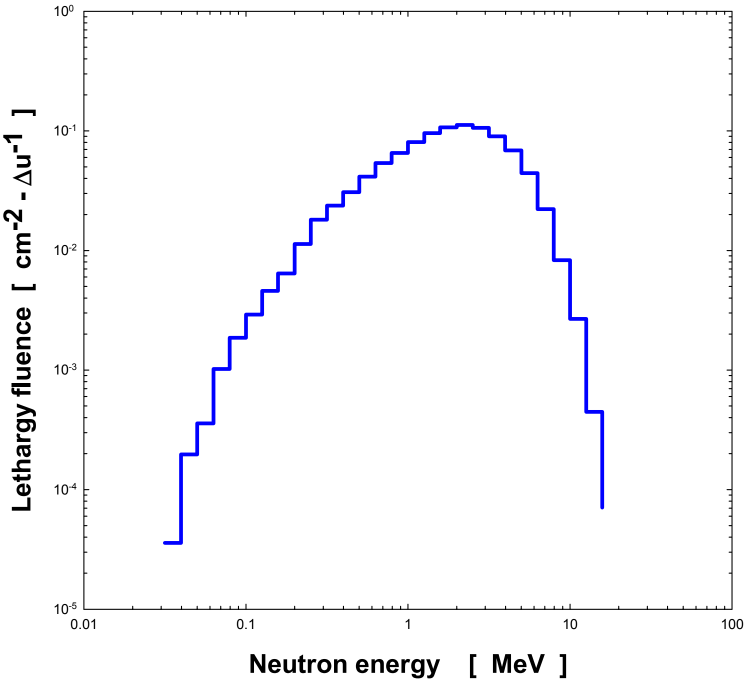

Figure 3.- ^{252}Cf neutron lethargy spectrum

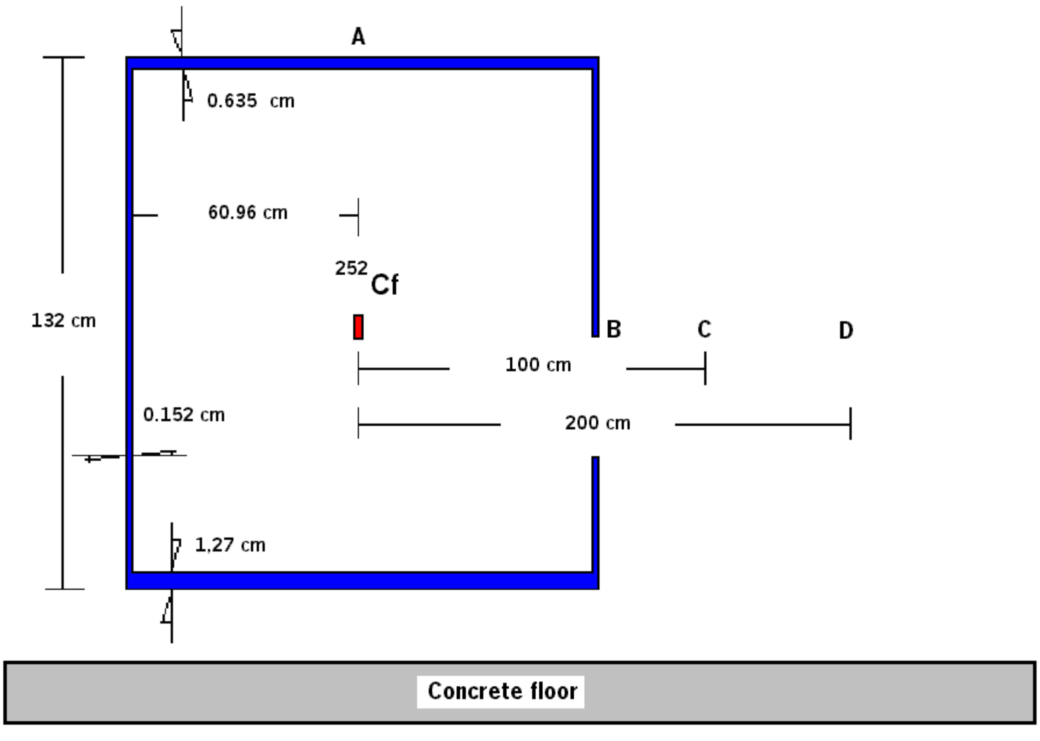

Figure 4.- WEP shield structure modeled in the Monte Carlo calculations.

To compare the WEP shielding performance, three extra calculations were also carried out: With the bare source capsule in vacuum, with the source capsule in the air and with the source capsule in the same shielding but assuming it is made of water instead of WEP.

All calculations were performed with MCNP 4C (Briesmeister, 2000) and with the ENDF/B6 neutron cross sections, the number of neutron histories was different for each case, but large enough to have an uncertainty less than 5%.

RESULTS AND DISCUSSION

In table 3 the calculated H(10) produced by a ^{252}Cf source with a strength of 1 neutron/s, in vacuum, air, water and WEP is shown.*

Table 3.- H(10) produced by unitary-strength ^{252}Cf neutron source.*

Point	Vacuum [pSv]	Air [pSv]	WEP shielding [pSv]	Water shielding [pSv]
A	$4.7965\cdot10^{-3}$ ±0.01%	$6.1550\cdot10^{-3}$ ±0.03%	$9.9755\cdot10^{-7}$ ±4.9%	$1.3381\cdot10^{-6}$ ±4.9%
B	$7.9747\cdot10^{-3}$ ±0.01%	$9.1300\cdot10^{-3}$ ±0.05%	$3.0420\cdot10^{-6}$ ±4.9%	$3.9536\cdot10^{-6}$ ±4.8%
C	$3.0656\cdot10^{-3}$ ±0.01%	$3.7571\cdot10^{-3}$ ±0.09%	$8.3155\cdot10^{-7}$ ±4.9%	$9.7042\cdot10^{-7}$ ±2.6%
D	$7.6644\cdot10^{-4}$ ±0.01%	$1.0511\cdot10^{-3}$ ±0.03%	$1.8784\cdot10^{-7}$ ±4.4%	$2.1583\cdot10^{-7}$ ±2.8%

Comparing the H(10) at all sites in vacuum and air it can be noticed that the presence of air increases the dose, the relative increment being proportional to the distance. The reason for that effect is the skyshine of neutrons in air. In vacuum, the ^{252}Cf source has an ambient dose equivalent coefficient in vacuum of 380 pSv-cm^2 at 1 m (point C); this is the ratio between H*(10) and the neutron fluence rate at this site (8.0672 10^{-6} cm^{-2}), this value is in agreement with the coefficient 385 pSv-cm^2, that is reported by ISO (1989) for a ^{252}Cf point-like source in vacuum.*

At point B the source in air produces an ambient dose equivalent 3001 times larger that the source inside the WEP shielding and 2309 times larger that the shield made with water.

At A, B, C and D locations the doses are larger than 10% with the water in comparison with WEP shielding, therefore WEP has a better performance.

According with NCRP (1991), one gram of ^{252}Cf produces $2.4 \cdot 10^{12}$ neutrons per second, using this parameter the ambient dose equivalent rate produced by 1 μg of ^{252}Cf is shown in table 4.

Table 4.- Ambient dose equivalent rate produced by 1 μg of ^{252}Cf.

Point	Vacuum [nSv/s]	Air [nSv/s]	WEP shielding [nSv/s]	Water shielding [nSv/s]
A	11.51	14.77	$2.39 \cdot 10^{-3}$	$3.21 \cdot 10^{-3}$
B	19.13	21.91	$7.30 \cdot 10^{-3}$	$9.49 \cdot 10^{-3}$
C	7.35	9.01	$1.99 \cdot 10^{-3}$	$2.33 \cdot 10^{-3}$
D	1.84	2.52	$4.51 \cdot 10^{-4}$	$5.18 \cdot 10^{-4}$

Assuming that the maximum permissible ambient dose equivalent rate for occupational workers is 2.78 nSv/s (which results from dividing the annual dose limit for workers of 20 mSv by 2000 working hours as maximum), it can be noticed that with the bare source in air, calculated doses in sites A, B, and C are beyond to be safe for a continuous work; the safe distance, measured from the center of the ^{252}Cf neutron source would be at 200 cm (location D). With the source inside the WEP shielding, the worst scenario is at point B (in the lateral surface of the shielding) where the ambient dose equivalent rate is $7.30 \cdot 10^{-3}$ nSv/s. Under this circumstance, this shielding could hold a ^{252}Cf up to 381 μg to allow full working time near the container.

With proper radiation safety rules the proximity of personnel can be easily limited to 100 cm from the center of WEP shielding; if here (point C) the maximum dose rate is set as 2.78 nSv/s, then the shield could host a ^{252}Cf neutron source as large as 1.397 mg, which can produce up to $3.35 \cdot 10^{9}$ neutrons per second. If the safety working distance would be limited to 200 cm (point D), then the source could be as large as 6.164 mg, thus producing $1.48 \cdot 10^{10}$ neutrons per second. Due to the spectrum features of ^{252}Cf such source strength would be suitable to perform thermal and prompt gamma-ray neutron activation analysis.

In Figure 5 the lethargy neutron fluence spectra of the ^{252}Cf source in vacuum, air, water and WEP, calculated at point C (100 cm from the source axis), are shown as they result from the MCNP calculation; the spectra in vacuum and air show similar features it the peak from 0.1 to 15 MeV; for energies less than 0.1 MeV the spectrum in air shows the presence of epithermal an thermal neutrons, this is probably due to the concrete ground layer that produces groundshine neutrons as well due to the skyshine neutrons in air.

In WEP and in water shielding, two peaks, in the thermal energies as well as around 5 MeV, can be noticed. The thermal peak and epithermal neutrons come from moderation effect produced by the hydrogen content in both shielding materials and the C content in WEP shielding. Both spectra have similar features, therefore they have alike moderating features, although in terms of dose, the WEP shielding shows a better performance.

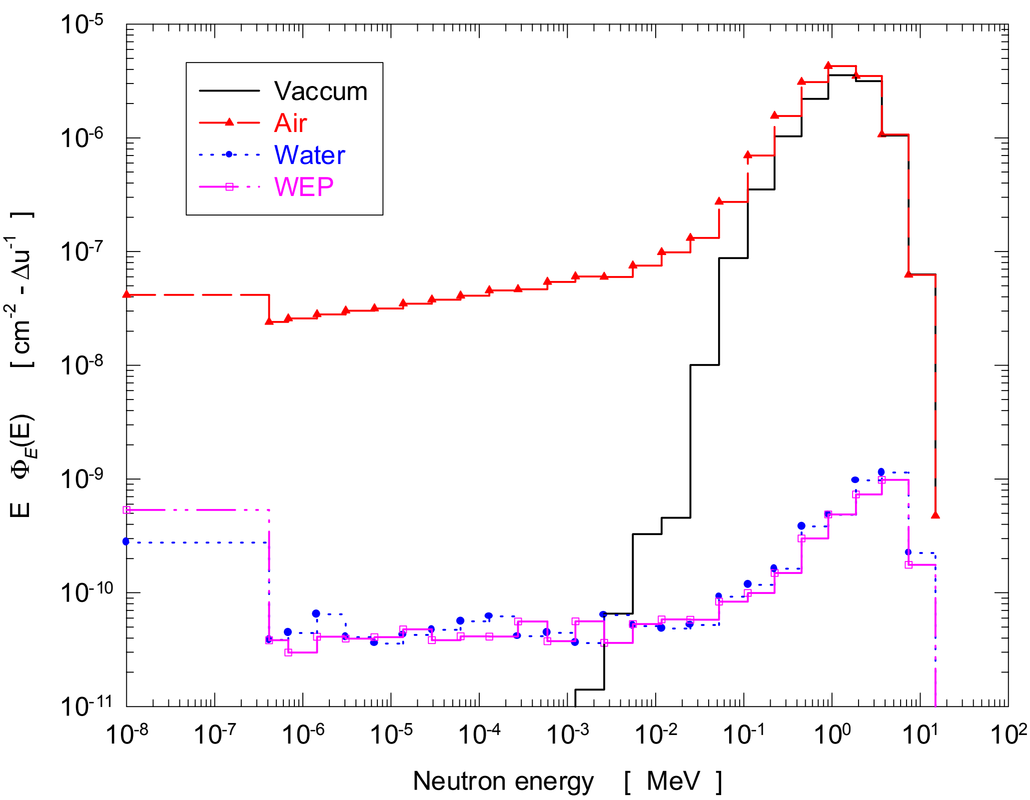

Figure 5.- ^{252}Cf lethargy neutron spectrum in vacuum, air, water and WEP

at point C located at 100 cm from source axial axis.

CONCLUSIONS

Neutrons emitted by ^{252}Cf suffer the in-scattering effect in air, this skyshine phenomenon tends to increase the number of neutrons at any location surrounding the source; the neutron fluence increase is also due to the scattering of neutrons in the concrete floor, named groundshine.

For the studied shield configuration with WEP material, the largest ambient dose equivalent is observed at point B (at 62 cm from the source axial axis) near to the shielding vessel surface, which is the closest site to the neutron source. At this point, the WEP shield can reduce the dose by a factor of 3001 in comparison with the source in air, while a water-made shielding would reduce the dose by a factor of 2309. At point C (at 100 cm from the source axial axis), the ^{252}Cf source in air produces an ambient dose equivalent 4528 times larger that the source inside the WEP shielding, and 3867 times larger that the shield made with water. Consequently, the WEP material results in better shielding than water.

If the closest distance for working conditions is fixed at 200 cm, the WEP shielding could hold a ^{252}Cf source of up to 6.164 mg. Such a source would produce $1.48 \cdot 10^{10}$ $n \cdot s^{-1}$. Due to spectrum features of ^{252}Cf, the shielding can be modified to perform activities related with thermal neutron activation analysis, prompt gamma-ray neutron activation analysis, and to calibrate neutron-measuring instruments with different spectra. With these features the capabilities of DIN-UPM facility could be largely expanded.

Acknowledgments

This work was partially supported by CONACyT (Mexico) under contract SEP-2004-C01-46893.

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