Neutron Flux at the Boundaries of Rectangular Subcritical Piles with a central Am-Be Neutron Source for Various Moderators

N. Myoteris*, N.P. Petropoulos**
Nuclear Engineering Laboratory, National Technical University of Athens,
15780 Athens, GREECE (*nikmyoteris@protonmail.com, **npetr@mail.ntua.gr)

1. Introduction

The Nuclear Engineering Laboratory of NTUA (NEL-NTUA) operates two subcritical piles. The first one has a cubic geometry tank of 1 m^3. A fast neutron Am-Be source with nominal radioactivity of 10 Ci is placed at the mass center of the tank. The tank is filled with water. The second pile has a cubic geometry box of 0.2 m^3. A fast neutron Am-Be source with nominal radioactivity of 5 Ci is placed at its mass center. The box is filled with solid paraffin. The properties of these neutron sources inside the subcritical piles (dimensions, composition, radioactivity etc.) were prepared in detail to be used as input for the OpenMC code. The neutronic analysis for the water pile and the paraffin pile followed. The results showed that the neutron leakage spectrum includes thermal neutrons (assumed with energies from 0 eV to 0.5 eV), epithermal (from 0.5 eV to 0.1 MeV) and fast neutrons (from 0.1 MeV to infinity). In the case of the water pile, more than half of the escaping neutrons are fast (~52%). In the case of paraffin, thermal and fast neutrons escape at equal shares (~45%). The overall neutron flux for the water pile was estimated to be 3-4 neutrons cm^{-2} s^{-1} while for the paraffin pile was estimated to be 25-30 neutrons $cm^{-2}s^{-1}$ in the least favorable part of the of the external surface.

2. Geometry, source spectrum and leakage results

Figs 1 and 2 present a visual and give the dimensions of the rectangular subcritical piles. The Am-Be point sources are not shown. Figure 3 gives the Am-Be neutron energy spectrum for such sources according to ISO 8529-3.

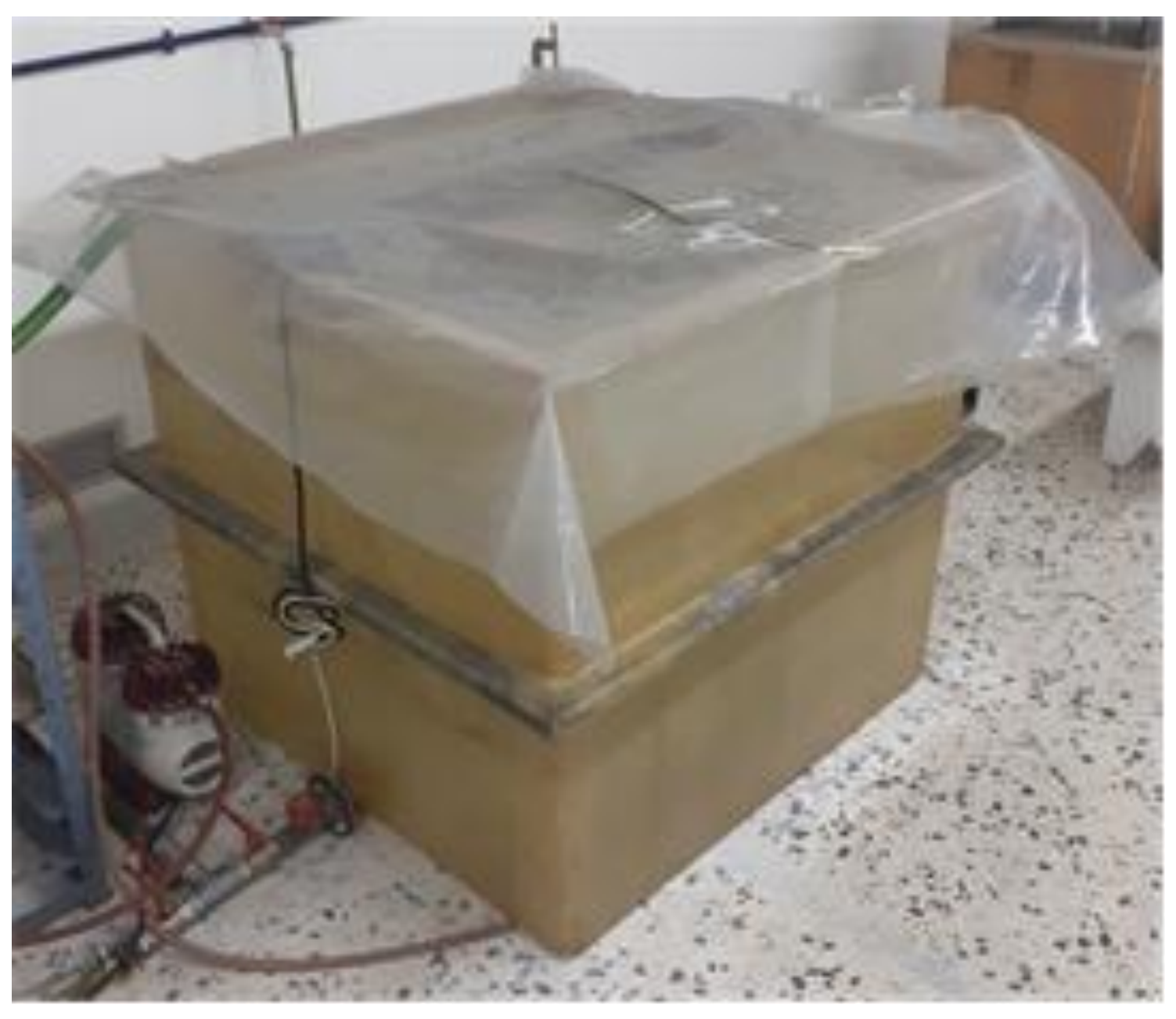

Fig. 1:
Water pile: H = 1 m, W = 1 m, D = 1 m

Fig. 2:
Paraffin pile: H = 0.63 m, W = 0.63 m, D = 0.63 m

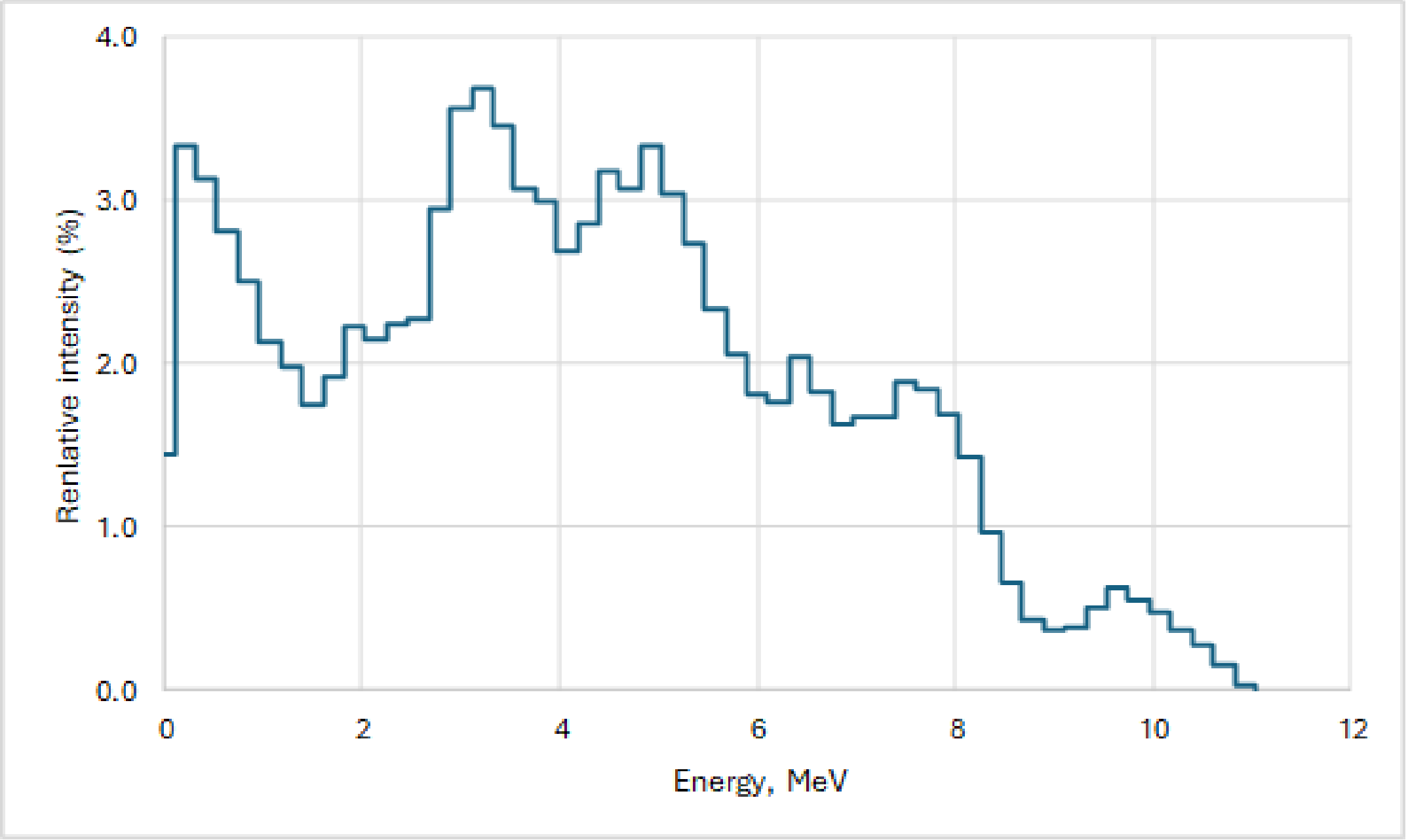

Fig. 3:
Am-Be neutron source energy flux as per ISO 85-29-3

Table 1: Type of leaking neutrons

	Water pile	Paraffin pile
Non leakage probability	0.998	0.990
Thermal (%)	37 ± 1%	45 ± 0.5%
Epithermal (%)	11 ± 0.5%	11 ± 0.2%
Fast (%)	52 ± 1%	44 ± 0.3%

Using the ENDF/B-VII.1 library for neutron reactions properties and OpenMC Monte Carlo simulations for these geometries and neutron energy spectrum, results in Table 1 demonstrate that the neutron leakage from the piles are a negligible part of the Am-Be sources strength, reassuring that keeping the piles within the NEL-NTUA well-defined, well-shielded and secure control zone does not produce any significant dose for the personnel. Able experimental time in the vicinity of the piles would not impose any consequence. These calculation results, indeed, performed for the first time, agree well with the measurements of the Greek Regulator using active and passive methods along with measurements of NEL-NTUA using active methods, within the framework of its internal quality system.

3. Verification measurements at NEL-NTUA

Two portable VICTOREEN type 488A neutron detectors, "#1" and "#2", were used for the verification of the above neutronic analysis. These detectors are boron lined Ar+CO_2 filled cylindrical proportional counters. When bare, the detectors can measure thermal neutrons only. When a suitable cylindrical jacket is added, other neutron types like fast only and thermal and fast combined can be also measured. For fast neutrons the jacket is a cadmium lined polyethylene cylinder. For fast and thermal neutrons, the jacket should be of polyethylene only. The detectors were placed near the center of an outside wall of each pile to measure the maximum local neutron flux. Table 3 presents the results of the measurements with both detectors, in neutrons cm^{-2} s^{-1}. All measurements were obtained with the highest integration time available for these particular instruments. The results of the two detectors are similar. All results agree with the calculations reported in sections 1 and 2.

Detector	Pile	Fast neutrons	Thermal and fast neutrons	Thermal neutrons
#1	Water	~2.5	~4	~2
#2	Paraffin	~20	~20	~2
#1	Water	~2	~4	~1.5
#2	Paraffin	~15	~20	~2

Table 3:
Neutron detectors measurements

Further to the above results, contour maps of the leakage at the external walls of the piles were produced. The output data were extracted in plottable image files formats as per the Figs 4 and 5. The mapping results agree with both the OpenMC calculations and the verification measurements.

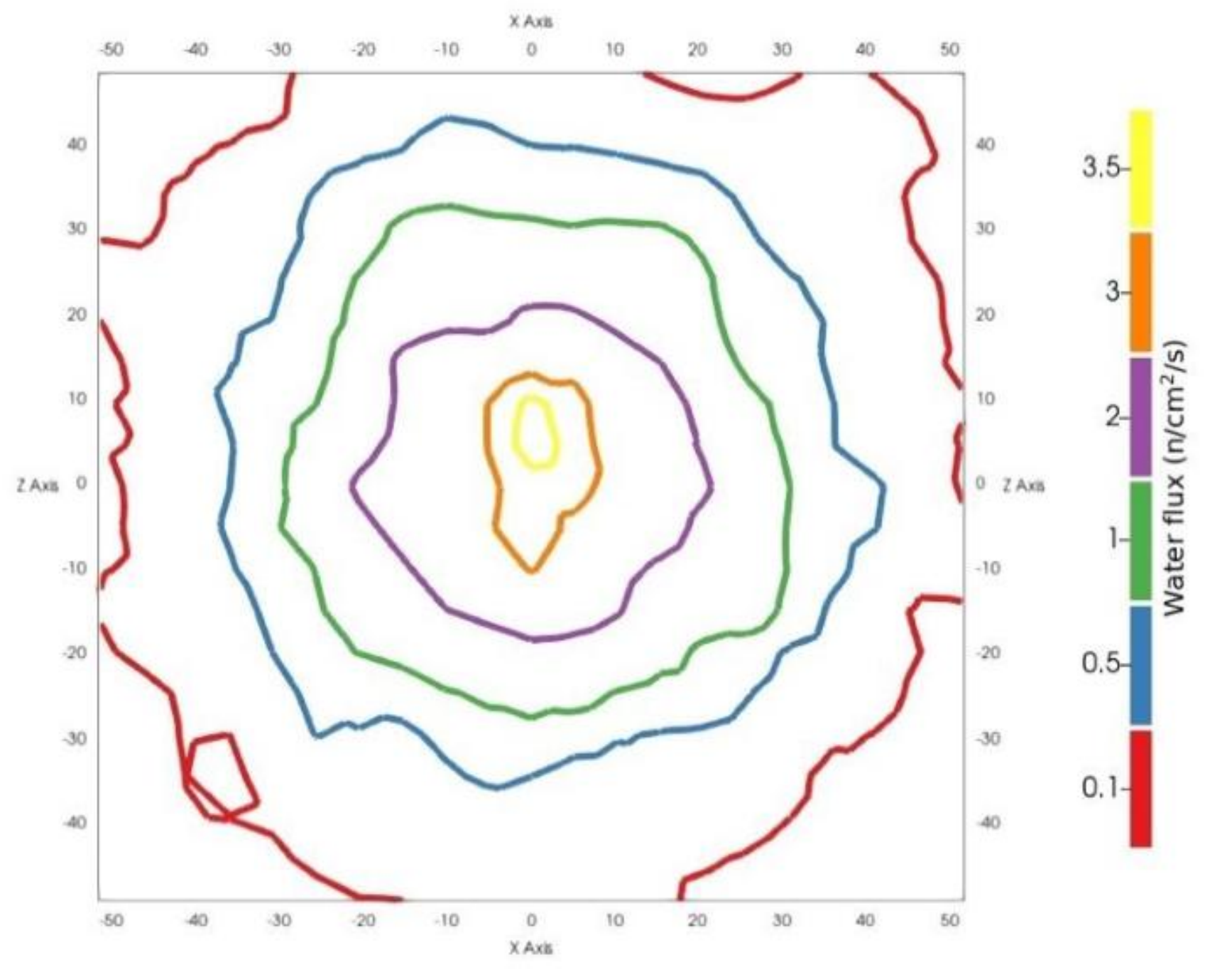

Fig. 4:
Contour map of the neutron flux at a vertical surface of the water pile

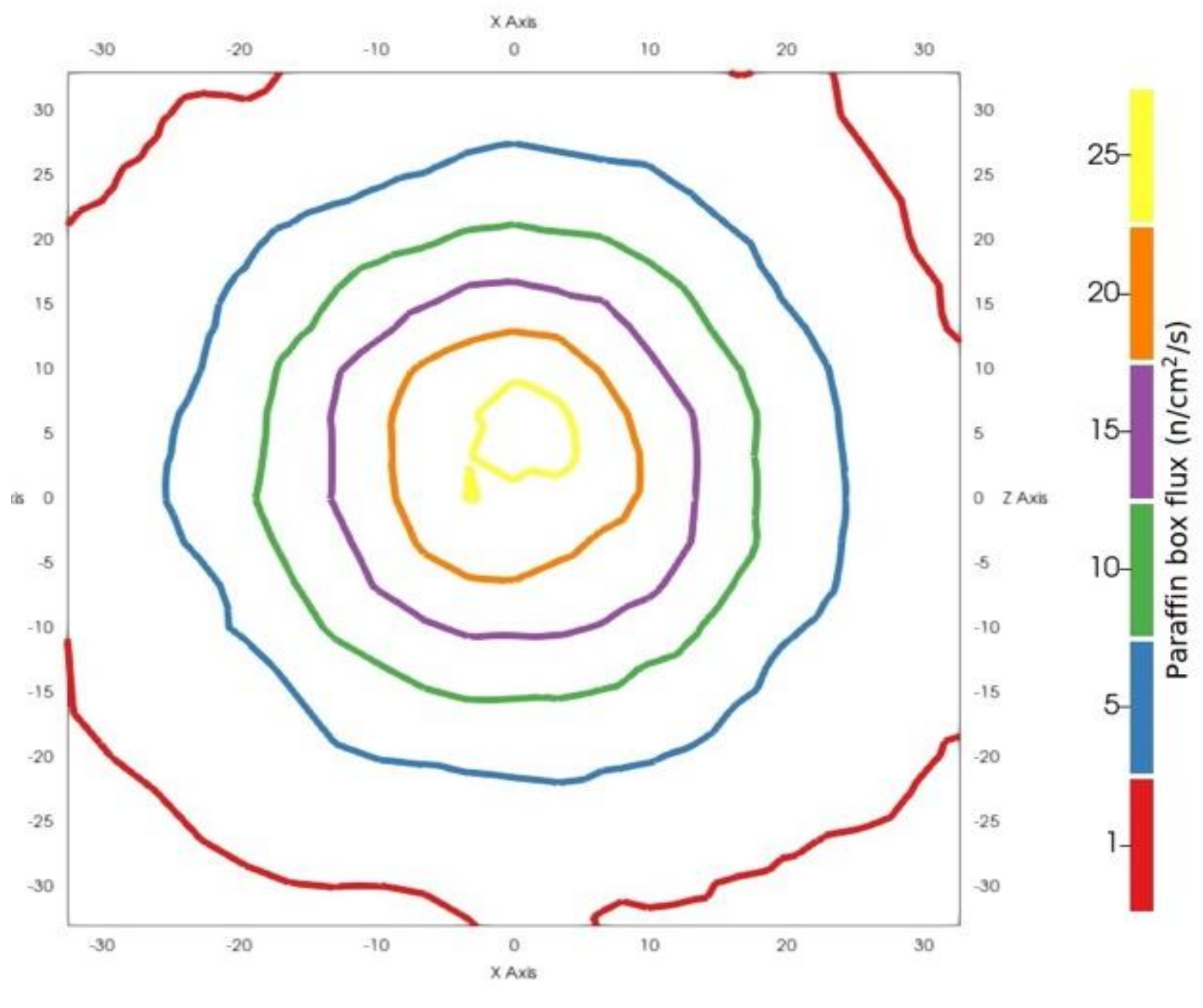

Fig. 5:
Contour map of the neutron flux at a vertical surface of the paraffin pile

4. Proposed water pile safety enhancement

The water pile passive safety may be questionable, due to the possibility of water leakage. The question was raised, if there are alternative solids to replace water. The necessary properties of such materials are high neutron absorption, non-flammability, non-toxicity, chemical and mechanical stability and low cost. Further, they should be in pellet form to ensure their capability to fill the water tank gradually, simultaneously expelling excess water. The studied materials were PET, POM, PS, PMMA, PA 6, PA 6.6 and sodium tetraborate decahydrate ($Na_2B_4O_7.10H_2O$ or borax), all in dry granular form. The apparent density of these granules was considered as 50% of their nominal density. Their 50% v/v mixtures with water were also studied. All the studied materials have nominal densities higher than that of water, so that their granules do not float. The 1% w/w sodium polyacrylate gel $(C_3H_3NaO_2)_n$ with water was also studied. The analysis outputs can be found in Table 4. PA 6 and PA 6.6 present the lowest leakage among the dry bulk plastics, thanks to their high hydrogen and nitrogen content. However, it is borax that presents the lowest leakage among the dry bulk materials. For aqueous mixtures, all the materials present significantly lower neutron leakage thanks to the addition of water hydrogen. Their leakage pattern is like that of the dry bulk configuration. POM, PMMA, PA 6, PA 6.6 and borax water mixtures perform better than water itself, whereas the gel performs similarly to water.

Table 4: Neutron leakage for various scenarios

Material	Leakage	Material	Leakage
PET	~21%	PET + water	~0.4%
POM	~5.5%	POM + water	~0.2%
PS	~9.5%	PS + water	~0.2%
PMMA	~6%	PMMA + water	~0.2%
PA 6	~2.6%	PA 6 + water	~0.1%
PA 6.6	~2.5%	PA 6.6 + water	~0.1%
Borax	~1.8%	Borax + water	~0.1%
		Gel 1%	~0.2%

Table 5:
$^{14}N(n,p)^{14}C$ neutron nuclear reaction percentages

Material	$^{14}N(n,p)^{14}C$ reaction
PA 6	~32%
PA 6.6	~32%
PA 6 + water	~20%
PA 6.6 + water	~20%

The materials containing nitrogen promote the ^{14}C producing reaction $^{14}N(n,p)^{14}C$. Table 4 clearly shows that a significant part of the pile neutrons are absorbed by ^{14}N to produce ^{14}C. However, thanks to the low strength of the neutron source, the ^{14}C production rate is low and not a reason to reject nitrogen-containing materials.

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