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Design of a delayed neutron detection system for the ASTRID Sodium-cooled fast reactor

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Abstract – **Delayed neutron detection systems are key apparati in Sodium cooled Fast Reactors to prevent safety accidents. Based on the feedbacks from Phenix and Superphenix, DND systems are studied by means of the Monte-Carlo particles transport code MCNP6. Promising designs are proposed and investigated as a result of the simulation study.**

***Index Terms*— Fast reactor; Sodium; Fuel failure; Fission products; Neutron detection.**

I. INTRODUCTION

IN 4TH generation reactors, the sodium coolant has to be kept free from any fuel contamination. The objective of DND systems in the safety policy of the reactor is to detect the release of fission products emitting delayed neutrons (FPDN) as bromine 87 or iodine 137. In-vessel fission chambers have been studied to efficiently detect the loss of FPDN but ex-vessel DND system is still a favorite, as immune to any interference from core-neutrons [1]. In this ex-vessel configuration, remaining interferences can arise from:

- original pollution of the cladding by fuel,
- photoneutrons produced by (γ,n) photonuclear reactions on deuterium nuclei when polyethylene is implemented as a moderator.

A solution for photoneutron interference removal has been developed in which graphite is implemented instead of polyethylene for neutron cooling. Previous work has proven detection limit improvements in the graphite configuration compared to older DND system design, and therefore a safety improvement for SFR is expected [2]. This new study shows the tuning of DND system designs where dimensions are optimized and detector technologies are compared (helium-3 and boron-10 proportional counters).

II. METHOD

To carry out the study, Monte-Carlo particle transport simulations have been performed using MCNP6 code. A digital model of the system has been designed allowing the simulation of an intrinsic counter behavior by estimation of deposited energy distributions from light ions (^{3}He(n,p) and ^{10}B(n,a) reactions), which is a new feature from MCNP6 code [3]. The response of simulated detectors is compared to the results of experimental tests, after an energy calibration.

The following specifications have been considered. The system has a cylindrical shape with a diameter equal to 70 cm and composed from the center by:

- A continuous circulation of sodium into a volume,
- A lead shied allowing limiting gamma dose rate from ^{24}Na on counters (pile-up),
- A graphite or polyethylene moderator maximizing capture probabilities in ^{3}He or ^{10}B nuclei,
- Helium 3 or boron 10 counters located into the moderator.

Fig. 1 shows a schematic view of an ex-vessel DND system. The primary sodium coolant is pumped from the hot pool, at the outlet of each assembly through the control plug or in different locations around the core. It circulates through a volume located at the outside of the vessel. This volume is thermally insulated and surrounded by a gamma rays shielding reducing photoneutron activity and gamma ray pile-up on the detectors. Neutron detectors are enclosed in a moderator.

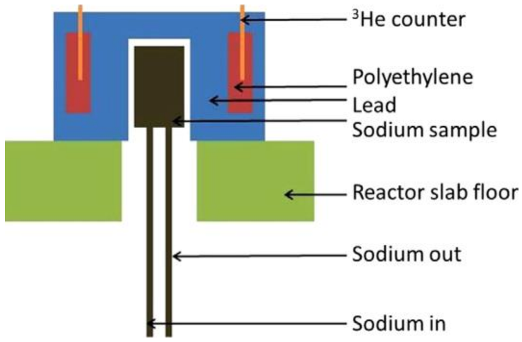

Fig.1. DND system schematic view.

III. RESULTS

The thickness required to ensure the operability of neutron detectors against gamma ray pile-up is firstly calculated. The gamma dose rate behind the shield is estimated for different values of lead thickness. A flux point tally (f5) is used and transformed in dose rate thanks to a transfer function provided by ICRP87 [4]. Fig. 2 shows the dose rate as a function of the lead thickness considering a

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^{24}Na activity equal to 310 GBq.kg^{-1} in a volume of 2.8 liters.

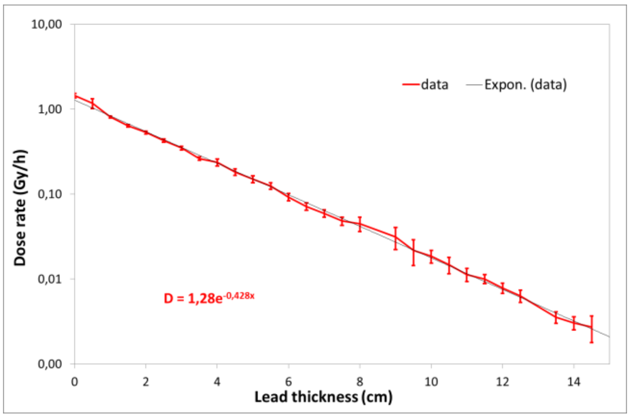

Fig.2. Dose rate as a function of the lead thickness.

According to this result and dose rate limits which are 10 mGy.h^{-1} for ^{3}He counters and 100 mGy.h^{-1} for ^{10}B counters, the obtained minimal thickness are therefore 12 cm and 8 cm for respectively ^{3}He and ^{10}B counters.

Two types of moderator are considered in this work: polyethylene and graphite. It has been observed on Phenix and Superphenix that a significant level of photoneutron signal is induced by (γ,n) reactions on deuterium isotopes naturally contained in polyethylene [5]. This background signal changes as a function of the reactor operating parameters, notably neutron power. Graphite has been proposed in previous work in order to suppress this interference signal [2]. Indeed, the photoneutron reaction thresholds for carbon isotopes lies above 5 MeV, far from the 2.74 MeV energy of the highest gamma ray in ^{24}Na spectral emission (see Fig. 3).

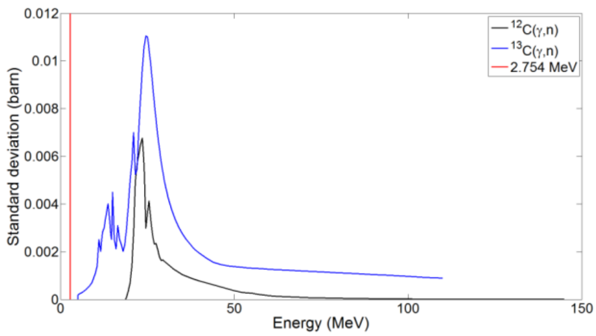

Fig.3. Photoneutron cross-section of carbon isotopes (ENDF-VII data base).

The neutron spectrum used in calculations is one of ^{87}Br (Fig. 4). Neutrons are emitted homogeneously into the sodium volume, and the reaction rate normalized to one emitted neutron is calculated by MCNP6 (F4 +SD4+ FM4 tally). The estimated count rate is obtained by weighting this result with fission product activity, fission product emission rate, and a factor taking into account the losses in detector (self-absorption into the deposit or deposition below the discrimination threshold).

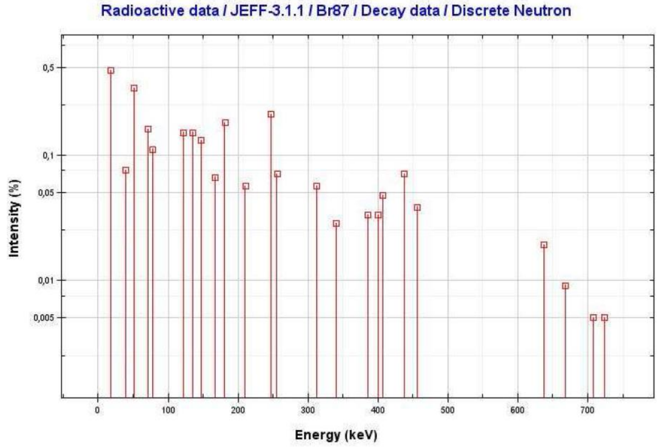

Fig.4. Neutron emission spectrum of ^{87}Br (JEFF-3 data base).

Two models of detectors have been retained for the study: ^{3}He proportional counter 65NH45 (MIRION) and ^{10}B proportional counter CPNB48 (PHOTONIS). The position of the detectors has been varied in order to find the configuration that maximizes neutron sensitivity. Fig. 5 shows the neutron sensitivity as a function of the position of counters into the moderator. The use of graphite moderator instead of polyethylene induces a sensitivity reduction of a factor approximatively equal to 3. It can be also concluded that ^{3}He counter provides sensitivity approximatively the twice higher than the ^{10}B counter.

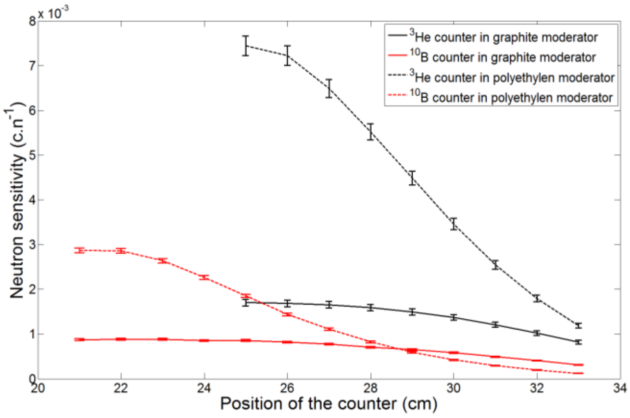

Fig.5. Neutron sensitivity as a function of counter locations and for different configurations.

Photoneutron noise is evaluated using photonuclear data LA150U implemented in MCNP6 [6]. The isotopic abundance of deuterium in polyethylene is equal to 2.145*10^{-3} %mass. In order to accelerate the calculation, this abundance is artificially increased and estimations are a posteriori corrected. A photoneutron signal equal to 0.5 cps in the ^{3}He counter in polyethylene and 23.5 cps in the case of ^{10}B counter in polyethylene has been estimated.

Table 1 presents the results obtained by simulation for each configuration:

- ^{3}He counter in graphite moderator (^{3}He/C),

- ^{10}B counter in graphite moderator ($^{10}B/C$),
- ^{3}He counter in polyethylene moderator ($^{3}He/CH_2$),
- ^{10}B counter in polyethylene moderator ($^{10}B/CH_2$),

Table 1. Results obtained by simulation.

	$^{3}He/C$	$^{10}B/C$	$^{3}He/CH_2$	$^{10}B/CH_2$
Lead thickness	12 cm	8 cm	12 cm	8 cm
Location in moderator*	2.25 cm	4.25 cm	1.25 cm	2.25 cm
Neutron sensitivity	$1.68.10^{-3}$ $c.n^{-1}$	$8.83.10^{-4}$ $c.n^{-1}$	$7.44.10^{-3}$ $c.n^{-1}$	$2.86.10^{-3}$ $c.n^{-1}$
Photoneutron signal	0 $c.s^{-1}$	0 $c.s^{-1}$	0.49 $c.s^{-1}$	4.7 $c.s^{-1}$

* from the lead surface to the detector axis

While photoneutrons can be suppressed, neutrons induced by the pollution will constitute a remaining background which will also change as a function of core parameters. Some algorithms are studied to better manage this background baseline [7-10].

IV. CONCLUSION

The DND system is a crucial part of the safety system of a sodium cooled fast reactor. A simulation study has been conducted in order to propose some designs allowing detecting efficiently and with reliability cladding failures.

Two types of detectors technology: ^{3}He and ^{10}B proportional counters and two types of moderator: graphite and polyethylene have been tested. The use of graphite suppresses the photoneutron signal while reducing the detection sensitivity by a factor three.

REFERENCES

[1] P. Filliatre, C. Jammes, N. Chapoutier, *et al.*, “In vessel detection of delayed neutron emitters from clad failure in sodium cooled nuclear reactors: An estimation of the signal”, *Nuclear Instruments and Methods* A, vol. 744, pp. 1-10, 2014.

[2] E. Rohée, R. Coulon, C. Jammes, P. Filliatre, *et al.*, “Delayed Neutron Detection with graphite moderator for clad failure detection in Sodium-Cooled Fast Reactors”, *Annals of Nuclear Energy*, vol. 92, pp. 440-446, 2016.

[4] “MCNP6 User’s Manual Version 1.0”. Technical report LANL LA-CP-13-00634, chap. 3, pp. 71-72, 2011.

[5] ICRP, 1987. Data for Use in Protection against External Radiation. ICRP Publication 51. Ann. ICRP 17 (2-3).

[5] C. Berlin, “Evolution of FFD-FFL instrumentation on French fast reactors”, *In proceedings of IAEA Fuel Failure Detection and Location in LMFBRs Meeting*, pp. 36-44, 1982.

[6] M.C. White, R.C. Little, M.B. Chadwick, “Photonuclear Physics in MCNP(X)”. *Proceedings of the ANS meeting on Nuclear Applications of Accelerator Technology,* 1999.

[7] R. Coulon, V. Kondrasovs, J. Dumazert, *et al.*, “Estimation of Nuclear Counting by a Nonlinear Filter Based on a Hypothesis Test and a Double Exponential Smoothing” *IEEE Transactions on Nuclear Science*, vol. 63, no. 5, pp. 2671-2676, 2016.

[8] R. Coulon, V. Kondrasovs, J. Dumazert, *et al.*, “Estimation of Nuclear Counting by a Nonlinear Filter Based on a Hypothesis Test and a Double Exponential Smoothing” *IEEE Transactions on Nuclear Science*, vol. 63, no. 5, pp. 2671-2676, 2016.

[9] P. Filliatre, C. Jammes, J.-P. Jeannot, F. Jadot, “In vessel detection of delayed neutron emitters from clad failure in sodium cooled nuclear reactors: Information treatment”, *Annals of Nuclear Energy*, vol. 65, pp. 385-389, 2014.

[10] O.I. Albutova, D.A. Lukyanov, “Investigation of dependence of BN-600 reactor sector fuel cladding leak detection system responses on the operation parameters”, *Nuclear Energy and Technology*, vol.1, pp. 248-252, 2015.