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Delayed Neutron Detection with graphite moderator for clad failure detection in Sodium-Cooled Fast Reactors

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ABSTRACT

In order to meet clean core challenges in Sodium-Cooled Fast Reactors (SFR), specific attention is paid to the cladding integrity. To monitor this integrity, Delayed Neutron Detection (DND) systems are implemented. During clad failures, neutron precursor fission products (mainly halogens: ^{137}I, ^{87}Br, ^{88}Br) escape into the primary coolant. The detection of these precursors through their delayed neutron emission ensures a diagnosis on clad failures events. In DND systems, ^{3}He proportional counters are selected as the best available technology for neutron detection purposes. Associated with ^{3}He counters, polyethylene blankets are required in order to thermalize neutrons. The first part of this study is dedicated to the optimization of the DND device by Monte-Carlo simulations in order to improve the detection capability. This optimization focuses on the device design presenting a graphite based alternative to polyethylene blankets in order to remove photoneutron noise from ^{2}D(γ,n) reactions in polyethylene in presence of a high ^{24}Na activity (emission of gamma rays at 2.75 MeV). The experimental part of this study is devoted to the validation of a measuring station including an ^{3}He counter with carbon for neutron moderation. Both Monte-Carlo simulations and experimental results highlight the potential for a low-noise DND system based on graphite moderation.

1. Introduction

Sodium-Cooled Fast Reactors (SFR) have been selected by the Generation IV International Forum, due to their double capability of reducing nuclear waste and saving nuclear energy resources by burning actinides. For maintenance and safety reasons, SFR comply with the “clean sodium concept” (4th Generation Sodium-Cooled Fast Reactors, 2012), i.e. the primary vessel must remain free of any contaminant potentially released by a clad failure in one of the pins an assembly is made of. For that reason, instrumentation devices are devised to continuously assess whether fission products (FP) are present in the primary sodium, highlighting a clad failure. In previous reactors such as PHENIX and SUPERPHENIX, this was performed via Delayed Neutron Detection (DND) systems, which detect delayed neutrons emitted by some FP, mainly ^{137}I, ^{87}Br, ^{88}Br. In this paper, a DND system is investigated following the framework of the French ASTRID project (Advanced Sodium Technological Reactor for Industrial Demonstration) (4th Generation Sodium-Cooled Fast Reactors, 2012). Two types of DND concepts are studied for SFR, a remote one and an integrated one (Filliatre et al., 2010; Filliatre et al., 2014a, b). The DND system discussed in this paper is a remote DND set outside the vessel and based on ^{3}He proportional counters. To extract a convenient DND response, the system has to be optimized in terms of detection capability. A complete design study based on Monte-Carlo particle transport simulation has been carried out and an innovative remote DND system using graphite moderator is proposed.

First of all, the remote DND concept used in SFR like PHENIX and SUPERPHENIX is exposed. DND signals perturbations from gamma dose rate, photoneutrons and cladding pollution are identified (Kim et al., 2006) and MCNPX Monte-Carlo simulations highlight the detrimental impact of the photoneutron noise on the detection capability. Secondly, the use of graphite instead of polyethylene is proposed and simulations reveal a satisfactory moderation power of graphite while remaining photoneutron-free. Finally, an experimental configuration implementing a ^{3}He counter positioned in an anthracite barrel and an AmLi source is tested to validate simulation results of a measurement station with carbon moderation for the Delayed Neutron Detection.

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2. DND device

2.1. Neutron signal

Sodium samples are continuously extracted from the outlet of fuel assemblies thanks to sample lines and transited out of the primary vessel through the heart stopper control. A traditional design of DND system is composed of a sodium volume of about 3 liters surrounded by few centimeters of lead shielding and polyethylene moderator. Three ^{3}He proportional counters (Ø25 × 450 mm, 4 atmosphere) assure thermal neutron detection (Eq. (1)). The system is usually set on the reactor vessel head as seen in Fig. 1. The use of polyethylene as a moderator slows down incident neutrons, which leads to an increase of the energy-dependent ^{3}He cross section (5314 barns at 25 meV). The ^{3}He(n,p) cross section used as an input in this study is extracted from ENDF/B-VI.8 data (http://www.oecd-nea.org). This efficient and low-cost moderator is commonly used in neutron detection systems as in PHENIX and SUPERPHENIX.

$$^3_2\mathrm{H} + ^1_0\mathrm{n} \rightarrow ^3_1\mathrm{t}(191\ \mathrm{keV}) + ^1_1\mathrm{p}(573\ \mathrm{keV}) \quad (1)$$

2.2. Photoneutron noise

Feedback from previous SFR like PHENIX and first simulations show that the traditional design suffers from several limitations. Indeed, photoneutrons are produced in polyethylene and form an additional noise (Coulon, 2013; Lipsett and Tseng, 1976; Sari et al., 2012) which degrades the delayed neutron signal. It appears that this noise originates from photonuclear (γ,n) reactions with naturally present deuterium in polyethylene (Eq. (2)) (Hara et al., 2003).

$$^2_1\mathrm{H} + ^0_0\gamma \rightarrow ^1_1\mathrm{H} + ^1_0\mathrm{n} \quad (2)$$

The ^{24}Na activation product is generated in significant amount (around 280 TBq m^{-3}) into the sodium coolant (Coulon et al., 2011, 2012). This radionuclide emits a gamma ray with energy (2.75 MeV) above the photoneutron reaction threshold (2.2 MeV) (Mobley and Laubenstein, 1950) and its activity evolves as a function of the reactor power level.

$$^{24}_{11}\mathrm{Na} \rightarrow ^{24}_{12}\mathrm{Mg} + ^{0}_{-1}e^- + ^0_0\bar{\nu}_e + ^0_0\gamma(1.39\ \&\ 2.75\ \mathrm{MeV}) \quad (3)$$

Even if the deuterium natural abundance and the photoneutron reaction cross section are low, respectively 0.015% and approximately 1.5 mb (Hara et al., 2003), the photoneutron contribution is not negligible regarding the low neutron signal level expected from delayed neutron precursors when confronted with a high ^{24}Na activity. To reduce the flux of high energy gamma rays from ^{24}Na, a lead blanket is used, therefore a tradeoff has to be found due to a lower delayed neutron signal in the presence of lead, hence limiting the interest of remote DND as a low noise and highly sensitive device for clad failure detection. Indeed, the neutron signal is reduced by the increase of the distance between the sodium sample and the detector (geometrical efficiency) and the neutron scattering into the lead.

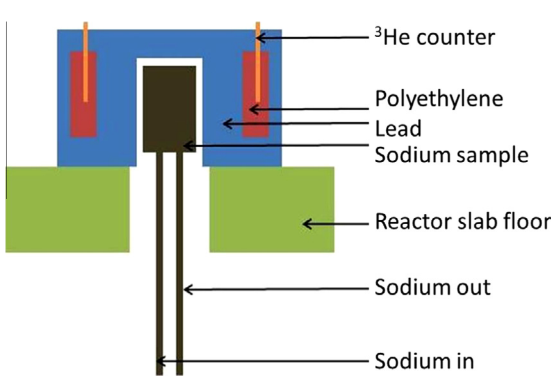

Fig. 1. DND system schematic view.

Table 1
Average number of collisions required to reduce neutron energy from 2 MeV to 25 meV by elastic scattering (Rinard, 1991).

Element	Atomic weight	Number of collisions
Hydrogen	1	27
Deuterium	2	31
Helium	4	48
Beryllium	9	92
Carbon	12	119
Uranium	238	2175

A new approach has been followed in this study which aims at completely removing the photoneutron noise which significantly overlaps with the delayed neutron signal. This innovative solution implements a hydrogen-free moderator, a requirement which justifies the choice of graphite material as a convenient substitute. Even if carbon is not as efficient as hydrogen in terms of neutron moderation (Table 1), its photonuclear reaction threshold lies around 5 MeV (Fultz et al., 1966) (Koch and Thies, 1976).

2.3. Gamma noise and cladding pollution

Another noise source lies within the gamma dose rate incident on ^{3}He proportional counters. An excessive gamma dose rate involves pile-up phenomena, generating gamma event pulses above the neutron/gamma discrimination threshold. Therefore, this noise has to be suppressed by design. The lead blanket used for this purpose has to be large enough to limit the dose rate impacting the detector. Pure ^{3}He counters without quenchers connected to a charge sensitive preamplifier have been implemented in past SFR. This setup can operate below a gamma dose rate around 10^{-1} Gy h^{-1} (Domenech, 2010; Beddingfild et al., 2000). CO_2 quenched ^{3}He counter linked with a large bandwidth current sensitive preamplifier can now be implemented. Improving the Signal to Noise Ratio (SNR) thanks to a faster charge carrier migration, a charge integration is still not required in this case. The pile up probability then decreases dramatically for a given dose rate. Feedback from dose rate robustness experiments shows that this new neutron detection system can provide gamma/neutron discrimination up to around 3 Gy h^{-1} in air with a loss of counting of around 30% with a 65NH45 ^{3}He counter which is largely used in DND devices (Fig. 2). The lead blanket thickness could be therefore reduced and the geometrical efficiency increased.

Finally, it is unavoidable to emphasize that the manufacture of fuel rods always brings about a slight fissile material deposit on the cladding at the weld plug places. This pollution is responsible for a residual FP production, providing a constant neutron signal of the order of 1 count per second as registered in SUPERPHENIX with a standard ^{3}He counter plus lead and polyethylene configuration (Coulon, 2013).

3. Methods

3.1. Source terms

To compute the optimization of the system, the Monte-Carlo particle transport code MCNPX 2.7.0 is used (Pelowitz, 2011). The DND device is built from a 3-liter sodium sample volume, a ^{3}He proportional counter inside the moderator blanket and two lead blankets surrounding the detector (Fig. 1).