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Primary Circuit Coolant Activation Products Distribution in a Small Modular Reactor

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1. Introduction

In most power reactors, water flows in the primary circuit performing coolant and neutron moderator functions in the reactor core while it suffers neutron activation. The main activation process to be considered for shielding considering short time decay contribution in dose rate, consists in the neutron nuclear capture reaction turning oxygen in radioactive nitrogen, mainly ^{16}N. In order to estimate the source term for reactor normal operation, the standard ANSI/ANS 18.1 could be used to design radioactive waste system, although for the reactor shielding evaluation, the ^{16}N activity concentration has been shown to be underestimated considering the mass flow rate and reactor primary circuit length. This work presents ^{16}N distribution in the primary circuit calculated from the Monte Carlo code Serpent for a small modular reactor (SMR) comparing it to ANSI/ANS 18.1.

2. Methodology

Oxygen activation in cooling water is caused by neutrons over 8 MeV emerging from $^{17}O(n,p)^{17}N$ reaction and over 10 MeV from $^{16}O(n,p)^{16}N$ reaction [1]. In order to analyze the phenomenon, typical water activation reaction rates and neutron flux spectra were obtained by modeling a single fuel cell lattice in Serpent 2 Monte Carlo code employing ENDF/B-VII.0 cross sections library [2]. The calculation aimed to acquire microscopic cross sections averaged over the spectra by dividing the activation rate by the neutron flux.

Nitrogen nuclides concentrations (^{16}N and ^{17}N) depend on average neutron flux in the core, activation cross sections and also the amount of time water has spent inside the core and primary circuit.

The amount of time water remains in each part of the primary circuit was inferred from a system thermohydraulic RELAP [3] code model in which the primary circuit was divided in several sections such as: hot leg, steam generator, cold leg, downcomer, lower plenum and core inlet, active core, core outlet, and finally, upper plenum. As the sections related to the active core correspond to the major contribution to coolant activation, other regions were neglected in the calculation for simplicity.

Afterwards, considering the time interval and production rate, a simple decay and production calculation was performed to evaluate the equilibrium concentrations from water iterations along the primary circuit in a Lagrangian reference system in which a fluid parcel is time-followed.

3. Results and Discussion

Figure 1 shows the neutron spectra per unit of lethargy in the coolant region inside the active core obtained from the fuel cell Serpent 2 code calculation. The average total neutron flux obtained is about $1x10^{14}$ $cm^{-2}.s^{-1}$ and barely 0,03% of the neutron flux is above 10.2 MeV, corresponding to $^{16}O(n,p)^{16}N$ reaction cutoff energy.

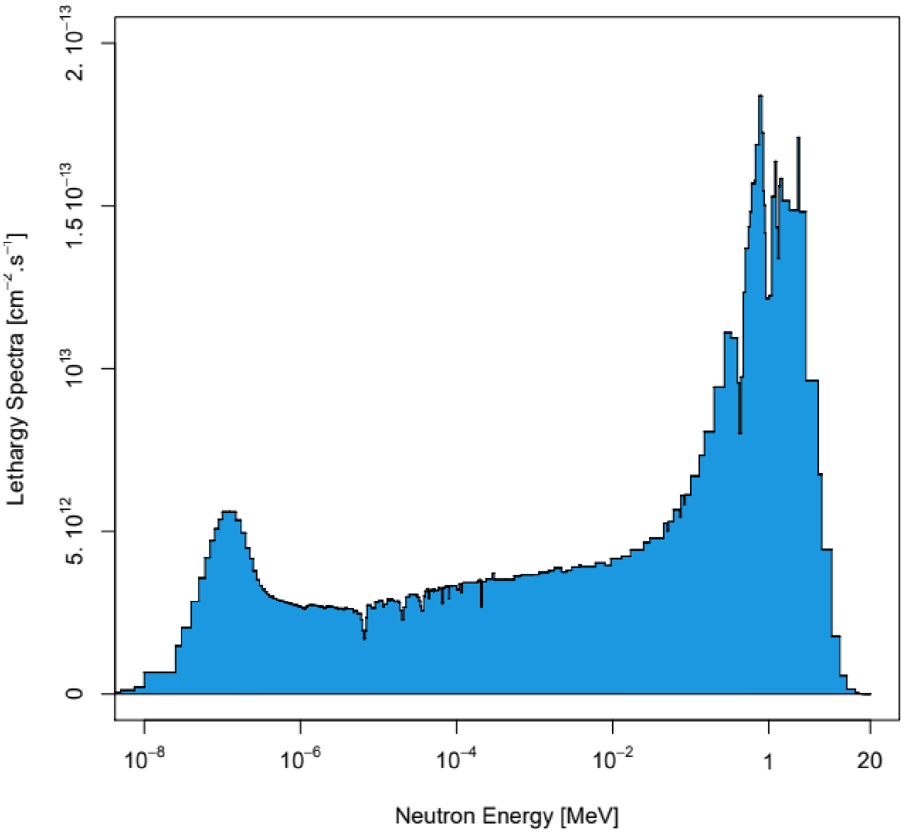

Figure 1: Neutron flux spectra normalized by lethargy width in the coolant region inside the active core.

Table I shows the amount of time that water remains in the SMR PWR circuit segments, whilst Table II shows the production rate of ^{16}N and ^{17}N using one group (n,p) averaged microscopic cross sections.

Table I: Amount of time of water remaining in each part of primary circuit.

Equipment	**Time [s]**
Active core	1.10
Core outlet and upper plenum	1.09
Hot leg	1.06
Steam generator	1.00
Cold leg	3.40
Downcomer	2.20
Lower plenum and core inlet	0.50

Table II: Production rate and averaged microscopic cross section.

Nuclide	**Half-life [s]**	**Production rate [Bq.g^{-1}.s^{-1}]**	**(n,p) Microscopic cross section [µb]**
^{16}N	7.13	2.59x10^{6}	8.32
^{17}N	4.14	9.04x10^{2}	3.92

Considering the typical transit time inside a SMR PWR, the equilibrium of ^{16}N concentration is achieved in about 60s, at constant reactor power. Figure 2 shows that ^{16}N concentration in the primary circuit calculated for this particular reactor (blue curve) is higher than 40 µCi/g (red curve) reported in ANSI/ANS-18.1 [4]. Since ^{17}N concentration is much smaller than ^{16}N, its contribution to the dose rate can be disregarded in a first analysis, although its decay release neutrons that can activate further materials at some scale.

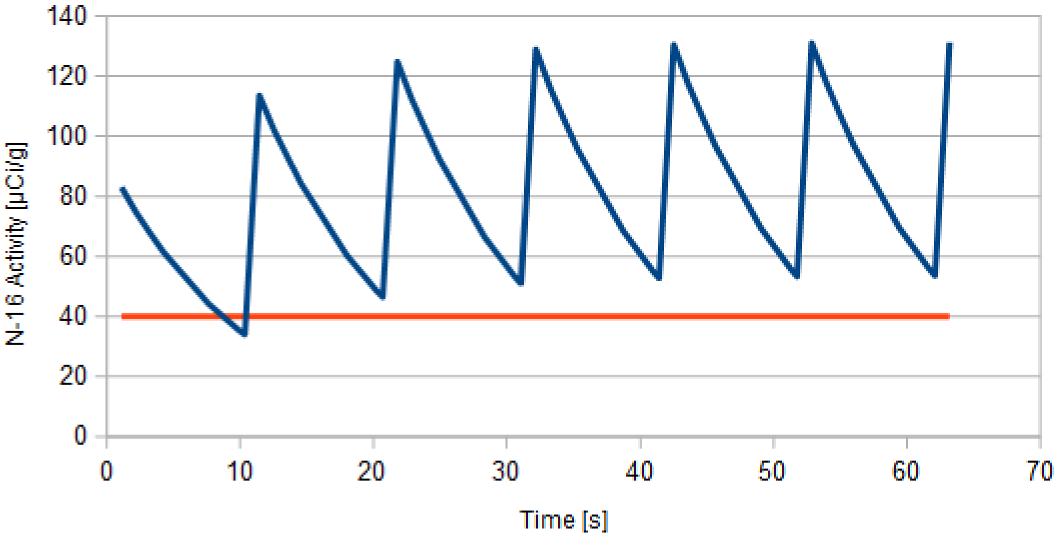

Figure 2: ^{16}N activity in the primary circuit considering six loops (iterations) through the active core. Peaks correspond to coolant exiting the active core and troughs, entering the core.

4. Conclusions

Water activation inside the reactor primary circuit was evaluated by first principles using averaged microscopic cross sections obtained from a single cell model in Serpent 2 Monte Carlo code as well as from water transit time estimated by RELAP thermohydraulic code. Since the results of ^{16}N activation are considerable above the 40 µCi/g reported in ANSI/ANS-18.1, as a preliminary conclusion, ^{16}N concentration should be evaluated to determine the radiation source term for SMR shielding design purposes.

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