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Simulation of a Sodium-deuterium Photoneutron Source in a Sodium-cooled Fast Reactor

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1. Introduction

In sodium-cooled fast reactors (SFRs), the sodium coolant activated by the ^{23}Na(n,γ)^{24}Na reaction decays by beta-emission with two gamma-rays with energies of 2.754 and 1.369 MeV. Taking advantage of these gamma-rays, deuterium targets in a SFR can act as a photoneutron source, similar to antimony-beryllium (Sb-Be) source used in pressurized water reactors. Deuterium produces photoneutrons through the ^{2}D(γ,n)^{1}H reaction with threshold energy of 2.2246 MeV, which requires the 2.754 MeV gamma-ray of the ^{24}Na to induce the photoneutron reaction. The feasibility of this sodium-deuterium (Na-D) source in SFRs is explored herein, with Monte Carlo simulations on the SFR core modeled homogeneously and heterogeneously.

2. Methods and Results

As a preliminary study, we propose replacing a fuel pin in the center of a SFR fuel assembly with a deuterium target (heavy water). To simplify the model, 10^9 particles of monoenergetic gamma-ray with 2.754 MeV are tracked with energy cutoff at 2.2246 MeV by Monte Carlo N-Particle code (MCNP6.1). Due to its high energy, Compton scattering and pair production are expected to be dominant for photons before reaching the target.

2.1 Homogeneous Model

The purpose of homogeneous model is to survey the mean free path of the gamma-rays and the gamma flux at the target with a simple model. Fig. 1 describes the model which is a right circular cylinder with 50 cm radius and 70 cm height. The cylinder is filled with a homogeneous material comprised of blended fuel (uranium and plutonium), steel clad (mostly iron, chrome and nickel) and liquid sodium coolant. The gamma-rays are emitted from the smeared region, which is evenly distributed, isotropic, volumetric gamma source. The gamma-ray flux is measured in the center fuel pin region with 0.271 cm radius and 70 cm height.

The result showed that the mean free path of the source gamma-rays is 4.185 cm and the normalized gamma-ray flux in the energy range from 2.2246 to 2.754 MeV at the center was 7.634×10^{-6} cm^{-2}. Almost 90% of these gamma-ray flux (6.903×10^{-6} cm^{-2}) had the energy from 2.7059 to 2.754 MeV. Taking the Compton scattering energy formula into account, the scattering angle for photon energy of 2.754 MeV in one collision should be $\pm8.124\times10^{-2}$ rad (±4.654°), to be measured at the center fuel pin with the energy of 2.7059 MeV. From the Klein-Nishina formula [1], the 2 MeV energy photon has a high probability of having scattered angle around 0°. Thus high flux ratio of flux with low energy reduction means most of the gamma-rays arrive at the center pin in almost straight way. The mean free path implies that a sodium-cooled fast reactor core (with dimensions on the order of 1 m height and 1 m diameter) is optically thick to 2.754 MeV gamma rays. Gamma rays produced within the coolant of the fuel assembly containing the deuterium target and directly adjacent assemblies will be the most important contributors to the gamma flux that can induce the ^{2}D(γ,n)^{1}H reaction.

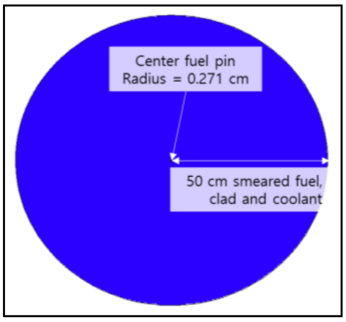

Fig. 1. Diagram of homogeneous model for SFR core.

2.2 Heterogeneous Model

To more accurately simulate gamma attenuation by a lattice of absorbing U-Pu fuel pins, we developed a realistic heterogeneous model of a hexagonal fast reactor fuel assembly. The assembly is loosely based on a driver-fuel assembly from the first core of the PHENIX prototype sodium-cooled breeder fast reactor. Fig. 2. shows the cross-sectional diagram of the model as a right hexagonal prism 110 cm height and 11.69 cm short diagonal filled with 217 fuel pins.

The gamma-ray photons are isotropically radiated from all the sodium coolant (yellow region in Fig. 2). Since the source is based on cells in which coolant is located, it is necessary to specify the lattice index (i,j,k) of the cell with the coolant in the SI card of SDEF card in the MCNP input. Also, to make the source sampling probability proportional to the volume, it requires a closed arbitrary and calculable volume in the universe card for the lattice.

The assembly is wrapped with a hexagonal steel clad and a ring of interstitial sodium. Reflecting boundary conditions are applied to the outer assembly surfaces to model the gamma rays that are produced in the adjacent assemblies and stream towards the center pin. The uranium and plutonium-mixed oxide fuel is cladded with helium gap and steel clad. Since active-fuel assembly height is assumed to be approximately 90 cm for PHENIX model, the gamma-ray flux is measured in the center fuel pin with 0.271 cm radius and 90 cm height. The additional 10 cm height of the fuel assembly below and above the active fuel region models the axial streaming of gamma rays from the coolant at the assembly inlet and outlet.

The normalized gamma flux calculated for the center fuel pin cell is 2.148×10^{-4} cm^{-2}. Approximately 90% of the gamma flux are either uncollided or glancingly scattered gamma rays from the 2.754 MeV source. From a radiation shielding perspective, the fast reactor fuel assembly and fuel pin lattice is a nearly-purely absorbing medium with respect to scattering and absorption of 2.754 MeV gamma rays. Only forward Compton scattering of a source gamma ray with scattering angle less than 17° results in secondary gamma energies above the 2.2246 MeV photoneutron reaction threshold energy.

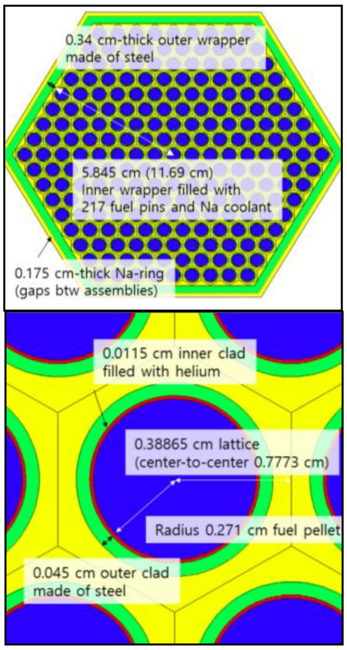

Fig. 2. Diagram of heterogeneous model of a SFR fuel assembly

2.3 Photoneutron Yield Calculations

The reaction rate equation ($S = \sigma N_D \Phi_p V_D$) calculates the number of photoneutron produced in the deuterium (heavy water) target by the gamma ray from the sodium coolant. Table I shows the estimated parameters in the equation.

Table I: Parameters in Reaction Rate Equations and Photoneutron Yield Calculations

Parameter		Values	Unit
σ	microscopic cross-section of $^2D(\gamma,n)^1H$ reaction	1.3366	(mb for 2.754 MeV gamma-ray)[2]
N_D	number of deuterium nuclei per volume	9.971×10^{-2}	(atoms/barn-cm for heavy water)[3]
Φ_p	photon flux	2.426×10^{9}	($\#/cm^2\cdot s$)
V_D	deuterium target volume	1.615×10	(cm^3)
S	total photoneutron yield	5.2×10^{6}	(neutrons/s)

Photon flux from the sodium source, Φ_p is obtained by multiplying normalized photon flux from MCNP simulation ($1/cm^2$) by the sodium activity (Bq). The sodium volumetric activity of BN-600 reactor (10^9 Bq/cm^3) was used, multiplied by sodium source volume of the assembly.

3. Conclusions

In this study, the feasibility of the idea of utilizing Na-D source as a SFR startup source was examined. The sequential approach staring from homogeneous model to heterogeneous one enhanced comprehensive understanding on the behavior of gamma-ray photons in the reactor. Replacement of one fuel pin with a deuterium target pin in a SFR fuel assembly can produce a photoneutron yield of approximately 5.2×10^6 photoneutrons/s relying on the gamma rays produced by the activated sodium coolant. The photoneutorn yield can be used as a reactor startup source for several days after a reactor SCRAM. Optimization of deuterium target placement within the core and assemblies and target material could improve the application of the Na-D source as a SFR startup source. Future work can consider the additional photoneutron yield from high-energy gamma rays emitted during the radioactive decay of fission fragments and daughter isotopes in the decay chains.

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