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Design of an equilibrium core 1000 MW_t Sodium-Cooled Heterogeneous Innovative Burner Reactor

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ABSTRACT

In this research a sodium-cooled fast reactor is designed for the transmutation of minor actinides (MAs). The equilibrium core was designed in ERANOS 2.1 and verified in MCNPX 2.6.0. The design is innovative in the use of moderated and unmoderated heterogeneous MA targets in the core. Additionally the driver fuel uses a Np-Pu-U oxide to further help reduce the radiotoxicity of wastes from used nuclear fuel (UNF). The core design improves the transuranic feed rate of the burner by 27% while maintaining low assembly peak-to-average power. All of the major core design parameters are similar to the homogeneous design and the maximum clad damage for discharged fuel is expected to be less than 120 dpa.

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1. Introduction

The purpose of this research was to develop a sodium-cooled fast reactor designed for enhanced transmutation of minor actinides (MAs) recycled from light water reactor (LWR) used nuclear fuel (UNF). There is continued interest in the reduction of the overall radiotoxicity associated with stored nuclear wastes. After plutonium, minor actinides are the primary long-term cause of radiotoxicity from UNF. It is now more important to recycle and reduce radioactive wastes in a time when the nuclear industry has plans to expand capacity and the U.S. high-level radioactive waste repository at Yucca Mountain is no longer being funded. Using a fast reactor to transmute and destroy MAs is one possible method allow future generations to use radioactive wastes to produce energy in a carbon-constrained world.

There have been several studies for the use of moderated assemblies in fast reactors (Wakabayashi and Higano, 1998; Hunter, 2000; Fujimura et al., 2001; Grouiller et al., 2003; Tucek et al., 2008; Tommasi et al., 1995; Newton and Smith, 2003; Sasa et al., 2008). This design is unique in how it uses moderating rods within the fast reactor core to soften the neutron spectrum and achieve a higher burnup of minor actinides. The minor actinide targets are irradiated in the first cycle with moderating rods interspersed in the assembly. When the fuel is shuffled, the target assemblies are moved from the outside of the core to the inside and the moderating rods are replaced by steel rods. This changes the spectrum within the assembly and allows the targets to remain in the core longer without having extremes of power peaking during the fuel cycle.

2. Sodium-Cooled Heterogeneous Innovative Burner Reactor (SCHIBR) model

2.1. Basis of model

The Sodium-Cooled Heterogeneous Innovative Burner Reactor (SCHIBR) model was based upon a design of a 1000 MW_t Advanced Burner Reactor (ABR) created at Argonne National Laboratory (ANL). This model was selected because it is an established, licensable and mature design that has been meticulously analyzed. Because the SCHIBR is a pre-conceptual design with a significant modification (i.e. the use of heterogeneous moderated targets) a model was selected whose characteristics were well-established and whose core physics and thermal hydraulics had been extensively studied.

The ABR was designed for metal or oxide fuel at several conversion ratios (CR). The base model for the SCHIBR was the 0.5 CR oxide-fueled core design (Hoffman et al., 2006). The major modification to the ANL model was the placement of transuranic (TRU) material within the core. The ABR was designed as a homogeneous

Abbreviations: ABR, Advanced Burner Reactor; ANL, Argonne National Laboratory; CEA, Commissariat à l'Energie Atomique; CR, conversion ratio; dpa, displacements per atom; ERANOS, European Reactor ANalysis Optimized calculation System; FR, fast reactor; HM, heavy metal; INL, Idaho National Laboratory; LANL, Los Alamos National Laboratory; LWR, light water reactor; MA, minor actinide; MCNPX, Monte Carlo Neutron Photon transport code X; PTA, peak-to-average; SCHIBR, Sodium-Cooled Heterogeneous Innovative Burner Reactor; TRIGA, Training, Research, and Isotope-production reactors-General Atomic; TRU, transuranic; UNF, used nuclear fuel; VISION, Verifiable Fuel Cycle Simulation Model.

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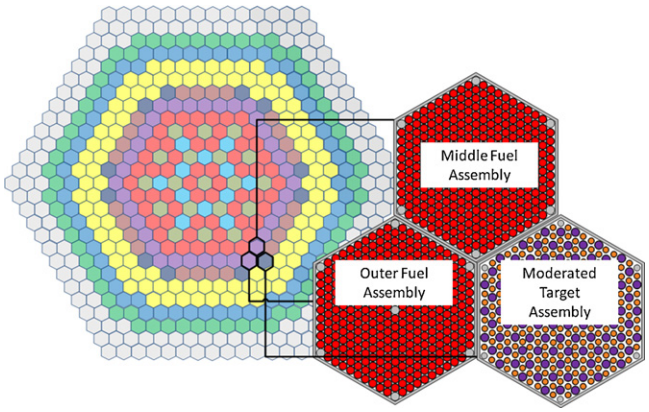

Fig. 1. SCHIBR equilibrium core layout with moderated ex-core targets highlighted.

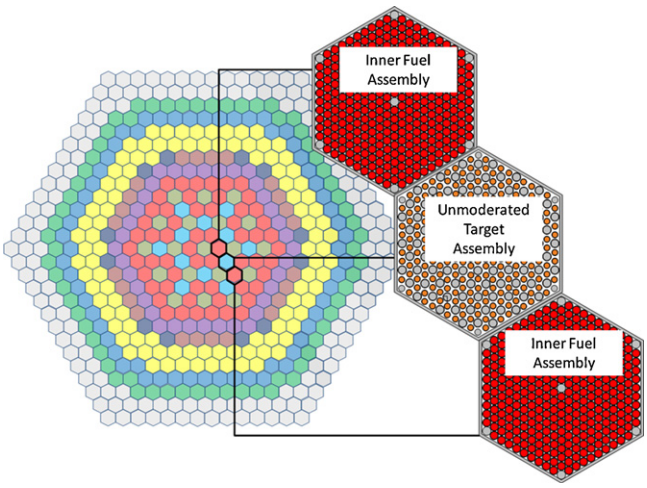

Fig. 2. SCHIBR equilibrium core layout with unmoderated in-core targets highlighted.

reactor with TRU throughout the fuel in a UO_2-$TRUO_2$ mixture. In the SCHIBR, the driver fuel is composed of a mixture of neptunium, plutonium, and uranium oxide while the minor actinides of americium and curium are placed in separate target assemblies. The target rods consisted of 20% MA oxides in an inert matrix of magnesium oxide. This mixture is similar to heterogeneous targets used in parametric studies at Idaho National Laboratory (INL) (Bays et al., 2008).

2.2. Use of moderated heterogeneous targets

In addition to using heterogeneous targets, the SCHIBR uses moderating rods of zirconium hydride in a composition similar to that found in Training, Research, and Isotope-production reactors-General Atomic (TRIGA) fuels. Because of the relatively low disassociation temperature of hydrogen within the ZrH_2, the moderating material was kept separate from the fuel rods and clad in HT9 stainless steel. The motivation for the use of moderated assemblies comes from work that has shown the benefit of a softer spectrum in the destruction and transmutation of MAs (Sanda et al., 2000). The transmutation performance of a moderated target in a fast reactor does not have the complications of a net overall increase MA production and the significant reactivity penalty associated with use of MAs in LWRs.

The use of heterogeneous moderated targets has been examined with the concern that the introduction of the moderating assembly can cause localized power peaking problems in the fast reactor (FR) core (Newton and Smith, 2003). Previous research on the SCHIBR model showed excessive power peaking when the moderated targets were located in-core or when they were in an ex-core location for longer than one cycle of approximately 507 days (Allen et al., 2011a). The cause of the power peaking was attributed to the production of ^{239}Pu in the transmutation process. The solution to the power peaking over the life of the core was to create a hybrid model design that used moderated targets in an ex-core location for one cycle (Fig. 1). After the first cycle, the moderating rods are replaced with HT9 dummy rods and the target assemblies are moved to an in-core location (Fig. 2). The moderating rod assemblies in the target would be fashioned similar to the burnable poison rod assemblies (BPRAs) used in pressurized water reactors (PWRs) for years. The BPRAs were inserted in the control rod guide tubes of the new fuel assemblies and were removed after the first cycle when the fuel was shuffled. In the SCHIBR design, the moderating rods are removed and replaced with HT-9 rods during a reload sequence. New moderated assemblies are then placed in vacant ex-core locations. Using the moderating rods for one cycle, and an unmoderated spectrum for a second cycle the SCHIBR takes advantage of a soft spectrum for MA destruction without excessive power peaking. Research also suggests that a soft spectrum generates an excess of ^{246}Cm which has a small thermal spectrum and builds up over time. In a thermal-only transmutation system, the ^{246}Cm would have to be separated periodically and burned in a FR (Iwasaki and Hirakawa, 1995). The SCHIBR reactor allows for the reduction of Cm produced in the moderated cycle with a fast spectrum cycle.

3. Methods

3.1. Equilibrium cycle for SCHIBR core in ERANOS 2.1

The core was modeled in MCNPX 2.6.0 from Los Alamos National Laboratory (LANL) and ERANOS 2.1 from Commissariat à l'Energie Atomique (CEA). Previous research benchmarked the code-to-code comparisons for fast reactor modeling using MCNXP 2.6.0 and ERANOS 2.1 (Allen et al., 2011b). Because no physical benchmarks exist for this pre-conceptual design, code-to-code comparison is the best available verification of the results. Because of its speed of calculation, ease of use and the extensive use and development of the code by CEA and others, ERANOS was chosen to model the core for multiple cycles until the mass flow reached equilibrium. The reference route was used for all materials with a fine (1968) group library used to calculate the resonance self-shielding effects. The cross sections were collapsed and condensed to a broad (33) group set. Cross section processing for all non-fuel elements followed the recommended steps in the user manual. The process did not include a fine-group step because broad-group source expansion is not appropriate for non-fuel elements (DANS-DEN-CEA 2009).

To create a multi-batch, multi-cycle core design, the fission products from burned fuel assemblies had to be modeled and transferred with the assembly when it was shuffled. Because ERANOS did not contain fine group libraries for all of the fission product isotopes generated during depletion, a surrogate fission product was created for multi-cycle applications. A test was created to make a surrogate that would adequately represent the fission products in the ERANOS multi-batch model. The baseline for the test was the detailed MCNPX model from Cycle 1 to Cycle 2 which transferred 117 isotopes in the burned fuel. The surrogate was created using a ratio of consisting of ^{95}Mo, ^{90}Zr, ^{91}Zr, ^{92}Zr, ^{93}Zr, ^{94}Zr, ^{96}Zr and ^{177}Hf through various trials in order to closely match the reactivity swing and burnup of heavy nuclides at end-of-cycle. The mass of the surrogate fission product was determined by examining the