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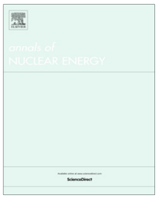

Reactor design strategy to support spectral variability within a sodium-cooled fast spectrum materials testing reactor

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ABSTRACT

A concept of a sodium cooled fast spectrum materials testing reactor is presented as one of the potential design configurations to achieve the performance versatility with respect to supporting a range of testing environments from current thermal-spectrum LWRs to Generation IV advanced fast-spectrum reactors. The objective is accomplished by designing a core with region-wise varying neutron spectra. This paper presents the design details and explores spectral variability examining feasibility to maintain thermal and fast energy spectra in the system. The core assemblies are designed using the EBR-II assembly as a prototype while implementing certain design modifications to meet performance needs. The fuel is 19.9%-enriched U-10Zr. Compare to EBR-II, the proposed core has larger pins, a taller active core, and thick reflector instead of depleted uranium breeding blankets. The MgO pins are analyzed as the reflector material to meet the needed versatility requirements. The design effort successfully concluded yielding a feasible 600 MW_{th}-configuration with sufficient neutron fluxes in material testing locations. A fast flux greater than 5.6E15 n/cm^2-s is maintained over the core lifetime in the central irradiation position. The volume of 63,000 cm^3 with a fast flux of $\sim$ 4.2E15 n/cm^2-s or greater is provided for materials irradiation options. The core has regions of high magnitude thermal flux in a large graphite region at the core periphery. Spectral variability, design choices and reactor physics characteristics are discussed to demonstrate the concept viability.

1. Introduction

The Nuclear Reactor Technology Subcommittee, a subcommittee of the Nuclear Energy Advisory Council, released a report on November 18, 2014 hat requested designs for a new materials testing reactor in support of the Advanced Reactor and LWRS programs. This paper will propose a design strategy for a new MTR that will meet the versatility requirements outlined in that report (Report, 2014). The NEAC report recommended the construction of a materials test reactor that could emulate the behavior of as many reactor types as possible, while still functioning as a demonstrator reactor for a specific reactor type.

The sodium cooled fast reactor is a promising breeding/burning uranium-plutonium fuel cycle reactor design. The proposed reactor would serve as a demonstrator reactor for the sodium fast reactor technology, while also being flexible enough to serve as a testing platform for alternative reactor designs. The report emphasized the need to test fuels and claddings to enable very long core lifetimes and to improve accident tolerance.

A high fast flux in the reactor would allow for accelerated neutron damage. This paper covers three different aspects of the proposed MTR: an outline of the overall design, an in-depth analysis of the driver region, and the burnup behavior of the core.

The fuel assembly was based on fuel assemblies used in EBR-II, a sodium cooled fast breeder reactor operated at Idaho National Laboratories from 1963 to 1994 (Fast Reactor Database, 2006). Metallic fuel was the favored fuel form for reasons outlined below, and EBR-II was designed and operated with metallic fuel, so its assembly was used as the baseline for this project.

Subsequent analysis modified the assembly but the pin diameter, pin pitch, and inter-assembly gap thickness, assembly wall thickness, and assembly pitch were not changed. The fuel assembly was designed for a high power density and had an as fabricated pitch of 5.893 cm. Smaller assemblies could allow more flexibility in core layout. The EBR-II core primarily used metallic fuel, but oxide fuel assemblies were tested in the core as well. Metallic fuels have varying material compositions, but the most promising fuel form was an initially uranium-zirconium alloy, with 10% zirconium by mass (Chang, 2007). Higher actinides accumulated with burnup and reprocessing, so the final fuel composition differed somewhat from the initial fuel composition.

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The benefits of metallic fuels are briefly outlined here and compared to oxide fuels. Metallic fuel has a low thermal conductivity, resulting in lower fuel temperatures. Although the melting point of metallic fuels is lower than that of uranium dioxide, the higher thermal conductivity more than compensates (Chang, 2007). Metallic fuels have higher thermal expansion coefficients than uranium dioxide, meaning that the fuel assemblies axially expand with increasing fuel temperature more than uranium dioxide fueled assemblies. This expansion increases neutron leakage (Chang, 2007).

The severe accident behavior of metallic fuels was clearly demonstrated when the EBR-II successfully underwent an unprotected loss of flow accident (Chang, 2007). Zirconium present in the fuel improves the irradiation swelling behavior of the fuel. Metallic fuel assemblies have been successfully irradiated to burnups of 19.9 atom percent (Chang, 2007).

Although metallic fuel does expand with burnup, an initial smear density of $\sim$75% leaves enough room within the fuel pin for the fuel to expand (Chang, 2007). Metallic fuels have a higher fissile density than oxide fuels. Metallic fuels have a higher uranium weight percent (Chang, 2007). A higher fissile density inserts reactivity into the core. These favorable characteristics underlie Terrapower's choice to use metallic fuels in the Traveling Wave Reactor (Hackett and Povirk, 2012).

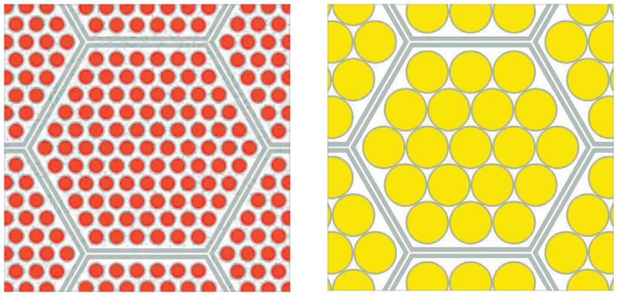
2. Design strategy

The assembly used in the present work was based on the EBR-II core design. The assembly layouts for the driver core and the outer reflector are shown in Fig. 1(a) and (b), respectively. Characteristics of the EBR-II assembly were acquired from the Fast Reactor Database, 2006 Update. Fuel pin diameter is 0.381 cm with a 0.0305 thick steel cladding.

The fuel was modeled as ^{234}U, ^{235}U, ^{236}U and ^{238}U with 10% natural zirconium by mass. The fuel composition was assumed to come from a mixture of HEU and DU (McConn et al., 2011). The maximum enrichment is assumed to be 19.9%.

The selected lower enrichment of the driver fuel can be counterbalanced in several different ways. Increasing the fuel volume fraction would compensate for the lower enrichment. This option was examined and the results will be presented below. Similarly, the core volume could be increased.

The temperature of 900 K for cross sections were used for the fuel. Fuel in the EBR-II had a 75% smear density measured relative to the theoretical density of 17.7 g/cm^3. The fuel was sodium bonded. In the present investigation, the fuel was assumed to occupy the entire volume of the fuel pin at a density of 13.275 g/cm^3.



a) Driver fuel assembly. Red is the fuel, light gray is the assembly casing and cladding regions, and white is the sodium. No gap is assumed between the fuel and cladding.

b) Outer reflector assembly. Yellow is the MgO, light gray is the cladding and assembly wall, white is the sodium.

Fig. 1. The driver and outer reflector assembly arrangements for a sodium-cooled fast spectrum materials testing reactor.

Although EBR-II used SS316, this reactor uses HT9. The use of HT9 will give the assemblies better irradiation swelling characteristics than SS316. The HT9 used in this investigation was modeled as 87% natural iron, 12% natural chromium and 1% natural molybdenum by mass (Hackett and Povirk, 2012). HT9 was simulated with a density of 7.8 g/cm^3. 600 K cross sections were used. EBR-II pins were wire wrapped; rather than model the individual wire wrappers the steel associated with the wrap was added to the cladding. For this reason, the cladding thickness was increased to 0.0429 cm. The sodium used in this investigation was modeled at a density of 0.8 g/cm^3 with 600 K cross sections.

The breeding blanket assemblies and driver assemblies had the same duct dimensions in the EBR-II. The fuel assembly pitch for the EBR-II was 5.893 cm at room temperature. The outer duct flat to flat thickness was 5.817 cm, and the duct walls were 0.1016 cm thick. The assembly lattice pitch, duct dimensions and duct material compositions are common to every position simulated except where noted. This is done to ensure adequate cooling of all parts of the core, but more importantly, it ensures that the core has an easily interchangeable geometry.

The core is meant to be easily adaptable to whatever conditions are needed; a common lattice and duct type facilitates that outcome. Light water may be used in this reactor; the 0.1016 cm thick steel walls are the primary barrier preventing energetic sodium-water interactions within the core.

The number of fuel pins per assembly (91) was provided in the Fast Reactor Database, so the fuel pin lattice pitch was determined to be 0.57192 cm. There is no breeding blanket regions in this reactor, only a thick MgO reflector. The MgO reflector pins were 1.2 cm in diameter with a 0.0305 cm thick cladding and a lattice pitch of 1.215 cm. This corresponds to 19 such pins per assembly. Such pins can be replaced with solid blocks of MgO.

Axial and radial dimensions for the EBR-II were provided in the Fast Reactor Database, as well as fuel loadings and total number of fissile and fertile assemblies. These characteristics are taken as a reference design parameters. Fig. 2(a) and (b), shows the overall axial and 2D radial core layouts, respectively, as developed in the present effort.

The modeling is performed using Serpent 2 (Leppänen, 2016). The analysis uses the equivalent critical reactor approach, without accounting for control features (effectively assuming the core state with all control features out).

To achieve the needed spectral variability and testing versatility at the same time (enough neutrons in the system in test locations at desired energies), the basic geometry of the reactor is a fast reactor driver region surrounded by a thick outer reflector, part of which is composed of a thermalizing material. Different experiments can be located in the thermalizing region to further profile energy distributions. For the demonstration purposes of the present work, it is assumed that the thermalizing material is graphite. Following this design development strategy, the center of the reactor provides a region of high fast flux while the outside of the reactor provides regions of lower energy fluxes as needed. The outer reflector is essential to maintaining criticality, while the moderating region provides low energy neutrons at the expense of a lower k_{eff}. For this reason, the volume of moderating region within the core has to be minimized. However, considering the modularity of the core, it is possible to reconfigure the outer reflector to whatever geometry is needed.

Fig. 2 gives the principal overview of the geometry. The active fuel height is 100 cm, taller than the EBR-II, which had an active fuel height of 34.3 cm. EBR-II had upper and lower breeding pins within a 19 pin lattice. The axial reflectors are each 50 cm tall, so the total core height is 200 cm. In Fig. 2, the MgO reflector assemblies are shown in yellow, 19.9% fuel is shown in shades of red, 16% enriched fuel is shown in orange, black-colored region is void, light