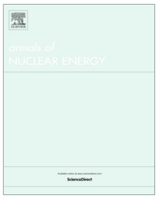
Annals of Nuclear Energy 110 (2017) 1091–1097

Contents lists available at ScienceDirect

Annals of Nuclear Energy

journal homepage: www.elsevier.com/locate/anucene



Fast spectrum reactor fuel assembly sensitivity analysis

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A R T I C L E I N F O

Article history:
Received 20 June 2017
Accepted 30 June 2017
Available online 1 September 2017

Keyword:
Sensitivity analysis
Fast reactor

A B S T R A C T

The Experimental Breeder Reactor-II was a sodium-cooled, metal-uranium-fueled fast-neutron reactor designed and built by Argonne National Laboratory. The reactor achieved initial criticality September 30, 1961, and continued operation until 1994. The reactor thermal power limit was 62.5 MW with a corresponding electrical output of 19 MW. To preserve important EBR-II reactor physics information, a benchmark evaluation is underway for proposed inclusion in the International Handbook of Evaluated Reactor Physics Benchmark Experiments. Coupled with development of the reactor physics benchmark evaluation, sensitivity analysis has been performed. Individual nuclide cross-section sensitivities for heterogeneous and homogeneous fuel assembly models were calculated using the multi-group adjoint method, the iterated fission probability (IFP) method, and the Contribution-Linked eigenvalue sensitivity/Uncertainty estimation via Track length importance Characterization (CLUTCH) method. Good agreement between the three methods was observed except for the sodium total and elastic cross-section and the uranium-235 total cross-section sensitivity coefficients where the multi-group adjoint method produced results approximately 14% and 7% lower than the IFP and CLUTCH methods, respectively.

1. Introduction

The Experimental Breeder Reactor-II (EBR-II) was a sodium cooled, metal uranium fueled fast reactor designed and built by Argonne National Laboratory in the late 1950′s. The reactor achieved initial dry criticality September 30, 1961, followed by criticality with sodium coolant present on November 11, 1963 (Koch, 2008). The ability to achieve criticality in the absence of coolant is a feature of fast reactors like EBR-II. The reactor thermal power was initially limited to 30 MW. The thermal power limit was eventually increased to 62.5 MW with a corresponding electrical output of 19 MW. EBR-II had unique capabilities some of which were proven during the Integral Fast Reactor program (Till and Chang, 2011). This program lasted from 1984 to 1994, when EBR-II was shutdown. The goal of the program was to solve many of the perceived problems with nuclear energy through scientific means. As a portion of the program, two landmark safety experiments were conducted in April 1986. The experiments involved loss of reactor coolant flow and loss of heat sink. For both experiments, the reactor was initially at full power and no automatic or manual reactor scram was used to terminate the transient. During both tests, the reactor shut itself down and achieved a safe steady state temperature due to the inherent design features of the reactor (Till and Chang, 2011).

To preserve important EBR-II reactor physics information, a benchmark evaluation is underway for proposed inclusion in the International Handbook of Evaluated Reactor Physics Benchmark Experiments (International Handbook of Evaluated Reactor Physics Benchmark Experiments, 2006). The reactor physics benchmark evaluation centers on the EBR-II core configuration associated with run 138B. The run 138B configuration was selected for the benchmark evaluation because it was the core configuration associated with the landmark reactor safety experiments conducted in 1986. The benchmark evaluation process involves creating a simulation model with as much detail as possible to match material and geometric conditions of run 138B. Results of the benchmark evaluation will benefit fast reactor development activities such as the South Korean fast reactor design (Yoo et al., 2016) and the French ASTRID design (4th-Generation Sodium-Cooled Fast Reactors/The ASTRID Technological Demonstrator, 2012).

Coupled with development of the benchmark evaluation, sensitivity analysis has been performed to help identify important EBR-II nuclide cross-sections. Sensitivity analysis helps quantify how strongly uncertainties in isotopic cross-sections and material compositions affect the calculated multiplication factor. There is a distinction between uncertainties in cross-sections and material densities. The uncertainties in the material densities reflect an unknown in the configuration that was created, and thus sets a

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http://dx.doi.org/10.1016/j.anucene.2017.06.058
0306-4549/

limit on the accuracy of what can be calculated even with perfect nuclear cross-section data. Similarly, uncertainties in the nuclear cross-section data limit how accurate a model can be even if an exact model were created. It is the latter that provides a purpose for the creation of benchmark models to aid in the improvement of nuclear data and reduce the uncertainties associated with the nuclear data. If calculation results do not match certain benchmark measurement values, a sensitivity analysis can help determine factors that might cause the difference. For this work, the goal was to determine how sensitive the effective neutron multiplication factor, k_{eff}, is to the various neutron cross-sections for isotopes in the system. Another goal in performing the sensitivity analysis was to determine the effect that the density of certain mixtures has on k_{eff}. Finally, the sensitivity analysis provided support for the homogenization effectiveness evaluation of the benchmark evaluation. Specifically, sensitivity results from a heterogeneous and homogeneous assembly model were compared to identify potential impacts of model homogenization.

2. EBR-II background

EBR-II was a pool type reactor rather than the more common loop type reactor. The reactor core, two primary coolant centrifugal pumps, and intermediate heat exchanger were all contained within a large stainless-steel vessel along with 337,000 liters of primary sodium coolant. With the pool type design, any leaks within the primary coolant piping would simply drain into the primary coolant pool. While such a leak would impact plant efficiency, no leakage of primary sodium coolant outside the vessel would occur. Heat from the primary coolant was transferred to a secondary sodium loop through a heat exchanger submerged within the primary pool. Thus, heat from the reactor was removed to the secondary sodium loop while minimizing neutron activation of the secondary sodium. Finally, the secondary sodium was used to generate superheated steam for electricity generation. Within the stainless-steel vessel, the EBR-II core was supported by a grid plenum structure and an upper reactor vessel cover that served as a neutron shield. Surrounding the core, within the reactor vessel, were radial layers of graphite and borated graphite shielding.

The design of EBR-II included many inherent safety features. For instance, the chemical compatibility between sodium and stainless-steel prevented corrosion and therefore minimized the risk of a radioactive material release due to corrosion. The sodium coolant was kept at near atmospheric pressure which made any leak easily controllable. The metal fuel, cladding, and metal coolant provided outstanding heat transfer. The large volume of sodium in the reactor vessel served as a large heat sink. Lastly, the reactor core would expand as the temperature increased resulting in greater neutron leakage. This extra leakage caused a large negative temperature reactivity feedback which automatically shut the reactor down. It is important to note that while EBR-II had a positive void coefficient, the overall reactivity coefficient was negative when the total reactivity feedback mechanisms were summed.

The EBR-II core consisted of 637 hexagonal shaped, removable assemblies. The assemblies were divided into three regions: the core, inner blanket, and outer blanket. The core region contained driver assemblies, each with 91 fuel pins. The driver fuel was 67% enriched uranium metal and was clad with stainless-steel. The core region also included two safety assemblies and eight control assemblies. Safety and control assemblies contained 61 driver pins instead of poison. Additional assemblies in the core region included stainless-steel dummies, half worth drivers, and experimental/instrumentation assemblies. The inner blanket region initially consisted of depleted uranium for demonstrating fuel breeding, however it was later replaced with stainless-steel reflectors. The run 138 B configuration included the stainless-steel reflectors. The outer blanket region consisted of depleted uranium. Fig. 1 shows a plan view of the EBR-II core layout.

Each EBR–II assembly was approximately 234 cm long, with the fuel section being just 34 cm long. Stainless–steel neutron reflectors were located above and below the fuel section. Additionally, orifices at the bottom of the assembly allowed for sodium coolant to flow through the assemblies. Fuel pins within each assembly were arranged in a hexagonal lattice as shown in Fig. 2.

3. Sensitivity analysis theory review

There are multiple methods for performing sensitivity analysis. The methods employed in this paper were direct perturbation, the multi-group adjoint method, continuous energy iterative fission probability (IFP) method, and the Contribution-Linked eigenvalue sensitivity/Uncertainty estimation via Track length importance Characterization (CLUTCH) method. Kiedrowski provides an in-depth examination of each method (Kiedrowski, 2017), whereas a brief synopsis is provided below.

A general sensitivity parameter S_{k,N_j} is defined as a response of k_{eff} to the atom density of N_j. In direct perturbation, the atom density of N_j is increased and decreased from the nominal value by a percentage which will generate a statistically significant response in k_{eff} (Rearden et al., 2011). The sensitivity parameter is defined in Eq. (1), where 0 is the initial unperturbed value for k_{eff} and the *jth* nuclide, and the + and − are results of the direct perturbation (Favorite et al., 2016).

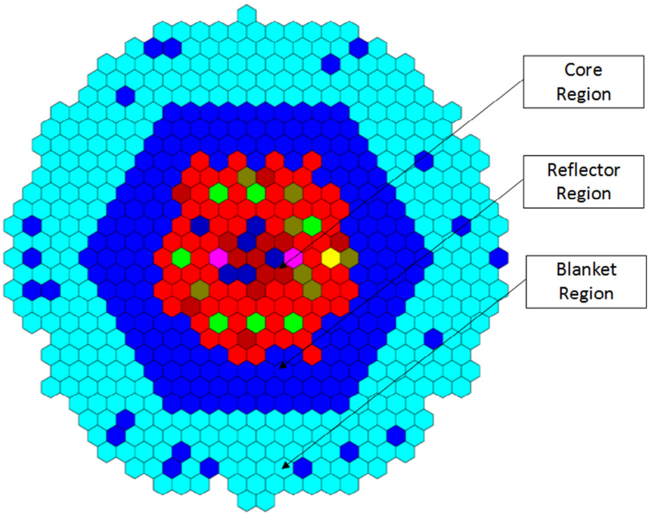

Fig. 1. EBR-II core layout.

Fig. 2. Fuel assembly fuel pin arrangement.