A One-Dimensional Benchmark Problem of Breed & Burn Reactor

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INTRODUCTION

The breed & burn reactor concept holds the great promise of significantly improving the nuclear fuel utilization such that the carbon-free electricity can be provided at current consumption rate for thousands of years. The commercial version developed at TerraPower is called traveling wave reactor (TWR) that aims at near-term deployment [1]. Among many technical challenges in designing such a reactor, the adequacy of nuclear analysis method is one area that deserves further examination. Typical design methods for fast reactors are based on deterministic methodology, e.g., the Argonne National Laboratory's tools, MC^2-2/DIF3D/REBUS-3 package [2]. Naturally, there is a need to benchmark the deterministic analysis suite. A one-dimensional benchmark problem of breed & burn reactor originally proposed by R. Petroski [3] is documented in this paper. In addition to the problem specification, the desired set of output neutronic parameters for comparisons are defined.

BENCHMARK PROBLEM SPECIFICATION

One-Dimensional Slab Model

In the infinite slab model, the fuel slab is modeled as a homogeneous mixture of uranium, sodium, and iron with a thickness of 5 cm. The breed & burn reactor core consists of 100 such fuel slabs operating at 48 W/cm^3. Note that the core volume includes all fuel slabs even though the power is only produced in the inner most region of 30-40 slabs. This core is symmetric with respect to the centerline and the vacuum boundary conditions are imposed on both core outer surfaces. Equilibrium cycles are assumed; where two depleted uranium (0.3 w/o enrichment) feed slabs are supplied every cycle from two outer-most locations and two burnt slabs are discharged in the center region. For simplicity, the refueling outage time is ignored between cycles.

Fuel Shuffling Sequence

From Table 1, the initial heavy metal loading density can be calculated as 9.5 gram/cm^3. The equilibrium cycle discharge fuel burnup is then calculated as:

$$B_d = \frac{100 \text{ slabs} \times 48 \frac{\text{W}}{\text{cc}} \times 450 \text{ days}}{2 \text{ slabs} \times 9.5 \frac{\text{g}}{\text{cc}}} = 114 \text{ MWd/kg}$$

The equilibrium cycle parameters depend heavily on the fuel shuffling sequence. In fact, the huge number of potential shuffling sequences provides enormous degrees of freedom for core designers to optimize the core performance. In order to describe the fuel shuffling in this benchmark, only half core will be considered and the slab locations are numbered from 1 to 50 sequentially from the center to the periphery. Only two shuffling sequences are considered:

A) Inward convergent shuffling: the fuel is sequentially shuffled inward.

B) Convergent divergent shuffling: the fuel is sequentially shuffled inward up to slab 11, and then skips to slab 1 and sequentially shuffled back out to slab 10.

Table 1. One-Dimensional Slab Model Specification

Slab thickness (cm)	5
Number of slabs	100
Power density (W/cm^3)	48
Equilibrium cycle length (days)	450
Feed fuel slab compositions (atoms/barn-cm, at 600 K)	
U-235	7.30×10^{-5}
U-238	2.40×10^{-2}
Na-23	6.52×10^{-3}
Fe-56	1.68×10^{-2}

Fuel shuffling sequence ($1 \le n \le 50$)

A) Inward convergent shuffling (discharge slab 1)

$$\begin{aligned} n &\leftarrow n+1, \quad n = 1,2,\cdots,49 \\ n &\leftarrow \text{Feed}, \quad n = 50 \end{aligned}$$

B) Convergent divergent shuffling (discharge slab 10)

$$\begin{aligned} n &\leftarrow 11, \quad n = 1 \\ n &\leftarrow n-1, \quad n = 2,3,\cdots,10 \\ n &\leftarrow n+1, \quad n = 11,12,\cdots,49 \\ n &\leftarrow \text{Feed}, \quad n = 50 \end{aligned}$$

REQUIRED RESULTS

The equilibrium cycle results are desired for both shuffling schemes. Three state points of interests are beginning of equilibrium cycle (BOEC), middle of equilibrium cycle (MOEC), and end of equilibrium cycle (EOEC). Specific required results are:

1) Global neutronic parameters including the eigenvalue k_{eff}, average number of fission neutrons per fission event $\bar{\nu}$, average recoverable

energy per fission $\overline{Q}$, at BOEC, MOEC, and EOEC.

2) Power density in units of W/cm^3 and the relative fission rate in each fuel slab at BOEC, MOEC, and EOEC.
3) Burnup distribution at EOEC. The slab burnup values should be reported in both MWd/kg and FIMA (Fissions per Initial Metal Atom).
4) Neutron balance sheet that includes isotopic number densities and reaction rates (nu-fission and absorption) in each fuel slab at BOEC and EOEC. The normalization is such that the neutron production (total nu-fission) is unity.

In addition to the numerical results, brief descriptions need to be provided such as the methods used in codes, the employed data libraries, the procedure of calculations including input/output files, and any additional assumptions made not stated in this paper. This benchmark problem is intended to offer a common target problem for neutronic analysis of breed & burn reactor cores, and users are encouraged to apply any of their analysis techniques to the problem.

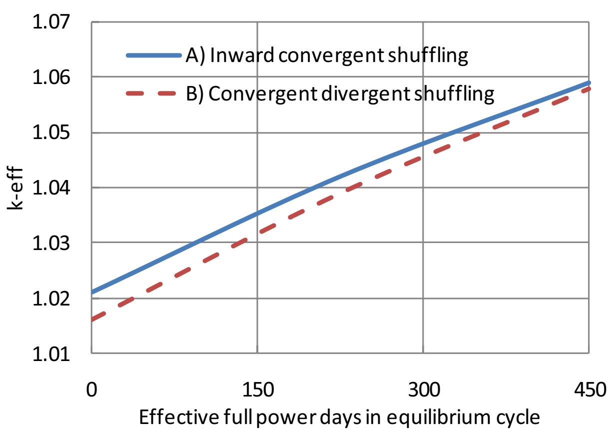

Fig. 1. Equilibrium cycle k-effective curves.

The example depletion curve results are shown in Fig. 1 (taken from Ref. [3]) using TerraPower's modified version of MCNPX [4,5]. In the future, as more results are available, it would be highly interesting to compare these results from various code systems based on different nuclear data libraries.

REFERENCES

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