Annals of Nuclear Energy 70 (2014) 90–95

Contents lists available at ScienceDirect

Annals of Nuclear Energy

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

Modeling space–time evolution of flux in a traveling wave reactor

Rijan Shrestha *, Rizwan-uddin

Department of Nuclear, Plasma and Radiological Engineering, University of Illinois, 104 S. Wright St, Urbana, IL 61801, USA

ARTICLE INFO

Article history:
Received 19 September 2013
Received in revised form 5 March 2014
Accepted 6 March 2014
Available online 28 March 2014

Keywords:
MCNPX
Traveling wave reactor
Flux profile

ABSTRACT

Simulations have been carried out using Monte Carlo code MCNPX to evaluate the space and time evolution of flux in a prototype traveling wave reactor under constant thermal power condition. A 3-D box-shaped model of the reactor is developed. The reactor core is divided into two primary regions: the smaller, enriched region with fissile material; and the larger non-enriched region with fertile material. This enrichment strategy is aimed to allow breed-and-burn in the core. The core, on the outside, is surrounded by shielding material of uniform thickness. To facilitate the study, these two primary regions in the core are further divided into thin slab-like regions referred to as cells. Results show propagation of flux profile from the enriched region to the non-enriched region at a near constant speed. Analyses of time evolution of local power density (power fraction) at specified locations in the core are presented. Space and time evolution of the overall core burn-up and localized burn-up are discussed.

1. Introduction

Limited availability of fissile isotopes in nature necessitates use of breeding for in situ production of fissile materials. Moreover, future nuclear reactor technology aims at achieving longer core life, higher burn-up and higher uranium utilization in a proliferation resistant fuel cycle. Fertile isotopes ^{238}U and ^{232}Th are, by neutron capture (n,γ) reactions, respectively converted to fissile isotopes ^{239}Pu and ^{233}U which could then be used as a fuel. This breed and burn mode was first suggested in 1958 by Feinberg. He proposed a self-regulating fast reactor without any long term reactivity control mechanism. Criticality in the core was to be maintained over long time by a combination of suitable fissile and fertile materials in an appropriate geometrical configuration. More recently, a Traveling Wave Reactor (TWR) which is to operate under the same principles of breed and burn using the ^{238}U–^{239}Pu fuel cycle was proposed (Feoktistov, 1989),

$$^{238}\mathrm{U}(n,\gamma)\rightarrow{}^{239}\mathrm{U}\rightarrow{}^{239}\mathrm{Np}\rightarrow{}^{239}\mathrm{Pu}\ (n,\mathrm{fission}) \quad (1)$$

The existence of a permanent plane solitary wave in a fertile medium modeled using one-group diffusion equation coupled with burn-up equations has also been shown (Chen and Maschek, 2008; Osborne et al., 2012). Teller, Ishiwaka and Wood designed a breed and burn model of a reactor using Monte-Carlo based TART95 code (Teller et al., 1996). CANDLE (Constant Axial shape of Neuron flux, nuclide densities and power shape During Life of Energy production) burn-up strategy was proposed soon after where overall neutron flux shape and power density distributions remain nearly the same over time but move along the axial direction (Sekimoto et al., 2001). Fomin and colleagues used multi-group diffusion equations and burn-up equations to demonstrate self-sustained regime of nuclear burn-wave in a critical fast reactor with mixed Th–U fuel (Fomin et al., 2011). TerraPower Inc. is currently conducting active research on this front (Ellis and Petroski, 2010). Preliminary results of a detailed study using Monte Carlo techniques to show traveling flux profile in a homogenized box reactor was reported by Shrestha and Rizwan-uddin in 2012. Saadi et al. demonstrated a constant power shape at equilibrium state by using a new code called MOBC that links MCNP and ORIGEN (2012). Very recently, Osborne and Deinert (2013) have reported results of a comparative study of fission wave carried out using Monte Carlo techniques and diffusion approximation.

The feasibility of propagation of a breed-and-burn wave in a fast reactor with an appropriate breeding region and an appropriate geometry has thus been established. Most studies conducted in the past have however analyzed breed-and-burn waves either with analytical techniques or using deterministic methods for simple one-dimensional cases. Detailed analyses for a 3-D case with continuous energy formulation using Monte Carlo methods are difficult to find in literature. This study uses Monte-Carlo MCNPX code to analyze a compact 3-D model of the TWR reactor with prescribed fissile and fertile (breeding) regions and provides results for space–time evolution of flux shape.

* Corresponding author. Tel.: +1 4015699731.
E-mail address: shresth3@illinois.edu (R. Shrestha).

http://dx.doi.org/10.1016/j.anucene.2014.03.011
0306-4549/

2. Core design and methodology

A box-shaped homogeneous core is modeled using MCNPX v27c (Pelowitz, 2011). The choice of using a rectangular core (over a right circular cylinder) is arbitrary since the primary motivation of this study is to analyze the evolution of flux profile over the core life as it moves axially. The leakage in the Cartesian geometry model will be a little higher compared to a right circular cylinder, but the *qualitative* results are expected to be the same. Hence, a right circular cylindrical core is better suited for a commercial design. The dimensions of the core are listed in Table 1. A schematic diagram of the core is shown in Fig. 1. The core consists of 85% fuel, 7% coolant and 8% cladding and structural material by volume. Owing to the relatively small size of the reactor core, a higher fuel volume fraction is needed to maintain criticality and to ensure a long core life. The low coolant volume fraction considered in this paper does not realistically represent the dimension of a real-sized reactor. It is chosen to make the reactor core compact with the aim of minimizing the computational cost associated with Monte-Carlo calculations.

Metallic fuel is chosen following the recommendation from ANL SMFR report (Chang et al., 2005). The fuel used is in the form of U-10 wt.% Zr. A higher peak burn-up of 12% was reported for metallic fuel compared to 9% for oxide fuel. Metal fuels are denser than oxide fuels, allowing for a higher specific power. In addition to that, lack of oxygen makes the neutron spectrum harder, which is desirable. Liquid sodium is used as a coolant and HT9 is used as cladding and structural material. In fast reactors, cladding and structural material should be corrosion resistant owing to irradiation by high fast flux ($\sim 10^{15}/cm^2$-s) in the core. HT9 has proven to be highly corrosion resistant in sodium (Allen et al., 2008).

Simulations were carried out with various combinations of enrichment region and enrichment levels. If the reactor core went sub-critical after startup and stayed sub-critical for extended period without automatically returning to criticality during a simulation, that combination of enrichment region and enrichment level was rejected and a new set of design parameters was chosen for the next simulation. This study was conducted with the set of parameters that kept the TWR core close to critical ($k_{eff} \sim 1$) for a core life of nearly 40 years.

Table 1
Core dimensions.

X (cm)	Length (axial)	140
Y (cm)	Width	90
Z (cm)	Height	90

Region A ($0\ cm < x < 30\ cm$) is enriched to 33% in U-235. By allowing enrichment greater than 20% and reducing the volume fraction of coolant and structural materials, leading to a compact and dense core, making a Monte-Carlo based criticality and subsequent burn-up calculations computationally cheaper. Region B ($30 < x < 140\ cm$) contains natural uranium (NU). Furthermore, the core is divided into smaller regions by planes parallel to the Y–Z plane. These planes are 2 cm apart. The model consists of 69 such planes, thus dividing the core into 70 smaller slab-regions stacked along the positive X-axis, henceforth referred to as cells. In Fig. 1, the left side of cell number1 is located at $x = 0$ cm, the left side of cell number 2 is located at $x = 2$ cm and so forth. Each cell has a volume of 16200 cm^3. The TWR core is surrounded on all sides by HT9 which has a uniform thickness of 10 cm.

Using the volume fractions of fuel, cladding, structure and coolant, corresponding absolute volumes occupied in each cell are calculated. Standard densities for these materials are used to calculate their masses in individual cell. Atomic weights are then used to compute the isotopic fractions of different nuclides in the cells. These isotopic fractions, given in Table 2, are used as input for MCNPX. The code is then used to simulate the core physics under constant thermal power of 350 MW. This condition of constant thermal power has obvious and interesting implications on the simulation results. In this study, MCNPX simulations are carried out with 145 cycles (40 inactive cycles) with 10,000 particles per history. The steady state (k) calculations are immediately followed by burn-up calculations in MCNPX. Convergence of k_{eff} in each steady state calculation is ensured by the 'normal distribution' at the 95% confidence level for collision, absorption and track length estimate of k. Furthermore, the standard deviation for each batch of steady-state k_{eff} calculation is found to be less than 0.0006. Time-steps are specified in the input deck for burn-up calculations. The first burn-up calculation is performed after 30 days of operation (to account for Xe buildup which starts accumulating after 2 days), and all subsequent burn-up calculations are carried out at time increment of 1200 days. Neutron fluxes in the cells are tallied at the end of each burn-up calculation.

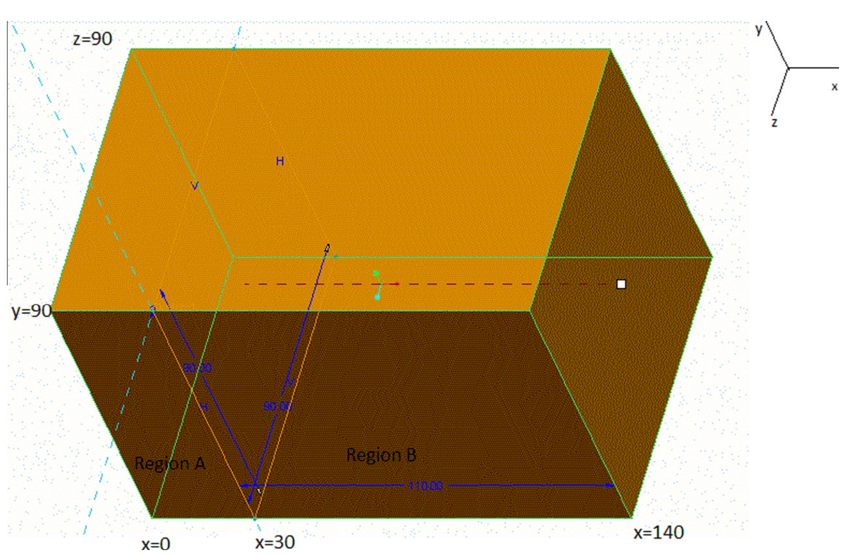

Fig. 1. Schematic diagram of TWR core.