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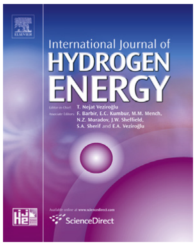

Asymptotic radial fuel shuffling mode for accelerator driven transmuter

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ABSTRACT

This paper deals theoretically with a radial fuel shuffling problem for an accelerator driven transmuter (ADT), which is similar to the concept of critical traveling wave reactor (TWR). The problem is formulated as a nonlinear eigenvalue problem based on the one-group diffusion theory, the macroscopic cross sections being approximated as functions of neutron fluence. A 2-D cylindrically symmetric core is considered and a discrete radial serial fuel shuffling scheme is modeled theoretically as a continuous process. Variations in mixed Uranium-Minor Actinide (U-MA) oxide fuel isotopic compositions fed in a lead cooled reactor are investigated numerically. It is shown that there are asymptotic (TWR) modes for certain fresh fuel compositions corresponding to certain eigenvalue k_{eff} and fuel drift speed. Up to about 40% MA content of total heavy metal (U + MA) k_{eff} reaches a value being slightly less than unity. The aim of this study is not to predict accurate results for a certain core design and fuel reloading scheme, but to show the existence of such fuel shuffling modes in an idealized TWR case. The showed possibility that the TWR charged with oxide fuel can be driven by an accelerator to destroy MAs by a large amount is of high interest for transmutation.

Introduction

A company called TerraPower, funded by Bill Gates, has developed a so-called traveling wave reactor (TWR) that receives a wide attention in the nuclear community. This concept is similar to those of studies mentioned in the following. It promises new advantages for the future nuclear energy, namely higher uranium utilization and less nuclear waste compared to once-through fuel cycle, but some technology and safety issues, which we do not address here, may have to be resolved. A TWR description based on the technology of sodium cooled fast reactor (SFR) can be found in Refs. [1,2]. It has been shown there that depleted or natural uranium is fed in a TWR by a radial fuel shuffling scheme and a standing breeding/burning wave is formed.

The radial fuel shuffling is today's conventional technique, where a fuel sub-assembly is taken out from one position and inserted into another one. If the fuel shuffling is carried out ring by ring in series, this can generate a fuel movement. On the other hand, the axial fuel shuffling is not common in convectional reactors, although the axial fuel shuffling (motion) can be dealt with theoretically and numerically much more easily than the radial one. This is why the TWR concept

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had been studied first in the axial direction, but its real design had to be considered later on in the radial direction through its fuel shuffling. Moreover the radial fuel shuffling is more suitable for an ADS with a target unit in the reactor center. Our recent studies [3,4] dealt with the mechanism of a standing wave generated by radial fuel shuffling and tried to get asymptotic solutions analytically as far as possible.

This paper is a continuation of those studies. It is shown that there are asymptotic TWR states for a certain reactor core fed with mixed Uranium (U) and Minor-Actinide (MA) oxide fuel, which are subcritical but near-critical, i.e. k_{eff} is less than but near unity, which can be driven by an accelerator and is suitable for MA transmutation purpose.

Formulation and modeling

The neutronics model applied in the following is the one-group diffusion theory coupled with burn-up equations neglecting radioactive decay processes, which has been studied extensively for critical TWRs [4,5], where both radial and axial fundamental traveling wave solutions have been obtained. Herewith we present the theoretical model briefly.

Diffusion model coupled by burn-up results

We consider a cylindrically symmetric core with a finite axial height (a 2-D case). The steady-state one-group diffusion equation in this 2-D case can be written for a critical configuration as

$$\nabla\cdot(D(\psi)\nabla\phi)+\left(\frac{\upsilon\sum_f(\psi)}{k_{eff}}-\sum_a(\psi)\right)\phi=0 \tag{1}$$

where the effective multiplication factor k_{eff} is introduced, which is an eigenvalue that measures the criticality of the asymptotic state in this nonlinear problem and for other variables we use standard notations, see Refs. [4,5]. The neutron fluence is defined as

$$\psi\left(\vec{\lambda},t\right)=\int_0^t\phi\left(\vec{\lambda},t\right)dt \tag{2}$$

where $\vec{\lambda}$ is the Lagrange coordinates of fuel material. If the fuel is not moving, then $\vec{\lambda}=(r,z)$ in the cylindrically symmetrical case.

The macroscopic data, such as D, Σ_f, Σ_a, in the above equation depend on the material composition that changes with fuel burn-up. This means that the diffusion equation has to be coupled with a burn-up model through the macroscopic coefficients D, Σ_f and Σ_a expressed as:

$$\Sigma_a=\sum_n N_n\sigma_{a,n},\quad \nu\Sigma_f=\sum_n N_n\nu_n\sigma_{f,n},\quad \Sigma_{tr}=\sum_n N_n\sigma_{tr,n},\quad D=\frac{1}{3\Sigma_{tr}} \tag{3}$$

where n is the isotope index of all materials (fuel, coolant, and structure treated as a homogeneous composition), N_n is the burn-up (time) dependent atom number density, Σ_{tr} is the macroscopic transport cross section, $\sigma_{a,n}$, $\nu_n\sigma_{f,n}$ and $\sigma_{tr,n}$ are the corresponding microscopic quantities.

In general, if the radioactive decay processes are neglected, the macroscopic data can be expressed as functions of neutron fluence for certain initial material compositions. These functions can be obtained by solving burn-up equations. In some special cases there are even analytic solutions, see Ref. [5]. For this study a cross-section generation and burn-up code, TRAIN [6], is applied for obtaining the macroscopic cross sections.

Radial fuel shuffling

As investigated in Refs. [3,4], the standing breeding and burning wave can be generated by a radial fuel shuffling. The fuel assemblies are shuffled ring by ring in series in the radial direction, either outward or inward. This causes a fuel drifting. Thereby a discrete radial fuel shuffling in practice can be approximated theoretically as a continuous fuel drifting process. We take the inward fuel drifting as an example, shown in Fig. 1.

Fuel is fed in at $r=R$ and discharged at $r=r_0$, where R is the outer radius of the core and r_0 the inner radius. Since the solid structure that supports fuel assemblies is not compressible, the fuel drift speed should be constrained by area conservation. Assuming the area of fuel sub-assemblies ΔA is loaded into the core or unloaded from the core in the time interval Δt, due to the area conservation we have, at any r,

$$\upsilon\cdot\Delta t\cdot 2\pi\, r=\Delta A\Rightarrow \upsilon(r)=\frac{\upsilon_A}{2\pi r} \tag{4}$$

where $\upsilon_A=\Delta A/\Delta t$ is the shuffling speed of the fuel element area, which is a constant in the problem, The neutron fluence has been derived in Ref. [4] as, for the asymptotic state with the inward fuel drifting,

$$\frac{\partial\psi}{\partial r}=-\frac{2\pi r}{\upsilon_A}\phi \tag{5}$$

This equation is a supplement to (1) presenting the relationship between ϕ and ψ.

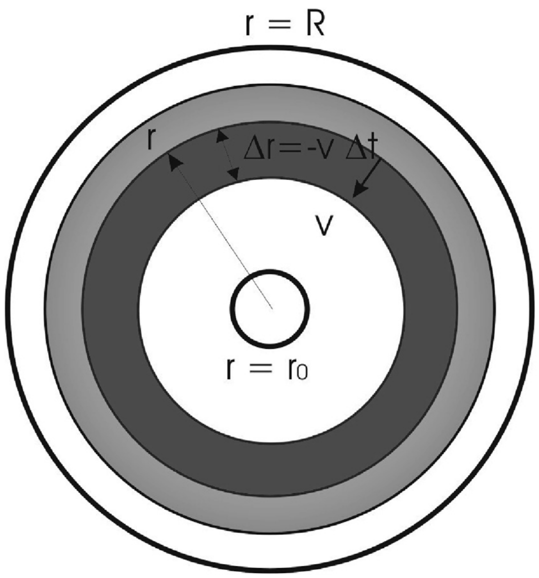

Fig. 1 – Continuous model of radial inward fuel shuffling.