Annals of Nuclear Energy 50 (2012) 44–49

Contents lists available at SciVerse ScienceDirect

Annals of Nuclear Energy

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

Startup of "CANDLE" burnup in a Gas-cooled Fast Reactor using Monte Carlo method

M. Kheradmand Saadi [a,*], A. Abbaspour [b], A. Pazirandeh [a]

[a] Department of Nuclear Engineering, Science and Research Branch, Islamic Azad University, Tehran, Iran
[b] Department of Electrical Engineering, Sharif University of Technology, Tehran, Iran

ARTICLE INFO

Article history:
Received 13 May 2012
Received in revised form 23 July 2012
Accepted 29 July 2012
Available online 21 September 2012

Keywords:
CANDLE
Gas cooled Fast Reactor
Monte Carlo depletion
Depleted uranium

ABSTRACT

During the past decade, the CANDLE burnup strategy has been proposed as an innovative fuel cycle and reactor design for complete utilization of uranium resources. In this strategy the shapes of neutron flux, nuclide densities and power density distribution remain constant but the burning region moves in axial direction. The feasibility of this strategy has been demonstrated widely by using the diffusion technique in conjunction with nuclide transmutation equations. On the other hand since the Monte Carlo method provides the exact solution to the neutron transport, the Monte Carlo technique is becoming more widely used in routine burnup calculations. The main objective of this work is startup of CANDLE burnup in a Gas cooled Fast Reactor using a Monte Carlo burnup scheme. In this case only natural or depleted uranium is required for fresh fuel region. However, the construction of the first CANDLE core is faced with a big problem. In equilibrium state the burning region contains a spectrum of fission products as well as higher actinides. These isotopes are not easily available for constructing the initial CANDLE core. The solution is startup of a special reactor using the enriched uranium in starter zone. At the end of core life the fuel for the next core is produced with the composition close to the equilibrium state. An originally MCNP–ORIGEN linkage program named MOBC has been used for criticality and isotopic evaluation of the core. The results of analysis showed that the use of burnable absorber rods for positive reactivity swing offset is necessary. In this regard the multiplication factor changes are limited in acceptable margin where the maximum reactivity swing is 655 pcm during a transient and 180 pcm during equilibrium state. On the other hand, although the power shape changes drastically in the earlier stage of core operation, it remains constant during the equilibrium state. In summary, by using the enriched uranium as a starter fuel the achievement of an equilibrium state is possible.

1. Introduction

1.1. History

Over the past two decades, the mankind long term energy supply has been of great concern. An optimal energy technology for the future must be economically attractive, environmentally benign, sustainable and scalable to global use. Nuclear energy is an only existing resource, comes close to fitting all of the societal requirements for an optimal energy source. However, the current nuclear fuel cycle has some attributes that make it challenging to expand to a global scale. The poor fuel utilization is an outstanding one. The present once through fuel cycle in light water reactors utilizes only 0.7% of natural uranium. For this case 80–90% of original natural uranium is left as depleted uranium. On the other hand the development of present fast reactors with closed fuel cycle becomes slow due to concerns about the risks of proliferation from reprocessing. In this regard various innovative nuclear reactor designs have been proposed for complete utilization of nuclear fuel resources. The capability to operate without reloading or shuffling of fuel for reasonable long periods of time is a unique characteristic in all of the designs. This characteristic is consistent with plant economy, proliferation concerns and considerations of energy security, with no fresh or spent fuel being stored at the site during reactor operation.

Historically, Teller et al. (1996) discussed an innovative approach for completely automated nuclear reactor for long term operation. Their concept is based on a cylindrical core comprised of a relatively small critical system that ignites a propagating region of criticality in a much larger, initially subcritical region. The Teller concept has been followed by Van Dam (2000, 2003) who proposed a fundamental analysis of self stabilizing criticality waves.

CANDLE is a similar innovative burnup strategy which has been proposed by Sekimoto and Ryu (2000) and Sekimoto et al. (2001) in the first decade of new century. CANDLE stands for Constant Axial Shape of Neutron Flux, Nuclide Densities and Power Shape, During Life of Energy Production. In this strategy which presents the candle-like burnup, the shapes of neutron flux, nuclide densities and power density distributions remain constant and burning region

* Corresponding author. Tel./fax: +98 21 44869656.
E-mail address: Mohsen.Kheradmand@gmail.com (M. Kheradmand Saadi).

0306-4549/$ - see front matter © 2012 Elsevier Ltd. All rights reserved.
http://dx.doi.org/10.1016/j.anucene.2012.07.019

moves at a speed proportionate to the power output along the core axis. At the end of each cycle when the burning region reaches the end of the core, the spent fuel region is removed and fresh fuel is added in the direction of burnup as shown in Fig. 1. Recently a similar concept known as Traveling Wave Reactor (TWR) is being developed by TerraPower Company for commercial usage (Ellis et al., 2010). The company says it is in licensing discussions with reactor manufacturers (Wald, 2009).

1.2. CANDLE burnup strategy

The feasibility study of CANDLE has been demonstrated widely by implementing this burnup on different reactor types (Ohoka and Sekimoto, 2004; Sekimoto, 2005a; Nagata et al., 2009; Nur Asiah et al., 2009; Yanti et al., 2010). In all cases, the reactor core design typically has a starter zone and a very tall axial fresh fuel zone. In the case of fast spectrum reactor, only natural or depleted uranium is required as fresh fuel and the most promising application of this burnup strategy belongs to this type. In this regard, the fresh fuel zone is known as depletion zone for fast reactors. The starter zone is used for initial power generation and ignition of burning region in the depletion zone. This is accomplished by use of leaking neutrons to transmute the ^{238}U to ^{239}Pu in the depletion zone. This in situ fissile material production and consumption is followed by significant power generation with continuing core operation. In the equilibrium state of a CANDLE reactor, the burning region contains a spectrum of fission products as well as higher actinides. These isotopes are not easily available for preparing the burning region of the initial core and hence it might be difficult to fabricate the burning region using only easily available stable isotopes. Burnable absorber rods may be necessary in the case where an ideal initial core could not be prepared and a positive reactivity swing exists. If this happens, it might be more appropriate to build a special reactor only for the first several cores with burnable absorbers installed to control the excess burnup reactivity. When the first several cores are burned, fuel for the remaining core is produced with the composition close to that of an ideal CANDLE core.

1.3. Article overview

In this work the startup of a CANDLE Gas cooled Fast Reactor (GFR) will be evaluated using Monte Carlo burnup technique. The enriched uranium as well as depleted uranium are accommodated in starter and depleted zones respectively. This analysis is a starting point to reach the equilibrium state where only depleted uranium is fed to the core. The CANDLE Gas cooled Fast Reactor will be introduced in Section 2. The method of analysis as well as simulation results will be discussed in Sections 3 and 4 respectively.

2. GFR CANDLE type

2.1. Reactor and fuel design

The Gas cooled Fast Reactor (GFR) is one of the six systems selected for viability assessment in the Generation IV program. The GFR combines the advantages of fast spectrum systems with those of high temperature systems. The fuel assembly geometry dimensions of a 2400 MW t GFR design described by Ramirez et al. (2010) are selected as the starting point for the CANDLE type GFR design. Table 1 gives the characteristics of GFR CANDLE reactor. In this work the reactor core has the $\frac{1}{6}$ symmetric shape and consists of identical fuel assemblies in radial direction. The fuel assembly and core models are given in Figs. 2 and 3 respectively.

The composition of fuel and clad are changed according to in progress researches. The UN^{15} is selected as a fuel. This fuel type presents high fissile density and thermal conductivity. Enrichment of N^{15} to 99.5–99.9% minimizes neutron losses and amount of radioactive C^{14}, produced as a byproduct of the reaction: $n + \mathrm{N}^{14} \rightarrow \mathrm{C}^{14} + \mathrm{P}$.

Nitride fuel exhibits higher swelling rates and hardness than oxide fuel, so a lower density would allow a greater control over the fuel fragmentation behavior and pellet clad mechanical interaction during power ramps (Feng et al., 2011). Therefore although it is possible to fabricate nitride fuel at 95% TD, the physics calculations in this work were performed with 85% TD. The clad is ODS (Oxide Dispersion Strengthened) this clad type is commercially available and has a large chromium and aluminum content which gives the material excellent oxidation resistance (Yarsky, 2005). The melting point of ODS is 1482 °C and the material is creep resistant up to 1300 °C. Also this clad presents a good neutronic performance via low parasitic absorption cross section and very low helium production rates.

2.2. Initial core design

As was discussed earlier the fission products as well as higher actinides are not available to construct the initial core design. Previously, the startup simulation of an initial CANDLE core has been studied by Sekimoto and Miyashita (2006). In their work, Actinides in equilibrium state are simulated by enriched uranium with changing enrichment along the core axis. However, this technique is an artificial one and is not practical. Moreover the core evolution to its equilibrium state is not sensible.

The present approach in realizing the equilibrium state is based on external neutron source supply (Teller et al., 1996). Although the power shape changes drastically in earlier stage of the initial core but it provides a practical scheme in realizing the equilibrium state and the core composition evolution can be monitored efficiently. Therefore, the design of initial CANDLE Gas cooled Fast Reactor has been performed by choosing the enriched uranium as a starter zone fuel and depleted uranium as a fresh fuel. The height of starter and depleted zones are 120 cm and 360 cm respectively. In order to enhance the axial propagation of the burning zone and smooth variation in flux and power density distributions, different enriched fuels are accommodated axially in starter zone: 13%, 7% and 3% from the core bottom with the length of 96 cm, 12 cm and 12 cm respectively.

3. Monte Carlo burnup analysis

The numerical analysis of previous works (Ohoka and sekimoto, 2004; Sekimoto and Udagawa, 2006; Ismail et al., 2007; Nagata

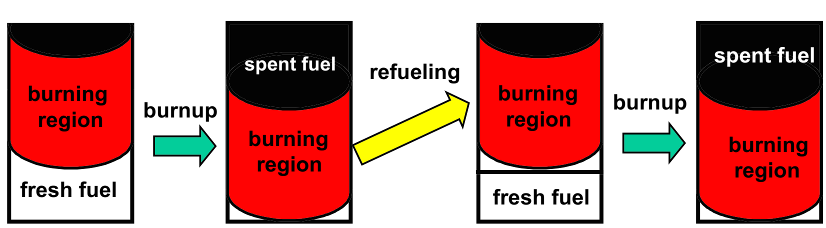

Fig. 1. CANDLE burnup strategy.