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Neutron Balance Method for Estimating Ignition Fuel Configuration in Candle Reactor

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Abstract

Candle reactor exhibits unique operational characteristics, where the configuration of the ignition fuel region directly influences the establishment of the wave propagation. This study employs neutron balance analysis throughout the lifespan of the reactor to estimate the optimal fuel configuration for the ignition region, providing valuable insights for the accurate and efficient establishment of a Candle mode of reactor.

Keywords

Neutron Balance Method; Candle Reactor; Ignition Fuel Configuration.

1. Introduction

The Candle reactor is a burning strategy for in-situ breeding and burning fast reactors, where the burning region in the core moves uniformly along the axial direction, resembling the burning process of a candle. This once-through fuel cycle strategy offers excellent neutron economy and deep burn-up, resulting in high utilization of uranium resources [1].

After the initial core establishment in the Candle reactor, self-sustained burning can be achieved by adding depleted uranium into the core. Currently, there are two approaches to realizing the initial core. One approach involves extracting all nuclide components in a simulated equilibrium state and reconstructing them according to their respective compositions. However, the extraction of plutonium requires post-processing facilities, making this method unsuitable for constructing the initial core [2]. The other approach is the exogenous neutron supply method, which involves placing additional ignition regions outside the breeding region [3]. Enriched fissile nuclides are loaded in the ignition region, and the excess neutrons produced by fission irradiate the depleted oil loaded in the adjacent breeding region, converting fertile nuclides into fissile nuclides. These bred nuclides are then burned in situ, exhibiting a wave-like propagation pattern with the breeding wave preceding the burning wave. The fuel configuration in the ignition region directly affects the establishment of the Candle burning mode and its performance. Therefore, it is of great significance to identify the minimum configuration that meets the requirements. However, due to the complex geometric structure and large number of nuclides in the core, the screening process is challenging.

This study proposes a neutron balance method to estimate the minimum configuration of the ignition region fuel based on the neutron requirements of nuclear fuel in the breeding region and the neutron excess provided by the ignition region fuel with different enrichments. The neutron excess can be conveniently calculated using an infinite medium (0-D) model, which not only reduces computational complexity but also improves analysis speed.

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2. Neutron Excess Method

2.1 Definition of Neutron Excess

The neutron excess (ΔN) is defined as the difference between the number of neutrons produced and absorbed per unit volume within a certain burnup evolution time [4]:

$$\Delta N = \int_{t=0}^{core\ life} dt\big(\Delta P(t) - \Delta A(t)\big) \tag{1}$$

where ΔP represents the neutron production rate per unit volume, including the fission rate of nuclear fuel and the rates of (n,2n) and (n,3n) reactions. ΔA represents the neutron absorption rate per unit volume, including fuel absorption, core boundary leakage, and control system absorption.

2.2 Analysis of Neutron Excess

Over the entire lifespan of a reactor, the cumulative neutron excess in the system is derived from the "reactivity deviation", which is the difference between the effective multiplication factor of the fuel ($\overline{k_{fuel}}$) and the effective multiplication factor of the system ($\overline{k_{eq}}$):

$$\int_{fuel} dV\big(\Delta N_{adj}\big) = \int dt\big(\overline{k_{fuel}} - \overline{k_{eq}}\big)\left(\int_{fuel} dV(\Delta A)\Big|_{cycle}\right) \tag{2}$$

Where ΔA represents the total number of neutrons absorbed per unit volume, $k \equiv \frac{\int_{fuel} dV\Phi V_f}{\int_{fuel} dV\Phi V_a}$ represents the total neutron production rate divided by the total neutron absorption rate within the fuel. Assuming that the transient state ($\overline{k_{fuel}}$) is approximately equal to the equilibrium state ($\overline{k_{eq}}$), the total neutron excess of the system remains conserved throughout the entire lifecycle of the reactor, with the cumulative neutron excess being the same at the initial and final moments. If $\overline{k_{fuel}} \neq \overline{k_{eq}}$, the cumulative neutron excess will be positively adjusted. However, it is desirable to minimize the excess reactivity during the transient state to reduce neutron losses in the control system and, consequently, the demand for ignition fuel loading.

The neutron excess in the system over the entire reactor operating cycle originates from three aspects: ignition fuel, transient state, and equilibrium state [5]:

$$\int_{fuel} dV\big(\Delta N_{adj}\big) = \int_{starter\ fuel} dV\big(\Delta N_{adj}\big) + \int_{transition\ fuel} dV\big(\Delta N_{adj}\big) + \int_{eq-cycle} dV\big(\Delta N_{adj}\big) \tag{3}$$

The third term on the right-hand side of Equation (3) can be directly obtained from the equilibrium state. For a Candle reactor, the burning wave moves slowly, and the breeding fuel is burned to a high burnup depth, exceeding the minimum burnup depth but not reaching the maximum attainable burnup. The breeding material remains in a neutron excess state throughout the equilibrium state operation, without the need for external excess neutrons. The transient state breeding fuel contains a small number of fissile nuclides and a large amount of fertile nuclides. It remains in a neutron-deficient state until it reaches the minimum burnup depth. Therefore, excess neutrons must be supplied from the outside to achieve neutron excess equilibrium in the system. This means that the second term, the total neutron excess (negative value) of the transient state breeding fuel, must always be balanced by the first term, the neutron excess (positive value) of the ignition fuel, providing recommendations for the configuration of the ignition fuel.

The actual neutron excess of the ignition fuel depends on its specific evolution history, which can be obtained by simulating the detailed evolution process using sophisticated models. Designing and

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simulating such transients is a complex fuel management problem, and analyzing numerous ignition fuel configuration schemes challenging. Fortunately, the neutron excess can be estimated directly using a simple infinite medium (0-D) model.

3. Candle Reactor Simulation and Neutron Excess Analysis

The simulated Candle model in this study is a sodium-cooled fast reactor utilizing U-Zr alloy fuel [6], as shown in Fig. 1. The core is divided into two regions: the ignition region, represented by the red area on the left side of the core, loaded with fuel enriched to 10.3%; and the breeding region, represented by the green area on the right side of the core, consisting of depleted uranium-zirconium alloy. The core has a diameter of 400 cm and is surrounded by a 50 cm thick depleted uranium reflector (yellow area). The volume ratios of fuel, coolant, and structural materials in all fuel regions are 37.5%, 30%, and 20%, respectively. The core is designed to operate at a rated thermal power of 3000 MWt, with a total initial heavy metal loading of 826 tons.

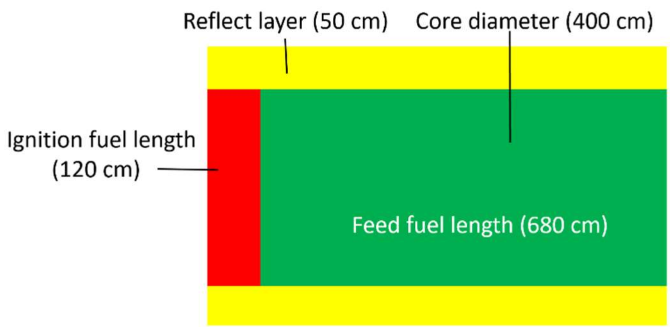

Fig. 1 Schematic diagram of core geometry

The evolution of the core throughout its lifetime is simulated using the Monte Carlo code MCNPX version 2.6 [7], with the burnup calculations performed by coupling MCNPX steady-state calculations with the CINDER90 burnup code [8].

3.1 Neutron Excess in Equilibrium State

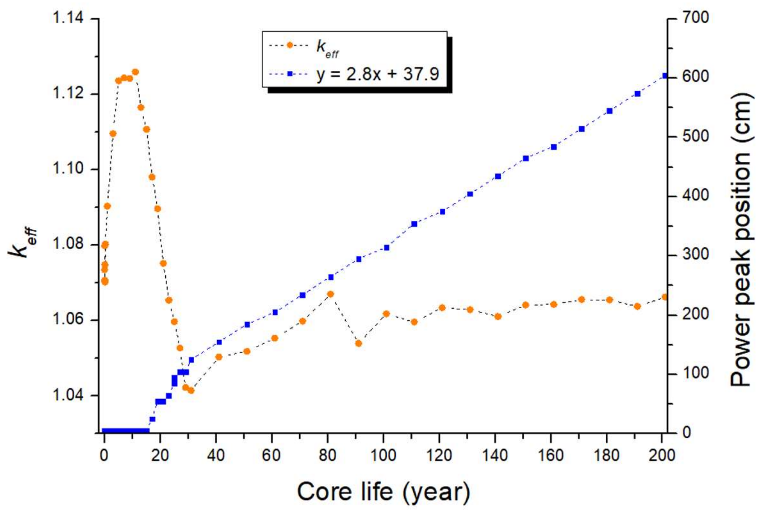

Fig. 2 The core effective multiplication factor and power peak position

By simulating and calculating, the axial positions of the effective multiplication factor and the peak power density in the core change with the operating time, as shown respectively by the orange dots and blue squares in Fig. 2. As indicated in the figure, at the beginning of the core lifetime, the effective multiplication factor (keff) gradually increases due to the rapid accumulation of fissile isotopes in the ignition region. It then decreases gradually as the fuel undergoes fission. Subsequently, it increases again as the breeding fuel accumulates in the breeding region, eventually reaching a stable state. Once the system reaches a self-sustaining equilibrium state, the effective multiplication factor remains stable, with a maximum variation of only about 0.5% over the core lifetime.

The power is concentrated within a narrow region, known as the burnup region, which moves uniformly with time, as shown by the blue squares in Fig. 2. The velocity of the burnup wave is proportional to the power, and at a total thermal power of 3000 MWt, it corresponds to a velocity of approximately 2.8 cm/year.

The temporal variation of the relative power distribution can be used to describe the characteristics of the burnup wave, as shown in Fig. 3. At the beginning of the lifetime, the power is mainly concentrated in the ignition region (0-120 cm), while the power distribution outside this region can be neglected. As the burnup of 235U and the accumulation of fission products progress, the power in the ignition region gradually decreases. However, in the breeding region adjacent to the ignition region, 238U is converted to 239U under the irradiation of excess neutrons, and 239U, after two β-decays, is transformed into fissile isotope 239Pu. As the accumulation and burnup of 239Pu occur, the power density near the breeding region also increases, resulting in the formation of a propagating wave. As the burnup wave gradually enters a self-sustaining stage, the Candle core transitions from a transient state to an equilibrium state, and the shape of the burnup wave no longer changes with time, slowly moving forward at a stable velocity.

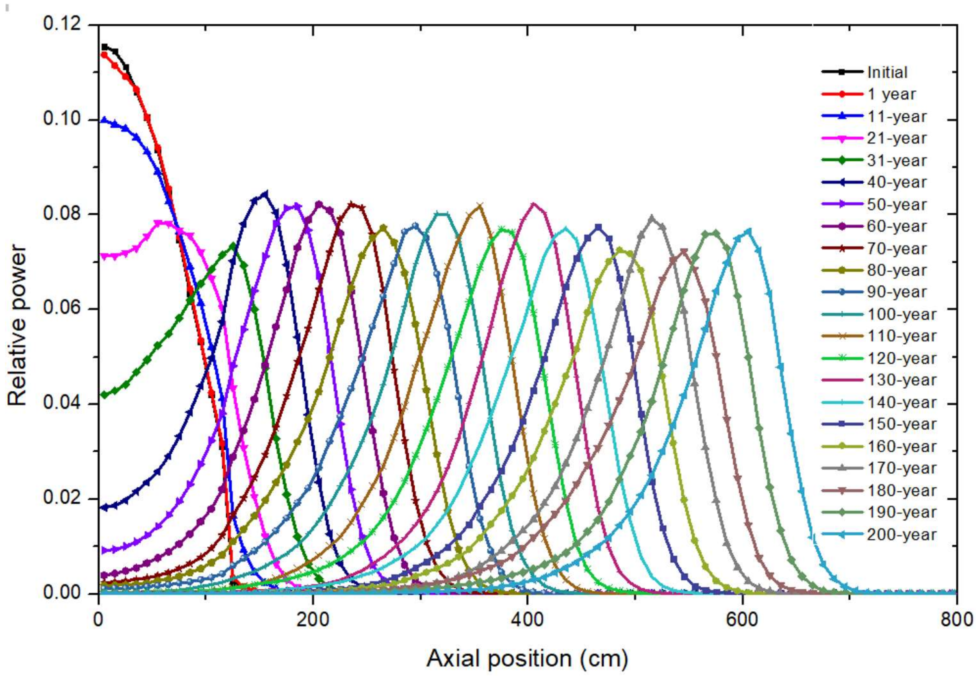

Fig. 3 Propagations of power density with axial position

The neutron excess at various locations in the core at the beginning of the equilibrium cycle (BOEC) and the end of the equilibrium cycle (EOEC) is calculated and integrated over the positions, resulting in a neutron excess of NEBOEC = 1.833×10-4 mol/cm2 at BOEC, and NEEOEC = 1.291×10-4 mol/cm2 at EOEC. It can be observed that throughout the equilibrium cycle, from the beginning to the end, the core remains in a neutron excess state, requiring no external neutron supply. The equilibrium state itself can sustain the reaction and even output excess neutrons to the surroundings.

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3.2 Fuel Configuration Estimation for the Ignition Fuel Region

The variation of neutron excess over time for the statistical core breeding fuel is illustrated in Fig. 4. It is evident that the transitional breeding fuel is in a state of neutron deficiency before reaching the minimum burnup requirement. The number of absorbed neutrons exceeds the number of generated neutrons, necessitating an external supply of neutron excess to achieve neutron balance within the system. Given that the neutron excess in the equilibrium state of the Candle core is positive, the crux of neutron balance lies in providing a sufficient positive neutron excess to the ignition zone fuel before the transitional fuel reaches its minimum burnup, while simultaneously neutralizing the negative neutron excess required by the transitional fuel.

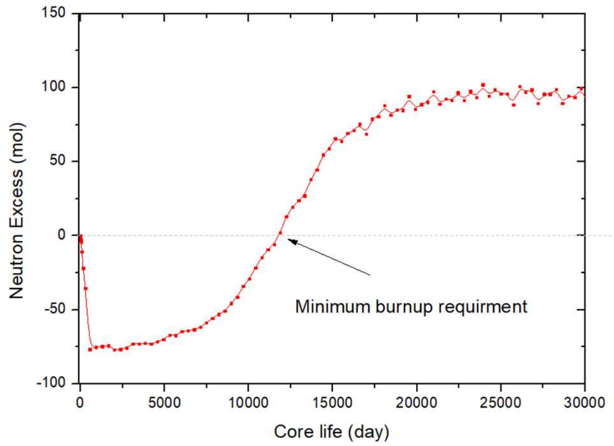

Fig. 4 Neutron excess of transition feed fuel

By integrating the neutron excess before reaching the minimum burnup requirement, the neutron excess demand of the transitional breeding fuel before the breakeven point can be obtained. This demand is illustrated by the red hexagon in Fig. 5 (taken in absolute value for ease of comparison). The evolution of neutron excess over time, corresponding to different enrichments of 7%, 8%, 9%, 10.3%, 11%, 12%, and 13% of 235U in the ignition zone, is depicted by the black dashed lines. The ignition zone is geometrically configured as a cylinder with a diameter of 400 cm and a height of 120 cm.

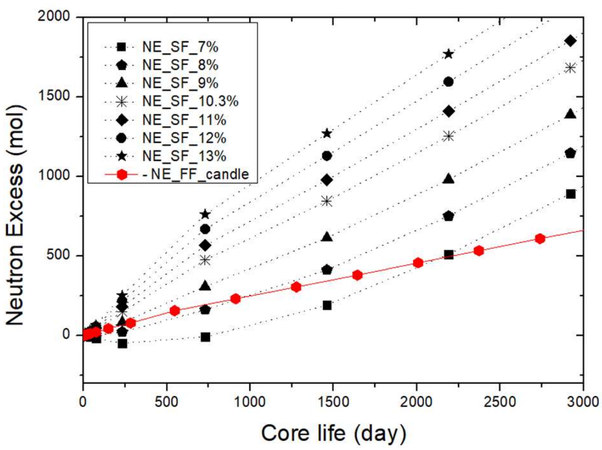

Fig. 5 Neutron excess of ignition fuel and feed fuel

For the reactor to operate, the system needs to be in a neutron balance state, where the cumulative neutron excess in the system is always positive. When the enrichment of the fuel in the ignition region is only 7%, the ignition region is in a neutron deficit state. As the enrichment increases to 8%, the ignition region reaches a neutron excess state, where it can provide excess neutrons to the breeding fuel. However, from the beginning to 1000 days of operation, the ignition region cannot provide enough excess neutrons to meet the demand of the transition breeding fuel, as indicated by the black dashed line below the red solid line. If the enrichment continues to increase to 9%, the excess neutrons provided by the ignition region can just meet the demand for the breeding fuel. Therefore, the ignition region can start the Candle reactor when the fuel enrichment in the ignition region is 9%t. When the enrichment in the ignition region exceeds 10.3%, the supply of excess neutrons greatly exceeds the demand, resulting in a neutron excess state in the Candle reactor, which leads to a decrease in uranium resource utilization.

The above calculation process assumes the geometry of the ignition region fuel and the total power of the core and uses the neutron balance method to estimate the enrichment configuration requirement for the ignition region fuel. However, in practical applications, the enrichment of the ignition region fuel and the total power of the core can be specified in advance, and the neutron balance method can be used to estimate the geometric size of the fuel.

4. Conclusion

This study has presented a neutron balance analysis method for estimating the fuel configuration in the ignition region of Candle reactors. By considering the neutron excess contributions from different fuel regions, the minimum fuel configuration that meets the neutron balance requirements can be determined. This estimation approach offers a practical and efficient way to optimize the performance of Candle reactors. Future research can focus on refining the neutron balance analysis method and incorporating more detailed fuel evolution models to further improve the accuracy of fuel configuration estimation. Additionally, experimental validation of the estimated fuel configurations can provide valuable insights for the practical implementation of the Candle reactor.

Acknowledgments

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