The optimization of Double Solitary Waves Reactor with depleted uranium

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Abstract

CANDLE reactors are a type of fast reactor that burn depleted uranium or natural uranium without chemical reprocessing. One of the crucial challenges in practice is high material radiation damage for the CANDLE reactor. The Double Solitary Waves Reactor (DSWR), with double separated ignition zones, was proposed to reduce material radiation damage while maintaining total output power. In this study, a fast spectrum reactor cooled by liquid metal was adopted and the optimization scheme of the DSWR was performed to reduce material radiation damage. The optimization schemes included ignition zone fuel enrichment and fuel density. The parameters, such as infinite medium factor, fuel burnup, the density of U-235, U-238 and Pu-239 were demonstrated to achieve the design goals, which was the reduction of discharged fuel burnup from 380 GWd/T to approximately 200 GWd/T to yield to engineering technology.

Full Text

Preamble

Optimization of a Double Solitary Waves Reactor with Depleted Uranium

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Abstract

CANDLE (Constant Axial shape of Neutron flux, nuclide Number Densities and power shape) reactors are a type of fast reactor that can burn depleted uranium or natural uranium without chemical reprocessing. One of the crucial challenges in practical implementation is the high material radiation damage in CANDLE reactors. Double solitary waves reactors (DSWR), featuring two separated ignition zones, were proposed to reduce material radiation damage while maintaining total output power. In this study, a fast spectrum reactor cooled by liquid metal was adopted, and optimization schemes for the DSWR were performed to reduce material radiation damage. The optimization schemes included variations in ignition zone fuel enrichment and fuel density. Key parameters such as the infinite medium multiplication factor, fuel burnup, and densities of U-235, U-238, and Pu-239 were analyzed to achieve the design goals, which were to reduce the discharged fuel burnup from 380 GWd/T to approximately 200 GWd/T to make the design compatible with existing engineering technology.

Keywords: Depleted uranium, Breed-and-burn reactors, CANDLE reactors

Introduction

Nuclear energy is a carbon-free energy source that helps mitigate global warming. However, traditional light water reactors have very low uranium utilization rates, below 1%, making them unsustainable. China's nuclear industry has proposed a Three-Step National Strategy for Nuclear Energy Development, encompassing thermal neutron reactors, fast neutron reactors, and fusion reactors. While conventional fast breeder reactors can enhance uranium utilization, they rely heavily on chemical fuel reprocessing, which presents several challenges including negative environmental impacts and rising fuel costs that may become unacceptable. Moreover, approximately 100,000 tons of accumulated depleted uranium resources, currently considered nuclear waste, await disposal. Breed-and-burn (B&B) reactors, first conceptualized by Feinberg in 1958, or CANDLE reactors, are designed to achieve high uranium utilization without chemical fuel reprocessing by using depleted or natural uranium.

Following earlier studies by Teller et al. (1996) and Seifritz (1997), the CANDLE burnup strategy was proposed by H. Sekimoto and colleagues (Sekimoto et al., 2001; Ohoka and Sekimoto, 2004; Sekimoto et al., 2006, 2009, 2014). The characteristics of the CANDLE burnup strategy were thoroughly revealed through numerical methods, with studies showing that discharged fuel burnup could reach as high as 380 GWd/Ton. Due to the constant profile of neutron flux and nuclide density, solitary wave theory from non-linear systems was adopted to explain this phenomenon. Various types of CANDLE reactors have been analyzed, including solitary burn-up waves (Seifritz, 1997; Chen et al., 2012), self-organizing breeding/burning waves (Fomin et al., 2005, 2008), self-stabilizing criticality waves (Dam, 2000), and solitary waves (Huang, 2015, 2022, 2025).

One significant challenge for deploying CANDLE reactors in practice is the limitation of current materials. The designed discharged fuel burnup of 380 GWd/Ton corresponds to approximately 500 displacements per atom (DPA) for fuel pellets or cladding, which exceeds current material capabilities. Several methods have been proposed to address this challenge. One approach adopts radial fuel shuffling schemes, similar to radial TWR concepts. Radial fuel shuffling resembles current batch loading modes but feeds with depleted or natural uranium. However, problems of extremely high discharged fuel burnup persist, with peak burnups of 28% FIMA (Fission of Initial Metal Atoms) (Hejzlar, 2021), ~48% FIMA (Widiawati et al., 2022), and average discharged fuel burnup of 27.8% FIMA (Zheng et al., 2016), all exceeding current technology limits and remaining unsolved.

Another proposed solution involves rotational fuel shuffling (Obara et al., 2018, 2019, 2021, 2022, 2023, 2024, 2025; Hoang, 2023) or spiral fuel shuffling (Obara et al., 2019) to establish a high neutron-economy B&B mode. Results show that rotational fuel shuffling schemes achieve average discharged fuel burnup of 25.7% FIMA and peak burnup of 37.2% FIMA (Sambuu et al., 2025), while spiral fuel shuffling (Obara et al., 2019) reaches peak burnup of 192.5 GWd/Ton.

Due to the use of liquid fuel, a breed-and-burn molten salt reactor (Kasam and Shwageraus, 2021) is considered capable of overcoming solid material radiation damage while achieving high uranium utilization. Since the in-situ breeding and burning mode in CANDLE reactors strongly depends on fertile fuel breeding, there exists a minimum fuel burnup of ~200 GWd/Ton required to maintain criticality (Greenspan and Heidet, 2011; Heidet and Greenspan, 2012). Consequently, the discharged fuel burnup cannot be reduced significantly due to this minimum requirement for B&B operation. Fortunately, the DPA corresponding to this minimum fuel burnup is expected to be tolerable for some advanced materials (Hejzlar, 2021).

One potential approach to overcoming these challenges is decreasing power density to reduce DPA accumulation. However, lower power density compromises the economic viability of the power plant. In this study, double separated ignition zones were proposed to decrease power density while keeping total output power constant compared to a single ignition zone configuration. The lower power density provides a safety margin for thermal-hydraulic performance. Optimization schemes were still needed to reduce discharged fuel burnup. Fuel density, fuel enrichment, and the location of enriched uranium fuel were varied to seek better combinations. The design goals were to reduce discharged fuel burnup from 400 GWd/Ton to ~200 GWd/Ton in the breeding zone while decreasing the ignition zone power density as much as possible while maintaining supercriticality.

2 Designed Models and Methodology

In this study, assembly-level analysis was used to evaluate the DSWR, as core-level analysis would consume excessive computational resources. The difference between assembly-level and core-level analysis is whether neutron leakage is considered. Neutron leakage rates are not accounted for at the assembly level due to the application of periodic boundary conditions, which means geometric shape effects are ignored. The assembly (Figure 1 [Figure 1: see original paper]) includes fuel rods and coolant (208Pb-Bi eutectic). 208Pb-Bi eutectic is a eutectic alloy with a low melting point and high thermal conductivity, providing better radiation protection and a hardened neutron spectrum. A hardened neutron spectrum benefits the breeding ratio and provides greater tolerance to ensure negative reactivity feedback. The U-Zr alloy, preferred for fast neutron reactors, was employed in the fuel rods. Each assembly contains 127 fuel rods with a pin pitch of 1.23 cm. A larger pin diameter was selected because it provides a better breeding ratio.

The DSWR mode with double separated ignition zones is shown in Figure 1 [Figure 1: see original paper]. The Monte Carlo code Serpent was chosen as the calculation tool. Criticality calculations and burnup calculations were emphasized, as criticality calculations serve as a preliminary standard for evaluating design schemes, while burnup calculations provide perspective on fuel utilization. The number of source neutrons per cycle is 20,000, with 120 active cycles and 20 inactive cycles. The relative error is ~0.0001 for criticality calculations.

To pursue accurate fuel burnup calculations, the assembly was divided into 21 axial slices, each 10 cm in length. This 10 cm length is similar to the neutron mean free path in a fast reactor. The ignition zones were located at the bottom and top, respectively, while the breeding zone was loaded with depleted uranium.

3.1 The Infinite Medium Multiplication Factor Versus Time

Fuel exposure in reactors is typically limited by fuel or material damage rather than reactivity control. However, less excess reactivity shortens the effective full power days (EFPDs) and reduces discharged fuel burnup to relax engineering limitations. Figure 2 [Figure 2: see original paper] shows the designed Scheme-A for the assembly. The fuel enrichment was set at 19.9% and 12% to easily maintain supercriticality and make the volume compact. The power density of depleted uranium in the breeding zones was reduced to decrease discharged fuel burnup to accommodate engineering technology. The infinite medium multiplication factor (K-inf) reflects the multiplication properties of the material and evaluates the performance of a designed scheme.

Figure 3 [Figure 3: see original paper] illustrates K-inf versus effective full power days (EFPDs). At the beginning of the cycle, K-inf decreased notably because enriched uranium was consumed significantly in the ignition zones. Simultaneously, fissile material was not converted sufficiently to compensate for the consumption of fissile material and the accumulation of fission products. Until about 2000 EFPDs, the fission waves moved into the breeding zones and sufficient Pu-239 was produced; therefore, the trend of K-inf changed to increase until reaching a summit at ~3600 EFPDs. The cycle length is ~5000 EFPDs.

Figure 4 [Figure 4: see original paper] shows the evolution of U-235 density versus EFPDs in the ignition zones. In the ignition zones, Zone 1, situated at the boundary, exhibited the highest neutron leakage and experienced slow consumption. Conversely, Zones 3, 4, and 5 had lower neutron leakage due to their greater distance from the boundary, resulting in significantly greater U-235 depletion compared to Zone 1. The burning of U-238 is presented in Figure 5 [Figure 5: see original paper]. U-238 can be fissioned or bred efficiently to Pu-239 in a fast neutron spectrum. The consumption of U-238 was approximately proportional to EFPDs, except that Zone 11 deviated slightly from linear behavior.

Due to spatial symmetry, Zone 5 versus Zone 17 and Zone 6 versus Zone 16 performed almost identically. The constant burning rate for U-238 indicated that its contribution remained consistent throughout the cycle.

The Pu-239 nuclides (see Figure 6 [Figure 6: see original paper]) were converted from U-238 in the DSWR. In the breeding zones, fission of Pu-239 primarily contributed to the output power, despite U-238 being capable of direct fission by fast neutrons. Additionally, the residual amount of Pu-239 at the end of the cycle was approximately $10^{21}/cm^3$, indicating potential for chemical processing to extract fissile nuclides. In the ignition zones (5 and 17), the density of Pu-239 increased until reaching a summit before 3000 EFPDs. In contrast, the breeding zones (6 and 16) exhibited lower residual Pu-239 densities compared to the ignition zones due to the lower fuel burnup in the ignition zone (Figure 7 [Figure 7: see original paper]).

Fuel burnup serves as a measurement of fuel utilization effectiveness. The DSWR is capable of achieving double fuel breeding due to its unique ignition zone configuration. Figure 7 [Figure 7: see original paper] illustrates the progression of fuel burnup relative to axial zone number. The fuel burnup in the breeding zone was lower than 50 GWd/Ton at 9.93 effective full power years (EFPYs), indicating that the dual ignition zones predominantly control the power output. At 12.06 EFPYs, the minimum burnup in the breeding zone exceeded 150 GWd/Ton, while the maximum burnup within the ignition zones increased to 350 GWd/Ton. The peak burnup of 380 GWd/Ton, observed in ignition zones 4 and 18, could potentially be reduced through optimization techniques such as using lower-enriched uranium.

4. Optimized Schemes for Ignition Zones

As mentioned, the peak discharged fuel burnup is 380 GWd/Ton in the ignition zone for Scheme A, which needs to be reduced. Two optimized schemes, Scheme B and Scheme C, were proposed to reduce fuel burnup by utilizing lower discharge burnup to relax material limitations. Scheme B (Figure 8 Figure 8:

see original paper) was designed by decreasing the fuel enrichment from 19.9% to 12% for zone numbers 4, 5, 17, and 18. Scheme C (Figure 8 Figure 8: see original paper) was designed to distribute 12% fuel enrichment in ignition zone numbers 3, 4, 5, 17, 18, and 19, while ignition zone numbers 6 and 16 were set at 7.7%. Lower fuel enrichment would result in lower discharged fuel burnup to accommodate engineering technology and improve fuel economy.

Due to different fuel distributions, the trend of K-inf differed. Compared with Scheme A (Figure 3 [Figure 3: see original paper]), K-inf decreased significantly at the beginning of the cycle (Figure 9 Figure 9: see original paper, Figure 9 Figure 9: see original paper), indicating that less excess reactivity needed to be suppressed. The results show that K-inf was smaller for Scheme C compared with Scheme B and had a higher peak value in the middle of the cycle. Therefore, Scheme C had longer cycle lengths. Even though the amount of fissile material loaded was almost the same, the schemes demonstrated different trends. The comparisons also illustrated that higher fuel enrichment is not always beneficial for DSWR performance, as higher fuel enrichment implies severe spatial self-shielding effects that reduce neutron current leakage into the breeding zone.

The fissile material loading in the core was consumed as shown in Figure 10 [Figure 10: see original paper]. The results exhibit that zone numbers 4 and 5 in both Scheme B and Scheme C show similar trends versus EFPDs, and the loaded U-235 was burned out at the end of the cycle. In optimized Scheme B (Figure 10 Figure 10: see original paper), the amount of U-235 in zone number 3 burned quickly, with almost no residual at the end of the cycle, because its central location in the ignition zone resulted in higher neutron flux.

Since U-238 is the dominant nuclide in depleted uranium and can be fissioned or transformed into Pu-239, its amount deserves attention. The evolution of U-238 density is presented in Figure 11 Figure 11: see original paper and Figure 11 Figure 11: see original paper. The results reflect that U-238 consumption was linear versus EFPDs, but the consumption rate differed. The consumption rate for U-238 in ignition zones was faster than in breeding zones. The burning speed of U-238 in zone number 11 was slightly slower than other breeding zones in the middle of the cycle but accelerated at the end of the cycle. This is explained by the fact that less neutron flux penetrated into the center of the core at the beginning of the cycle, while more neutron flux was produced adjacent to zone number 11 at the end of the cycle as the dominant burning zone moved. Approximately 40% of U-238 was burned in the breeding zones, illustrating that the DSWR has excellent performance for utilizing depleted uranium.

Most U-238 was transformed into Pu-239, which fissions to release energy. Figure 12 [Figure 12: see original paper] presents residual Pu-239 in the assembly versus EFPDs. The residual amount of Pu-239 showed similar trends versus EFPDs for both Scheme B and Scheme C, reaching a summit in the middle of the cycle. Some Pu-239 was produced but fissioned immediately; hence, this portion is not represented in Figure 12 [Figure 12: see original paper]. At the end of the cycle, all residual fissile nuclide Pu-239 was approximately 70% compared with the initial loading amount of U-235. Since Pu-239 provides more average fission neutrons than U-235 per fission reaction, less critical mass is needed when loading Pu-239.

Fuel burnup measures the energy obtained from irradiating fuel. As previously indicated, the maximum burnup in the ignition zone is 380 GWd/Ton for Scheme A, and optimization schemes were desired to further lower this maximum burnup. Figure 13 Figure 13: see original paper and Figure 13 Figure 13: see original paper illustrate fuel burnup varying with EFPDs for different schemes. The maximum discharged fuel burnup for Scheme B was 324 GWd/T, located in zone numbers 3 and 19 at 12 EFPYs. For Scheme C, the maximum discharged fuel burnup was 329 GWd/T, located in zone numbers 5 and 17. Both optimized schemes B and C achieved lower discharged fuel burnup compared with Scheme A (380 GWd/T). It is possible that discharged fuel burnup could be further reduced by extending the lengths of ignition zones or decreasing fuel enrichment. The discharged fuel burnup in the breeding zone was approximately 250 GWd/T, indicating that 25% of depleted uranium was consumed.

5. Conclusions

The crucial challenge for CANDLE reactors or B&B reactors is material limitation arising from radiation damage. Current concepts for CANDLE reactors or B&B reactors exceed engineering technology capabilities. In this study, optimized schemes for the DSWR were performed to reduce discharged fuel burnup and relax material limitations. The optimization schemes included different fuel enrichment and location distributions. After optimization, discharged fuel burnup decreased from 380 GWd/T to ~320 GWd/T in the ignition zone and from 380 GWd/T to ~250 GWd/T in the breeding zone for depleted uranium, significantly reducing material radiation damage, particularly in the breeding zone. The results illustrate that CANDLE reactors or in-situ B&B reactors still have broader prospects and only require slight optimization rather than abandoning the roadmap. The studies also indicate that discharged fuel burnup could still be reduced by extending ignition zone lengths or decreasing fuel enrichment in ignition zones.

Future work will include more reactor physics calculations, including cell pitch, reactivity feedback coefficients, power distribution, and other parameters.

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Note: Figure translations are in progress. See original paper for figures.