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Time-Dependent Neutronic and Burn-up Analyses of in a Thorium-Based ADS cooled with Various Coolants

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Abstract

This study presents the investigation of thorium utilization in an ADS with Lead-Bismuth Eutectic (LBE) target. To effectively burn thorium, the ThO_2 fuel rods cylindrically prepared, and cladded with SiC, are mixed with $^{233}UO_2$ at volumetric ratio of 1%. These fuel rods are placed in the fuel zone in hexagonal arrangement. Three different coolant cases, helium (He) gas, light water (H_2O) and heavy water (D_2O), are individually examined for cooling of fuel zone. The volumetric percentages of fuel, clad and coolant are 60%, 10% and 30%, respectively. The LBE-target is bombarded by protons amplified to 1000 MeV in linear accelerator (LINAC) which in turn releases 29-30 high-energetic neutrons per proton via the spallation reactions. Proton beam power is assumed as 20 MW corresponding to $1.24828 \cdot 10^{17}$ protons per second. The steady-state neutronic and subsequent time-dependent burn calculations are performed by using MCNPX 2.7 with LA150 library and CINDER computer codes, respectively. The ADSs can be operated under subcritical mode until the value of k_{eff} increases to 0.980-0.985. Subject to this constraint of k_{eff}, the maximum operation times are determined as 184, 825 and 2215 days and at end of these times, the values of gain (G) increase up to 17.362, 12.909 and 9.100, in the cases of H_2O, D_2O and He coolants, respectively.

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I. INTRODUCTION

At the first-time, Rubbia et al. [1] proposed Accelerator Driven Systems (ADSs) as an energy amplifier. Also, at the ThEC13 Conference [2], Carlo Rubbia said “Thorium is a source of energy essentially sustainable on the human time scale”. Thorium element, which occurs mainly as ^{232}Th isotope, is about three times more abundant in nature compared to uranium element. The ^{233}U fissile fuel can be bred from ^{232}Th isotopes in various nuclear reactors such as Accelerator Driven System (ADS) by means of capture reactions due to the fact that it is a fertile isotope. Therefore, thorium becomes a valuable and attractive nuclear fuel for nuclear reactors. However, it can only be used as a fuel in conjunction with a fissile material such as ^{233}U, ^{235}U and ^{239}Pu fissile fuels. One way of thorium utilization as a nuclear fuel is ADSs with high-energetic proton source, which are innovative reactors.

Recently, several investigations on thorium utilization in ADSs are performed by many researchers. Vu and Kitada [3,4] design multi-cycle core to improve thorium utilization and transuranium (TRU) transmutation. They can realize transmutation of TRUs in a high level by using the seed-blanket ADS. Barros et al. [5-7] study on the thorium and spent fuel utilization in a lead cooled ADS. They place $^{232}ThO_2$ in some of fuel rods to produce ^{233}U fissile fuel, and place the Pu-minor actinide (MA) fuel mixture in other fuel rods. The results of this study show that significant amount of ^{233}U from ^{232}Th can be produced. Pazirandeh and Shirmohammadi [8] simulate an

ADS fuelled with uranium-thorium fuel mixture. Also, they use MOX (U-Pu) as fuel. Yapıcı et al. [9] investigate on the neutronic data of many infinite target mediums irradiated with a proton source of 1000 MeV. They consider lead-bismuth eutectic (LBE), uranium and thorium, etc. as target material. Furthermore, in previous works of Bakır et al. [10-12], the utilizations of thorium and spent fuel in ADSs fuelled with various fuel compositions in the shape of TRISO particles are investigated. The results of these studies show that the investigated ADSs have a high capability in terms of energy amplify as well as fuel transmutation.

II. ACCELERATOR DRIVEN SYSTEM

Figures 1 shows the vertical section view of the investigated cylindrical ADS. As is apparent from this figure, the ADSs mainly contain three parts: LBE-spallation neutron target (SNT), sub-critical fuel zone (FZ), graphite reflector zone (RZ). The cylindrical fuel rods, cladded with SiC and contain (Th,^{233}U)O_2 fuel mixture, are placed in the fuel zone in hexagonal arrangement. ^{232}Th isotope, which is not a fissile fuel, is a fertile isotope. However, because of fissile fuel need at the beginning of operation, ThO_2 fuel is used by mixing with $^{233}UO_2$ at volumetric ratio of 1%. Three different coolant cases, helium (He) gas, light water (H_2O) and heavy water (D_2O), are individually examined for the fuel zone coolant, and the volumetric percentages are 60, 10 and 30, respectively. The materials used in the investigated ADS are given in Table 1.

Table 1. Materials used in the investigated ADS

Zone	Percentage		Material	Density [g/cm^3]	Nuclide
Target	100		LBE	11.344 9.8	45% Pb 55% Bi
Fuel	30	Coolant	H_2O	1	^{1}H
			D_2O	1.1	^{2}H
			He	0.001786	He
	60	Fuel	ThO_2	9.88	99% ^{232}Th
			UO_2	10.54	1% ^{233}U
	10	Clad	SiC	3.18	^{28}Si ^{12}C
Reflector	100		Graphite	2.10	^{12}C

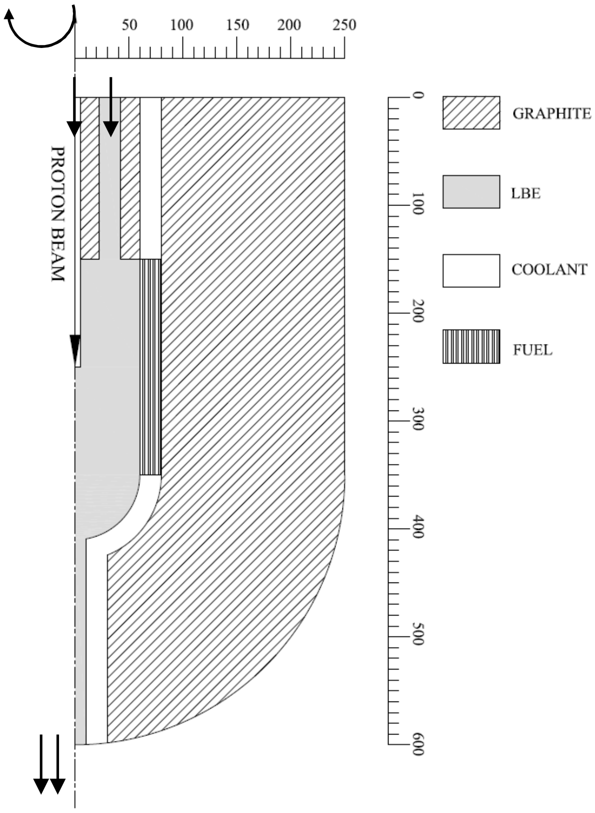

Figure 1. Axisymmetric vertical section view of the investigated cylindrical ADS (Dimensions are in cm.)

The energy of protons, amplified to 1000 MeV (E_p) in a linear accelerator (LINAC), bombard the LBE-target, which in turn releases 29-30 high-energetic neutrons per proton via the spallation reactions. The numerical results show that about 97% of these neutrons penetrate the fuel zone to produce fissile fuel and energy. It is assumed that the target is bombarded with $1.24828 \cdot 10^{17}$ protons of 1000 MeV per second which corresponds to a proton beam power (PBP) of 20 MW.

III. TIME-DEPENDENT NUMERICAL RESULTS

Calculation Tools

In order to accurately obtain numerical results, the MCNPX 2.7 computer code [13] with LA150 library [14], which is widely used in neutronic calculations of ADSs, is selected. Furthermore, the time-dependent burn calculations are carried out by using the CINDER90 computer code [15]. In addition to these two codes, CBURN interface computer code [16], is developed to accurately evaluate the time-dependent CINDER90 outputs.

Neutronic Data

Effective neutron multiplication coefficient: The effective neutron multiplication coefficient (k_{eff}) is defined as the ratio of one generation of neutrons to the previous one. In ADSs, the value of this coefficient must be less than 0.98-0.99. Figure 2 shows the increases of k_{eff} up to 0.98 for all coolant cases during the operation times. As apparent from this figure, the fastest increase of k_{eff} is in the case of H_2O coolant, and in this case, its value reaches to 0.98 in 184 days. The times to reach 0.98 in the cases of D_2O and He gas coolants are 217 days and 2215 days, respectively. These times (184, 217 and 2215 days) are the maximum operation time for each coolant case. These results bring out that the time to reach 0.98 is much longer in the case of He gas coolant than the cases of other coolants.

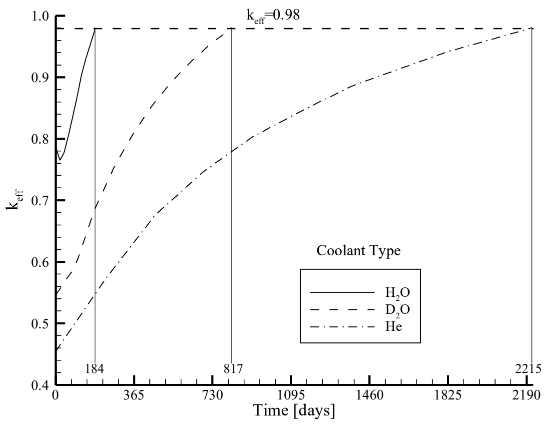

Figure 2. Increase of the effective neutron multiplication factor during the operation times

Cumulative Fissile Fuel Enrichment: The increase of Cumulative Fissile Fuel Enrichment (CFFE) during operation times is plotted in Figure 3 for all coolant cases. The profiles of CFFE in the cases of H_2O and D_2O coolants are the same until 184 days. The values of CFFE increase up to 2.076%, 5.621% and 6.717% in the cases of H_2O, D_2O and He gas coolants at the end of their maximum operation times, respectively. These CFFE levels, being quite high, demonstrate that these enriched fuels can be used in conventional thermal reactors after the maximum operation times.

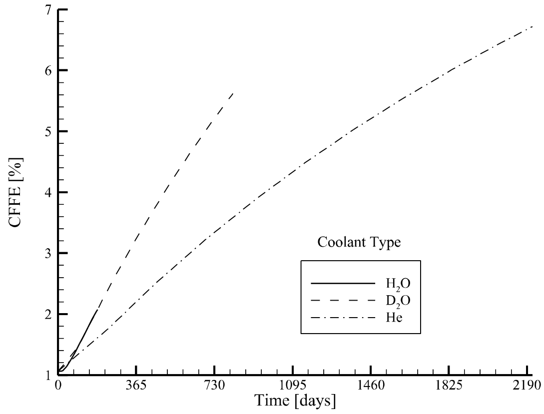

Figure 3. Increase of CFFE during the operation times

Production of ^{233}U: Production of the ^{233}U fissile isotope from capture reaction of ^{232}Th fertile isotope is given with Eq. (1) as follows:

$$^{232}Th + n \xrightarrow{\gamma} {}^{233}Th \xrightarrow{\beta} {}^{233}Pa \xrightarrow{\beta} {}^{233}U \quad (1)$$

Figure 4 exhibits the increase of ratio of ^{233}U mass (m_{U-233}) to initial ^{232}Th mass ($m_{0-Th-232}$) for all coolant cases during the operation times. Because these ratios are directly proportional to CFFE, their profiles are similar. The ^{233}U fissile fuel productions from capture reactions of ^{232}Th fertile fuel (see Eq.(1)) increase up to 187.197 kg, 498.540 kg and 589.509 kg in the cases of H_2O, D_2O and He gas coolants at the end of their operation times, respectively. These values present that effective thorium utilization can be realized in the investigated ADS in all coolant cases.

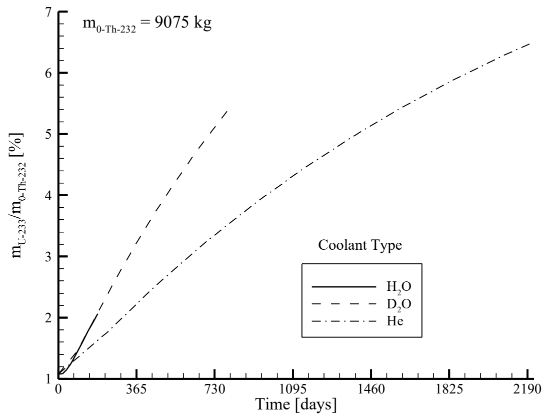

Figure 4. Increase of ratio of ^{233}U mass (m_{U-233}) to initial ^{232}Th mass ($m_{0-Th-232}$) during the operation times

GAIN: The energy gain (G), which is the ratio of the total fission energy production in fuel zone to the proton energy, is one of the most important parameters of an ADS. The value of G can be obtained from the following equations:

$$G = \frac{R_f \cdot E_f}{E_p} \qquad (2a)$$

or

$$G = \frac{P_{th}}{PBP} \qquad (2b)$$

where R_f is total fission reaction per proton, P_{th} is the thermal fission power and E_f is the energy per fission (200 MeV).

The increase of G is plotted in Figure 5 for all coolant cases during the operation times. At the end of their maximum operation times, the values of G increase up to 17.36 (P_{th}=347.20 MW), 12.87 (P_{th}=257.40 MW) and 9.10 (P_{th}=182 MW) in the cases of H_2O, D_2O and He gas coolants, respectively. These values are lower compared to the cases with more fissile fuel. Nevertheless, in this study, the main aim is thorium utilization. Therefore, the fissile fuel ratio is kept low (1%).

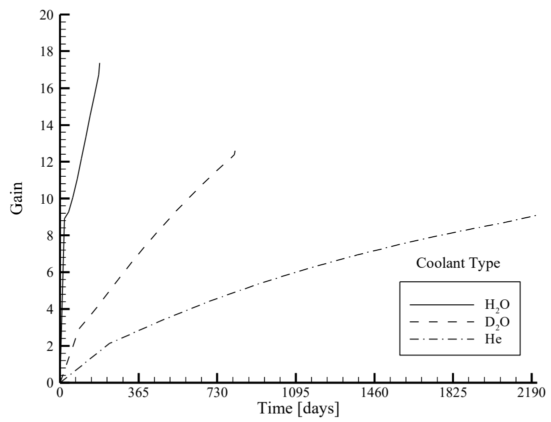

Figure 5. Increase of GAIN during the operation times

Fuel Burnup: The total generated energy per unit fuel mass initially loaded is defined as fuel burnup (BU). Its value can be calculated as:

$$BU(t + \Delta t) = BU(t) + \frac{\text{Fission Power}}{\text{MTU}} \Delta t$$

in GWd/MTU (3)

As is apparent from this equations, the fuel burnup is directly proportional with the number of fission reactions and the operation time. At the end of operation times, in the cases of H_2O, D_2O and He gas coolants, its values increase up to 5.019, 14.209 and 29.388 GWd/MTU, respectively.

IV. CONCLUSION

In order to achieve accurate neutronic data, several time-dependent burn calculations are performed by using MCNPX 2.7 and CINDER 90 computer codes. Main results are shortly presented as follows:

1. The maximum operation times when k_{eff} reaches to 0.98 are 184, 217 and 2215 days in the cases of H_2O, D_2O and He gas coolants, respectively.
2. The values of CFFE increase up to 2.076%, 5.621% and 6.717% in the cases of H_2O, D_2O and He gas coolants at the end of their maximum operation times, respectively.
3. The ^{233}U fissile fuel can be produced up to 187.197 kg, 498.540 kg and 589.509 kg in the cases of H_2O, D_2O and He gas coolants at the end of their operation times, respectively.
4. The value of G can increase up to 17.36, 12.87 and 9.10 in the cases of H_2O, D_2O and He gas coolants at the end of their operation times, respectively.

As a result, in all coolant cases, significant amount of energy production can be realized by using thorium mixed with a low percentage of ^{233}U in the investigated ADS.

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