**ADS FOR ENERGY PRODUCTION AND 233U**

**BREEDING IN HEU-THORIUM OXIDE SYSTEM**

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**Abstract**

For power production and 233U breeding from thorium, a preliminary neutronic design of an Accelerator-Driven Sub-critical System (ADS) is presented. The ADS reactor core design with “HEU–Thorium Oxide fuel” was coupled with proton accelerator and spallation target. The neutron source (ADS system) feasibility of HEU burning and isotopes production was evaluated. The multiplication factor Keff, the production of 233U and depletion of 235U were computed using the MCNPX 2.7.0 code. The results indicated that the introduction of thorium fuel with HEU into the ADS core gives an efficient method to produce 233U isotopes and to burn 235U isotopes more efficiently. Additionally, less minor actinides (MA) production and generation of energy can be achieved.

1. INTRODUCTION

Recently, the accelerator-driven sub-critical system, known as the Accelerator- Driven System (ADS), was studied for uses to attain specific objectives in several countries. In the USA, some European countries, and Japan, the main goals of ADS are to incorporate inherent safety in the system of nuclear energy and to provide long-term solutions to nuclear waste disposal by burning higher actinides (as 239PU) and minor actinides (as 237Np, 241Am, 242Cm) and long-lived fission products transmutation [1].

The improvement of ADS for safe, effective breeding of 233U isotopes from 232Th resources and for providing sustainable nuclear energy security is the major goal of the nuclear power program in India [1]. The most important concepts of the ADS being studied are:

* The Energy Amplifier (EA) of CERN Group suggested by Carlo Rubbia[2],
* The National Laboratory of Los Alamos for Waste Transmuter developed by Bowman[3],
* The fast neutrons ADS incinerator of higher actinides suggested at Brook-haven National Laboratory (Phoenix-project) and executed as a part of the OMEGA (Options for Making Extra Gains from Actinides and fission products) programme in Japan [4], and
* The accelerator-driven technologies project in Russia [1].

The ADS is composed of three main components [1]:

* The proton accelerator, that produces protons with energy about 1 GeV.
* The “target” (as Lead or Lead-Bismuth alloy) able to release 20 – 30 neutrons by spallation reaction with energy below 20 MeV per proton accelerated with an energy of 1 GeV, and
* A blanket sub-critical reactor with Keff in the range between 0.95 and 0.98 [1].

In addition, the ADS includes heat removal and electricity generation equipment. The safety characteristics requirements are supported by the fact that the ADS works in a non-self-sustained chain-reaction mode that reduces the criticality issues. The ADS runs in a sub-critical state and remains sub-critical, irrespective of the accelerator being off or on. Furthermore, the accelerator may offer a convenient control mechanism for subcritical systems that would scale back the necessity of control rods. The sub-criticality itself presents an extra level of operational safety relating to criticality insertion accidents [5]. The fast energy amplifier is appropriate for the following cores partially loaded with thorium fuels [1]:

* Mixed 239Pu – 232Th oxide or mono-nitride for transmuting plutonium isotopes.
* Mixed 232Th – 233U nitride or oxide for the production of energy.
* Mixed HEU – 232Th nitride or oxide for HEU burning.

Accelerator-Driven Sub-critical System (ADS), with a number of energy amplifiers (EA), and 232Th as a blanket fuel for breeding provides substantial benefits in the thorium fuel cycle (“once-through” or “closed”) in regards of reducing the nuclear waste radiotoxicity to the minimum levels and to simultaneously ensuring proliferation resistance. Denaturing the thorium by adding 238U may mitigate the proliferation risks as the presence of 238U reduces the effective enrichment in 233U of the reprocessed uranium (as the chemical reprocessing can’t separate the 233U isotopes from the 238U). The fissile materials utilization in nuclear explosive devices (NED) will be complicated by denaturing the fissile materials by their isotopes [6].

In the second stage of the India’s three-stage programme**,** Fast Breeder Reactors (FBRs) are loaded with Plutonium mixed with reprocessed Uranium recovered from reprocessing the spent fuel of the first stage. 232Th will be used as a blanket material for 233U isotopes production [7].

Barros, et al. [8] considered the development of nuclear fuel for a lead-cooled accelerator-driven system adopted for energy production. The fuel was a mixture of 232Th and 233U. They used the MCNPX 2.6.0 code with the depletion/burn-up capability. The Keff and the nuclear fuel applying ADS source (SDEF) and Kcode-mode were evaluated throughout the burn-up. They concluded that despite the low Keff, the fuel cycle with thorium fuel may be applied for long-time electricity generation and fuel regeneration in accelerator-driven reactors. Ali Pazirandeh and Laia Shirmohammadi [9] studied the Simulation of an ADS core with Uranium-Thorium Fuel. The main goal of this simulation was to analyze the behavior of the ADS system with thorium assemblies. In this work, a subcritical ADS core in the experimental scale was simulated by MCNPX Monte-Carlo code. The core included two fuel assemblies’ types: 15% UO2+85% ThO2 and MOX (U-Pu). In the first step, they loaded only the fuel assemblies containing thorium into the ADS core. Criticality calculations by MCNPX code showed that the Keff is so low that the fuel assemblies can't drive the sub-critical core. Therefore, the MOX (U-Pu) assemblies had to be placed as well into the ADS core. The final results showed that neither uranium enrichment nor plutonium is required with the new generation of nuclear fuel (e.g., Minor Actinides (MA) and MOX (Th-U) or MOX (Th-Pu)). Graiciany Barros, et al. [10] displayed a study on GANEX and UREX+ reprocessed fuels within the ADS system. This study aimed to examine the neutronic performance of the ADS core applying thorium and reprocessed fuel. The fuel utilized in some rods was 232ThO2 for U-233 generation. In the other rods, two various reprocessed fuels were used. One of the examined fuels was a mixture based upon Pu-MA, extracted from the spent fuel of PWR, reprocessed theoretically by the GANEX process and spiked with 50% of thorium. The other fuel was a reprocessed fuel theoretically obtained from the UREX+ (Uranium Extraction) process and spiked with 50% of thorium. Monte burns 2.0 (MCNP5/ORIGEN 2.1) code was utilized to simulate the neutronic characters of the fuels. The results showed that the utilization of UREX+ or GANEX fuel spiked with thorium allowed 233U isotopes generation and high radiotoxicity isotopes reduction.

Although several works have been done to study the ADS behavior with thorium fuel for 233U breeding, most of these works utilized thorium with reprocessed fuel or MOX fuel in homogeneous or heterogeneous approaches; which is an impractical option for the countries that don’t have spent nuclear fuel. Consequently, in the paper, a design of an ADS for high enriched uranium (HEU) seed fuel burning in addition to power production using thorium (as a blanket fuel) for 233U breeding has been applied. The MCNPX 2.7.0 Monte Carlo code has been used to calculate neutronic parameters such as the Keff of the system. The neutron source (ADS system) feasibility of HEU burning, 233U, and 239Pu isotopes production and 235U isotopes depletion was also evaluated using the MCNPX code.

1. ACCELERATOR-DRIVEN SUB-CRITICAL CORE SIMULATION
	1. **Seed and Blanket HEU - Thorium Fuel ADS**

The ADS model applied in this simulation is based on the lead-bismuth ADS with fast neutron spectrum adopted by Trellue [11].By bombarding 1 GeV proton beam into a cylindrical Lead-Bismuth Eutectic (LBE) target, neutrons can be generated by the spallation reaction. The ADS reactor is a cylinder of 140 cm radius and is loaded with 180 fuel assemblies. However, in the work, instead of loading the ADS reactor core with reprocessed fuel as in the original design, 84 blanket assemblies of thorium and 96 seed assemblies of HEU were put in the ADS reactor core. This heterogeneous approach will facilitate the fuel assembly fabrication and the in-core fuel management.

The capture rate in fertile fuel would be optimized by separating the fertile and fissile materials; in addition, 233U conversion ratio within the blanket may well be increased. The 233U isotopes breeding from thorium fuel will compensate for the burnt EU within the HEU fuel, therefore decreasing the swing of core reactivity.

Fig. 1. presents the seed-blanket ADS vertical and horizontal sectional views. In order to reinforce the neutron economy, most of the thorium assemblies are located at the periphery of the ADS core. The remaining assemblies of the 232Th fuel are distributed in the core along with the HEU seed fuel assemblies around the ADS target. The coolant used within the system is Sodium. In table 1., the main ADS reactor design parameters are given.



FIG. 1. ADS vertical and horizontal sectional views (scale is given in cm)

TABLE 1. MAIN DESIGN PARAMETERS OF THE ADS REACTOR

|  |  |
| --- | --- |
| Core diameter (cm)  |  280 |
| Core length (cm)  | 300 |
| Active core length (cm) | 107 |
| Fuel type |  UO2 / ThO2 |
| Fuel pin radius (cm)  | 0.315 |
| Cladding thickness (cm)  | 0.031 |
| Pin pitch (cm)  | 0.89 |
| Array Type | Triangular |
| Lattice Pitch (cm) | 14.71 |
| No. of Fuel Rods / Assembly | 271 |
| Thorium assemblies / HEU fuel assemblies  | 84 / 96 |
| LBE target radius (cm)  | 15.0 |
| Accelerator current (mA)  | 13–30 |
| Spallation yield (n/s)  | 30 |
| Power output (MWth)  | 840 |
| Cycle length (days)  | 1200 |
| Keff | 0.96 |

The initial composition of the ADS core (Thorium and HEU fuels) was determined to obtain approximately a Keff equal to 0.96 at the beginning of the cycle (BOC). This was achieved by trying different 235U enrichments and evaluating the Keff value in each case. In table 2. the composition of uranium (HEU) and thorium fuel of the ADS core is given.

TABLE 2. COMPOSITION OF HEU AND THORIUM FUEL

|  |  |
| --- | --- |
| Nuclides | Number density(atoms/b-cm) |
| HEU |
| 235U238U16O | 5.268E-031.923E-024.900E-02 |
| Thorium fuel |
| 232ThGd16O | 2.1641E -029.2607E -084.3282E -02 |

* 1. **Simulation Code**

MCNPX 2.7.0 code was employed to perform the calculations in the work. It's a general Monte Carlo code for the radiation transport purpose-designed to trace any type of particles over a wide range of energies. In 1994, MCNPX program started as MCNP4B and LAHET 2.8 extension for supporting the Accelerator Tritium Production Project (APT). The work contributed a formal MCNP extension to all particles with all energies; an enhancement of physics simulation models and an increase of neutron, proton, and photo-nuclear libraries to 150 MeV [12].

The growth of computing power gave rise to a sustainable increase in the share of Monte Carlo codes in nuclear reactor and nuclear criticality analysis and development. These Monte Carlo codes can offer the most accurate locally dependent neutronic characteristics in realistic 3D geometries of any complexity. Between them, only MCNPX code is totally capable of treating ADS-related issues, since it tracks most particle types of all energies [12, 13].

In the region with higher energy (above 20 MeV) it depends on the model calculations using various intra-nuclear cascades, pre-equilibrium and equilibrium model combinations. However, recent improvement in nuclear data library extensions to greater energies (up to 200 MeV) permits implementing nuclear data evaluation in the neutronic analysis of ADS systems [13].

1. NEUTRONIC PERFORMANCE CALCULATIONS FOR SIMULATED ADS CORE
	1. **Model verification**

K-CODE option in MCNPX code was utilized to calculate the neutron multiplication factor for the ADS core. To validate our model, we considered the system studied by Barros et al. [10] and calculated the Keff versus the Effective Full Power Days (EFPDs). Fig. 2. shows that our results agree well with those obtained in reference [10].

FIG. 2. Keff versus EFPD

* 1. **System performance parameters**

Then, the system described in section 2 was simulated with HEU-Th fuel assemblies packed as shown in Fig. 1. The ADS system performance parameters was calculated and given in table 3. The cycle length was adjusted as the reference [14] depending on the Keff value at the beginning of cycle (BOC) and the end of cycle (EOC), respectively, 0.960 and 0.89. These values of Keff from the BOC to the EOC give about 1200 EFPD, as shown in fig .4.

TABLE 3. SYSTEM PERFORMANCE PARAMETERS FOR ADS CORE

|  |  |
| --- | --- |
| Radial power peaking factor at BOC | 3.03 |
| Radial power peaking factor at EOC | 1.67 |
| Keff |
| BOC  | 0.96044± 0.00070 |
| EOC  | 0.89279± 0.00063 |

* 1. **Neutron spectrum**

Fig. 3. shows the average neutron energy spectrum for three regions in the ADS core, namely target-region, thorium fuel-region, and uranium fuel-region. The graph shows that the flux at the fuel regions is higher than the flux at the target region, therefore, the fuel contributes most of the neutron flux (fast neutrons) inside the ADS reactor core. Also, the figure at the target region shows that there are high-energy neutrons achieved to 200 MeV due to the spallation reaction of protons with the target. But in both fuel regions, the energy of the neutrons (mainly from the fission of fissile materials) doesn’t exceed 20MeV. The fast neutrons are favorable for the actinide transformation because the fission to capture ratio for the actinides with the fast system is higher compared with the thermal system [15]. The 2.85 KeV neutron resonance of sodium is displayed in the figure regardless of the region, causing flux reduction at this energy [16].

FIG. 3. Neutron energy spectrum at the ADS core different regions

* 1. **Effective Multiplication Factor (Keff)**

The variations in the rate of decrease of Keff depend on the balance between the consumption of fissile materials through fission and the fissile materials production through the neutron captures in the fertile materials. Efficient conversion gives a continuous build-up of new fissile isotopes (233U and 239Pu) sustaining Keff at a higher level. Fig. 4. presents the variation of Keff with EFPD for the ADS core. It can be noticed that Keff decreases gradually with time mainly due to the consumption of fissile materials in the ADS reactor core.

FIG. 4. Keff versus EFPD of the ADS reactor core

* 1. **Core Actinides**

The mass evolution is a significant parameter to prove the 233U isotopes breeding and HEU fuel burning and within the ADS seed and blanket fuels. Table 4. displays the element inventory in the 840 MWth ADS employing thorium - HEU fuel. It can be noticed from the table that the quantity of 235U is about 1.84E+03 Kg at the BOC while it is about 9.07E+02 Kg at the EOC, indicating that about 51% of the initial content of 235U was burnt. Meanwhile, a great quantity of 233U was bred. The data shows that the amount of thorium present in the core is reduced by about 8% during the operation time due mainly to the conversion of thorium to 233U and 233Pa. On the other hand, 2.8 E+02 Kg of 233U in addition to small fractions of other actinides such as 233Pa are produced. This gives a ratio of about 5.06% of thorium converted into 233U. In addition, an amount of 239Pu equal to 3.49E+02 Kg is produced as a result of the conversion of 238U and presents an important contribution to the thermal power generation.

TABLE 4. MASS INVENTORY OF ELEMENTS INSIDE THE ADS RECTOR CORE

|  |  |
| --- | --- |
| Isotope | Isotope inventory (g) |
| BOC | EOC |
| 232Th | 5.70E+06 | 5.24E+06 |
| 235U | 1.84E+06 | 9.07E+05 |
| 233U | 0.00E+00 | 2.80E+05 |
| 239Pu | 0.00E+00 | 3.49E+05 |
| 233Pa | 0.00E+00 | 1.43E+04 |

* + 1. *235U*

Fig. 5. shows the depletion of 235U content as a result of its interactions with neutrons either emerging from the fission process or the ADS system. The 235U concentration decreases gradually as a result of the exposure of the seed fuel to the neutron flux. Each neutron absorbed by 235U isotopes reduces the amount of the fissile isotopes and thus the macroscopic fission cross-section, which leads to the reactivity reduction.

FIG. 5. Mass variation of 235U in the ADS rector core

* + 1. *232Th*

On the other hand, the neutron capture by 232Th produces 233U. Fig. 6. illustrates the depletion ratio of 232Th. The percentage variation in 232Th isotopes mass concentration is not vital because of its high contents in the ADS reactor core. The concentration of this isotope was reduced by about 8% during the reactor operation time due to the conversion of 232Th isotopes to 233U and 233Pa isotopes.

FIG. 6. Mass variation of 232Th in the ADS reactor core

* + 1. *233Pa*

After the reactor shutdown, the 233Pa is converted into 233U leading to a rise in the reactivity. Fig. 7. presents the 233Pa concentration during the operation of the ADS reactor. It can be noted that this isotope is created on a wide scale that leads to a negative effect on the ADS core reactivity. From the figure, it can be noted that after approximately 200 EFPD the concentration of 233Pa reaches the saturation state until the EOC.

FIG. 7. 233Pa concentration in the ADS reactor core

* + 1. *233U*

However, the production of the little quantity of 233U is very important for the performance of the ADS core. Fig. 8. presents the 233U isotopes breeding rate from the BOC to the EOC inside the ADS reactor core. As can be observed from the figure, the concentration of the 233U isotope increased with time due to the conversion of 232Th.

FIG. 8. Mass variation of 233U in the ADS reactor core

* + 1. *239Pu*

Finally, Plutonium is formed from 238U. 239Pu is generally created in nuclear reactors by transmutation of 238U within the fuel rods. Fig. 9. presents the mass variation of 239Pu in the ADS reactor core. From this figure, it can be noted that the quantity of 239Pu in uranium fuel increases with time because of the 238U irradiation.

FIG. 9. Mass variation of 239Pu in the ADS reactor core

* 1. **Isotopic inventory**

Fig. 10. presented that the ADS core with UO2 seed fuel is empty from some of the actinide types such as Am and Cm. Besides, it has fewer amounts of other actinide types like Pu and Np than that generated from such fast breeder reactor.

FIG. 10. Isotopic inventory (g) in the ADS reactor core at the BOC and the EOC

1. CONCLUSION

MCNPX code is employed to simulate the lead-bismuth ADS with fast neutron spectrum adopted by Trellue [11] but loaded heterogeneously with 84 blanket assemblies of thorium fuel and 96 seed assemblies of HEU fuel. An important target for using thorium fuel is to breed as much fissile isotope 233U as possible besides decreasing the quantity of 239Pu produced for safeguards concerns.

The use of ADS loaded with HEU and Thorium blanket fuel achieves both goals. As deduced from the obtained results, about 5.06% of the initial content of thorium-232 isotopes is converted into 233U. Moreover, the production amount of 239Pu isotopes in the ADS system was around 62 kg/GWe/yr at 50GWd/tHM, which was lower than that yielded from the other nuclear reactors like the PWR about 125 kg/GWe/yr at 50GWd/tHM [17].

The ADS also displays a high capability for 235U isotope burning, as about 51% of the 235U initial content was burnt through the first cycle. Therefore, energy production can also be achievable by using the ADS fuelled with HEU and Thorium without needing MOX or reprocessed fuel (spent fuel), besides the significant fertile-to-fissile conversion attained.

Future work will involve using different fuel types as UN with ADS system, studying the effect of fuel changing on 233U breeding ratio and the reactor cycle and comparing the results with the case of reprocessed fuel.

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