Swing Reactivity Calculation of Accelerator Driven System
Subcritical Reactor 100 MWth

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Abstract. Accelerator driven system (ADS) applied subcritical reactor which can effectively transmute plutonium, minor actinide, and thorium as nuclear waste. In order to lower the amount of nuclear wastes sent to the geological repository, an optimized scattered reloading scheme for ADS is proposed to maximize the discharge burnup and lower the burnup reactivity loss. Accelerator Driven System (ADS) system lead store due of the amount of the Pu and Th, so it’s not only can create the addition of energy source, but also high safety reactor. The fuel used in this reactor is obtained from LWR’s spent fuel and thorium - based fuel. The use of thorium-based fuel can lower k-eff of the core and generates U-233, which is a nuclear fuel for critical reactor. Neutron obtained from spallation reaction of Pb-Bi target is placed in the center of the core. This ADS design produces subcritical k-eff during the operation of the reactor and can decrease the amount of fission products of LWR’s spent fuel and produce U-233. The objective of the calculation are criticality as a function of burn up (swing reactivity) in the subcritical assembly fuel. This ADS fuel is originated from UO2 PWR spent fuel with enrichment of 3.4% and burn up level 64 GWD or 100 MWt for 1825 days calculation of accelerator driven system subcritical reactor 100 MWth has been performed. This research done by using Origen2.1, SRAC2006 and MCNP6 Code. Based on the results swing reactivity of the calculation by using Origen2.1 Code, indicates that Kinf whose value be low subcritical condition (k-eff<1) is Kinf resulted from Th-232 with percentage from 10% to 5%(as U-238 substitution), the calculation by using SRAC2006 Code indicates that at the beginning of life (BOL), the k-eff of ADS design with 50 cm thickness is 0.9821491 and at the end of life (EOL) k-eff is 0.9396284 and the calculation by using MCNP6 Code. At beginning of life (BOL), the k-eff of ADS design is 0.9823 and the end of life (EOL) is 0.9823. The presence of plutonium and major actinides makes k-eff get slightly lower. Arrangement at this ADS model is performed to produce subcritical condition, in which an increase in fuel volume cause k-eff>1.

1. Introduction
To increase nuclear power reactor safety and transmutation of spent fuel, the accelerator driven system (ADS) is an interesting choice. Completed in March 2006, the Texas phase of the reactor–accelerator coupling experiment (RACE) showed that it is feasible for the training research isotopes general
atomic (TRIGA) research reactor to operate in a subcritical configuration, which was driven to a significant power by an electron LINAC neutron source (photon neutron) [1]. The subcritical core was affected by high energy neutrons. To analyze their effects to the core, Youqi Zheng et al. (2017) developed two models to cover the features of current experimental facilities and industrial-scale ADS in the future. The investigators found out that, even though only small fraction (2.6%) of high-energy neutrons with En > 20 MeV in the neutron source, their contribution to the source efficiency for large scale ADS reaches about 23% [2]. Burn up for the ADS core was analyzed by Takanori Sugawara et al. (2018) using SAR. The authors found out that there was a decrease in the maximum proton beam current from 20 to 13.5 mA during the burn up cycle. They also carried out coupled analysis; particle transport, thermal hydraulics and structural analyses. The results include the most robust beam window design; the hemisphere shape, the outer radius=235 mm, the thickness at the top of the beam window=3.5 mm and the factor of safety for the buckling=9.0. They obtained 2.2 times larger buckling pressure than the previous one and more feasible beam window concept [3].

By utilizing MCNP and fixed source calculation (nps) and criticality calculation (Kcode), Ned Xoubi et al. computed the amount of energy produced by the subcritical assembly in order to approximate the absolute neutron flux along the radial and axial axis and to determine Keff and other coefficients [4].

Time-dependent diffusion theory was employed by W.F.G. van Rooijen et al. (2017) to compute the multiplication factor, and prompt neutron decay constant (a-eigenvalue). It was concluded that the multiplication factor could be in general predicted very well for limited number of void regions in the core [5].

MCNP code was used by Marco Pecchia et al. (2017) to analyze the weighting function starting from the neutron history database. This method excels in the simultaneous evaluation of the weighting functions in a user-given Cartesian coverage mesh [6].

Experimental sub-criticality was conducted by Cheol Ho Pyeon et al. (2017) using the pulsed neutron source method, the Feynman-a method, and the neutron source multiplication method. Level of sub-criticality applied had wide range between near critical and 10,000 pcm [7]. The use of ORIGEN-S and MCNP4C codes to substitute some fuel elements with mixed oxide fuel elements was performed by Ismail Shaaban et al (2015). The researchers concluded that replacing the MTR-22 MW fuel elements with mixed oxide fuel elements causes a decrease more than 20% in the enrichment level and the amount of 235U in the reactor core [8].

ORIGEN cross section libraries were developed by Ugur Mertyurek et al. for reactor-grade mixed oxide (MOX) fuel assembly designs. These cross section libraries were used for computing fast and accurate depletion in order to estimate nuclide inventories, radiation sources and thermal decay heat whose information is required in spent nuclear fuel safety evaluation and safeguards verification measurement [9]. To predict decay heat, SCALE nuclear analysis code needs to be validated for its capability. To do so, measurement of decay heat for pressurized and boiling water reactors spent fuel was used by Germina Ilas et al [10]. MCNP5 was coupled with ORIGEN by Hocine Benkharfia et al. to compute burn up and criticality [11]. Derivation of algebraic equations using simplified burn up chains of major actinides was performed by Do-Yeon et al. to calculate burn up and uranium enrichment. ORIGEN-S code was employed to improve the values of burn up and enrichment and was applied in iBEST to maximize the ORIGEN-S capabilities in having better accuracy [12]. ORIGEN2 code developed by Radiation Safety Information Computational Center (RSICC) of Oak Ridge National Laboratory (ORNL) can be used to estimate fission yield inventory based on time-dependent. Foudil Z et al (2017) utilized this code to calculate core inventory and source term in Algerian Nuclear Research Reactor (NUR) [13]. Recently-developed computer code for nuclear power plant, ORIGEN-Automatic Rapid Processing (ORIGEN-ARP) is bundled in SCALE 5.1 module package, so that the code can be obtained with other codes, i.e. Gee Wiz, Keno 3D, and SAS 4. On the other hand, ORIGEN2 can be employed for research reactor and nuclear power plant. Hong, L.P. and Sembiring T.M. in 2013 developed new ORIGEN2 data library for research reactors and light water reactors [14][15].
The objective of the calculation are criticality as a function of burn up in the subcritical assembly fuel. This ADS fuel is originated from UO\textsubscript{2} PWR spent fuel with enrichment of 3.4 % and burn up 64 GWD or 100 MWt for 1825 days calculation of accelerator driven system subcritical reactor 100MWh has been performed. The scope of this research include of Swing reactivity calculation of accelerator driven system subcritical reactor 100MW this studied. k-eff EOC of ADS subcritical assembly, k-eff as a function of burn-up. Relation between Power ADS, the inventory radio activity of ADS, Changes in k-eff for various thorium blanket thicknesses and densities during ADS operation using 3 computer code different tools i.e.Origen2.1, SRAC2006 and MCNP6 codes package which available in BATAN.

2. Methodology

Criticality calculation done by using ORIGEN, 2.1, SRAC 2006 code and MCNP6 code as a function of the minor actinides fraction in the subcritical assembly fuel. This ADS fuel is originated from UO\textsubscript{2} PWR spent fuel with enrichment of 3.4 % and burn up level 64 GWD or 100 MWt for 1825 days

2.1 Modelling of swing reactivity calculation by using ORIGEN2.1 code.

Technical Data of Mass Composition of UO\textsubscript{2} Pellet. The objective of this analysis study of transmutation system using ADS with Origen2.1 code is to observe of transmutation of transuranic nuclides with ORIGEN2.1. To running this program need spent fuel technical data as fuel for ADS. ADS Specific Parameters is shown in Table 1. This ADS fuel is originated from UO\textsubscript{2} PWR spent fuel with enrichment of 3.4% and burn up 64 GWD or 100 MWt for 1825 days. The dimension of pellet UO\textsubscript{2} has radius of 0.4096 cm and height of 1 cm and linear power of 1.31506E-03 MWt/cm, ADS specific parameters is shown in Table 1.

| Items                        | Units                  |
|------------------------------|------------------------|
| Thermal power                | 100 MWt                |
| Proton Beam Energy           | 1500 MW                |
| Target:Target material       | Liquid Lead Bismuth (Pb-Bi) |
| Equivalent height            | 50 cm                  |
| Equivalent diameter          | 50 cm                  |
| Core:Equivalent height       | 100cm                  |
| Equivalent diameter          | 340cm                  |
| Pindiameter                  | 0.929cm                |
| Pin-Pitch to diameter ratio  | 1.4(-)                 |
| Fuel: Chemical form of fuel type | UO\textsubscript{2} Spent fuel of PWRw/o 3.4% enrichment |
| Fuel/Clad+Structure/Coolant  | 40% Pu + 60% MA        |
| Inert/Matrix                 | Th-232 with 10% to 15% (as U-238 substitution) |
| Materials of coolant         | Helium                 |

Preparing input data for ORIGEN2.1 Code, in addition to mass composition of nuclides of ADS fuel, other technical data needed for ORIGEN2.1 input areas follows: power, operation cycle, cooling time, related library for ADS device (fast neutron library), and gamma energy groups used. Moreover, variation of mass is also required by addition of Th-232 as U-238 substitution. The variation so mass are 120%,100%,75% ,50% and 25% of U-238 mass. The compilation of these Input data for ORIGEN2.1 is shown in Table 2.
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**Tabel 2. Input data for ORIGEN2.1**

| No. | Parameter          | Description               |
|-----|--------------------|---------------------------|
| 1   | Power              | 100 MWt                   |
| 2   | OperationTime      | 1825 days                 |
| 3   | Cooling time       | 5 years                   |
| 4   | Library            | LMFBR FFTF Pu/U           |
| 5   | Gamma Energy       | 18 groups                 |
| 6   | MassVariations     | U238, Th232(120%, 100%, 75%, 50%, 25%) |

The results of input that is successfully run are analyzed for k-inf and changes in mass at the end of cycle (EOC) and during cooling time. The analyse is of output of ORIGEN2.1 includes as the followings observation of Comparison of k-inf for various fuel types at ADS power 100 MWth, observation of the optimum fuel 7%Th-232 is supported by the observation of fuel burn-up generated, observation of the Transmutation Ratio at various level of Pu and MA, observation on decay heat (thermal power) at various fuel composition and observation on the inventory radioactivity of ADS Subcritical Assembly.

2.2 Modelling Of Swing Reactivity Calculation By Using SRAC2006 Code

The schematic diagram of the calculation using SRAC 2006 is shown in Figure 1

*Figure 1. Flowchart diagram of subcritical reactor calculation using SRAC 2006*

ADS design calculated in this research has the following specifications: fuel used is obtained from PWR spent fuel, i.e. UO2 with 3.4% enrichment and 64 GWD burn-up or 100 MWth or 1825 days. The LWR spent fuel composition of pellet is given in Table 3.
Table 3. The LWR spent fuel composition (UO2 with 3.4% enrichment) [16]

| No | Nuclide | Mass(gram) | No | Nuclide | Mass(gram) |
|----|---------|------------|----|---------|------------|
| 1  | U-234   | 6.43E-01   | 12 | Pu-242  | 6.80E+00   |
| 2  | U-235   | 1.25E+01   | 13 | Am-241  | 3.19E+00   |
| 3  | U-236   | 2.27E+01   | 14 | Am-242G | 5.95E-08   |
| 4  | U-237   | 1.97E-07   | 15 | Am-242M | 4.62E-03   |
| 5  | U-238   | 4.37E+03   | 16 | Am-243  | 1.98E+00   |
| 6  | Np-237  | 3.78E+00   | 17 | Cm-242  | 1.27E-05   |
| 7  | Np-239  | 1.71E-06   | 18 | Cm-243  | 4.76E-03   |
| 8  | Pu-238  | 2.29E+00   | 19 | Cm-244  | 9.17E-01   |
| 9  | Pu-239  | 2.80E+01   | 20 | Cm-245  | 1.11E-01   |
| 10 | Pu-240  | 1.52E+01   | 21 | Cm-246  | 2.24E-02   |
| 11 | Pu-241  | 6.22E+00   |    |         |            |

2.3 Modelling of swing reactivity calculation of by using MCNP6 code
Based on a modeling design of ADS-based subcritical reactor in MCNP6 code is shown in Figure 2.

![Figure 2](image_url)

**Figure 2.** Vertical and horizontal cross section of pin and cylinder assembly

For more detail, the pin assembly is shown in Figure 3.
Figure 3. Pin Assembly

ADS design is made in layers with different Pu-MA concentration. Their respective thickness is shown in Figure 4.

Figure 4. Thickness of each fuel assembly (cm)

3. Results and Discussion

A) The result swing reactivity calculation of accelerator driven system subcritical reactor 100 MWth by using Origen 2.1 Code. Based on k-inf calculated by Origen 2.1, the optimum fuel is Th-232 with percentage 5%-10%, 7% Th-232 to be exact. Comparison of k-eff EOC of ADS subcritical assembly for various fuel types is shown in Table 4.

| No. | Fuel Type       | K-eff (EOC) |
|-----|-----------------|-------------|
| 1   | U-238 (default) | 0.5064      |
| 2   | 120% Th-232     | 1.0641      |
| 3   | 100% Th-232     | 1.0696      |
| 4   | 75% Th-232      | 1.0746      |
| 5   | 50% Th-232      | 1.0745      |
| 6   | 25% Th-232      | 1.0547      |
| 7   | 20% Th-232      | 1.0547      |
| 8   | 15% Th-232      | 1.0228      |
| 9   | 10% Th-232      | 0.9857      |
| 10  | 9% Th-232       | 0.9743      |
| 11  | 8% Th-232       | 0.9606      |
| 12  | 7% Th-232       | 0.9445      |
| 13  | 6% Th-232       | 0.9243      |
| 14  | 5% Th-232       | 0.8947      |

In accordance with the results shown in Table 4 above, it indicates that k-inf whose value below subcritical condition (k-eff < 1) is k-inf resulted from Th-232 with percentage from 10% to 5% (as U-238 substitution). Substitution of U-238 with Th-232 is done in order to reduce produced transuranic elements, i.e. plutonium (Pu) and minor actinides (MA). U-238 radioisotope is a source of
Pu and MA, which are the main contributor of radio nuclides generated by nuclear wastes. Based on k-eff values shown in Table 4, it can be justified that further analysis can be performed on ADS assembly using Th-232 fuel with percentage 5% - 10% of U-238 mass. Further detail analysis on 5% - 10% range, it is justified that 7% Th-232 is the optimum concentration added to ADS fuel as U-238 substitution if the ideal subcritical condition is assumed to have k-eff is 0.950.

The result of Swing reactivity calculation of accelerator driven system subcritical reactor 100 MWth as a function of burn-up for 5% -20% Th-232 obtained is shown in Figure 5.

![Figure 5. The results of Swing reactivity calculation of accelerator driven system subcritical reactor 100 MWth as a function of burn-up for 5% -20% Th-232](image)

It can be seen from Figure 6, the burn-up level is simulated from 10% to 100% and further detailed observation is done for under 10%, i.e. 1%, 3%, and 5%, to obtain the k-inf trend. Figure 4 shows that k-eff tends to rise at burn-up <20% and is relatively stable at burn-up 20%. Subcritical k-eff at burn-up 100% reaches 0.8947 (5% Th-232), 0.9445 (7% Th-232), and 0.9857 (10% Th-232).

This k-eff trend justifies the sub-critical condition in ADS at different burn-up level, especially for Th-232 with 7% concentration. The results of swing reactivity calculation of accelerator driven system subcritical reactor 100 MWth as a function of burn-up for 5% - 20% Th by using SRAC 2006 Code. Using the above parameter specification, the result of k-eff is initially less than 0.5 so that the calculation using CITATION code could not be completed, because the minimum k-eff allowed is 0.5. Furthermore, material improvisation is applied by using LWR spent fuel and thorium fuel with slightly different composition. The result of Swing reactivity calculation of various thorium blanket thicknesses is shown in Figure 6.
Figure 6. The result of Swing reactivity calculation of various thorium blanket thicknesses of 30 cm, 40 cm, and 50 cm

It can be seen from Figure 7, at the beginning of life (BOL), the k-eff of ADS design with 50 cm thickness is 0.9821491 and at the end of life (EOL) k-eff is 0.9396284. The swing reactivity is -4.33% k/k. The presence of thorium makes k-eff slightly lower. The blanket thickness is initially 30 cm, which gives critical reactor. Then, the thickness is increased by 10 cm and k-eff< 1 is obtained at 50 cm thickness, so that the reactor is subcritical as expected for ADS. The Result of calculation by using MCNP6 Code. The result of Swing reactivity calculation of operation ADS subcritical reactor for 720 days during ADS Operation is shown in Figure 7.

Figure 7. The results of swing reactivity calculation of operation ADS subcritical reactor for 720 days during ADS Operation

The k-eff calculation using MCNPX code is aimed to determine expected subcritical condition of ADS system, so that the use of nuclear fuel in the reactor does not cause k-eff to reach 1 or higher. It is estimated that the cycle of this system in sub-critical condition is 720 days.

8
4. Conclusion

Based on the results swing reactivity of the calculation by using Origen 2.1 Code, indicates that k-eff whose value below subcritical condition (k-eff < 1) is k-eff resulted from Th-232 with percentage from 10% to 5% (as U-238 substitution). Substitution of U-238 with Th-232 is done in order to reduce produced transuranic elements, i.e. plutonium (Pu) and minor actinides (MA). U-238 radioisotope is a source of Pu and MA, which are the main contributor of radio isotop generated by nuclear wastes. It can be justified that further analysis can be performed on ADS assembly using Th-232 fuel with percentage 5% - 10% of U-238 mass. Further detail analysis on 5% - 10% range, it is justified that 7% Th-232 is the optimum concentration added to ADS fuel as U-238 substitution if the ideal subcritical condition is assumed to have k-eff is 0.950.

Based on the results swing reactivity of the calculation by using SRAC 2006 Code, indicates that at the beginning of life (BOL), the k-eff of ADS design with 50 cm thickness is 0.9821491 and at the end of life (EOL) k-eff is 0.9396284. The presence of thorium makes k-eff slightly lower. The blanket thickness is initially 30 cm, which gives critical reactor. Then, the thickness is increased by 10 cm and k-eff < 1 is obtained at 50 cm thickness, so that the reactor is subcritical as expected for ADS.

Based on the results swing reactivity of the calculation by using MCNP6 Code, at beginning of life (BOL), the k-eff of ADS design is 0.9847 and at the end of life (EOL) is 0.9823. The presence of plutonium and mayor actinides makes k-eff get slightly lower. Arrangement at this ADS model is performed to produce subcritical condition, in which an increase in fuel volume cause k-eff > 1.

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