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# Modeling of the External Neutron Source Effect in a Subcritical Reactor Analysis

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## 1. Introduction

A few concepts of the innovative subcritical reactors have been under intensive consideration in many countries [1, 2, 3, 11]. Proposed benefits of these reactors include: (1) safety – as these reactors lack sufficient amount of fuel to go critical without external fixed source of neutrons, (2) environment friendliness - thanks to their harder spectra, they are expected to perform better in TRU burning as well as less production of the same in their own cores than critical reactors (3) overall cost effectiveness – economics may not be worse due to their less utilization of fuel and introduction of the innovative technologies [4].

Although, there is no rebuttal to the need of transmutation reactors which should eliminate the radio toxicity and decay heat from long lived fission products (LLFP) and transuranic (TRU) isotopes. Subcritical reactors are somewhat different from their critical counter parts. They need employment of an external source, use of special materials at source facing zone, and design of reactor at near critical level, etc.

In this paper benefits of harder spectra from a typical fixed neutron source are assessed in terms of TRU burning and increase in effective multiplication factor. Later is taken as a measure of the core reactivity increase and hence fuel saving.

## 2. Calculation Model

A subcritical reactor model, as shown in Fig. 1, consisting of an external source in a cylindrical zone I, followed by a TRU section i.e. region II and finally enclosed by a radial reflector and a neutron shield in region III and IV respectively. Similar models are already used in literature like in Volodymyr [4], but they lack inclusion of the neutron shields.

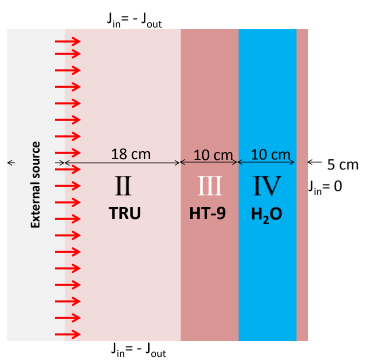


Fig. 1. Reactor model with reflective top & bottom

### *2.1Material composition of the model*

Choice of Plutonium content in the TRU core region II depends on many factors, and due to associated benefits different compositions have been suggested for different purposes. For instance, Artioli et al. [10] suggested using Pu/TRU ratio of 1.2, due to constant value of the resulting multiplication factor over the entire cycle length and hence making the coupling with accelerator easier. Using such a composition is possible only with recycling option rendering the fuel cycle useable to only selected countries. Region II, which is a TRU core region, contains driver fuel i.e. all the nongaseous isotopes from the spent fuel of a 1,000 MWe PWR, present after ten years of so called cooling time. This driver fuel constitutes 6 % of the total volume of the region. Remaining share of 94 % is occupied by the coolant, core structural materials, cladding etc. Exact composition of this 94 % portion is obtained from the previous study [5]. Pure light water is used as neutron shield and composition of HT-9 steel reflector is given in reference [6].

### *2.2 Dimensions of the model regions*

External source sizes for different subcritical reactors vary from one another drastically. For instance in a fusion fission hybrid reactor, entire fusion reactor acts as an external source while in an accelerator driven subcritical system (ADS) a very small beam of charged particles impinges over the target. ADS do not require more than few centimeters of space at the center of the core. We use ADS space requirement (10 cm radius cylinder) in the current representative model. Both reflector and shield are also 10 cm thick walled cylinders. TRU section is chosen (18 cm thick walled cylinder) such that it gives the typical desired effective multiplication factor of about 0.96. Top and bottom boundaries in Fig.1 are assumed to be infinite. This is not a realistic assumption because of small radius, but may show external source effect near the source boundary more clearly.

## 3. External Source Effect

Due to higher proportion of the high energy neutrons in fusion (all neutrons start at 14.1 MeV) and ADS (with about half of the neutrons above 1.98 MeV limit) sources than only fission source, as shown in Fig. 2, there is reasonable expectation to get the higher multiplication factor, also, to burn larger amount of TRU due to high fission to capture cross section ratio [7].

### *3.1 Calculation tools*

To compare the fixed neutron source effectiveness, two Monte Carlo neutronic analysis codes MCNPX 2.6.0 [8] and McCARD [9] were used. McCARD gave an additional option of making depletion calculations with external source effect included but without eigenvalue search. In this study, to include the effect of external source with eigenvalue search in a so called reactor problem, appropriate changes were made to the source files of MCNPX.

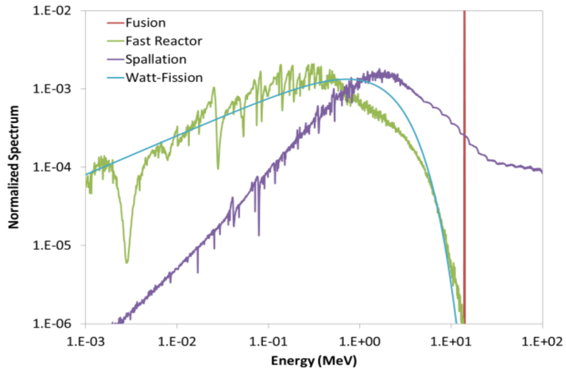


Fig. 2. Initial spectrum from selected external sources

### *3.2 Modifications to MCNPX2.6.0*

Few changes were made to the relevant subroutines in order to account for the external source with BURN option of MCNPX, which in turn is limited to the KCODE option only. The major change implicated is augmentation of the existing subroutine 'hstory.F' with a new external source spectrum reading subroutine 'ATZ.F'. Since, we are interested to take account of the neutron energy only, so, other parameters like direction of motion were not disturbed. Effective multiplication factors obtained from different spectra of neutrons are compared in table I below.

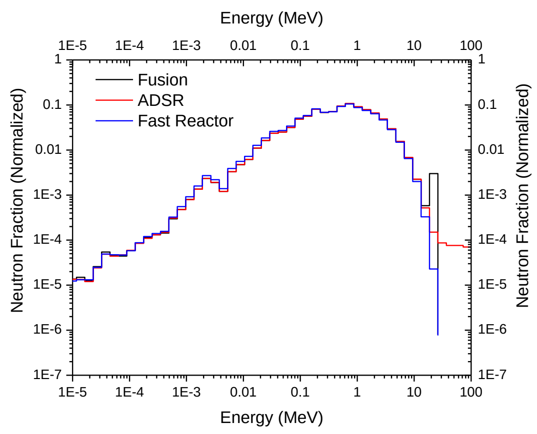


Fig. 3. core averaged neutron spectra with external source sampling

A comparison of the space averaged neutron spectra averaged over the entire core is given in Fig 3. Although a reasonable fraction of the neutrons (~0.02532 for fusion driven, 0.03129 for ADSR and 0.04459 for FR i.e. $(1\text{-}k_{eff})$ from last column of table I) is sampled from the respective external sources. The core averaged spectrum, however, is very similar for all cases except in the tails. Such a dwindling population of the characteristic neutrons may not show the desired source specific different burn characteristics. As discussed later, loss in this number from more than 3% to less than a fraction of a percent might be attributed to the lead coolant and TRU itself. Though, small in comparison with the dedicated moderators, unwanted cooling phenomenon is clearly present there.

Table I. Model for fission neutron spectrum

| Case No. | Neutron Source | $k_{eff}$ |
|---|---|---|
| 1 | Modified MCNPX ($\chi_{Watt}(E)$) | 0.96062 |
| 2 | $\chi(E)=\chi_{Fast\ Reactor}(E)$ | 0.85595 |
| 3 | $\chi(E)=\chi_{ADSR}(E)$ | 1.19568 |
| 4 | $\chi(E)=\chi_{Fusion}(E)$ | 1.57957 |
| 5 | $\chi(E)=(1-k_{eff})\chi_{FR}(E)+k_{eff}\chi_{Fission}(E)$ | 0.95541 |
| 6 | $\chi(E)=(1-k_{eff})\chi_{ADSR}(E)+k_{eff}\chi_{Fission}(E)$ | 0.96871 |
| 7 | $\chi(E)=(1-k_{eff})\chi_{Fusion}(E)+k_{eff}\chi_{Fission}(E)$ | 0.97468 |

Table I enlists some specific cases of inclusion of external source with the eigenvalue search (KCODE) option of MCNPX. Details of each of these cases are given in the following paragraphs.

Case 1 shows result from revised MCNPX version in which eigenvalue calculation is done with built-in fission spectrum only. After modification, there was negligible difference in $k_{eff}$ because of minor changes. Here, in table I, $\chi_{FR}(E)$ represents the average neutron spectrum found in the fast reactor core, $\chi_{ADSR}(E)$ represents the neutron spectrum from the Pb target with proton beam, and $\chi_{Fusion}(E)$ represents a mono-energetic beam from fusion plasma.

Cases 2, 3 and 4 are fictitious cases to differentiate an external source effect. Eigen value search was done with both fission and the external source neutrons sampled from a typical fast reactor (case 2), from a spallation neutron source (case 3) and from fusion plasma emitting mono-energetic 14.1 MeV neutrons (case 4). Cases 5, 6 and 7 are more realistic simulations. In this model, it is assumed that dominant fraction (ratio of $k_{eff}$) of neutrons is coming from fission with Watt spectrum but some part (ratio of $1\text{-}k_{eff}$) are contributed from external source; fast reactor (case 5), ADSR targets (case 6) and fusion plasma (case 7) respectively.

Table I shows that if all the neutrons at the start of each cycle were mono-energetic fusion neutrons then effective multiplication factor from case 3 would be the highest as it is expected in fast neutron system. According to the level of spectrum hardness shown in Fig. 2, $k_{eff}$ values are ranked in the order of fusion, ADSR, watts and fast reactor.

The reason for reduction in $k_{eff}$ (by ~ 500 pcm) with inclusion of fast reactor spectrum as external source spectrum (case 5) when compared with case 1 is because it is softer than the default Watt fission spectrum. Thanks to the harder spectra in other two cases (case 6 and case 7) $k_{eff}$ is increased by roughly 800 pcm and 1400 pm respectively.

### *3.3 Comparison of McCARD and MCNPX results*

TRU depletion characteristics calculated with MCNPX and McCARD are given in Fig. 4 and Table II. Effect of fusion neutrons in TRU burning (25,937 g vs. 25,579 g) over 500 days is very small. In current study a relatively fine time step size was used. Calculation was done at 1, 10, 25, 50, 75, 100, 125, 150, 175, 200, 225, 250, 300, 350, 400, 450, and 500 days. The difference in TRU masses burnt or produced is so insignificant that effect of choosing some worse burn time step in McCARD (e.g. a single step of 500 days) is more discernible (25,579 g vs. 23,650 g) than the external source effect.

In an attempt to get more clearer difference, the TRU fuel was burnt at very high specific power (273 kW/kg) for 500 effective full power days, leading to a proportionately high burnup of (136.5 GWD/THM) in all three cases. Due to material integrity constraints no existing nuclear facility allows such a high levels of irradiation.

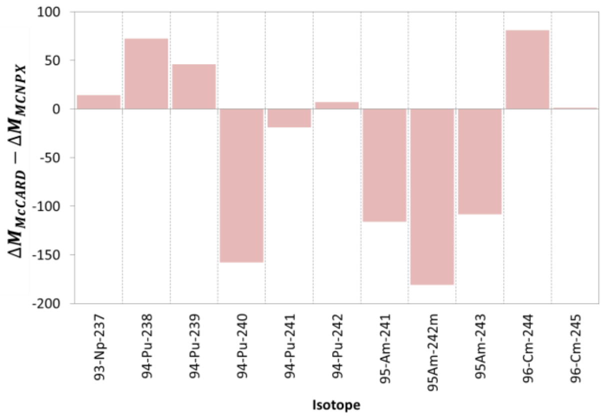


Fig. 4. Difference in the McCARD burnt/produced masses of selected isotopes from MCNPX

Effective multiplication factors and flux levels at the beginning and end of the cycle are very much comparable from kcode option of MCNPX and C_Source option of McCARD. A minor difference in burnt TRU masses (25,937 g vs. 25,579 g) might be attributed to the difference in modules i.e. CINDER and ORIGEN working in the back ground, or more precisely to their respective cross section libraries.

Table II: External source effect on depletion of TRU

| **Property** | **MCNPX (kcode)** | **McCARD (C_Source)** | **McCARD (S_Source)** |
|---|---|---|---|
| TRU (14.96 $^w/_o$) | 183.2 kg | 183.2 kg | 183.2 kg |
| Initial keff | 0.96063 ± 0.00032 | 0.96045 ± 0.00030 | - |
| Keff after 500 days | 0.83863 ± 0.00030 | 0.84602 ± 0.00029 | - |
| Initial Flux | 2.673E15 | 2.639E15 | - |
| Flux after 500 days | 3.248E15 | 3.206E15 | - |
| Burnup (MWD/kg) | 136.5 | - | - |
| TRU Burnt (g) | 25,937 | 25,579 | 25,570 |

### *3.4 TRU depletion with distributed external source*

Effect of external source is incorporated with revised MCNPX and compared with the original one. External source i.e. fusion is assumed to be uniformly distributed over entire TRU region. In other words the surface source is approximated by a volume source with a fraction of the fission neutrons emitted at 14.1 MeV. As shown in Fig. 5 and Fig. 6, the amount of different TRU isotopes transmuted in 500 days differs very lightly.

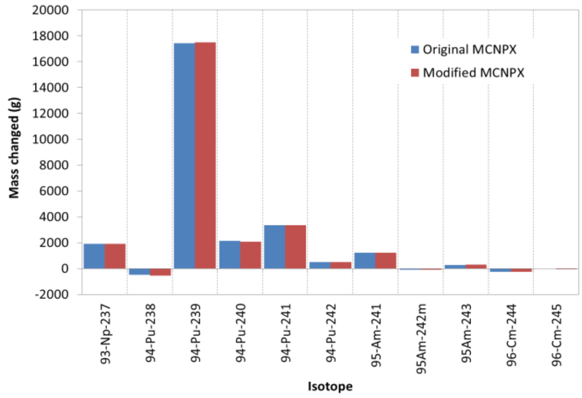


Fig. 5. Comparison of total amount of selected isotopes burnt or produced in 500 days with external source (Modified MCNPX) and without external source (Original MCNPX)

Fig. 6 shows the difference in the mass of different isotopes changed (burnt or produced) in 500 days cycle which is no more than few grams and it is not necessarily from the external source. Partly, it could be from other differences like use of different set of the random numbers, a small difference in $k_{eff}$ and hence minor differences in operating power and flux levels etc. The difference, to some extent at least, fairly matches the expectations as Np-237, Pu-239, Pu-240, Am-241 and Am-243 are burnt more heavily with external source. At the same time Pu-238, Am-242m and Cm-244 are produced in larger quantities when driven with external source. There is only one isotope with anomalous behavior: that is fusion driven system burns Pu-240 in lesser quantity while it was desired otherwise.

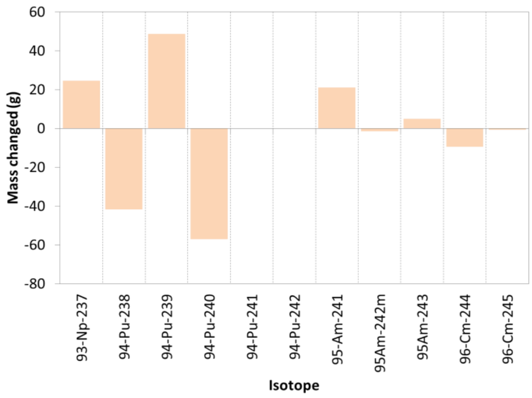


Fig. 6. Difference of changed mass of selected TRU isotopes in 500 days with and without external source

Fig. 7 shows the effect of fission neutron energy on effective multiplication factor. In this hypothetical analysis where all the fission neutrons are assumed to be mono-energetic it is clear that there is no considerable benefit of spectrum hardening up to about 6 MeV. This is the main reason for not observing some big effect from ADSR and fusion sources in TRU depletion. By inclusion of these sources average energy of the prevalent neutrons still dangles around 2 MeV and does not go beyond the 6 MeV limit. Fig. 7 also gives a criterion that we should expect some plausible increase in fission cross sections or benefit in TRU burning if external source can provide a reasonable fraction of the neutrons above 6 MeV.

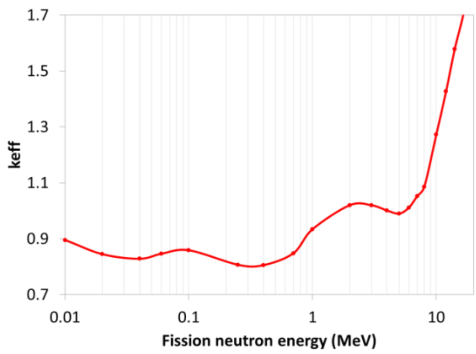


Fig. 7. Dependence of $k_{eff}$ on fission neutron energy

## 6. Conclusions

Although fusion and spallation neutron sources have harder spectra than a typical fast reactor, their effectiveness in the transmutation and incineration of TRU depends heavily on the prevalent material composition of the core. Due to obvious practical reasons, existence of coolant and other integral parts of the core is essential. These materials heavily suppress dependence of the prevailing neutron spectrum on the original source. Moreover, subcritical systems like fusion-fission hybrid reactor, ADSR, etc. are operated close to critical levels i.e. with effective multiplication factor close to unity. Hence neutron fraction from external sources in these systems is already very small and its effectiveness is even more subdued by their rapid slowing down in the core. So, it is concluded that subcritical systems might be preferred due to some other reasons but, as long as TRU incineration is concerned they do not make a better choice than a typical fast reactor.

To collect more substantial evidence it is suggested to farther extend this study to highly subcritical scenarios. A minor change in the calculation model i.e. reduction in wall thickness and increase in the TRU volume fraction from 6% and a better approximation to the surface source should give more accurate results.

## References

1. Ming Jin et.al. “Thermal and stress analysis of window target for accelerator-driven sub-critical system during beam trip transients”, *Progress in Nuclear Energy*, **85,** (2015).
2. Hesham S et.al., “Investigation of subcritical multiplication parameters in TRIGA Mark II accelerator driven system”, *Annals of Nuclear Energy*, **81**, (2015).
3. Alejandro C et.al., “Feasibility study of a hybrid subcritical fission system driven by Plasma-Focus fusion neutrons”, *Annals of Nuclear Energy*, **78**, (2015).
4. Volodymyr G, Alan H and Tkaczyk, “Cost optimization of ADS design: Comparative study of externally driven heterogeneous and homogeneous two-zone subcritical reactor systems”, *Nuclear Engineering and Design*, **270**, (2014).
5. Siddique MT and Kim MH, “Conceptual design study of Hyb-WT as fusion fission hybrid reactor for waste transmutation”, *Annals of Nuclear Energy*, 65 (2014).
6. Chen Y, Irradiation effects of HT-9 martensitic steel”, *Nucl. Eng. And Tech.*, **45**, issue 3 (2013).
7. Chadwick MB et al, “ENDF/B-VII.0: Next generation evaluated nuclear data library for nuclear science and technology”, *Nucl. Data Sheets*, **107** (2006).
8. Pelowitz DB, MCNPX Version 2.6.0 user’s manual, LA-CP-07-1473 (2008).
9. Shim HJ, Han BS, Jung JS, Park HJ and Kim CH, "McCARD: Monte Carlo Code for Advanced Reactor Design and Analysis," Nucl. Eng. Technol., 44 (2012).
10. Artioli C et.al., Minor actinide transmutation in ADS: the EFIT core design, PHYSOR-08, International Conference on the Physics of Reactors (2008),
11. Romanello V et.al., Comparison of the waste transmutation potential of different innovative dedicated systems and impact on the fuel cycle, ICENES 2011, International Conference on Emerging Nuclear Energy Systems (2011).