Study of the External Neutron Source Effect on TRU Burning in a Sub-critical Reactor

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1. Introduction

As the electrical power demand is growing worldwide, alternative energy source to nuclear power has been searched in many ways. In order to compete with renewable energy options, next-generation nuclear power should comply with environmental sustainability. One of the drawback points of nuclear power is the production of highly radioactive and long lasting waste isotopes during power production. Therefore, most important design requirement of future nuclear option should have a potential to burn selectively long-lived fission products (LLFP) and long-lived minor actinides (LLMA).

However, there is no way to burn them selectively in the reactor core. Practical method of waste transmutation should rely on selective separation of them from spent nuclear fuel of power plants. Under the proliferation concern, direct separation of trans-uranic isotopes (TRU) from pyro-reprocessing plant became a feasible option in our country. Even though social-political agreement is not matured as well as technical feasibility, current study is done based on basic assumptions; TRU and LLFP is separated from spent fuel of nuclear power plants.

There are many options to burn TRU or LLMA. As an innovative reactor options which have transmutation capability, fast spectrum reactor is known to be better than thermal spectrum system. In this study, three candidate options are concerned to be compared; (1) fast critical reactors, (2) fission-fusion hybrid reactors, (3) accelerator driven subcritical systems [1-3]. Option 2 and 3 are dependent on subcritical fast reactor driven by external neutron sources either from plasma fusion tokamak or neutron producing target with proton accelerators.

In this study, as a preliminary work relationship of external neutron source to the transmutation performance is tested herein. Calculation is done in parallel for three different core model; MESOF for fast reactor core [4], Hyb-WT for fusion-fission hybrid reactor [2] and ideal lead-cooled subcritical fast reactor for ADSR.

2. Methodology

2.1 Hypothetical Reactor Model

To make the comparison un-biased, an identical hypothetical reactor was employed for all the fixed neutron sources. Simple geometrical model with dimensions and constituting materials are given in Fig. 1. TRU obtained from pyro-processing of the spent fuel of a pressurized water reactor (PWR) after a cooling time of ten years is used as the driver fuel [5]. HT-9 steel was used as reflector and water as neutron shield. Reflector thickness was ascertained on the basis of infinite multiplication factor. With current reflector size of 5.0 cm k_{eff} is of the order of 94% of k_{inf}, and is considered adequate. TRU loading and its ratio to the structural materials, coolant etc. is obtained from reference [2].

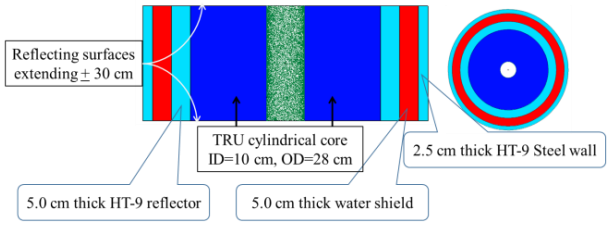

Fig. 1. Dimensions and materials of the hypothetical reactor with top and bottom reflecting (infinite) surfaces

Numerous materials like B_4C, boron doped steels etc. can be used as neutron shield material outside of the reflector but, light water is chosen for its abundant availability and engineering simplicity. It is worth noting that shield water has no effect on the in-core neutron spectrum and hence can be used as a shield material without de-grading the fast neutron flux. Outermost layer of HT-9 steel is just to hold the shield water.

Fixed neutron source is assumed to be a cylindrical surface source with uniform axial neutron distribution i.e. the TRU core is like a blanket around the external neutron source. Definition of neutron energy spectrum driving the TRU transmutation and neutron multiplication is the prime interest at this stage.

2.2 Calculation Model

Two well renowned and validated computer codes, MCNPX 2.6 and ORIGEN2 V2.1 were used in this study in order to calculate isotope transmutation under the neutron spectrum driven by external source. Depletion studies can be made by MCNPX 2.6 alone but, its BURN card option is limited to the eigenvalue problems, i.e. with option of KCODE. KCODE on the other hand is hard wired to use Watt fission spectrum only – except for the first generation of neutrons which

are provided by the user using KSRC, SDEF or SSR cards [6]. Thus, to account for the external source spectra, ORIGEN2 was used. The entire study was structured as the followings:

1. MCNPX 2.6 was used to calculate
   a. 63-group (n,γ), (n,f), (n,2n) and (n,3n) reaction cross sections for actinides,
   b. 63-group (n,γ), (n,2n), (n,α) and (n,p) reaction cross sections for non-actinide isotopes present in the core, and
   c. Corresponding 63-group neutron scalar flux averaged over the entire core region.
2. For every TRU isotope, 63-group cross sections were condensed to one-group with neutron spectrum obtained in step 1 using equation (1).

$$\sigma^i = \frac{\sum \sigma_j^i \varphi_j}{\sum \varphi_j} \qquad (1)$$

Where, σ^i is cross section for the reaction 'i' and sums range over 63 energy groups.

3. One-group point depletion code ORIGEN2 V2.1 [7] was used to ascertain the TRU inventory remaining after continuous burning with constant neutron flux of 1.0×10^{14} n/cm^2-s for 1000 days.

3. Comparison of the Neutron Spectra

Neutron spectrum is the key parameter in cross section and hence, actual reaction rate determination. This section covers the comparison of the external source spectra in isolated and in core averaged conditions.

Fixed neutron source spectrum at the source position (isolated) and the spectrum averaged out over the core, as shown in Fig. 2 and Fig. 3 respectively, are different from one another. Although there was no dedicated moderator in the core, the coolant - Li17Pb83 eutectic – seemingly, caused sufficient moderation to outshine the staggering external source neutron population effect.

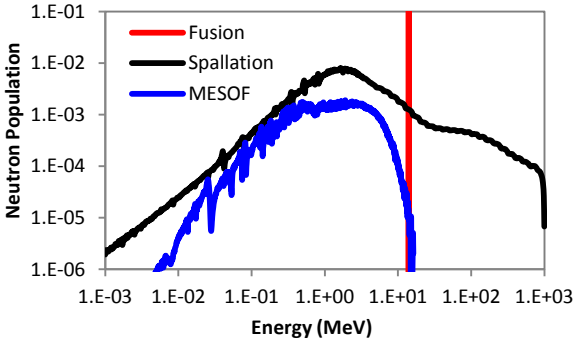

Fig. 2. External source spectra at the source position

In the core averaged external source spectra, as given in the Fig. 3, there is hardly any difference for the mentioned three sources, up to about 3 MeV. Source neutrons lost their characteristics in collisions with the coolant. Numerically, 99.3% of the MESOF neutrons (neutrons from a Multi-purpose Experimental Sodium cooled Fast reactor [7]) and 79.2% of the spallation neutrons lie below 3 MeV.

A very minor fraction of the total neutrons - 0.021% for the MESOF fixed source and 0.625% for the spallation fixed source are above 3 MeV limit. Spallation source not only has higher neutron population above 3 MeV, these are also more energetic and hence initiate more fission reactions per neutron.

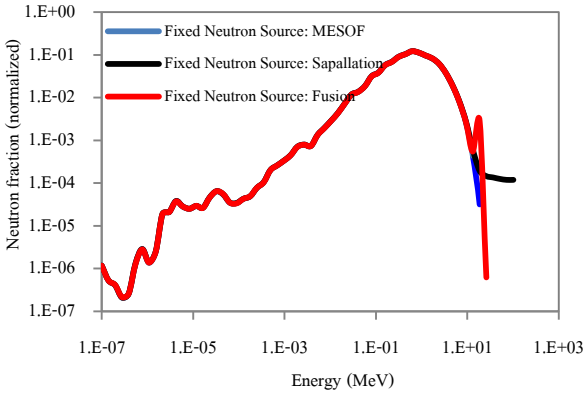

Fig. 3. Core averaged neutron spectra

4. TRU mass burnt in 1000 days at 1×10^{14} n/cm^2-s

In this section TRU burnt in a dedicated SFR is compared to the TRU burnt in the current hypothetical reactor using ORIGEN2. Prima facie, fusion neutrons are more effective than a SFR spectrum in burning TRU, as depicted in the Fig. 4. For a subcritical reactor with k_{sub}=0.97 and run by a fusion source, all the isotopes get burned except Am-241 and Cm-242. On the other hand if there were neutrons only from SFR, seven out of eleven isotopes are produced instead of getting burnt. The most important is the burning of the obnoxious isotopes of americium and curium. The high amount of Pu-239 and Pu-240 consumed in a SFR is because of its design and not because of its spectrum.

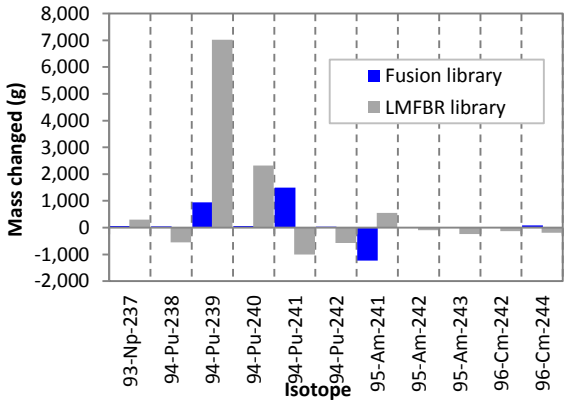

Fig. 4. Mass burnt for different isotopes in 1000 days (ORIGEN)

For a fusion driven sub-critical reactor and a MESOF, as compared in Fig. 5 below, one does not seem by any means, better than the other in burning TRU. The minor difference (~7%) visible in the column heights is because the MESOF core operates at critical level and has about 7% more TRU loading. Consequently, as expected, a similar excess amount of the TRU is burnt in the MESOF core.

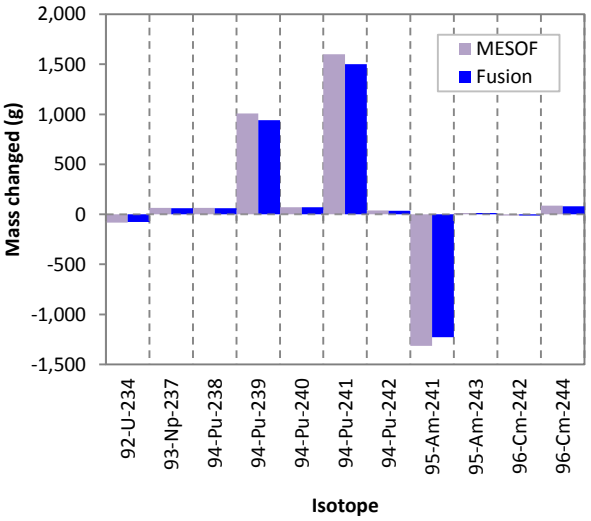

Fig. 5. Comparison of the isotopic mass change of TRU in 1000 days, about 7% more TRU is loaded in the MESOF core.

5. Conclusions

Moderation effects afforded by different materials present in the core, seemingly, diminish the effect of the weak population of external source neutrons - most important reason being the fact that these systems are usually operated close to critical levels i.e. with k_{sub} close to unity. Therefore, dominant number of the neutrons is always from fission process. For instance, if a subcritical reactor is operating with k_{sub}=0.97 it has 97 percent of the total neutrons from fission. Among the remaining 3%, mostly get moderated and lie below few MeV range. The remaining neutrons (among the external 3%) – very few in number (less than 1% in any case) – being very energetic (above three MeV or so) do cause much more fissions per neutron than their counterparts but, because of their overall low population they do not have any significant and decisive influence in the overall reactor performance.

Currently, entire study is limited to the source neutron energy of 20 MeV only. In future, it is expected to get reasonably plausible fixed source dependent difference in the TRU burning by using tabulated data for the neutrons of higher energy (up to 250 MeV at least). Secondly, a clearer picture is expected if the TRU loading was increased from the current value of 133 kg to few metric tons, as is the case in most of the existing reactors.

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