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Analysis of Transmutation Performance in the Fast Spectrum Systems

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1. Introduction

There are only very few emission free sources with minimal footprint on this planet – nuclear is one of them, however, despite of rapidly increased funding in last couple of years, total amount of electricity that can be generated with reliable confirmation from all of renewable sources except nuclear is very limited [1]. Nuclear energy, being the most appealing and nonpolluting source has a big issue left i.e. managing the spent nuclear fuel. There are many technological ideas in the design phase or under construction to come up with this limitation. Among the many strategies to incinerate transuranic isotopes (TRU), fission products (FP), and also produce electricity different types of critical and subcritical reactors are proposed. Two most widely studied subcritical reactor options being Accelerator Driven System and a Fusion Fission Hybrid System [2-5].

In this study, we compare the amount of TRU burnt in different system spectra. To compare the performance, an identical model of a subcritical reactor is used for all the cases, with driving source taken from the potential candidates. A typical fast reactor spectrum is taken as a reference case. It is then compared with an accelerator driven subcritical reactor (ADSR) and a fusion spectrum i.e. 14.1 MeV mono-energetic neutrons. Both later types of driving sources are under extensive investigation but possess totally different pros and cons. Expected price tags for the latter two options are also very different from one another. We take net amount of TRU burnt as the criterion to judge these systems for their performance and worth.

2. Reactor Model

As shown in Fig. 1 below, an ideal model reactor is used in all the cases. External source neutrons (symbolically shown as white arrows entering the TRU region) are sampled from the external sources. The choice of Plutonium content in the TRU core region, marked as red, depends on many factors. If purpose of the reactor is to burn Pu then Artioli et al. [6] suggested using Pu/TRU ratio of less than 1.2. For both accelerator and fusion driven systems, however, it is strongly desired to keep the effective multiplication factor constant. A changing (usually decreasing) multiplication factor means a monotonically increasing requirement of accelerator/fusion neutrons which itself is not proven yet. So, from the external source point of view they suggest Pu enrichment as close to 42% as possible. Resultantly there is negligible variation in the k_{eff} over entire cycle length and external source can be designed for running at a constant current. Such a "non-natural" Pu content needs extraction of Pu from the spent nuclear fuel which is not an option for many countries.

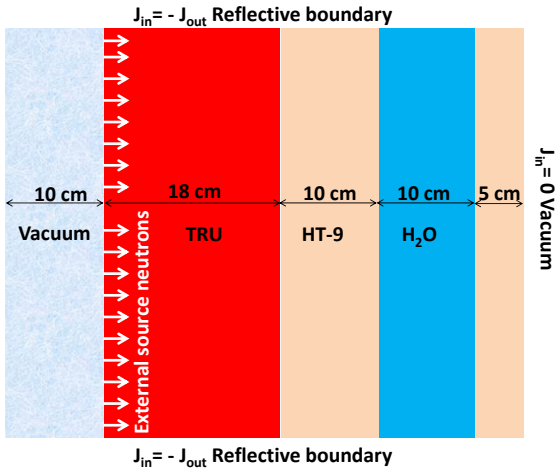

Fig. 1. Ideal reactor model

To make analysis more open and useful, TRU content resulting from nongaseous isotopes of a typical 1000 MW PWR after ten years of cooling time is used. No isotope or element is extracted or doped. TRU fuel constitutes only 6 % by volume of this region, coolant, cladding, grid spacers etc. [7] make up the other 94 %. The inner and outer HT-9 regions represent reflector and water holder respectively. H_2O region is pure light water used as a representative shield material. Detailed isotopic composition of the TRU and HT-9 regions is given in table 1.

Fig. 1 also shows the dimensions of the different regions used. TRU region is sized with only purpose of making initial k_{eff} close to unity (about 0.96). External source region size is selected from the usual requirement for a typical ADSR i.e. 10 cm thick walled imaginary cylinder. Reflector size (10 cm) is chosen to bridge the gap between a bare reactor effective multiplication factor (k_{eff}^{bare}) and effective multiplication factor with an infinite reflector ($k_{eff}^{infinite}$) by roughly 80%. Water and water holder sizes are not

designed to some certain requirements. Top and bottom surfaces of the model reactor are taken as specular reflecting surfaces.

Table I: Material Composition of TRU and Reflector

TRU Region				HT-9 Steel Region	
Isotope	Mass fraction	Isotope	Mass fraction	Isotope	Mass fraction
82208	1.224E-09	96248	3.503E-08	6000	2.000E-03
90228	5.544E-10	97249	2.648E-13	14028	3.675E-03
90230	5.173E-08	98249	8.087E-10	14029	1.933E-04
90232	1.827E-08	98250	7.025E-11	14030	1.320E-04
90234	1.027E-10	98251	8.520E-11	23000	2.500E-03
91231	1.088E-08	98252	5.268E-12	24050	5.008E-03
91233	2.276E-10	3006	8.937E-04	24052	1.004E-01
93235	4.533E-13	3007	3.575E-03	24053	1.161E-02
93236	1.726E-08	82204	9.175E-03	24054	2.945E-03
93237	6.701E-03	82206	1.595E-01	25055	6.000E-03
93238	2.095E-12	82207	1.470E-01	26054	4.773E-02
93239	2.016E-09	82208	3.502E-01	26056	7.770E-01
94236	1.609E-09	14028	1.459E-02	26057	1.826E-02
94237	4.898E-33	6000	6.240E-03	26058	2.473E-03
94238	3.199E-03	11023	2.154E-02	28058	3.360E-03
94239	4.905E-02	40090	7.234E-02	28060	1.339E-03
94240	2.323E-02	26056	9.014E-02	28061	5.917E-05
94241	9.083E-03	24052	1.493E-02	28062	1.917E-04
94242	7.885E-03	22048	9.595E-04	28064	5.041E-05
94243	8.483E-18	42098	3.198E-04	42092	1.416E-03
95241	6.122E-03	39089	2.099E-04	42094	9.044E-04
95242	1.152E-05	8016	5.665E-05	42095	1.574E-03
95243	2.343E-03			42096	1.669E-03
96241	6.623E-45			42097	9.666E-04
96242	3.011E-08			42098	2.471E-03
96243	6.375E-06			42100	9.979E-04
96244	7.250E-04			74182	1.311E-03
96245	4.894E-05			74183	7.120E-04
96246	9.768E-06			74184	1.533E-03
96247	2.440E-07			74186	1.438E-03

In table I we have used the isotope nomenclature of MCNPX. In TRU region, listed isotopes include coolant and structural materials too.

3. Comparison of the Neutron Spectra

Fig. 2 gives the neutron spectrum from external source. All the neutrons from fusion source have energy 14.1 MeV but none of the neutrons from fast reactor is that energetic. On the other hand there is a reasonable fraction (26.5 %) of the neutrons from ADSR that have energy even more than fusion neutrons. One may expect a huge difference in TRU burning because of the totally different driving source spectra and correspondingly different cross sections for different reactions. Spectra of Fig. 2 are a characteristic of the each neutron source.

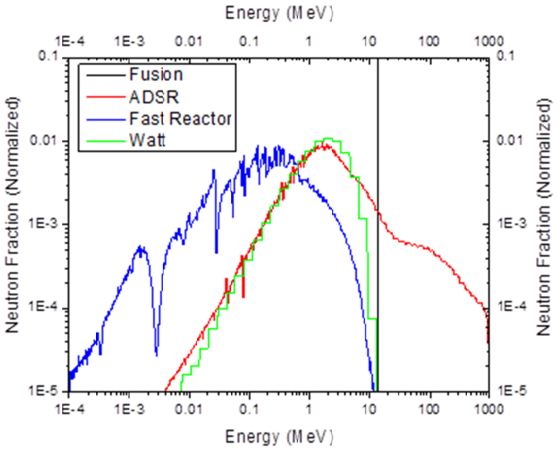

Fig. 2. External source spectra

However, when we look at Fig. 3, which is the core average neutron spectrum, we see that the source specific neutron population lies at the tails only. Mainly the spectrum is identical, one main reason being high value of k_{eff} i.e. about 96 % of the total neutrons are from fission source which is common to all the systems. Remaining fraction (roughly 4 %) loses its signature upon interacting with the coolant and other materials present in the core. So, as a result in Fig. 3 fraction of total neutrons different for each source is less than 0.4 %.

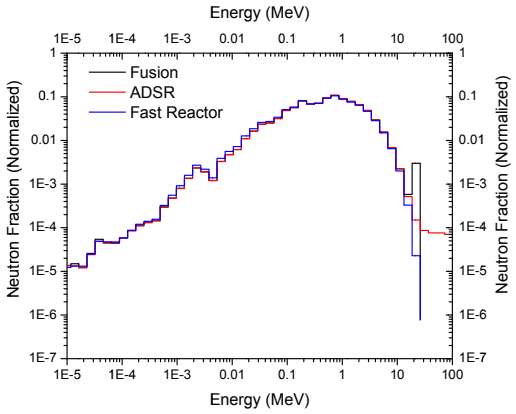

Fig. 3. Core averaged total neutron spectrum

4. Comparison of the TRU mass burnt

As shown in Fig. 4, if intention is to Pu-239 only then the best option is a relatively softer spectrum of the fast reactors as compared to ADSR and fusion driven systems is the better option. The difference is not negligible. The only reason for the difference in the amount of Pu-239 burnt being the high fission cross section of Pu-239 at lower energies.

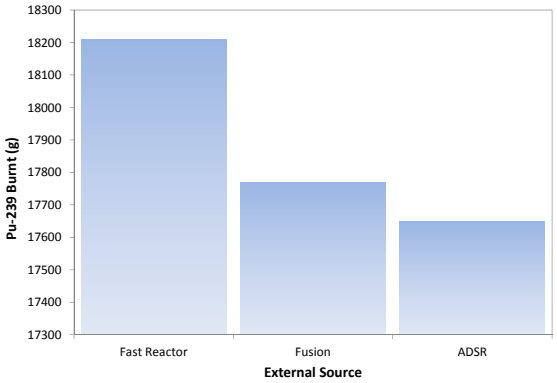

Fig. 4. Pu-239 burnt in one cycle length (EFPD = 500 days)

Fig. 5 gives the actual benefit of using a certain source spectrum. This is the ultimate target of any TRU burner. It is obvious that Fusion source having the highest average neutron energy burns the largest amount of TRU (except Pu-239). Due to softest spectrum, fast reactor is least effective among three. The difference of 289 g (roughly 0.3%) between Fusion and fast reactor driven systems is very small. It is worth noting that the difference in the masses burnt from ADSR and Fusion driven systems is negligible (160 g i.e. 0.087 % of the initial loaded TRU).

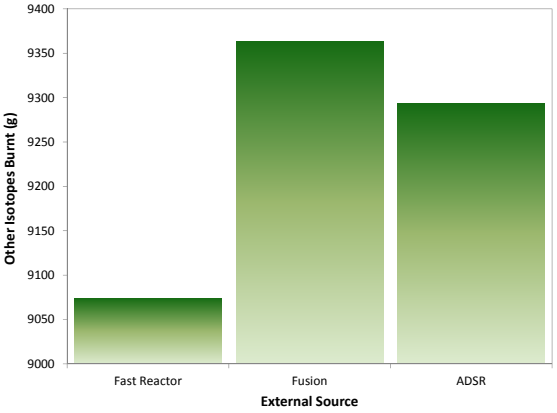

Fig. 5. TRU isotopes other than Pu-239 burnt in a full single cycle length i.e. 500 EFPD

In every reactor, due to higher absorption cross section for most of the TRU isotopes than fission cross sections and also because of the presence of relatively lower energy neutrons in the core, many isotopes are produced by transmutation. Fig. 6 lists those isotopes for which net amount at the end of the 500 day cycle is higher than their initially loaded amount. As expected, fast reactor spectrum being the softest among three produces highest amount of TRU and ADSR driven system (just opposite of Fig. 5) produces the least, though difference between TRU isotopes produced with ADSR and fusion driven system is very small (160.3 g).

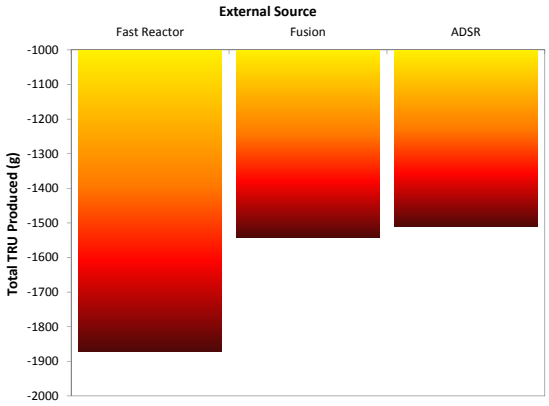

Fig. 6. Total amount of the TRU isotopes produced in a full cycle length i.e. 500 EFPD

Table II. Change in the TRU isotope inventory

Sr. No.	Isotope	Mass produced or burnt (g)		
		External Source		
		Fast Reactor	Fusion	ADSR
1	92234	-58	-56.5	-57
2	93236	-0.47	-3.8	-1.1
3	93237	2034	1949	1926
4	94238	-784	-576	-574
5	94239	18210	17770	17650
6	94240	1590	1980	1990
7	94241	3400	3380	3370
8	94242	380	480	470
9	95241	1380	1281	1251
10	95242	-101	-93	-92
11	95243	290	293	286
12	96242	-526	-490	-470
13	96244	-350	-277	-273
14	96245	-52.5	-45	-44.5
Total		**25412**	**25591**	**25432**

If we juxtapose the amounts of all the TRU isotopes produced or burnt and try to ascertain the effectiveness of these systems it is easy note from table II that net difference is even less than 200 grams. In the 500 day cycle depletion calculations this difference is less than 100 ppm of the initial TRU loaded.

5. Conclusions

Although there is extensive research in progress to design and develop the accelerator or fusion driven systems with many targets in mind. In the current study it is concluded that the notion of TRU burning with accelerator driven systems as the most efficient and the best option to burn TRU has little base when employed in some real system. Presence of coolant and other

necessary materials in the core cannot be eliminated. Same is the case with fusion driven systems. So, difficulty in manufacturing an ADSR or a Fusion driven system is not proportionate to the higher amounts of TRU burnt or lower amounts of some TRU isotopes produced.

Preference of these subcritical systems over their critical counter parts due to reasons other than TRU burning is not treated in this study.

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