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Embedded fission source approach to analyze external source effect in a subcritical reactor

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ABSTRACT

A simple modification of the fission source spectrum is proposed for the Monte Carlo calculation for externally driven subcritical reactors. Embedded fission source (EFS) approach replaces the fission spectrum with the collective spectrum of the external source and fission working in a small region near to external source only. This model provides eigenvalue search with external source contribution resulting in direct connection with isotope depletion calculation within Monte Carlo simulation. MCNPX 2.6.0 is modified for EFS and tested for three kinds of reactor problems; critical fast reactor driven subcritical reactor, accelerator driven subcritical reactor and fusion-fission hybrid reactor. The effectiveness of the external sources is determined by the extra amount of the TRU isotopes burnt and increase in the core multiplication level. The tests were performed for two subcritical cases; k_{eff} ~ 0.986 and k_{eff} ~ 0.959, with initial TRU loading of 188.8 kg and 183.2 kg, respectively. The EFS approach is validated by simulating a fission source driven system which gave the multiplication factor comparable to the original MCNPX within one standard deviation (32 pcm). The difference in TRU burn-up for both subcritical cases is of the order of 0.1% for each driving neutron source option. The study showed that the EFS can be a simple and a reliable approximation for the external source analysis.

1. Introduction

Accumulation of spent nuclear fuels becomes a crucial issue in national agenda as well as worldwide interest. About thirty tons of high-level radioactive waste is produced from each GWe-year operation of a nuclear power reactor (IAEA, 2007). A probable solution for burning of the transuranic (TRU) isotopes in a conventional thermal reactor after reprocessing has been studied rigorously. As an innovative reactor option for future, fast spectrum reactors are expected to outperform the thermal spectrum systems especially in transmutation capability (Taczanowski, 2003). Compared with critical fast reactors, a subcritical reactor with an external source is favored because of enhanced operational safety, higher public acceptability and hopefully less production of nuclear waste, even though practical use may be far away from realization in next couple of years (Gulik and Tkaczyk, 2014). There is another presumption that accelerator driven subcritical reactors (ADSR) and fission-fusion hybrid reactors (FFHR) like hybrid waste transmutation (Hyb-WT) system etc., if developed, would spare no TRU isotope and will burn the existing nuclear waste stockpiles in the most efficient, cleanest and the safest ways(Chwaszczewski and Słowinski, 2003; Gokhale, et al., 2006; Gulik and Tkaczyk, 2014; Salvatores et al., 2001; Taczanowski, 2003).

Critical reactors, both thermal and fast, totally rely on the fission neutrons born with the energy spread described by the Watt fission spectrum (Ikeda et al., 2011). In a subcritical reactor, however, the external source also provides a reasonable fraction of the neutrons supply to operate the reactor for an extended duration of time. The energy spectrum of the neutrons coming from the external source is usually much harder than fission neutrons (e.g. ADSR and Hyb-WT). Consequently, an external source contributes positively in two ways. Firstly, it hardens the prevalent neutron spectrum, and secondly, it increases the neutron flux level. The increase in the neutron flux level (from continuously decreasing to some equilibrium value) corresponds to an analogous increase in the operating power level and more rapid TRU burning or production.

Conventionally, the subcritical reactor problem is treated by invoking the in-built option of the Monte Carlo N-Particle Code MCNP (Pelowitz, 2008), known as a fixed source problem in a multiplying region (Xoubi, 2016). In this mode, the external source is located in the physical region occupied by the source itself. Moreover, neutron spectrum of the external source could also be defined precisely. The fission source comes from the fissionable material in the region occupied by the fuel. Then, this combined neutron energy spectrum (fixed source mode spectrum) is used for fuel depletion using some dedicated

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depletion code like CINDER-90 (Oak et al., 2010) or ORIGEN (Bell, 1973). This technique has widely been used previously (Mirza et al., 2010; Sommer et al., 2010; Xoubi, 2016). In addition to the extra effort required in carrying the fixed source mode neutron spectrum towards the depletion code, there are also some other implicit assumptions in this conventional technique. For instance, relative strength of the two sources (external and fission) is given at the beginning and it is assumed that this ratio remains the same. This assumption is reasonably valid provided the external source is similar to the fission source, both in location and energy spread. Secondly, in the fixed source mode, life events of the each neutron (coming from source and fission) are followed till the neutron leaks from the system or gets absorbed. Hence, the computation time becomes large for the subcritical cores with k_{eff} close to unity (Pelowitz, 2008).

In this study, an embedded fission source (EFS) approach is suggested to incorporate the external neutron source to assess the change in effective multiplication factor (due to increased η value) as well as in transmutation performance (due to decreased capture to fission cross sections ratio). Since, the life history of a neutron depends mainly on three parameters i.e. its place of birth in the core, initial direction of motion and initial energy. So, it is proposed that the effect of an external source could be incorporated by dedicating a small region of the subcritical core as a cradle of the external neutrons. To do so, the energy of the fission neutrons from this selected region is taken from the external source spectrum instead of the Watt fission spectrum. However, their place of birth and the initial direction of propagation are not changed. This way, we get a group of the neutrons having all characteristics of fission neutrons, but energy spectrum from the external source. If the chosen core region is such that it closely surrounds the external source, then initial locations of these neutrons are not very different from the true external source neutrons. Similar is the matter of the initial direction unless the external source is highly collimated (which is not the case usually). Moreover, in the Monte Carlo code MCNPX 2.6.0 all results are normalized to 'per source neutron', so, the precise number of the source neutrons (from the external source and the fission source combined) is not important (Pelowitz, 2008). It is their relative ratio that matters more. After selecting the suitable region (hence, an appropriate fraction from the external source) and modifying the neutron energy appropriately, the MCNPX 2.6.0 is used to analyze the life events of each neutron. These modifications imparted to the selected group of the neutrons are collectively termed as embedded fission source (EFS) approximation. The mathematical treatment for external source and its inclusion into MCNPX 2.6.0 was the main purpose of this work.

The MCNPX 2.6.0 code (Pelowitz, 2008) from LANL is used to show the functioning of the EFS approach. MCNPX 2.6.0 is capable of modeling arbitrary geometry and using arbitrary material composition at arbitrary places in the geometry. Its depletion workhorse i.e. CINDER2008 is a widely validated depletion module evoked by the BURN card in the input. However, its current eigenvalue search option is limited to the fission source only and it cannot incorporate the external source effect. So, we incorporated the EFS approximation into the MCNPX 2.6.0 code with BURN card to read an arbitrary spectrum and use this user-defined spectrum for the depletion calculations. The feasibility of using EFS for the externally driven systems using different external sources is tested for three types of the external sources and under two geometrical models of the core. The three concepts of the external sources are (1) a fast critical reactor (Ikeda et al., 2011; Sohail, 2014), (2) a fusion-fission hybrid reactor (FFHR) for waste transmutation (Hyb-WT) (Siddique and Kim, 2014) and (3) an accelerator driven subcritical reactor (ADSR) (Taczanowski, 2003). The two geometrical models correspond to the most promising subcritical reactors i.e. ADSR and FFHR. Lastly, to validate the results from the EFS approximation, the identical models of the both geometries of the subcritical reactors are subjected to the EFS and the conventional method.

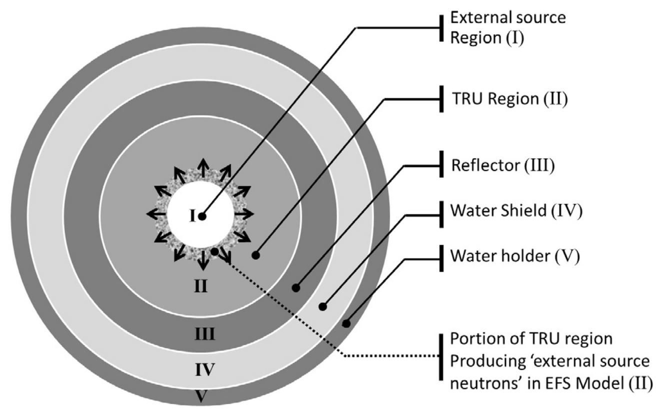

Fig. 1. Top view of the horizontal cross section of the ideal reactor model in XY plane.

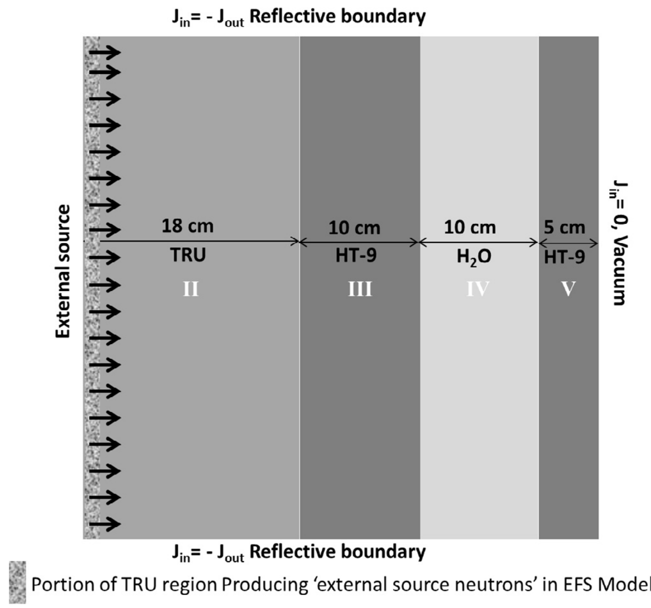

Fig. 2. Cross section of the reactor model in positive half of YZ plane.

2. Reactor model

The ideal reactor model (Fig. 1 and Fig. 2) is similar to Gulik et al. (Gulik and Tkaczyk, 2014), and differs mainly in the fuel composition and water shield region. Moving radially outwards, the coaxial cylinders (Fig. 1) constituting; core region, HT-9 steel (Chen, 2013) reflector, water shield and the water holder regions, have wall thicknesses of 18 cm, 10 cm, 10 cm, and 5 cm respectively. Dimensions of these regions are chosen to be more appropriate for the current analysis. This model is not intended to be developed for practical applications; however, it is designed for the comparative study of external sources in simple geometry and in-depth numerical analysis. Top and bottom surfaces of the model reactor are specular reflecting surfaces making the model reactor axially infinite. The outermost radius of this small cylindrical reactor is 53 cm only. The external source is located at the central cylindrical zone of 10 cm radius i.e. the source region. An identical size of the source region is used for all cases (Fig. 1). In real situations, the source region should obviously be much larger than 10 cm, especially for the fusion source. The reactor is surrounded by vacuum with zero probability of re-entry for any escaping neutron. The basic purpose to use this ideal reactor model is to get generalized results and draw global conclusions.