ENERGYWISE CONTRIBUTIONS OF Th, Pu & U ISOTOPES TO THE REACTIVITY FEEDBACKS OF (Th-LEU) FUELLED AHWR

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ABSTRACT

Advanced heavy water reactor (AHWR) has been designed with thorium based fuel cycle and boiling light water as coolant. The Coolant Void Reactivity (CVR) and Fuel Temperature Reactivity (FTR) are the main reactivity feedback mechanisms. In the present work, we have attempted to understand the physics behind CVR and FTR by estimating the energy wise isotopic contributions for AHWR fuelled with (Th, LEU) fuel. The normalised reaction rate approach was used to quantify the individual contributions from $^{232}$Th, U, Pu, H and other isotopes. It has been shown that $^{232}$Th captures plays a major role in making these coefficients negative. This led us to study the sensitivities of these isotopes to the reactivity coefficients to the basic nuclear cross section set. The sensitivity due to nuclear data to CVR and FTR from ENDF/B-VI.8 and JENDL 3.3 has been calculated. It is seen that FTR is less sensitive to the dataset whereas the CVR is 16% lower in the JENDL3.3 dataset as compared to the ENDF/B-VI.8.

Keywords: AHWR-LEU fuel, CVR, FTR, D5 cluster, Isotopic reaction rates.

INTRODUCTION

AHWR is a boiling water reactor with light water as the coolant and heavy water as the moderator. The LEU design of AHWR has been considered for the current purpose [1]. The fuel is composed of thorium and LEU oxide with 19.75% of $^{235}$U and 80.25% of $^{238}$U. The LEU cluster having 30% LEU in inner 12 pins, 24% LEU in middle 18 pins and an average of 16% LEU in outer 24 pins is considered for these calculations [1]. Two of the inner 12 pins contain 5% gadolinium to suppress the initial excess reactivity. The cross section of the AHWR LEU fuel cluster is given in Fig 1.

The spread in the safety reactivity coefficients like CVR and FTR due to the uncertainty in nuclear data has been already established [2,3]. The effect of individual isotopes and their contributions to the safety coefficients can be calculated based on the approach detailed by Ganda and Greenspan [4]. In this method, the normalised reaction rate differences give a direct estimate

![Fig.1 Cross section of AHWR LEU fuel cluster](image-url)
of the components from each constituent energy and isotope. In an earlier work, the energy-wise isotopic components of CVR for an older fuel design of AHWR with (Th, $^{233}$U) MOX and (Th,Pu) MOX fuel has been done, where the effect of $^{232}$Th, $^{233}$U and Pu isotopes on CVR had been quantified in the 69 group WIMS library structure [5].

In this paper, the current fuel design with LEU fuel has been considered. Here too, the energy wise contributions of the individual isotopes to these reactivity feedbacks have been quantified through isotopic reaction rates. The break-up of the individual feedbacks have been done in the 172 WIMS energy group structure. This has been carried out in two parts, in the first part the contribution of different isotopes to CVR and FTR has been calculated, and in the second part the sensitivity in contribution due to difference in basic nuclear data has been studied.

METHODOLOGY

A number of techniques to quantify the reactivities either by integral parameters or by normalised reaction rates exist in literature. In our present study of AHWR lattice normalised reaction rate approach by Ganda and Greenspan [4], has been used. This method of determining the constituent contribution to reactivity coefficients is subdivided into two classes: normalised per absorbed neutron and normalised per fission neutron. Components of reactivities are determined by normalisation to one fission neutron for problems in which the major contributors to the reactivity are fissile isotopes. In such problems it is convenient to rank the isotopes by the number of fission neutrons they emit per neutron absorbed in the system. In normalising 'per absorbed neutron' the system $k_{o}$ is expressed as -

$$k_{o} = \eta_{f} = \frac{\sum_{i} v_{i} E_{f,i} \phi_{i}}{\sum_{l} E_{a,l} \phi_{l}} = \frac{v_{n} E_{f} \phi_{1}}{E_{a} \phi_{1}} + \frac{v_{2} E_{f} \phi_{2}}{E_{a} \phi_{2}} + \frac{v_{3} E_{f} \phi_{3}}{E_{a} \phi_{3}} + \ldots \ldots$$

$$= \eta_{1} \bar{f}_{1} + \eta_{2} \bar{f}_{2} + \ldots \ldots$$

where, $\eta_{l} = \frac{\sum_{i} v_{i} E_{f,i} \phi_{i}}{\sum_{l} E_{a,l} \phi_{l}}$, $\bar{f}_{i} = \frac{E_{a,l} \phi_{l}}{\sum_{l} E_{a,l} \phi_{l}}$.

Thus the contribution to reactivity is computed as –

$$\rho = \frac{k_{p}^{\infty} - k_{0}^{\infty}}{k_{0}^{\infty}} = \left( \eta_{1} \bar{f}_{1} |_{p} - \eta_{1} \bar{f}_{1} |_{n} \right) + \left( \eta_{2} \bar{f}_{2} |_{p} - \eta_{2} \bar{f}_{2} |_{n} \right) + \ldots \ldots$$

Here n stands for normal operating power and p stands for perturbed state.

Normalisation to per fission neutron is used when absorbing nuclei like burnable poison is the major contributor of reactivities. In this approach the system $k_{o}$ is expressed as –

$$k_{\infty} = \eta_{f} = \frac{\sum_{i} v_{i} E_{f,i} \phi_{i}}{n_{f} \phi_{fuel}}$$

Thus,

$$\frac{1}{k_{\infty}} = \frac{E_{a} \phi_{1}}{v_{f} \phi_{fuel}} + \frac{E_{a} \phi_{2}}{v_{f} \phi_{fuel}} + \ldots \ldots = \bar{\Sigma}_{a}^{1} + \bar{\Sigma}_{a}^{2} + \ldots \ldots$$

where the absorption of system constituent i, per fission neutron is, $\bar{\Sigma}_{a}^{i} = \frac{E_{a} \phi_{i}}{v_{f} \phi_{fuel}}$.

Isotopic contribution to reactivity is calculated as –

$$\rho = \frac{k_{p}^{\infty} - k_{0}^{\infty}}{k_{0}^{\infty} k_{\infty}^{p}} = \left( \bar{\Sigma}_{a}^{n} - \bar{\Sigma}_{a}^{p} \right) + \left( \bar{\Sigma}_{a}^{n} - \bar{\Sigma}_{a}^{p} \right) + \ldots \ldots$$
The D5 cluster of AHWR has been simulated as circular arrayed cluster using WIMS-D lattice code [6] with 172 group nuclear data library. The Boltzmann's transport equation has been solved for this highly heterogeneous cluster using collision probability methods with white boundary conditions. The reaction rates from fissions and captures for each nuclide can be calculated from the effective cross section and the neutron flux. The multi-group spectrum has been obtained from lattice simulations and the spectrum corresponding to core average burnup is shown in Fig 2. The neutron spectrum over the lattice has been studied to understand its effect on the capture or absorption from individual isotopes.

![Fig. 2 AHWR spectrum in 172 neutron energy groups from lattice simulations at core average burnup](image)

**ISOTOPIC COMPONENTS OF CVR**

As a first step, the fission reaction rates and absorption reaction rates of each isotope has been estimated using the flux from the transport equation solution. Energy wise isotopic contribution to CVR and FTR has been calculated with these reaction rates using 'normalisation to per fission neutron' approach of Ganda and Greenspan [4]. The major energy regions have been defined as fast region ranging from 20 MeV to 9.118 keV, resonance from 9.118 keV to 0.625 eV and thermal below 0.625 eV. The components of CVR in fast, epithermal and thermal energy ranges are -9.8mk, -52.9mk and +55.0 mk respectively. The total CVR at any instantaneous burnup step would be an integral sum over all the energies. The individual components have also been determined using equation 6. The isotopic contribution to CVR in 172 energy groups from few nuclides at core average burnup i.e. at 30GWD/T has been shown in Fig. 3.

From the isotopic contribution it is seen that H and Pu isotopes have a positive component whereas, $^{232}$Th, $^{233}$U and $^{235}$U have components of negative magnitude. When the coolant voids, the absorption in hydrogen is reduced which increases the neutron thermalisation and hence a higher reactivity. Thus component of hydrogen in CVR is positive and of large magnitude. Due to voiding the average neutron energy increases from 0.397eV to 0.69eV, which implies spectral hardening and this facilitates the absorption in the resonance region. This effect results in negative contribution from resonant absorbers like $^{232}$Th, $^{233}$U, $^{235}$U and $^{238}$U. The maximum
negative magnitude is from epithermal captures in $^{232}$Th. Thermal captures in $^{235}$U and $^{239}$Pu decreases with spectral hardening due to voiding, which gives a positive contribution to CVR.

**ISOTOPIC COMPONENT OF FTR**

The isotopic contribution to FTR in 172 energy groups from all nuclides at core average burnup has been calculated and a few are shown in Fig. 4. It is very clear from the figure that the captures in resonance energies give a large negative contribution. Epithermal absorptions in Th$^{232}$ and U$^{238}$ are the major negative contributors of FTR, due to Doppler broadening of the capture resonances of these nuclides. The energy wise component of FTR is -0.17mk, -5.12mk and
0.002mk in fast, epithermal and thermal energies respectively. The 0.3 eV fission resonance of $^{239}\text{Pu}$ gives a positive contribution to FTR.

**SENSITIVITY STUDIES OF THE ISOTOPIC COMPONENT OF THE REACTIVITIES**

JENDL 3.3 dataset has been recommended for Th-U fuel systems as the resolved energy range for $^{233}\text{U}$ has been increased to 150 eV as compared to 60 eV in ENDF/B-VI.8. $^{232}\text{Th}$ cross sections are also significantly different in the two datasets [3]. From the sensitivity study done earlier on the total reactivity swings, it was seen that JENDL-3.3 dataset result in 16% and 5.6% difference in CVR and FTR respectively as compared to the ENDF/B-VI.8 data [2].

In this paper, the deviations in the individual isotopic components were studied to quantify this sensitivity. The comparison between the individual isotopic components in the CVR and FTR between ENDF/B-VI.8 and JENDL 3.3 for AHWR-LEU fuel at core average burnup is given in Table 1. The CVR as calculated from JENDL 3.3 data is -6.46 mk and is lower than the value from ENDF/B-VI.8 which is -7.72 mk. It is observed that the deviation in CVR from JENDL 3.3 set is mainly due to the contributions from $^{232}\text{Th}$ and $^{233}\text{U}$ which is -18.58% and -30.56% respectively and that due to plutonium isotopes are only -2.33%. However it is evident from the table that the isotopic contributions to FTR are not sensitive to the basic nuclear data.

### Table 1 Isotopic contributions to CVR and FTR in AHWR lattice at core average burnup

<table>
<thead>
<tr>
<th>Nuclides</th>
<th>Components of CVR (in mk)</th>
<th>Components of FTR (in mk)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>ENDF/B-VI.8</td>
<td>JENDL 3.3</td>
</tr>
<tr>
<td>Th$^{232}$</td>
<td>-11.09</td>
<td>-9.03</td>
</tr>
<tr>
<td>Pa$^{233}$</td>
<td>-0.54</td>
<td>-0.57</td>
</tr>
<tr>
<td>U$^{233}$</td>
<td>-3.23</td>
<td>-3.57</td>
</tr>
<tr>
<td>U$^{235}$</td>
<td>-1.44</td>
<td>-1.00</td>
</tr>
<tr>
<td>U$^{238}$</td>
<td>-3.30</td>
<td>-3.40</td>
</tr>
<tr>
<td>Total U</td>
<td>-8.81</td>
<td>-8.90</td>
</tr>
<tr>
<td>Pu$^{239}$</td>
<td>3.07</td>
<td>3.07</td>
</tr>
<tr>
<td>Pu$^{241}$</td>
<td>0.61</td>
<td>0.61</td>
</tr>
<tr>
<td>Total Pu</td>
<td>2.57</td>
<td>2.51</td>
</tr>
<tr>
<td>H$_2$</td>
<td>17.32</td>
<td>17.53</td>
</tr>
<tr>
<td>Zr</td>
<td>-2.84</td>
<td>-3.57</td>
</tr>
<tr>
<td>Fission Products</td>
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<td>-3.15</td>
</tr>
<tr>
<td>Other nuclides</td>
<td>-1.20</td>
<td>-1.28</td>
</tr>
<tr>
<td>Total</td>
<td>-7.72</td>
<td>-6.46</td>
</tr>
</tbody>
</table>
CONCLUSIONS

The energy wise isotopic components of CVR and FTR have been estimated for AHWR-LEU fuel and it is observed that Th$^{232}$ plays a major component of CVR. The breakup of the components has given an insight into role of fission and captures to the reactivity feedback coefficients. Sensitivity to the different nuclear datasets also was studied for the isotopic components. It was observed that the CVR is highly sensitive to basic cross sections and the variation in CVR is mostly attributed to difference in nuclear data of Th$^{232}$. It is worth noting that the isotopes of the thorium cycle namely Th$^{232}$ and U$^{233}$ received more attention and have been revised in the JENDL 3.3 dataset. The isotopic contributions to FTR for different nuclear data libraries are comparable.

REFERENCES