STRONG ABSORBER NUCLEAR DATA FOR DIFFUSION CODES CALCULATIONS: CONTROL ROD WORTH

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Abstract

Global core calculations use the diffusion equation to predict theoretically the nuclear reactor core behaviour. However this equation is not valid in strong absorbing media where the neutron spectrum is a rapidly varying function of the position, such as control rods or burnable poisons. To overcome this misleading the blackness theory is used. In this theory the absorbing media nuclear data are replaced by some effective value in such a way that the diffusion equation can be applied within this medium. This methodology was adopted to calculate the control rod worth of NUR research reactor. A comparison between the calculated and measured results is presented in this article. The agreement is generally good.

1. INTRODUCTION

The control rod data is one of the most important parameters for the safety evaluations of research reactors and a key data in reactor design calculations. Generation of such data is not straight forward and more elaborate calculations procedures have to be applied because of the strong absorbing character of the control rod.

The diffusion approximation of the transport equation is obtained by using Fick’s law. In a strong absorbing media this law is invalid and under this circumstance the diffusion theory cannot be used to evaluate control rod worth in thermal research reactors. The blackness theory provides a method for modifying diffusion parameters in a strongly absorbing media so that diffusion theory may be used in regions where Fick's law is not adequate.

Two blackness coefficient $\alpha$ and $\beta$ are defined [1]:

$$
\alpha = \frac{J_1 + J_r}{\phi_1 + \phi_r}, \quad \beta = \frac{J_1 - J_r}{\phi_1 - \phi_r}
$$

Where $\phi_1$ and $\phi_r$ are the asymptotic left and right surface neutron fluxes of the absorber slab and $J_1$ and $J_r$ are the left and right surface currents into the slab.

The $\alpha$ and $\beta$ blackness coefficient form a pair of internal boundary conditions applicable on the surface of the absorber slab. However, most diffusion codes are not programmed to handle internal boundary conditions of this type. Therefore, it is convenient to determine a set of effective diffusion parameters ($D_{eff}$ and $\Sigma_{a-eff}$) in terms of the blackness coefficients which preserve the current-to-flux ratios on each side of the absorber slab. These effective diffusion parameters depend on the mesh interval size $h$ and therefore allow the use of a very coarse mesh in the absorber for the diffusion theory calculations. Expressions for the effective diffusion parameters in terms of the blackness coefficients are then given by:
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\[
D = \frac{h}{2} (\alpha + \beta) \frac{\tanh k \tau}{\sinh kh} \left[ \frac{1}{2} (1 + \cosh kh) \right]
\]

(2)

\[
\Sigma_a = \frac{2D}{h^2} [\cosh kh - 1]
\]

(3)

Where

\[
k = \frac{1}{\tau} \ln \left[ \frac{\beta^{1/2} + \alpha^{1/2}}{\beta^{1/2} - \alpha^{1/2}} \right]
\]

(4)

These blackness coefficients can be evaluated throughout one-dimensional transport calculations and by using these parameters, effective diffusion parameters are obtained.

The purpose of this study is to use this methodology to calculate the control rod worth of the NUR research reactor. Standard computer codes ANISN [2], WIMS-D4 [3] and CITATION [4] were employed to calculate blackness coefficients and control rod worth. A comparison between the calculated and measured results is presented in this paper.

2. DESCRIPTION OF NUR REACTOR

NUR reactor was first brought to criticality on March 23, 1989. It is an 1 MWth, open pool, MTR-LEU fuel type research reactor. The reactor core is surrounded by graphite reflector blocks and water. The latter serves as coolant, moderator and reflector. The reactor is equipped with several vertical and horizontal irradiation channels (see Figure 1).

The reactivity control system of the reactor is made of five Ag-In-Cd absorbing rods: four control and safety rods (C1, C2, C3 and C4) and one fine regulating rod (F). The NUR

![Fig. 1 Top cross-sectional view of the NUR reactor.](image-url)
core includes two types of fuel elements: the Standard Fuel Elements (SFE) and the Control Fuel Elements (CFE) (see FIG. 2). [5].

3. METHODOLOGY ADOPTED

The calculation procedure starts with a reference flux and reaction rate distribution calculation in the control rod. Then equivalent diffusion parameters are applied to all situations in which the control rod may be used. The fewgroup parameters are limited to the absorber itself and diffusion theory is assumed to become valid immediately outside the rod.

The transport code ANISN from MTR-PC package [2] is used to perform transport calculations. The currents and the fluxes which will be used in equation (1) to determine \( \alpha \) and \( \beta \) coefficients are calculated. The effective \( D_{\text{eff}} \) and \( \Sigma_{\text{a-eff}} \) are then obtained. The lattice code WIMS/4 [3] was used to generate fewgroup cell cross section data and diffusion coefficients. A series of cell calculations were performed for the different cell types of the NUR core. The cell calculations were performed under the collision probability option (SEQUENCE=2) of the WIMS code [3] and in the whole 69 group partition of the WIMS library.

The retained unit cell model for the SFE was three-slab model with:

— Slab1: representing the \( \text{U}_3\text{O}_8\)-Al meat;
— Slab 2: Al-clad+structural aluminium and;
— Slab 3: \( \text{H}_2\text{O} \) moderator.

A macro-cell was selected for the representation of the CFE. It was divided into two regions (Figure 3) and cross section for material of region 1 was taken the same as for the SFE [5].

The second step included global core calculations using CITVAP code [6], the 3D diffusion code CITATION [4] to calculate the control rod worth. These calculations were performed in 3D and five energy groups (table1). The adopted energy group structure was found to minimize errors in the effective multiplication factor \( k_{\text{eff}} \) [7].
In this analysis the blackness coefficients [1] were used in energy group 4 and 5 for the representation of internal boundary conditions at the absorber blade.

**TABLE 1: NEUTRON ENERGY GROUPS**

<table>
<thead>
<tr>
<th>Energy group</th>
<th>Energy range</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>10 MeV to 0.821 MeV</td>
</tr>
<tr>
<td>2</td>
<td>0.821 MeV to 5.53 KeV</td>
</tr>
<tr>
<td>3</td>
<td>5.53 KeV to 0.625 eV</td>
</tr>
<tr>
<td>4</td>
<td>0.625 eV to 0.08 eV</td>
</tr>
<tr>
<td>5</td>
<td>0.08 eV to 0.0 eV</td>
</tr>
</tbody>
</table>

4. RESULTS

The methodology of calculating $\alpha$ and $\beta$ has been applied to the NUR research reactor. The obtained results for $\alpha$ and $\beta$ coefficients are summarised in Table 2.

**TABLE 2: $\alpha$ AND $\beta$ PARAMETERS**

<table>
<thead>
<tr>
<th>Group</th>
<th>$\alpha$</th>
<th>$\beta$</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>3.836E-4</td>
<td>6.58</td>
</tr>
<tr>
<td>2</td>
<td>1.70591E-3</td>
<td>2.8757</td>
</tr>
<tr>
<td>3</td>
<td>0.06060678</td>
<td>1.71648203</td>
</tr>
<tr>
<td>4</td>
<td>0.17641989</td>
<td>0.826889</td>
</tr>
<tr>
<td>5</td>
<td>0.18314937</td>
<td>0.5257427</td>
</tr>
</tbody>
</table>

In figure 3 we have plotted the $\alpha$ and $\beta$ variation as a function of $\Sigma_a \tau$ and the black absorber limit has been verified.

*Fig. 3 $\alpha$ and $\beta$ parameters for Ag-In-Cd control region.*
Criticality calculations were performed using the 3D diffusion code CITATION and the modified diffusion constants in the control rod regions. The results are given in Table 3 below:

### TABLE 3: 3D DIFFUSION CALCULATIONS OF CRITICAL CONFIGURATIONS

<table>
<thead>
<tr>
<th>% Rods inserted</th>
<th>k&lt;sub&gt;eff&lt;/sub&gt;</th>
</tr>
</thead>
<tbody>
<tr>
<td>C1 C2 C3 C4 C5</td>
<td>Exp.</td>
</tr>
<tr>
<td>72</td>
<td>1.0</td>
</tr>
<tr>
<td>75</td>
<td>1.0</td>
</tr>
<tr>
<td>50</td>
<td>50</td>
</tr>
<tr>
<td>100</td>
<td>58</td>
</tr>
</tbody>
</table>

The rod worth measurements of control and safety rods (C1, C2, C3 and C4) and the fine regulating rod (F) of NUR reactor were performed using the rod drop method. The experimental [5] [8] and calculated results using the effective diffusion parameters in Ag-In-Cd region are given in Table 4 below.

### TABLE 4: CALCULATED AND MEASURED WORTH OF CONTROL AND SAFETY RODS (IN $)

<table>
<thead>
<tr>
<th>Rod</th>
<th>C1</th>
<th>C2</th>
<th>C3</th>
<th>C4</th>
<th>C5</th>
</tr>
</thead>
<tbody>
<tr>
<td>Calculation worth</td>
<td>5.9</td>
<td>5.5</td>
<td>3.9</td>
<td>4.3</td>
<td>0.98</td>
</tr>
<tr>
<td>Measurement</td>
<td>6.0</td>
<td>5.7</td>
<td>4.2</td>
<td>4.5</td>
<td>0.89</td>
</tr>
</tbody>
</table>

5. CONCLUSION

To calculate the worth of control rods in thermal research reactor we need a special method because of steep flux gradients near the surface of the strong neutron absorbers. This method provides a set of effective diffusion parameters characterizing the strong absorbing media and reasonably accurate control rod worth can be computed within the framework of diffusion theory.

In this paper we have presented the methodology used to calculate the effective diffusion parameters D<sub>eff</sub> and Σ<sub>a-eff</sub> in terms of the α and β blackness coefficients and the mesh spacing in the absorber. This method has been illustrated by calculating the control rod worth of NUR research reactor. The diffusion theory worth calculations using this method is found to be in good agreement with experimental measurements. However, use of Monte Carlo code, such as MCNP, is recommended.

REFERENCES

[6] MEFTAH, B., BOUSBIA-SALAH, A., 1999a, Neutronics, thermal hydraulics and
