Available online at www.sciencedirect.com

ScienceDirect

Nuclear Energy and Technology 2 (2016) 312–334

www.elsevier.com/locate/nucet

Study of VVER-1000 OECD LEU and MOX Computational Benchmark with VISWAM Code System

Suhail Ahmad Khan[a,*], V. Jagannathan[a,1], Umasankari Kannan[a], Arvind Mathur[b]

[a] *Reactor Physics Design Division, Bhabha Atomic Research Centre, Mumbai, India*
[b] *Indian Institute of Technology, Mumbai, India*

Available online 1 December 2016

Abstract

The expert group at OECD/NEA has proposed a computational benchmark to certify the calculation codes for utilizing weapons grade (WG) plutonium by converting it to mixed-oxide (MOX) fuel for nuclear reactors. The benchmark model consists of two different assemblies of low enriched uranium (LEU) and MOX that are typical of the advanced designs for the VVER-1000 reactors. We have analysed these benchmark problems using the VISWAM code system. The lattice analysis method initially implemented in VISWAM code was based on a combination of 1D multigroup transport and a 2D few group diffusion theory. We have recently developed the interface current method based on 2D collision probability (CP) and incorporated the same in VISWAM code. The present VISWAM code considers the angular flux expansion up to P2 Legendre polynomials in hexagonal geometry which is new and not reported in literature to the best knowledge of authors. The present paper studies the benchmark problem using the two models present in VISWAM and studies the effect of different flux anisotropies on the benchmark results. The results obtained with VISWAM are compared with the other benchmark evaluations given in benchmark specification report.

Keywords: Integral transport theory; 2D Collision Probability; Interface current Method; VVER-1000; Triangular pitch; Lattice OECD/NEA benchmark.

Introduction

The United States and Russian Federation have each declared significant quantities of weapons grade (WG) plutonium to be surplus to their defence needs. One option to dispose this WG plutonium is by converting it to mixed-oxide (MOX) fuel for nuclear reactors. For this purpose an International Experts Group has been established at the OECD/NEA to facilitate the sharing of existing information and experience in the physics and fuel behaviour of MOX fuel as it relates to the disposition of WG plutonium. The expert group has proposed a computational benchmark for this purpose [1].The benchmark model consists of two different assemblies that are typical of the advanced designs for the VVER-1000 reactors. In Russia the WG MOX fuel will be used in both fast (BN-600) and light water reactors (VVER-1000).

India is pursuing an active three stage nuclear power programme. The 1000MWe VVER type reactor commissioned at Kudankulam has recently attained full power operation and another similar unit is in an advanced stage of commissioning. To cater to the physics design requirements, a comprehensive code system VISWAM [2] is being developed. The lattice analysis method initially incorporated in VISWAM code is based on pincell and supercell calculations by 1D multigroup collision probability (CP) method followed by 2D few group diffusion theory. Recently, we have implemented the interface current method based on 2D collision probability (CP) in VISWAM [3]. We have applied the CP method at individual lattice cell levels and linked the cells using interface currents with double P2 (DP2) expansion of angular flux at

* Corresponding author. Fax: +91 2225505151.
E-mail addresses: suhailak@barc.gov.in, suhaillovesphysics@gmail.com (S.A. Khan), v_jagan1952@rediffmail.com (V. Jagannathan), uma_k@barc.gov.in (U. Kannan), akmathur@iitb.ac.in (A. Mathur).
[1] Retired from Reactor Physics Design Division, Bhabha Atomic Research Centre, Mumbai, India.

Peer-review under responsibility of National Research Nuclear University MEPhI (Moscow Engineering Physics Institute).

http://dx.doi.org/10.1016/j.nucet.2016.11.008

cell boundaries. The use of DP2 expansion of angular flux applied to hexagonal geometry in VISWAM is new and is not present in the extant reactor physics codes using interface current method such as CASMO [4], PHOENIX [5], APOLLO [6] HELIOS [7], and DRAGON [8]. The objective of present paper is to study the effect of angular flux expansion on the solution and study its effect on the pin power distribution of heterogeneous light water fuel assembly. The computational methodology of VISWAM code system and the benchmark details are briefly described in Sections 2 and 3, respectively. The benchmark details are described in greater detail in Ref. [1]. Section 4 gives the results and discussion of the analysis. Broad conclusions of the analysis are presented in Section 5.

Description of VISWAM Code System

Nuclear Data Used

VISWAM uses multi group cross section libraries in WIMS/D format for lattice level calculations. The present calculation was done using a high temperature library 'HTEMPLIB' [9], based on JEFF-3.1 nuclear data library. This library has cross section data for 185 nuclides in 172 energy groups. The burnup chain in HTEMPLIB library is extended up to ^{252}Cf. The library has resonance tabulation for 48 nuclides. The resonance integral tables are available up to a temperature of 2500 K. Equivalence relations are used for obtaining resonance self-shielded cross sections. Mutual shielding of a mixture of resonance nuclides is treated in accordance with the procedures described by Stammler and Abbate [10]. For the burnable poison nuclide Gd, only five isotopes viz. ^{154}Gd, ^{155}Gd, ^{156}Gd, ^{157}Gd, ^{158}Gd are available in the HTEMPLIB library. The isotopes ^{152}Gd and ^{160}Gd are not available. Since their absorption cross sections are negligible compared to those of ^{155}Gd or ^{157}Gd, the concentration of ^{152}Gd and ^{160}Gd given in benchmark specification were added to those of ^{154}Gd and ^{158}Gd respectively. It is believed that this approximation would have negligible influence on the quality of results of the analysis.

Lattice models of VISWAM for fuel assembly analysis

The lattice burnup model of VISWAM code system has been developed [11,12]. Currently, two models are available in VISWAM for fuel assembly (FA) lattice calculations.

One model is based on a combination of 1-D multi group transport and 2-D few group diffusion theory. A typical fuel assembly cell consists of fuel pins of different enrichments and various heterogeneous cells like control rod, water rod or burnable absorber rod (BAR) cells. In this model, the fuel pins are classified into various pin cell types based on the enrichment and Dancoff factors. The pin cells are treated using a series of 1-D transport calculations in multi-groups using the first flight collision probability method (P_{ij}). The square or hexagonal cell boundary is cylindricalised to allow 1-D treatment of the Wigner-Seitz cell. Heterogeneities present in the fuel assembly are treated using appropriate 1-D supercell simulations. The pincell homogenized cross sections are collapsed to few groups using appropriate supercell spectra. For non-fuel cells, the few group cross sections are obtained from the respective supercell calculation of a given heterogeneity. The fuel assembly cell is treated by 2-D few group diffusion theory using centre-mesh finite difference method.

The second model uses interface current method based on 2D collision probability. In this model, a lattice cell may be a fuel pincell, water rod cell or an absorber rod cell. The geometry of the cell is not changed, i.e., the outermost region of the cell is retained as the square or hexagonal shape without cylindricalisation. The collision probabilities are calculated for single lattice cell in 2D geometry. For fuel assembly (FA) calculation, the lattice cells are linked using interface currents by using the DP2 expansion of angular flux at the pincell boundary. In this method, the neutron transport equation for group 'g' (the group index 'g' is omitted for simplicity), when descretised over a region consisting of N_V zones and N_S surfaces reduces to linear flux and current equations (assuming flat flux approximation)

$$\Sigma_j V_j \phi_j = \sum_{\alpha=1}^{N_S} \sum_{\nu=0}^{N_\nu} P^{\nu}_{j\alpha} S_\alpha J^{\nu}_{-,\alpha} + \sum_{i=1}^{N_V} P_{ji}\ q_i. \tag{1}$$

$$S_\alpha J^{\nu}_{+,\alpha} = \sum_{\beta=1}^{N_S} \sum_{\mu=0}^{N_\mu} P^{\nu\mu}_{\alpha\beta}\ J^{\mu}_{-,\beta} S_\beta + \sum_{i=1}^{N_V} P^{\nu}_{\alpha i}\ q_i. \tag{2}$$

$$J^{\nu}_{-,\alpha} = \sum_{\beta=1}^{N_S} \sum_{\mu=0}^{N_\mu} A^{\nu\mu}_{\alpha\beta}\ J^{\mu}_{+,\beta}. \tag{3}$$

The summation over ν in above equations represents the order of expansion of angular flux at pincell boundary. We have used the following properly-orthonormalised angular representation functions for DP2 expansion of angular flux

$$\psi^0_{\pm,\alpha} = 1. \tag{4a}$$

$$\psi^1_{\pm,\alpha} = 2 \sin\vartheta \sin\phi. \tag{4b}$$

$$\psi^2_{\pm,\alpha} = 3\sqrt{2}\left(\sin\vartheta \cos\phi - \frac{2}{3}\right). \tag{4c}$$

$$\psi^3_{\pm,\alpha} = \frac{20}{\sqrt{17}}\left(\sin^2\vartheta - \frac{3}{5}\sin\vartheta\cos\phi - \frac{7}{20}\right). \tag{4d}$$

$$\psi^4_{\pm,\alpha} = \sqrt{306}\left(\sin^2\vartheta\cos^2\phi - \frac{2}{51}\sin^2\vartheta - \frac{20}{17}\sin\vartheta\cos\phi + \frac{16}{51}\right). \tag{4e}$$

$$\psi^5_{\pm,\alpha} = \frac{30}{\sqrt{11}}\left(\sin^2\vartheta\cos\phi\sin\phi - \frac{8}{15}\sin\vartheta\sin\phi\right). \tag{4f}$$

where ϑ is the angle between neutron tracking direction and polar axis, and ϕ is the angle which projection of the neutron direction on 2D plane makes with the outward (+) or inward (−) normal to surface α. Here first function corresponds to the P0 expansion, the first three functions correspond to the