RESEARCH REPORT

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BWR group constant generation models for the CBH benchmark

Authors: Ville Valtavirta

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Written by	**Reviewed by**
Ville Valtavirta, Senior Scientist	Antti Rintala, Research Scientist

VTT's contact address
VTT Technical Research Centre of Finland Ltd, P.O. Box 1000, FI-02044 VTT, FINLAND

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Date:	
Signature:	
Name:	Silja Häkkinen
Title:	Research Team Leader

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1. Introduction

The two-step Serpent-Ants neutronics calculation chain is developed for reactor core neutronics of current and upcoming Finnish reactors. Group constants describing the averaged neutron interaction properties of different core regions are precalculated with Serpent for various momentary states using various historical conditions. These group constants are then parametrized to allow the evaluation of their value at any point in the relevant parameter space during the reduced order Ants calculation. If the group constant calculation, parametrization and evaluation are done in a proper manner, the results of the nodal diffusion calculations can be very close to the continuous energy Monte Carlo solution and, preferably, the real world behavior of the reactor.

In recent years, this two-step calculation chain has been verified and validated for fuel cycle simulations of pressurized water reactors (PWRs) at the small modular reactor (SMR) scale [1] and in full scale VVER-1000 reactors [2]. The performance of the Serpent-Ants calculation chain has not been evaluated for boiling water reactors (BWRs). The large variations in the local momentary and historical coolant void fraction in BWRs as well as the long term insertion of control rods for reactivity control and power shaping during the cycle bring additional variables to the group constant parametrization compared to pressurized water reactors. The cruciform control rods inserted between the assemblies in BWRs bring an asymmetry to the system, somewhat countered and made more complex by the asymmetric radial profiling of the fuel in the fuel assembly.

This work begins the evaluation of the Serpent-Ants performance in BWR modelling in the context of the control blade history benchmark [3]. Only preparatory work is made in 2023 in the manner of formulating the research question, obtaining the benchmark specifications and reference results and setting up the Serpent models required for generating the group constants for the benchmark. The group constant generation and Ants solution to the benchmark is planned to be conducted in 2024.

2. Background

This chapter provides the relevant background information regarding the GenPoly group constant parametrization used in the Serpent-Ants calculation chain as well as the control blade history benchmark, which will serve as the BWR test case.

2.1 GenPoly group constant model

The Serpent-Ants calculation chain and the relevant processing routines in KrakenTools utilize the generic polynomial (GenPoly) group constant format originally specified in Ref. [4]. The parametrization of data Σ with respect to momentary local feedback conditions (fb) is done using a polynomial fit $\mathcal{P}_\Sigma$ with the nominal value Σ_{nom} and the polynomial coefficients tabulated at a set of burnup points (bu):

$$\Sigma_{\mathrm{fb}}(\mathrm{bu}) = \Sigma_{\mathrm{nom}}(\mathrm{bu}) + \mathcal{P}_\Sigma(\mathrm{fb}, \mathrm{bu}) \tag{2.1}$$

The list of momentary feedback variables that can be used for the polynomial representation is given in Table 1. The momentary conditions for a BWR assembly can likely be well represented with these feedback variables using DCO and TCO for coolant conditions, BDCO and BTCO for bypass/moderator conditions and TFUSQRT for fuel temperature. The momentary presence of a control rod in the assembly is handled in the GenPoly-format by tabulating the nominal values $\Sigma_{\text{nom}}(\text{bu})$ and coefficients for polynomial $\mathcal{P}_\Sigma$ separately for rodded and unrodded states of the assembly.

The representation of the historical conditions of the BWR assembly may prove to be more difficult. At the moment, the GenPoly-parametrization accounts for the historical conditions of the local material using the plutonium (spectral) history approach. The idea behind this approach is that historical conditions of the assembly are reflected in the local ^{239}Pu content of the node with harder historical spectrum resulting in an increased nuclide density compared to a softer one. By precalculating the group constants separately with two different spectral histories, using e.g. different coolant density, fuel temperature and/or control rod presence, the historical dependence of $\Sigma_{\text{nom}}(\text{bu})$ and $\mathcal{P}_\Sigma$ can be parametrized with respect to the momentary atomic density of ^{239}Pu. If the local atomic density of ^{239}Pu is then tracked in the nodal code using a microscopic depletion approach, the history effect can be easily evaluated. This works very well for PWRs [5], but BWR group constants may need to separate the two historical effects coming from the presence of the cruciform control rod and from the local historical void distribution as the spatial (intra-nodal) effects of the two are very different.

The performance of the GenPoly group constants is thus expected to be good at zero burnup, but may see significant degradation with the accumulation of burnup. Modelling the CBH benchmark using GenPoly group constants is the first step in evaluating their performance and planning the extension of the parametrization to better account for BWR phenomena.

2.2 CBH benchmark

The control blade history benchmark [3] is a neutronics benchmark designed at Westinghouse Electric Sweden and Studsvik Scandpower for the evaluation of the predictive capabilities of nodal codes for the fuel rod power peaking considering the control blade history effect. This effect is seen in fuel rods close to the control bladed corner of a fuel assembly, which has been depleted with partially inserted control rod. Depletion with an inserted control rod leads to depletion under a harder spectrum due to the combination of thermal absorption by the boron in the control rod and the reduced moderation due to displacement of moderator by the control blade. This leads to increased breeding of fissile ^{239}Pu from fertile ^{238}U especially in the fuel rods closest to the control blade. After the control rod is retracted (or completely removed as in the benchmark), the fuel rods with increased ^{239}Pu content exhibit a strong power peaking effect.

The benchmark considers a radially periodic, axially finite four (2x2) fuel bundle 3D geometry (shown in Figure 1). The fuel bundle geometry is based on a real world design, but has been approximated by modelling the water channels inside the bundle using Serpent pin-structures instead of the actual geometry. The fuel bundles contain partial length fuel rods (PLFRs) and a realistic horizontal fuel enrichment profile.

Table 1. Feedback variables available in the GenPoly-format

name	as variable	description
`TFU`	x_1	Fuel temperature (K)
`TFUSQRT`	x_2	Square root of fuel temperature ($\text{K}^{\frac{1}{2}}$)
`DCO`	x_3	Density of coolant (g/cm^3)
`TCO`	x_4	Temperature of coolant (K)
`BOR`	x_5	Boron content (ppm)
`BORDENS`	x_6	Boron density, `BOR*DCO`, ($\text{ppm}\,\text{g}/\text{cm}^3$)
`XEN`	x_7	^{135}Xe atomic density ($1/\text{cm}^3$)
`SAM`	x_8	^{149}Sm atomic density ($1/\text{cm}^3$)
`BDCO`	x_9	Density of “bypass” coolant (g/cm^3)
`BTCO`	x_{10}	Temperature of “bypass” coolant (K)
`BORDENS2`	x_{11}	Boron density, `BOR*DCO`, ($\text{ppm}\,\text{g}/\text{cm}^3$)

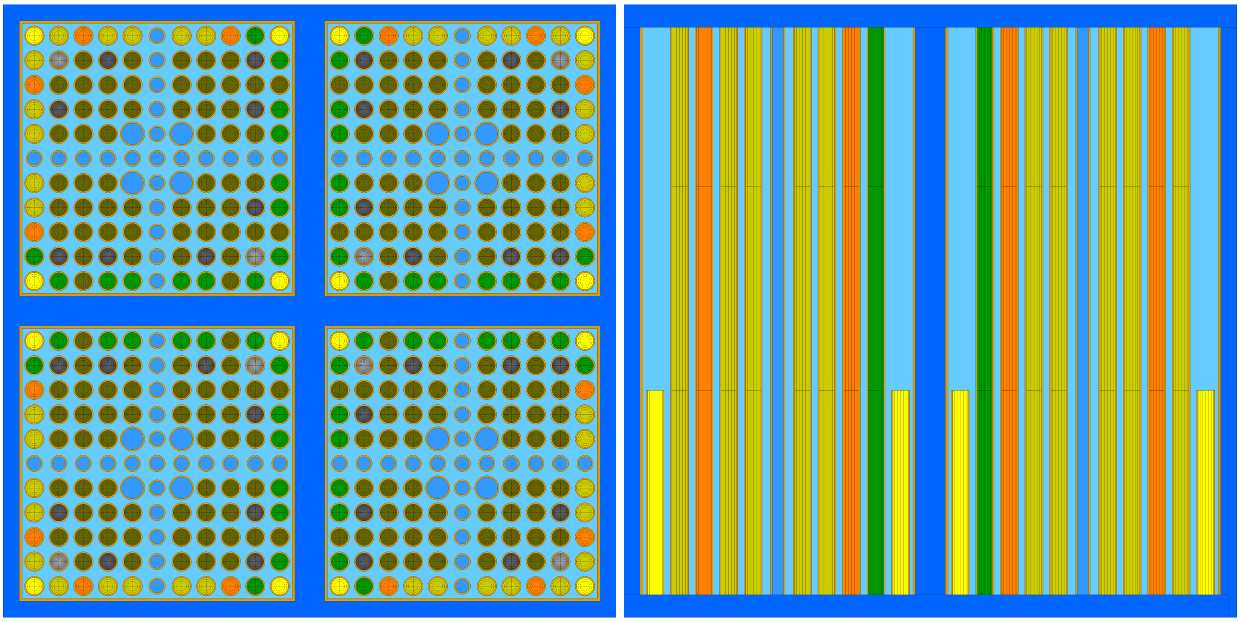

Figure 1. The 2x2 fuel bundle geometry in the benchmark. Horizontal geometry plot is at the lowest section of the model, where the partial length fuel rods are present. Vertical geometry plot is through the first pin row.

A constant axial void profile (coolant density profile) is defined in the specifications.

The calculations of the benchmark consist of modelling the depletion of the system with one control blade partially inserted from 0 MWd/kgU to 5 MWd/kgU after which the blade is retracted from the core. The system is further depleted until 10 MWd/kgU in this configuration. The pin powers in the fuel bundle closest to the control blade are to be calculated at different burnup points at different heights of the fuel bundle and compared to the reference results evaluated with a high fidelity depletion calculation of the Serpent 2 Monte Carlo code.

3. Group constant generation models

Serpent models, to be used for generating the required group constants for Ants were modified from the full Serpent model obtained from Studsvik Scandpower.

3.1 Axial reflector homogenization

The axial reflector will be homogenized directly using the system geometry with the control blade retracted to its lowest extent. The thermal hydraulic conditions of the benchmark are applied here and only a single set of group constants needs to be calculated both for the top and the bottom reflector regions as their thermal hydraulic conditions are constant over the benchmark.

3.2 Fuel assembly homogenization

The different axial layers of the fuel bundles have been separated as their own two dimensional Serpent models, which can be used for the group constant generation. The homogenization should be conducted using reflective boundary conditions in order to properly represent the 2x2 loading pattern.

In the case of PWR assemblies with finger type control rods, the fuel assemblies have been homogenized at the quarter assembly level in order to better capture the internal inhomogeneity. Quarters with different enrichment and burnable absorber profiles have then had different group constants and flux discontinuity

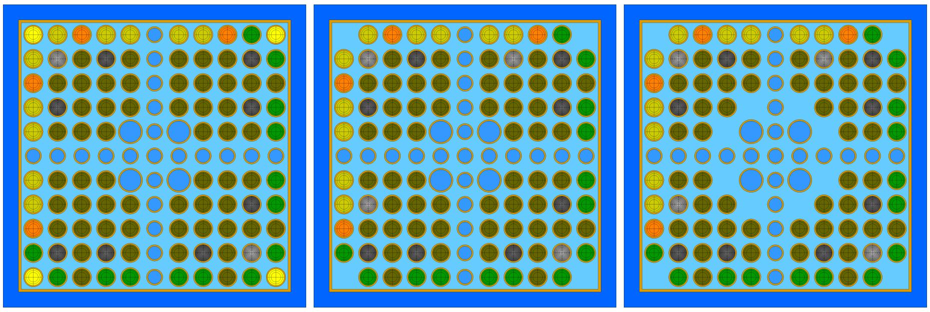

Figure 2. Serpent geometry plots of the three 2D fuel bundle models to be used for group constant generation.

factors have been generated also for the in-assembly interfaces of the quarters. A similar approach may be detrimental in the case of the BWR group constants as the control blades are inserted asymmetrically external to the fuel bundle.

4. Future work

The work planned for 2024 will start with the generation of the group constants with Serpent. The calculation matrix proposed in the benchmark specifications is transcribed to Table 2. It should be noted that the proposed calculation matrix includes history calculations using multiple coolant void fractions and separately history calculations with control rod (CR) inserted and extracted. The control rod insertion branches are proposed to be calculated, likely for the unrodded depletion history whereas control rod withdrawal branches should be evaluated for the rodded depletion history. Such a historical representation of the data is not compatible with the GenPoly group constant model, meaning that the initial set of group constants could be evaluated using a single off-nominal history calculation.

Once the group constants have been generated, the benchmark can be modelled with Ants and the performance can be evaluated against the Serpent reference solution and the SIMULATE5 solution by Studsvik Scandpower.

A dedicated boiling water reactor group constant model could then be formulated and implemented, either

Table 2. An example calculation matrix for the fuel homogenization in the CBH benchmark

State parameter	**Unit**	**Range of values**
Unrodded depletion burnup steps	MWd/kgHM	0.0 – 20.0 (step sizes from 0.001 to 0.5)
Rodded depletion burnup steps	MWd/kgHM	0.0 – 20.0 (step sizes from 0.001 to 0.5)
Branch burnup steps	MWd/kgHM	0.0 – 20.0 (step sizes from 0.001 to 1.0)
Coolant void histories	%	00, 30, 60, 90
Coolant void branches	%	00, 30, 60, 90
Void branches with zero xenon	%	00, 30, 60, 90
Void branches with CR insertion	%	00, 30, 60, 90
Void branches with CR withdrawal	%	00, 30, 60, 90
Void branches with zero xenon and CR insertion	%	00, 30, 60, 90
Void branches with zero xenon and CR withdrawal	%	00, 30, 60, 90

as an extension of the GenPoly-model or as a completely separate model.

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