



USE OF WIMS 3.1 FOR MODELLING THE FUEL BUNDLES OF A POWER UPGRADE REFIT OF PHWR

G. LeRoy¹, R. Lounsbury², and I. Attieh³

¹ GL Nuclear Inc., Georgetown, Ontario, Canada

² Suretech Development Limited, Deep River, Ontario Canada

³ Attieh Nuclear Innovations Inc, Port Credit, Ontario, Canada

GLNuclear@protonmail.com

lounsbur@sdl.on.ca

ibrahim@ani.engineer

Abstract

The power output of current Pressurized Heavy Water Reactors (PHWR) can be doubled by refitting them with a higher temperature and pressure primary heat transport system [1]. The refit involves a modular replacement of the primary heat transport system and fuel channels that requires work similar to the work undertaken during current refurbishments. While the refit fuel channels interface similarly with the existing reactor calandria, there are differences between the refit and existing reactors that result from different coolant conditions, fuel enrichments, fueling scheme and in-core materials.

The WIMS 3.1 code is used for generation of the irradiated fuel compositions of PHWR fuel bundles by using the “endregion” modelling capability or by “smearing” the fuel bundle materials, over the entire bundle length. The refit fuel bundle contains enriched and natural uranium pellets and additional structural materials. Both, “smearing” and “endregion” WIMS approaches are used to model it and compare against the MCNP 6.2 models of an approximate, “smeared” refit bundle, and a detailed refit bundle. The comparisons indicate that the “smearing” method results in a less accurate reactivity estimate, whereas the agreement with the detailed MCNP 6.2 fuel bundle is improved significantly by using the “endregion” modelling capability.

1. Introduction

The demand for electricity in North America is increasing and so is the need for nuclear power. While small and large scale new nuclear reactors are being investigated and built, they have long lead times. Another option is to examine ways to get significantly more power from existing nuclear generating stations with established infrastructure and traditions.

The power output of existing PHWR/CANDU type power plants can be doubled through a modular replacement of the primary heat transport system (PHTS), fuel, fuel channels and fuelling machines. The PHTS will have higher temperature (max 625 °C) and pressure (Max. 25 MPa) for higher output and thermal efficiency. Further details on how the power is doubled and the plant heat balance are provided in a description of the systems and plant [1,2]. These system replacements are hereafter referred to as a PHWR Refit. There are several advantages to obtaining increased nuclear generating capacity through refitting existing PHWR/CANDU plants:

- The construction time is much shorter than that of large plant new builds (3 versus 10 years)
- No new site is required, thereby enhancing land use and simplifying approvals
- Project management relies on methods proven during refurbishments
- No new operating organization is required

While the construction time is much shorter than for new builds, development work and first prototype design will be needed for the first refit. The development program has been detailed [3] and is estimated to require seven years, during which the first prototype design can be done in parallel with development.

Nuclear generation alternatives, such as, SMRs have relatively low power output requiring many units for regions of concentrated electricity demand. While construction may be faster than large nuclear power plants, the economics of building and maintaining a large number of plants is uncertain. The PHWR refit has only a slightly increased number of components compared to existing PHWRs. With double the power output, per MWh operating and maintenance costs will improve over existing PHWRs. Updated versions of large power reactors (e.g. EPR, AP1000) require long new build construction times and have encountered significant cost and schedule overruns on their first plants. The PHWR refit can be constructed in much shorter times while benefitting from project management experience developed during PHWR refurbishment.

The modular concept of the PHWR refit limits the extent of changes to the existing plant. The reactor core; however, undergoes some significant changes due to the need for different higher temperature and strength, materials. These will require the use of some enriched uranium for the first PHWR refits, although the prospect exists with material and component improvements to eventually have a natural uranium version of the PHWR refit. The new materials, coolant conditions and some enrichment will require some new and refined reactor physics analysis methods. This paper examines the use of the WIMS transport code, traditionally used in PHWR reactor physics analyses, for PHWR Refit analyses and fuel material composition generation.

2. Modelling of the Refit Fuel Bundles with WIMS3.1

The Refit PHWR has a two-zone reactor core that consists of an inner and an outer zone. The channels in inner zone contain twelve Forward fuel bundles and the channels in the outer zone also have twelve Return fuel bundles of the same geometry and enrichment as the Forward ones but they are exposed to heavy water coolant with higher temperature and lower density. Each fuel bundle consists of 43 fuel elements/pins arranged in three concentric rings and a central pin. The pins are assembled to two end plates with “lenses” attached to the outer ring of fuel elements to provide a bearing surface on the insulator. The “lenses” are of the same material as the fuel pin cladding - single crystal sapphire – Al_2O_3 . The fuel channels consist of insulator (Fused Silica) and pressure tube (Silicon carbide (SiC) composite) with a small heavy water gap between them. The moderator is heavy water (see Figure 1) with higher purity than the coolant.

Each Refit fuel pin contains 31 fuel pellets with two enrichments – 27 pellets with slightly enriched uranium (EU) $<1\text{wt}\% \text{U}^{235}$ and four pellets with natural uranium (NU). The NU pellets are located at both ends of each fuel pin to suppress the bundle end flux/power peaking. The fuel pins also contain additional absorbing components (Inconel washers) to further reduce the end flux peaking as well as springs between selected fuel pellets to control the spacing of the axial pellet gap that changes with irradiation. Along the fuel channels there are coolant temperature and density gradients for both the

inner and the outer core zones, which together with the complex structure of Refit bundle creates a challenge to the traditionally used reactor physics tools for CANDU PHWR reactors.

WIMS3.1 [4] is used as a first attempt to model the Refit fuel bundles and generate the irradiated fuel compositions. Two WIMS models are created for the average Forward and Return fuel bundles. It is assumed that a straight average of the bundles' temperatures, coolant temperature and density and other temperature dependent parameters will be representative for the average bundle in the channel. The WIMS models are created based on the initial WIMS models developed by D. Altmarmakov and further updated based on the new research and development information. The WIMS3.1 uses the 89-group library E70LIB1 based on ENDF/B-VII.0.

The WIMS code is a 2-dimensional code and 3-D effects cannot be modelled explicitly. For the existing PHWR bundles, stylized WIMS models are created by adding the Zr fuel pin caps and Zr end plates to the Zr cladding materials of the fuel pins. The radial geometry dimensions are preserved but the cladding density is increased to conserve the total Zr mass. The fuel pellets (length of 48.1 cm) are also smeared over the entire length of the fuel bundle (49.53 cm) including the portions occupied by the end plates and the total fuel mass is conserved by reducing the fuel density. For these axially homogenized over the total length of the fuel bundle WIMS models, the MULTICELL sequence is used. However, if important 3-D effects of the fuel bundle ends are to be incorporated, the MULTICELL sequence does not have end region modeling capability and the WIMS Pij sequence must be used.

For the Refit fuel bundles both sequences are used.

2.1 WIMS Homogenized Approach for the Refit Fuel Bundles

The Refit average fuel bundles in the Forward and the Return channels have the same geometry and fuel enrichments, but they differ due to the different fuel temperatures, cladding and coolant temperatures, coolant densities, etc. Each homogenized WIMS model consists of infinite repetition of a single two-dimensional lattice cell that represents either the Forward or the Return channel and the same spatial mesh subdivision is used in the two models. As the WIMS lattice cell models are two-dimensional all 31 pellets are homogenized and uniformly spread up along the entire bundle length, keeping the radial dimensions of the fuel pellets and cladding as per specifications. The fuel mass is preserved by adjusting the fuel density appropriately. The same procedure is applied to the cladding where the new homogenized cladding material contains all bundle structural materials, the washers, the springs, fuel pins cladding, endcaps, endplates and the "lenses" (refit reactor equivalent of bearing pads). The density of the new complex cladding mixture is adjusted accordingly.

For the Refit fuel bundles, there is no collapsing of the cladding onto the fuel as in existing PHWR bundles. The gap between the fuel pellets and the cladding is explicitly modelled and filled with He gas. The gas composition will eventually change with the fuel irradiation and should be updated in the WIMS models as the fission gases start to fill it. Eventually, there will be an equilibrium X^{135} concentration in the gap between the cladding and the fuel. This phenomenon is not modelled or assessed yet.

Outside the fuel bundle are the insulator (Fused Silica) and the pressure tube (Silicon carbide (SiC)). There is a small gap between them filled with heavy water. In the process of creating the WIMS

models, a mixture of insulator and water was modelled instead of a single annulus of heavy water, as the thickness of the water annulus is too small for WIMS to tolerate it.

2.2 End Region Approach Using WIMS

Due to the higher heterogeneity of the Refit fuel bundle especially toward the bundle ends, there might be an artificially increased absorption of the structural materials due to smearing them, as part of the cladding materials, over larger surfaces. To assess this, a more realistic WIMS models for both Forward and Return bundles were created by using the WIMS3.1 “end region” modeling capability.

In the “end region” models, the fuel density was adjusted to reflect that it is smeared over the fuel pellets length only. The cladding density was increased to reflect the addition of the outside “lenses” mass. New “end region” materials for both Forward and Return bundles were created as mixture of structural materials, springs, cladding, endcaps, endplates and coolant. The densities and the compositions of the “end region” materials for the two bundle types are slightly different as the mixtures contain coolant with different densities.

The WIMS “endcap” card is used, where there is an “end flux peaking” input parameter required. This parameter is a representative parameter for whole bundle, and it is not yet well established for the Refit bundles. Therefore, a parametric study was performed to estimate the reactivity effect of it by varying the end flux peaking between 1.0 and 1.15 which is in the range of the end flux peaking to CANDU bundles.

2.3 WIMS Results and Comparison to the MCNP Predictions

The WIMS Forward and Return average bundle models are used to make design decisions on the fuel enrichment, selection of structural bundle components, etc. The WIMS results for the Forward and Return fuel bundle are presented in Table 1 and will be later discussed in greater detail. Sensitivity tests were performed for the case of “end region”, where the end region flux was varied in the interval [1.0 1.15].

It was found that the reactivity effect due to variation of the end flux is not significant < 0.31 mk for the whole interval (see Table 2) and even very slightly decreases with the increase of the end flux peaking. This weak dependence could be explained by the higher neutron absorption in the end region materials and the lower than CANDU coolant density that does not significantly affect the end region mixture.

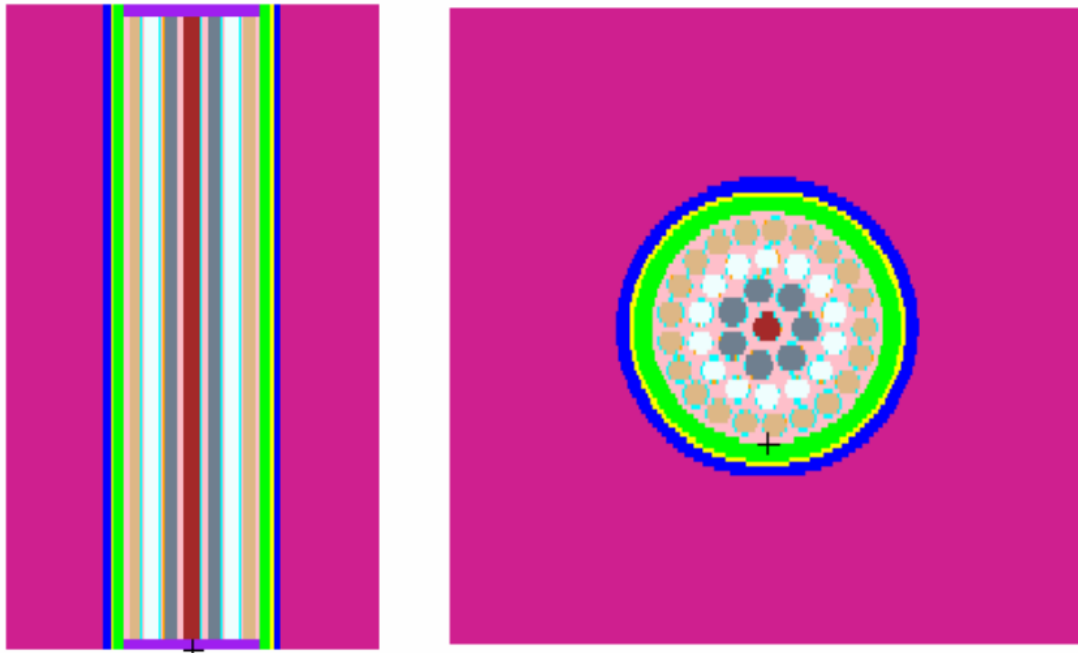
It is imperative to validate WIMS predictions against independent computational methods. The ideal candidate is MCNP6.2 [5] that is based on a stochastic method and provides an independent means to verify WIMS calculations. The ENDF/B8.0 nuclear data library is used with MCNP models whereas WIMS 3.1 uses the 89-group library E70LIB1 based on ENDF/B-VII.0.

A Detailed MCNP Forward Half- Bundle model was created [6] with all fuel pellets and other bundle components explicitly modelled. This is the WIMS models benchmark, and all results will be compared against the predictions of this model. As the Detailed MCNP Return Half-Bundle model is not ready yet, most of the MCNP comparisons are made for the Forward bundle only.

To estimate the effect of the different WIMS and MCNP computational methods, two simplified MCNP models were created: MCNP Forward fuel bundle smeared, where the materials are smeared

over the bundle length (in a similar fashion as in WIMS) and MCNP Forward bundle with end region that is equivalent to the WIMS Forward model with end region (see Figure 1). On this figure, X-Z and X-Y views of a Refit fuel bundle are shown. As can be seen the fuel pins are organized in three rings and a central pin. The whole bundle is inside a pressure tube with an insulator layer between the pressure tube and the coolant in the channel. There is a small gap between the insulator and the pressure tube with heavy water with the same purity as the coolant inside the insulator. As WIMS cannot tolerate very small annuli, a wider annulus was modelled that contains a mixture of the gap's heavy water and a small portion of insulator. The end regions are modelled as solid disks of "end region" material at the both bundle ends.

Figure 1 MCNP Presentation of a Refit Fuel Bundle with End Region



As with the geometry, all materials and temperatures in both WIMS and MCNP models are the same. The reactivity differences can be attributed to the different computational methods, different nuclear data libraries and potentially could point out to potential WIMS limitations. Additionally, a MCNP Return fuel bundle smeared is created and compared with the corresponding WIMS Return fuel bundle smeared predictions.

As can be seen in Table 1, comparison between the WIMS smeared bundle models and MCNP smeared bundle models shows < 4mk reactivity difference, which is an acceptable agreement. This is true for both, Forward and Return, smeared fuel bundles. The k-eff uncertainties in the table are the statistical MCNP uncertainties. The reactivity comparison of the WIMS Forward fuel bundle with "end region" with the Detailed Forward MCNP fuel bundle shows an excellent agreement of 2.86 mk.

The effect of fuel pellets homogenization against the precise pellet modelling is analyzed. In the MCNP Detailed model, the materials of the EU and NU pellets were both replaced by a mixture of the two fuels weighted by the number of pellets for each fuel. As can be seen in Table 1, there is only a slight reactivity effect, and the difference between WIMS end region and MCNP detailed model increases slightly to 3.47 mk.

The MCNP cases were repeated with the ENDF/B7.1 data library and they show the same trends but in general the use of ENDF/B8.0 results in a ~1mk higher keff.

The reactivity comparison between the two WIMS Forward fuel bundle smeared and the WIMS Forward end region fuel bundle models, shows a difference of ~10mk. The same is true for the WIMS Return fuel bundle smeared i.e. there is a penalty of adding all absorbers (washers, springs) to the cladding.

For the case of “end region” modelling, there is a difference between MCNP Forward fuel bundle model with end region and the WIMS Forward fuel bundle with end region of ~12mk which, as all materials used are the same, is still in process of investigation.

Table 1: WIMS and MCNP Predictions for K-eff for Fresh Fuel

Case Description	WIMS k-infinity, MCNP keff	Reactivity diff between MCNP and WIMS, mk
WIMS Forward Fuel Bundle Smeared	1.16209	3.90
MCNP Forward Fuel Bundle Smeared (WIMS equivalent using WIMS material composition)	1.15685 +/- 0.00006	
WIMS Forward Fuel Bundle with End Region, FPF = 1.0	1.17552	11.98
MCNP Forward Fuel Bundle with End Region (WIMS equivalent using WIMS materials)	1.15920 +/- 0.0007	
MCNP Detailed Forward Fuel Bundle Model*	1.17948 +/- 0.00009	-2.86
MCNP Detailed Forward Fuel Bundle Model with all fuel pallets replaced with the same mix of EU and NU fuel and weighted average fuel density*	1.18033 +/- 0.00008	-3.47
MCNP Return Fuel Bundle Smeared (WIMS equivalent using WIMS materials)	1.17042 +/- 0.00007	
WIMS Return Fuel Bundle Smeared	1.17562	3.78

*Note: Reactivity difference between MCNP Detailed Forward Fuel Bundle Model and WIMS Forward Fuel Bundle with End Region, FPF = 1.0

Table 2: Reactivity Effect for different flux Peaking Factors

Flux Peaking Factor (FPF)	k-inf WIMS3.1 Forward End Region Model	Reactivity Effect of the FPF for Forward Bundle, mk (The reactivity change is from FPF=1.0)
1	1.17552	0.00
1.12	1.17518	-0.25
1.14	1.17512	-0.29
1.15	1.17509	-0.31

3. Conclusion

The Refit fuel bundle has complex structures with the use of fuel pellets of two enrichments and presents of additional neutron absorbers toward the end of the bundle. The reactivity comparison of the



two WIMS Forward fuel bundle models, one with smeared bundle materials along the entire bundle length and the second with the “end region” option, to the Detailed MCNP Forward fuel bundle model shows that using the WIMS 3.1 “end region” modeling capability results in a better agreement with MCNP model and should be used as the WIMS modelling approach for the Refit fuel bundles.

4. References

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