TIME-AVERAGE CANDU MODEL WITH FUEL RESHUFFLING

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Abstract

The CANDU time-average model when used in conjunction with the diffusion equation provides a generalized view of the core during regular operation. It gives an average picture of the reactor operation and provides values of 3-dimensional core flux, power, burnup, and refuelling-frequency distributions to be followed for reactor operations. In order to minimize fuel requirements for a CANDU core, reshuffling some of the fuel exiting the reactor has been considered. A time-average model with fuel reshuffling has been added to an existing diffusion code [DIF2G3D].This paper describes the code created to do time-average calculations with reshuffling, and some of the results achieved.

1. Introduction

The CANDU time-average model is a computational device used in the design and analysis of a CANDU core. It gives an average picture of the reactor operation, and it provides operating targets for 3-dimensional core flux, power, burnup, and refuelling-frequency distributions to be followed during reactor operation. The basis of the time average model is to calculate the lattice properties of each bundle at each location in the core over the time it resides in the core. The properties thus obtained are used as input in the neutron diffusion equation to obtain time-average core distribution of flux, power, burnup and refuelling frequencies. The model coded is a CANDU-6 core with 12 bundles in each of the 380 channels. The refuelling scheme was assumed to be the eight-bundle-shift scheme.

To improve the fuel usage, maximize burnup and minimize the fuel needed for the reactor we consider fuel reshuffling. Instead of refuelling with fresh fuel, used fuel bundles that have already achieved burnup in the core are reshuffled back into other positions in the core.

2. Time-Average Model

The time-average model [1] works by calculating lattice properties at each location in the core and then averaging these properties over the time the fuel has been in that location. The averages are modeled to replicate the number of reactions taking place in the fuel. The properties are then used in the diffusion equations to obtain the time-average core distribution of flux, power and burnup. The values of channel exit-irradiation values (ω_{exit}) and the dwell time (D_c), which is defined as the average time between refuellings of the channel, are interdependent and both of these values are calculated using the neutron flux distribution $\Phi_{tav,\,cb}$. The flux distribution is the solution of the neutron-diffusion equation. The ratio $\boldsymbol{F}$ between the fuel and cell fluxes comes from the lattice

(or cell) calculation. The interdependence of these values means that the time-average model must be solved iteratively.

Fresh bundles enter the core at an entrance irradiation of 0, i.e. $\omega_{entrance} = 0$. Since incremental irradiation is the product of flux and time, they pick up an irradiation of $\phi * D_c$ during their residence time at their entrance position, so that their exit irradiation from that position is $\omega_{exit} = \omega_{entrance} + (\phi * D_c)$.

Bundles that are moved due to a refuelling are assigned an entrance irradiation at their new position equal to that of their exit irradiation in the previous position.

The average channel exit irradiation $\omega_{exit,\,c}$ for channel c is the average of the exit irradiations of the bundles in which exit the channel, as follows:

$$\omega_{exit} = \frac{1}{E_c}\sum_{\beta=1}^{E_c}\omega_{exit}$$ where E_c is the number of bundles replaced on refuelling. Upon replacing the exit irradiation with the relation shown above we get,

$$\omega_{exit} = \frac{1}{E_c}\sum_{\beta=1}^{E_c}(\omega_{entrance} + \phi * D_c)$$

Rearranging and solving for dwell time:

$$\omega_{exit} = \frac{1}{E_c}\sum_{b=1}^{N_c}(\phi * D_c) \rightarrow D_c = \frac{E_c * \omega_{exit}}{\sum_{b=1}^{N_c}\phi}$$

This gives the relation between dwell time, irradiation of fuel, fresh or old and flux

The reaction rate in the core is given by

Reaction Rate = $\Sigma(\omega) * \Phi(t) = \sum(\omega) * \phi(t) / F$

Integrating the above reaction over dwell time we get

Reactions per cycle between refuelling = $\int_0^{D_c}\Sigma_{x,cb}(\omega) * \phi_{cb}(t)dt / F$

Equating the two equations and making the approximation that *F* is constant with time (irradiation), F is removed from within the integral sign and the following is obtained:

$$\Sigma_{x,cb,tav} = \frac{\int_0^{D_c}\Sigma_{x,cb}(\omega) * \phi_{cb}(t)dt}{\int_0^{D_c}\phi_{cb}(t)dt} \qquad \Sigma_{x,cb,tav} = \frac{\int_0^{D_c}\Sigma_{x,cb}(\omega) * \phi_{cb}(t)dt}{\int_0^{D_c}\phi_{cb}(t)dt}$$

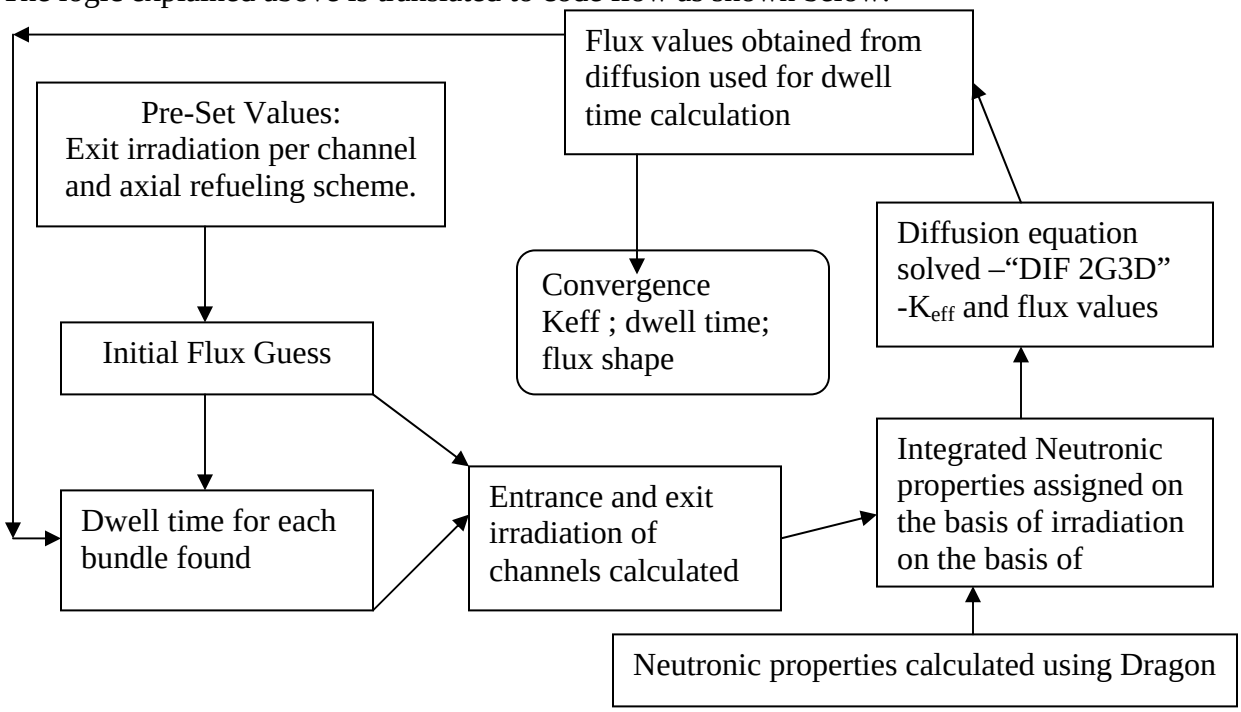
And since irradiation is flux*time, the equation is rewritten using a substitution

$$\Sigma_{x,cb,tav} = \frac{\int_{\omega_{entr,cb}}^{\omega_{exit,cb}} \Sigma_{x,cb}(\omega) d\omega}{\int_{\omega_{entr,cb}}^{\omega_{exit,cb}} d\omega} = \frac{\int_{\omega_{entr,cb}}^{\omega_{exit,cb}} \Sigma_{x,cb}(\omega) d\omega}{(\omega_{exit,cb} - \omega_{entr,cb})}$$

Therefore using entrance and exit irradiations at each position, these cross sections can be computed for all positions in the core. These are then entered into the neutron-diffusion equation for a core diffusion model to be solved to find the time-average flux. The basic independent data which needs to be input to the time-average model are the axial refuelling scheme, which are the bundle shift and the channel average exit irradiation.

The reactor multiplication constant k_{eff} is obtained by solving the diffusion equation. It should be close to 1 for a realistic reactor model. The absolute and relative channel average exit irradiations, which have a significant influence on radial power distribution and thereby refuelling frequencies, are initialized. An increase in these values leads to a low reactivity over time while decreasing will lead to the opposite. These values are chosen on the basis of criticality and power distribution.

The logic explained above is translated to code flow as shown below:

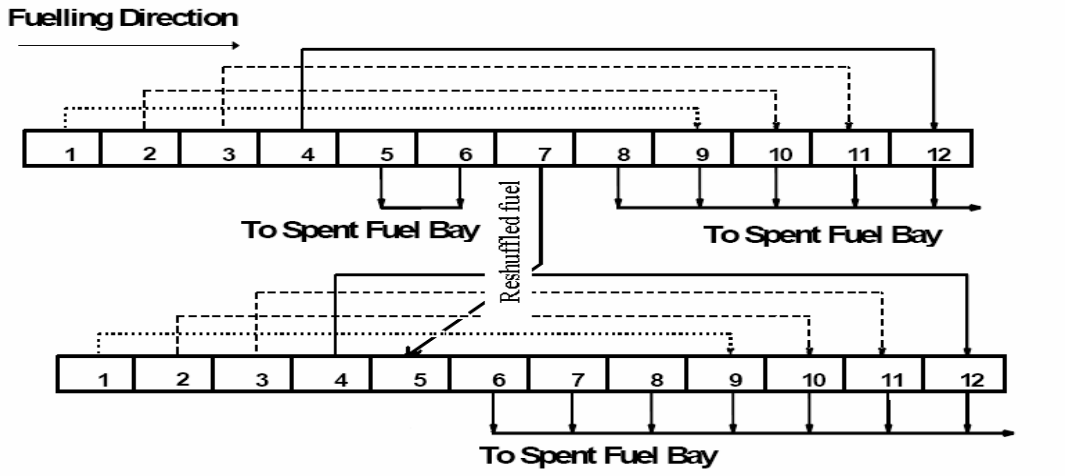


3. Time-Average Model with Fuel Reshuffling

Fuel reshuffling in CANDU may be considered in the future, taking into account the rising cost of uranium. This was the incentive in developing a time-average model with fuel reshuffling.

To code reshuffling into the model, the core is divided into a FROM region and a TO region. Bundles in specific axial positions in channels in the FROM region are assumed to be reshuffled into specific axial positions in channels in the TO region. The axial positions before and after refuelling are not necessarily the same, and are up to the code user.

Fuel that is reshuffled has an existing irradiation; it is assigned this value in its new core position where it picks up further irradiation.



In the case shown above an 8-bundle shift is considered. The shift shows that bundles 5-12 are removed from the core and the bundles from position 1-4 move into the position 9-12. Positions 1-4, 6-8 are then filled with fresh bundles while 5 is replaced with fuel that was in position 8 taken from a different channel. The criterion for region selection was based on the flux distribution in the core. The highest flux values in the core are present in the center of the core and gradually decrease outwards. Therefore the irradiation value per bundle will be lesser in the outer regions than in the inner regions of the core. On the basis of this argument the outer region of the core is selected as the FROM region and the inner region towards the center of the core is selected as the TO region. The average of all the irradiation values in the identified FROM region are taken. This new average exit irradiation of the bundles from the 'from' channels is then reassigned to each of the entrance irradiation of the reshuffled bundles into the 'to' region. Once this is done the subroutine then replaces the bundle irradiation from the time average model and iteration continues as per the time average model.

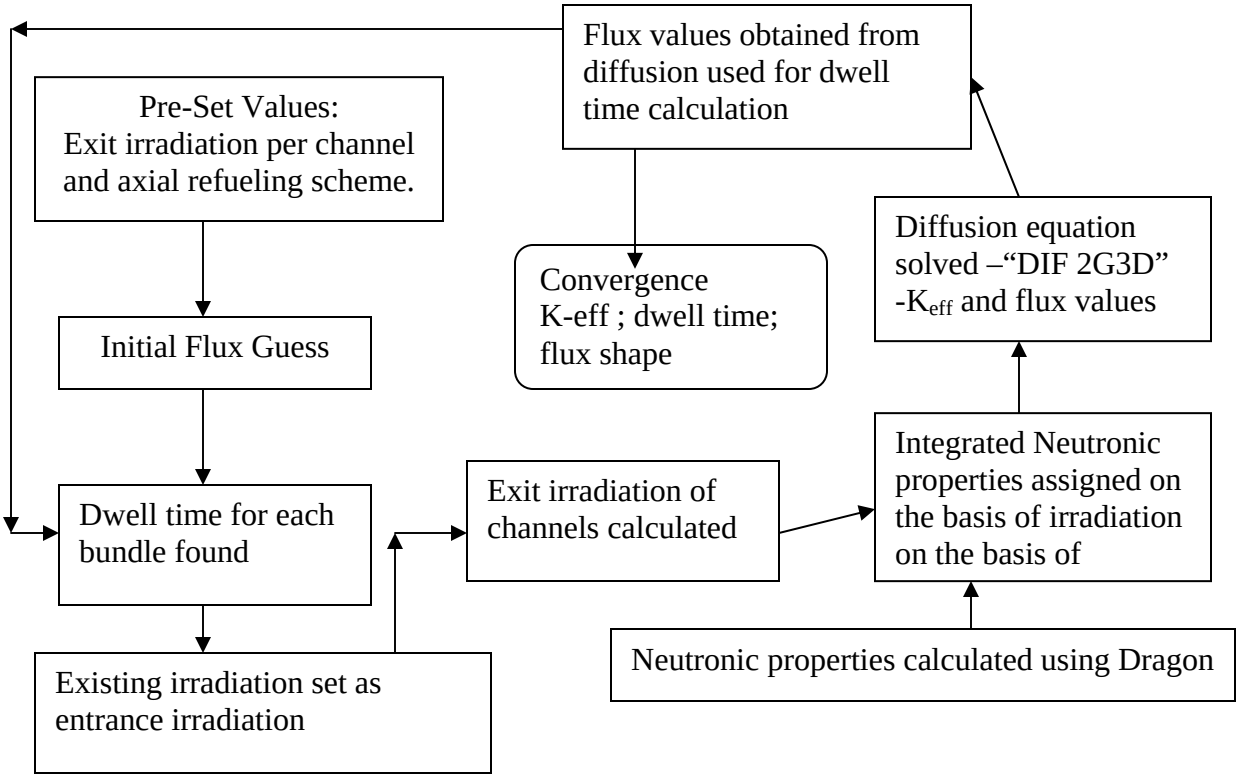
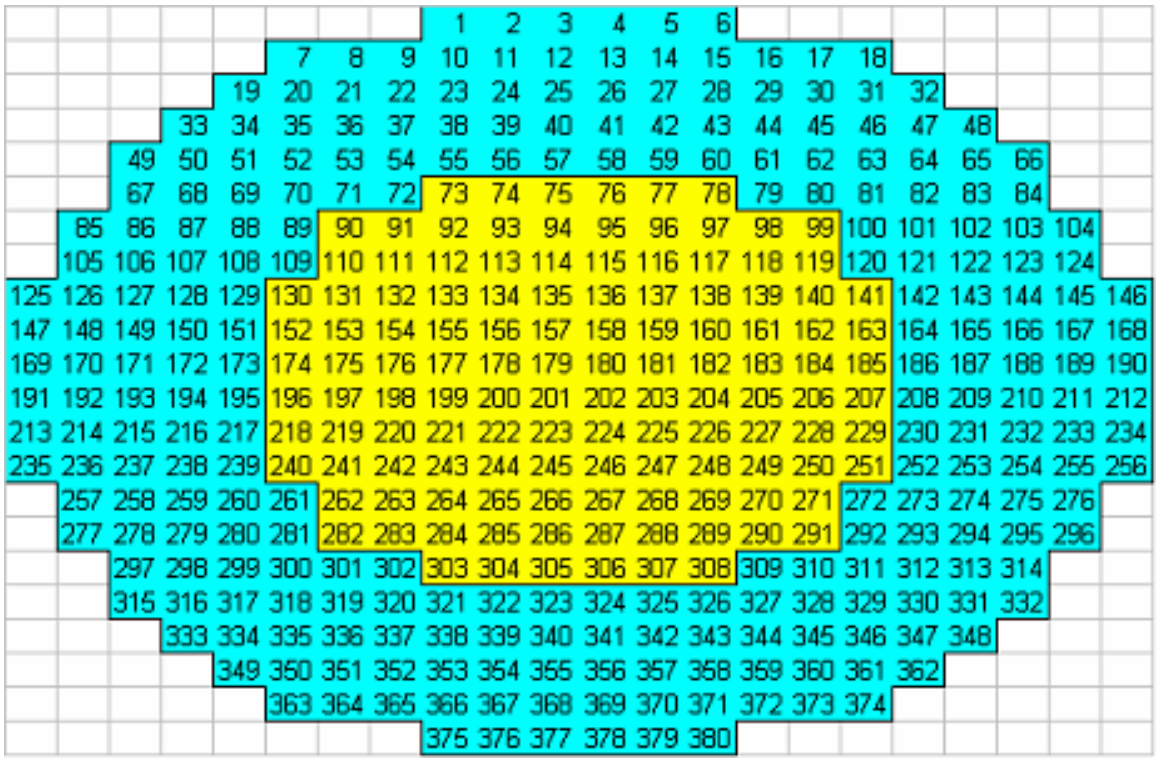


Figure: Program flow for the time-average model with fuel reshuffling.

4. Preliminary Results Obtained with the Time-Average Model with Reshuffling

This model is designed to be very flexible and thus can be used to simulate a variety of situations. The selection of the TO and FROM region is up the user. The selection of the bundles to shuffle, to and from, are also up to the user. Because the model takes into account that channels are refuelled bidirectionally, bundle positions are always numbered starting from the entrance end of the channel.

This model has been applied to a sample case with the following FROM and TO regions (coloured green and yellow respectively):



The bundles in axial position 8 from the FROM region are reshuffled into axial position 5 in the TO region. Because it cannot be known ahead of time from which specific channel and to which specific channel the reshuffling will be done, the exit irradiations of the bundles in position 8 in the FROM region are averaged before being assigned as the entrance irradiation of bundles in position 5 in the TO region.

The model was run both with and without reshuffling, and the results obtained. The results for this particular sample run were a decrease of ~5% in overall bundle throughput per day and an increase in burnup of reshuffled bundles by a factor of 1.7. As this is just a sample computation for sample results, this model can be modified to study other reshuffling schemes for analysis and optimization.

5. Conclusion

The objective of designing and implementing a time-average model with reshuffling is complete as shown by sample results.

The reshuffling fuel performance and fuel-handling issues are not within the scope of this study. The purpose of the model is only to study the neutronics of reshuffling.

6. Reference

[1] "Review of the CANDU Time-Average Model and Calculations", by B. Rouben, in Proceedings of 28th Annual Conference of Canadian Nuclear Society, Saint John, New Brunswick, Canada, 2007 June 3-6.