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Modification of RFSP to Accommodate a True Two-Group Treatment

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Abstract

RFSP is a computer program to do fuel management calculations for CANDU reactors. Its main unction is to calculate neutron flux and power distributions using two-energy-group, three dimensional ieutron diffusion theory. However, up to now the treatment has not been true two-group but actually 'one-and-half groups". In other words, the previous (1.5-group) version of RFSP lumps the fast fission erm into the thermal fission term . This is based on the POWDERPUFS-V Westcott convention. Also, here is no up-scattering term or bundle power over cell flux (H1 factor) for the fast group. While 'OWDERPUFS-V provides only 1.5 group properties, true two-group cross sections for the design and inalysis of CANDU reactors can be obtained from WIMS-AECL. To treat the full two-group properties, he previous RFSP version was modified by adding the fast fission, up-scatter terms, and H1 factor. This wo-group version of RFSP is a convenient tool to accept lattice properties from any advanced lattice code e.g. WIMS-AECL, DRAGON, HELIOS ...) and to apply to advanced fuel cycles. In this study, the nodification to implement the true two-group treatment was performed only in the subroutines of the 'SIMULATE module of RFSP. This module is the appropriate one to modify first, since it is used for the racking of reactor operating histories. The modified two-group RFSP was evaluated with true two-group ross sections from WIMS-AECL. Some tests were performed to verify the modified two-group RFSP nd to evaluate the effects of fast fission and up-scatter for three core conditions and four cases orresponding to each condition. The comparisons show that the two-group results are quite reasonable nd serve as a verification of the modifications made to RFSP. To assess the long-term impact of the full -group treatment, it is necessary to simulate a long period (several months) of reactor history. It will also e necessary to implement the full two-group treatment of reactivity devices and assess the eactivity-device worths.

. Introduction

RFSP (Reactor Fuelling Simulation Program)[1] code consists of 16 major modules, 20 minor modules, 7 control and data input modules, and 940 subroutines.

RFSP is a computer program to perfom fuel management calculations for CANDU reactors. Its main inction is to calculate neutron flux and power distributions using two-energy-group, three dimensional eutron diffusion theory. However, up to now the treatment has not been true two-group but actually one-and-half groups" (see below). It is capable of calculating time-average (in the *TIME-AVER

module) and instantaneous (in the *INSTANTAN module) flux distributions and of simulating reactor operations, including refuellings and burnup steps. Simulations of operating history may also be done using a nodal expansion technique to compute the flux. The code is also capable of performing kinetics calculations (power transients) by solving the time-dependent neutron diffusion equation (in the *CERBERUS module), with delayed-neutron, using the Improved Quasi-Static (IQS) method.

RFSP calculates flux and power distributions in three dimensions using two-group finite-difference diffusion theory. RFSP obtains cross sections as functions of fuel irradiation from tabulated input, or as calculated by the lattice-code module *POWDERPUFS. RFSP simulates reactor operation by taking time steps with the irradiation distribution updated from the previous step. Alternatively the flux can be calculated by expansion in a set of pre-calculated flux modes, using vanadium detector readings (site data) as input. The resulting bundle fluxes can be used to track the reactor history.

Some characteristics of the diffusion equation solved by the previous version of RFSP need to be noted. These characteristics amount to what is called the 1.5-group treatment:

- The production cross section acts on the thermal group only and produces fast-group neutrons only; i.e., there is an implicit assumption that all fissions originate in the thermal group and that all fission neutrons are born in the fast group. Fast fission is taken into account by lumping it into an "effective component" of the thermal production cross section. For example, the lattice code POWDERPUFS-V accounts for fast fission in U-238 only, and incorporates it as a component of the thermal-group $\nu\Sigma_f$. In other words, the previous version of RFSP lumps the fast and thermal fission terms together and this is based on the PPV Westcott convention.
- There is no up-scattering, i.e., no scattering of thermal-group neutrons into the fast group.
- There is no bundle power to cell flux ratio (H factor) for the fast group.

While POWDERPUFS-V provides only 1.5 group properties, true two-group cross sections for the design and analysis of CANDU reactors can be obtained from WIMS-AECL[2]. To treat the full two-group properties, the previous RFSP version was modified by adding the fast fission and up-scatter terms. The modified two-group RFSP was evaluated with true two-group cross sections from WIMS-AECL.

In this study, the modification to implement the true two-group treatment was performed only in the subroutines of the *SIMULATE module of RFSP. This module is the appropriate one to modify first, since it allows the tracking of reactor operating histories.

2. RFSP Modification for Full Two-Group Treatment

2.1 Two-Group Formulation of Diffusion Equation in RFSP

RFSP solves the static neutron-diffusion equation in two neutron energy groups for eigenvalue problems. Group-1 is the fast energy group, while group-2 is the thermal energy group.

The previous (1.5-group)[3] form of the two-group equation solved by RFSP is the following:

$$\begin{aligned} -\nabla \cdot D_1(\vec{r})\,\nabla\phi_1(\vec{r}) \;+\; (\Sigma_{a1}(\vec{r}) + \Sigma_m(\vec{r}))\,\phi_1(\vec{r}) - \frac{\nu\Sigma_f(\vec{r})}{k_{eff}}\phi_2(\vec{r}) &= 0 \\ -\nabla \cdot D_2(\vec{r})\,\nabla\phi_2(\vec{r}) \;+\; \Sigma_{a2}(\vec{r})\,\phi_2(\vec{r}) \qquad - \Sigma_m(\vec{r})\,\phi_1(\vec{r}) &= 0 \end{aligned} \tag{2.1}$$

where, at position $\vec{r}$

$\phi_1(\vec{r})$ and $\phi_2(\vec{r})$ are the group-1 and group-2 neutron fluxes, respectively,

$\Sigma_{a1}(\vec{r})$ is the group-1 (fast) absorption cross section,

$\Sigma_m(\vec{r})$ is the moderation (down-scattering) cross section,

$\nu\Sigma_f(\vec{r})$ is the neutron thermal production cross section,

$\Sigma_{a2}(\vec{r})$ is the group-2 (thermal) absorption cross section,

$D_1(\vec{r})$ is the group-1 (fast) diffusion coefficient,

$D_2(\vec{r})$ is the group-2 (thermal) diffusion coefficient, and

k_{eff} is the reactor multiplication constant and is the inverse of the eigenvalue of eq. (2.1).

The modified (full 2-group) form of the 2-group equation to include the fast fission and up-scattering is the following:

$$-\nabla \cdot D_1(\vec{r})\nabla\phi_1(\vec{r}) + (\Sigma_{a1}(\vec{r}) + \Sigma_m(\vec{r}))\,\phi_1(\vec{r}) - \left\{\frac{\nu\Sigma_{f1}(\vec{r})\phi_1(\vec{r}) + \nu\Sigma_{f2}(\vec{r})\phi_2(\vec{r})}{k_{eff}} + \Sigma_{s21}(\vec{r})\phi_2(\vec{r})\right\} = 0 \qquad (2.2)$$

$$-\nabla \cdot D_2(\vec{r})\,\nabla\phi_2(\vec{r}) + (\Sigma_{a2}(\vec{r}) + \Sigma_{s21}(\vec{r}))\,\phi_2(\vec{r}) - \Sigma_m(\vec{r})\,\phi_1(\vec{r}) = 0$$

where the new terms are as follows:

$\Sigma_{s21}(\vec{r})$ is the up-scattering cross section,

$\nu\Sigma_{f1}(\vec{r})$ and $\nu\Sigma_{f2}(\vec{r})$ are the fast and thermal production cross sections, respectively.

2.2 Modification of Subroutines for *SIMULATE Module

The *SIMULATE module simulates a power burnup history starting from a known initial condition and proceeding for a given number of time steps. Channels to be refuelled are defined in input. Data produced at each step are retained so that the simulation may be restarted at any step.

The flux distribution is calculated either from diffusion theory, using an iterative solution scheme with standard over-relaxation acceleration, or is taken from a *FLUXMAP calculation based on a flux synthesis method using the readings of in-core detectors.

The time history of the flux and power distribution is calculated at discrete time steps with the irradiation distribution incremented from the previous step using the previous flux distribution. This type of calculation is used to obtain the initial transient from startup to equilibrium, and to investigate the effect of various fuelling rules.

3. Production of Two-Group Cross Sections for RFSP by Using WIMS-AECL

The calculation steps[4] for producing two-group cross sections for RFSP in the fuel and reflector region is as follows. First, a WIMS-AECL calculation is performed for the reference lattice cell model with the ENDF/B-V cross section library. Cross section data and fluxes for each region of the model are saved on Tape 16. Second, the cross section data stored on Tape16 are condensed by the CONDENS code from the 33-energy group structure used in the WIMS-AECL calculation to the two-energy-group

structure required for the RFSP calculation. The energy boundary between the fast and thermal groups is chosen as 0.625 eV by convention. CONDENS operates on the original Tape 16 file to produce a new Tape 16-format file in which the energy group structure has been modified. Finally, the WRFSP code forms tabulated input for RFSP from the two group data on the new Tape 16-format file.

4. Evaluation of Two-Group RFSP with True Two-Group Cross Sections from WIMS-AECL

Some tests were performed for the following three core conditions and four cases corresponding to each condition. These cases are presented in Table 1 and use the same two-group reflector properties for all cases. Table 1 also shows the results for the major parameters for all cases.

Condition A : no burnup step and no refuelling at 100% FP, 173276670 MWH, and average zone level of 36.87 %.

Condition B : 4 burnup step and no refuelling at 100% FP, 173276670 MWH, and average zone level of 36.87 %.

Condition C : 4 burnup step and refuelling at 100% FP, 173276670 MWH, and average zone level of 36.87 %, where the 4 channels (R09, K07, G16, and Q18) are refuelled.

Cases A-1, B-1, C-1 : fuel properties with pseudo two group at conditions A, B, and C, respectively.

Cases A-2, B-2, C-2 : fuel properties with full two group but no up-scatter at conditions A, B, and C, respectively.

Cases A-3, B-3, C-3 : fuel properties with full two group but no fast fission at conditions A, B, and C, respectively.

Cases A-4, B-4, C-4 : fuel properties with full two group at conditions A, B, and C respectively.

Table 1 shows that the upscattering effect is much smaller than the fast fission effect on the reactivity change. The reactivity for the case with true 2-group properties (case A-4) is increased about 1 mk in comparison with the case with 1.5-group properties (case A-1). The maximum channel and bundle powers for case A-4 are slightly increased in comparison with case A-1 while the maximum channel and bundle overpowers are slightly decreased.

The results in the case of a burnup increase for 4 FPD show the same trend in comparison with those in the case of no burnup increase for 4 FPD . Also, the results in the case of refuelling of 4 channels show the same trend in comparison with those in the case of a burnup increase for 4 FPD.

These comparisons show that the two-group results are quite reasonable and serve as a verification of the modifications made to RFSP.

5. Conclusion and Future Work

This two-group version of RFSP is a convenient tool to accept lattice properties from any advanced lattice code (e.g. WIMS-AECL, DRAGON, HELIOS ...) and to apply to advanced fuel cycles.

It will be necessary to implement the full two-group treatment of reactivity devices and assess the reactivity-device worths. It is recommended that at least one full-power-year of reactor operating history be simulated, and that the trends in k_{eff} and power distributions be assessed. If possible, a comparison to in-core detector readings from site should be made.

The other modules, such as *TIME-AVER, *INSTANTAN, and *CERBERUS, should be modified later to complete the modification of the entire RFSP code for treating the true two-group structure.

Many of the subroutines used in the *SIMULATE module are the same as those in the *TIME-AVER and *INSTANTAN modules. But the *CERBERUS module has different subroutines because this module solves the time-dependent two-group diffusion equation.

6. References

1) D.A. Jenkins and B. Rouben, "Reactor Fuelling Simulation Program – RFSP: User's Manual for Microcomputer Version", TTR-321/COG-93-104, Rev. 1, July, 1993.

2) J.V. Donnelly, "WIMS-CRNL A User's Manual for the Chalk River Version of WIMS", AECL Report AECL-8955, 1986.

3) B. Rouben, "Reactor Fuelling Simulation Program RFSP: Program Description for Microcomputer Version", TTR-370, December, 1991.

4) J.V. Donnelly, "Using the WIMS-AECL/MULTICELL Calculations with SPH", Memo to H. Chow, File 91-03311-000-0004, December 19, 1995.

Table 1. Comparison of major parameters for each case at conditions A, B, and C

Condition A : no burnup step and no refuelling at 100% FP, 173276670 MWH, and average zone level of 36.87 %.

	Case A-1	Case A-2	Case A-3	Case A-4
Reactivity (mk)	-6.704	-5.743	-6.348	-5.730
Maximum Channel Power (MW)	6.946 (O05)	6.957 (O05)	6.956 (O05)	6.958 (O05)
Maximum Bundle Power (kW)	863.371 (O05/6)	866.152 (O05/6)	865.405 (O05/6)	866.225 (O05/6)
Maximum Ripple	1.099 (F06)	1.100 (P04) 1.096 (F06)	1.111 (P04) 1.109 (F06)	1.100 (P04) 1.096 (F06)

Condition B : 4 burnup step and no refuelling at 100% FP, 173276670 MWH, and average zone level of 36.87 %.

	Case B-1	Case B-2	Case B-3	Case B-4
Reactivity (mk)	-8.084	-7.482	-8.024	-7.469
Maximum Channel Power (MW)	6.938 (O05)	6.939 (N05) 6.932 (O05)	6.934 (O05)	6.940 (N05) 6.932 (O05)
Maximum Bundle Power (kW)	859.747 (O05/6)	858.438 (O05/6)	858.409 (O05/6)	858.447 (O05/6)
Maximum Ripple	1.101 (F06)	1.088 (F06)	1.100 (F06)	1.088 (F06)

Condition C : 4 burnup step and refuelling at 100% FP, 173276670 MWH, and average zone level of 36.87 %, where the 4 channels (R09, K07, G16, and Q18) are refuelled.

	Case C-1	Case C-2	Case C-3	Case C-4
Reactivity (mk)	-7.258	-6.571	-7.067	-6.555
Maximum Channel Power (MW)	6.890 (O05)	7.004 (O17) 6.877 (O05)	6.920 (O17) 6.873 (O05)	7.005 (O17) 6.878 (O05)
Maximum Bundle Power (kW)	853.569 (O05/6)	851.598 (O05/6)	850.680 (O05/6)	851.683 (O05/6)
Maximum Ripple	1.085 (P04)	1.086 (Q18) 1.074 (P04)	1.089 (Q18) 1.084 (P04)	1.086 (Q18) 1.074 (P04)

- Cases A-1, B-1, C-1 : fuel properties with pseudo two group at conditions A, B, and C, respectively.
- Cases A-2, B-2, C-2 : fuel properties with full two group but no up-scatter at conditions A, B, and C, respectively.
- Cases A-3, B-3, C-3 : fuel properties with full two group but no fast fission at conditions A, B, and C, respectively.
- Cases A-4, B-4, C-4 : fuel properties with full two group at conditions A, B, and C respectively.