History of RFSP for CANDU Fuel Management and Safety Analysis

D.A. Jenkins[1], B. Rouben[2] and W. Shen[1]

[1] Reactor Core Physics Branch, AECL Sheridan Park, Mississauga, Ontario, Canada
jenkinsd@aecl.ca and shenwei@aecl.ca
[2] 12 & 1 Consulting, Toronto, Ontario, Canada roubenb@alum.mit.edu

Abstract

RFSP (Reactor Fuelling Simulation Program) is the main scientific code for full-core neutronics simulation and analysis of CANDU reactors. RFSP has a long history, dating from the 1970s and spanning a large number of versions, some of which diverged. However, these eventually converged back to the Industry Standard Toolset version RFSP-IST. The list of people actively involved in the development of RFSP is, correspondingly, very long. In a bid to retain memory of the main steps in the development of RFSP, this paper attempts to document in a summary manner these major milestones. While Prof. Daniel Rozon was not personally involved with RFSP, this paper relates to Prof. Rozon's central work on reactor physics computational codes and methods, and the paper is dedicated to Prof. Rozon's memory.

1. Introduction

The neutronics analysis of CANDU reactors is typically a three-stage process:

1. Neutron-transport calculation of basic-lattice properties with irradiation or burnup, as well as homogenization and energy-collapsing of lattice properties;
2. Neutron-transport calculation of reactivity-device incremental properties; and
3. Neutron-diffusion calculation in a three-dimensional, full-core model.

The full-core neutronics computer code which has been used in the past few decades in the analysis of CANDU reactors is RFSP (Reactor Fuelling Simulation Program). RFSP has a long history, dating from the 1970s and spanning a large number of versions, some of which diverged. The versions eventually converged back to the Industry Standard Toolset version RFSP-IST [1]. This document provides a history of the main steps in the development of RFSP and of the computational methods incorporated within it. It attempts to recall in a summary manner the major milestones in the development of RFSP and its capabilities. The list of people actively involved in the development of RFSP is, correspondingly, very long. It is certain that many names will be missed in the history here depicted. This is solely due to the inadequate memory of the authors, who wish hereby to apologize for if any names or facts have been missed.

2. The Beginnings

One of the first codes used for full-core calculations for CANDU reactors was called CHEBY. It had been installed in the early 1970s by Adi Dastur and David Buss. It used two-energy-group lattice properties from the POWDERPUFS-V cell code [2]. Reactor models used with CHEBY

were very simplified. Nuclear properties were assumed to be axially uniform along channels; this is consistent with the "continuous fuelling" approximation and the bidirectional fuelling of neighbour channels, which, when averaged together, results in constant axial properties (averaged from 0 to the exit irradiation in the channel). Also, the models used were divided into at most two irradiation zones (inner core and outer core). To reduce the computation time in those days, partial-core models (half-core, quarter-core and even eight-core models) were often used, taking advantage of the (not-so-perfect) symmetry of the core.

The two-group diffusion equation solved in CHEBY incorporated two simplifications: the upscattering from the thermal group to the "fast" group was ignored, and the fast-fission cross section was set to 0, by lumping it into the thermal-fission cross section. This scheme has often been labelled the "1.5-group model". Compatible reactivity-device incremental cross sections for use with CHEBY models were obtained from codes such as MULTICELL [3], developed by Adi Dastur, Dave Buss and V.K. Mohindra, or SHETAN [4], developed by Mustapha Roshd and Hank Chow. Ben Rouben developed a utility program, MATMAP, to simplify the preparation of models for CHEBY.

In spite of its simplifications, CHEBY signalled the start of ever-increasing accuracy in full-core CANDU analysis.

3. FMDP

It was clear that to improve the sophistication of the core models it was important to be able to assign bundle-specific lattice properties, corresponding to bundle-specific irradiation values. An obvious application was "instantaneous" core models, sequential "snapshots" in a core-follow simulation. Another important application at the reactor-design stage was to model the equilibrium, "time-average" core with lattice properties determined at each bundle location as averages taken over the residence time of fuel at that specific location (see a review of this in [5]).

This capability was incorporated by Al Wight into a much more powerful program, FMDP (Fuel Management Design Program). Rick Sibley assisted Al Wight in this work. FMDP enabled the self-consistent solution of the time-average equations, allowing consistency between flux, irradiation, and refuelling-frequency distributions with the axial refuelling scheme, and with as many irradiation zones as desired, thereby truly taking advantage of the great flexibility of CANDU reactors in their on-line refuelling. FMDP was coded with a modular structure, and it introduced the saving of all model data and outputs in a tree-like, random-access database, which allowed very easy restarts and continuations of calculations (as in a core-follow simulation). Many people, for example Marv Gold, were involved over time in coding various capabilities in FMDP. For specific applications on new reactor designs, Marv Gold developed the capability for generalized axial refuelling schemes, beyond the usual push-through refuelling schemes. He also incorporated new geometric modelling capabilities, such as "obround calandrias".

In spite of retaining the 1.5-group model, FMDP was really a quantum leap ahead; it allowed the routine application of much more realistic models. Also, the use of partial-core models decreased quickly with FMDP.

4. The Start of RFSP

RFSP started life as a subset of FMDP. Oleh Trojan, Manager of the Reactor Core Physics "B" Branch at AECL Power Projects, required a version of FMDP to be used with the off-shore CANDU 600s (most notably Wolsong 1) for core-follow simulations. This version would be lightened by trimming it to the modules necessary for core follow, in particular by dropping the time-average module. This subset of FMDP, which was labelled RFSP (Reactor Fuelling Simulation Program), was created largely by Dave Jenkins, the first RFSP code holder.

5. Xe-135 Modelling

Xe-135 is an important nuclide to take into account in reactor operation. It has important effects both in steady state, where it offers intrinsic "power flattening", and in power manoeuvres, where Xe-135 transients have an important impact on reactivity and on flux shape. While earlier modelling assumed a uniform Xe-135 concentration in core, it was very important to model a spatially varying Xe-135 concentration both for steady-state and for transients ("quasi-static" calculations). The modelling of the I-135/Xe-135 kinetics spatially through the core was incorporated in a new FMDP module, XEMAX, by Al Wight and Marv Gold (it had been present earlier in an offshoot version of CHEBY, called CHEBXEMAX). In particular, Marv Gold incorporated into FDMP the analytic solution of the equations in the case of a flux changing linearly with time.

6. OHRFSP at Ontario Hydro

When Al Wight moved from AECL to Ontario Hydro, he installed FMDP on its computer system and named it OHRFSP. Development of FMDP continued at AECL, while OHRFSP was developed at Ontario Hydro. The versions naturally started to diverge.

7. Xenon Kinetics in RFSP

The importance of adopting the capability to model spatially-dependent Xe-135 concentrations in core-follow calculations led to the XEMAX module being imported into RFSP. A number of years ensued when both FMDP and RFSP were used at AECL, RFSP for core-follow simulations and FMDP mostly for time-average calculations and other applications.

8. Kinetics Calculations: CERBERUS

The Chernobyl accident in 1986 initiated a strong flurry of Large-break Loss-of-Coolant (LLOCA) safety analysis for CANDU reactors. It was important to show that the CANDU shutdown systems could mitigate LLOCAs from a range of power levels and non-standard configurations, such as spatial tilts in the power distribution. For instance, would a bottom-high flux tilt impair the efficacy of shutoff rods falling from above?

The most accurate fast-kinetics code for CANDU was CERBERUS, developed in the early 1970s by Adi Dastur and Dave Buss. The code was based on the Improved Quasi-Static (IQS) method [6] for time-dependent calculations. The cross-consistency of the flux shape, the

amplitude function, and the delayed-neutron-precursor spatial distributions was later improved (by repeated passes through each flux-shape "long time step") by André Baudouin, Jean Koclas, and Ben Rouben.

Early CERBERUS models could accommodate only very simplified LLOCA transients, i.e., a uniform density per coolant loop. The requirement for more accurate safety analysis pushed the development of more realistic models in both the thermalhydraulics and neutronics areas, e.g, with (at least) the critical pass subdivided into a number of representative channels, according to reactor power zones and according to elevation. The physics models for the stand-alone CEREBRUS code were built by means of MATMAP.

9. Local-Parameter Capability

Modelling bundle-specific properties in FMDP and the spatial distribution of Xe-135 both showed that models could be made even more realistic by using at each core location lattice properties corresponding to values of all the specific lattice conditions at that location. In other words, more local conditions beyond fuel irradiation and Xe-135 concentration should be modelled. For instance, as demanded by the safety analysis, distributions of lattice parameters such as fuel temperature and coolant density should be modelled – and ideally this should not be limited to safety-analysis calculations.

Using a distribution of these lattice conditions to calculate lattice properties was labelled "local-parameter modelling" [7][8]. This was carried out by carrying out "branch" calculations over a two-dimensional grid of values of, specifically, fuel temperature and coolant density for each burnup step. The grid of values would span anticipated values of these conditions. Then, in addition to interpolation in irradiation (or burnup), interpolation could be carried out over fuel temperature and coolant density as well, to find the lattice properties for any position in core.

10. Changes in Computing Platforms and Reunification of RFSP into RFSP-IST

Starting in the late 1970s, computers changed. The AECL Computing Centre moved from the CDC systems to the CYBER systems. This forced a large effort in porting all codes to the new platform. Ben Rouben (the RFSP code holder at the time) and Dave Jenkins carried out a large part of the porting of RFSP. The CDC architecture was based on a 60-bit computer "word", while the CYBER functioned on the more standard 4-byte (32-bit) word. Since 60-bit calculations are akin to double-precision (64-bit) calculations on the CYBER, the porting required verification that single-precision computation was sufficient for most purposes; only a small amount of recoding in double precision was required. In addition, a new accommodation had to be found for all 10-letter alphanumeric data used in RFSP (and there was indeed a great amount of such data: input code words, database record names, etc.). Such data could be accommodated in 60 bits earlier. The solution chosen, which had the great advantage that it did not require changing the code words or record names, was to store this data as "double integers" (which provide 64 bits of information).

Since there was little point in duplicating all this effort in porting FMDP, it was decided instead to port into RFSP the FMDP modules which were not already there. When that was done, RFSP then had all the capabilities which had been in FMDP. From that point on, FMDP and RFSP existed together as RFSP.

In 1990, RFSP was converted to run on the APOLLO UNIX platform. In 1993, RFSP was converted to run on the Hewlett-Packard UNIX (HP-UX) platform, and in 1999, a Y2K-compliant version was developed. Dave Jenkins, Benoit Arsenault, Ron Davis and many others were involved in these porting activities over the years.

In the mid to late 1990s, the Industry Standard Toolset initiative recommended the adoption of WIMS-AECL, DRAGON, and RFSP as the IST codes for lattice, reactivity-device, and full-core calculations respectively, and mandated the development of a unique IST version of each code.

In 1999 June, the first Industry Standard Toolset version, RFSP-IST version 3-00, was created by merging AECL's RFSP version 2-17 and Ontario Power Generation's OHRFSP version R1.06. This involved many people from both organizations, e.g., Dave Jenkins and Benoit Arsenault at AECL, Marv Gold, Larry Blake and Bill Kelly from Ontario Power Generation.

In 2001 RFSP was ported from the HP-UX platform to the PC platform, by I. Patrulescu and I. Dumitrache (on attachment to AECL from ICN Pitesti, Romania) and Wei Shen and Dave Jenkins [9]. Later on, a single platform-independent RFSP source code was developed by Wei Shen so that RFSP can be directly compiled on three platforms (HP-UNIX, PC Windows, and LINUX) with the Fortran 90 compiler.

11. The CERBERUS Module of RFSP

The capability for local-parameter calculations had been incorporated earlier on in RFSP by Dave Jenkins and Ben Rouben, but the impetus for large-scale use of this functionality came from the large effort in LLOCA analysis.

The CERBERUS capability was incorporated into RFSP as a separate module, *CERBERUS, which could make use of local-parameter models and calculations. Porting this capability into RFSP also allowed for the first time the use of distributed delayed-neutron fractions β, according to the irradiation of each fuel bundle – this had not been practical before.

12. History-Based Local-Parameter Calculations

History-Based Local-Parameter (HBLP) [10]-[12] calculations went a major step ahead of grid-based local-parameter calculations. In this capability, the depletion calculation for each individual fuel bundle followed the precise history of the local lattice conditions at each irradiation step. Thus, as a core follow was performed, each run of RFSP performed automatically a separate incremental depletion calculation for each fuel bundle over the incremental time step for the run. This meant that each fuel bundle had its own individual depletion history, taking into account every change in lattice condition (coolant density, fuel

temperature, local power, Xe-135 concentration, etc.), including those corresponding to the shift in position of the bundle following a refuelling.

History-based local-parameter calculations allowed perturbation calculations to be carried out, for example, for any irradiation value, from any specific initial coolant density to any perturbed coolant density.

The jump to history-based local-parameter calculations was possible at the time because a very fast lattice code, POWDERPUFS-V, was in use. Its speed of execution was such that the thousands of incremental depletion calculations needed for the number of bundles in core could be performed in about a second.

The history-based capability was by design functional on “snapshot” models - where each fuel bundle has a well defined “instantaneous” irradiation. It had no meaning in time-average models. In order to apply LLOCA calculations with the history-based local-parameter capability, this had to be done either on snapshots (e.g., instants in a core follow) or on a Time-Average-Equivalent model, in which each fuel bundle was assigned a single irradiation which replicated the time-average properties of the bundle. In order to accomplish the latter, the TAVEQUIV module of RFSP was created [13].

13. The CERBRRS Module

The CERBRRS module was developed by Hank Chow and Ben Rouben [14]. It was meant for fairly long time-dependent calculations, e.g., those involving power manoeuvres, incorporating also automatic actions of the Reactor Regulating System (RRS), e.g., movement of reactivity devices, and evolution of the Xe-135 concentration.

The CERBRRS module was based on the RRS coding in the Gentilly-2 version of SMOKIN. It was thus not completely general and only applicable to calculations for CANDU-6 reactors.

14. Two-Energy-Group Modelling

In the 1990s the void reactivity predicted by POWDERPUFS-V for irradiated fuel was found to have a high uncertainty. This contributed to the adoption of WIMS-AECL [15] as the accepted lattice code. As WIMS-AECL provides a full set of two-group lattice properties (including the fast-fission and up-scattering cross sections), the diffusion equations had to be updated to accommodate the full two-group model [16]. Many RFSP modules had to be converted to accommodate two-group modelling, so this required a significant effort from many people, e.g., Dave Jenkins, C.J. Bae (on attachment from KAERI) and Ben Rouben (SIMULATE module), Benoit Arsenault (TIME-AVER module), Eleodor Nichita (CERBERUS and CERBRRS modules), Wei Shen (SUMMARY, INSTANTAN, and MONIC modules), Tahar Sissaoui (FLUXMAP, MODES, RIPPLE, MAPMATRIX and ONLINEMAT modules for the fluxmapping calculation), Peter Schwanke (K-CHANGE and INTEGRALS modules) and others.

15. Use of WIMS-AECL as Lattice Code

With the adoption of WIMS-AECL for lattice calculations, the functionality of the uniform-parameter and local-parameter modelling has been maintained directly. However, the much longer running times of WIMS-AECL put the history-based capability in jeopardy. In response, Jim Donnelly developed the Simple-Cell Model (SCM) [17], a fast-running (at a speed two orders of magnitude faster than WIMS-AECL) few-group neutron-diffusion calculation in a simplified cell model by using the superhomogenisation technique, which replicated closely the results of WIMS-AECL. Benoit Arsenault implemented the SCM in the SIMULATE module of RFSP for core-tracking simulations, and Eleodor Nichita implemented the SCM in the CERBERUS and CERBRRS modules of RFSP for kinetics analysis. Thus the POWERDERPUFS-V HBLP method was replaced by the SCM HBLP method in RFSP in two energy groups. This made history-based-type calculations possible with WIMS-AECL-type results.

Though the SCM HBLP method has been successfully used for the CANDU natural-uranium (NU) fuel, it showed large errors when used for other fuels (such as the ACR-1000 fuel) that were significantly different from the CANDU NU fuel. In order to use the WIMS-AECL properties directly without appealing to the SCM surrogate, the micro-depletion method was developed and implemented in the SIMULATE module of RFSP by Wei Shen [18] for core-tracking simulations. The program was soon enhanced by Wei Shen and Benoit Arsenault [19] and extended for the kinetics calculation. The micro-depletion method is as simple as the local-parameter method, but it tracks both the microscopic cross section of a nuclide and its number density, which depends on the depletion history. With the micro-depletion model, not only the bundle-average nuclide concentrations, but also the nuclide concentrations for different fuel regions in a bundle, can be tracked explicitly. The micro-depletion method is state-of-the-art and proven technology and it can be used for any reactor and fuel type. Since the depletion history is tracked in the core analysis, codes used for LWRs are switching the micro-depletion method.

Preliminary, investigative history-based core-follow calculations with lattice calculations being shared in parallel by a number of computer nodes were also carried out by Adriaan Buijs. Though this method is more rigorous, it is still impractical for routine calculations at this time because of the computational effort required. Currently, its primary value is for benchmarking purposes.

16. Multicell Methodology

The homogenized lattice properties employed in RFSP are usually calculated for a single lattice cell (considered as a heterogeneous medium) with reflective or periodic boundary conditions, without considering the effect of the environment due to nearby lattice cells. In some cases, multiple lattice cells (multicells) are needed to correct for the effect of the neighbourhood on a single lattice cell or the effect of the presence of the reflector for advanced CANDU reactor or CANDU reactor with advanced fuel cycles. This is especially important in configurations where there are large heterogeneities in the reactor core. With the development of the multicell capabilities in WIMS-AECL version 3.1 by Dimitar Altiparmakov [20], the multicell methodology was developed [21] in RFSP-IST version 3-04 by Wei Shen to account for the

effects of the environment for 3-dimensional static and kinetics simulations, while maintaining the basic structure of the single-lattice-cell-based micro-depletion method intact.

17. More Recent Developments

RFSP continues to evolve and further development work have been done recently in the latest release of RFSP, version 3.5.1. Some examples are:

- Enhancement of geometrical models, such as implementation of the mini-bundle model by Peter Schwanke, implementation of radial and axial space-dependent extrapolation factors by Elisabeth Varin, implementation of the capability to model sagged and axially displaced fuel channels by Iouri Martchouk and Elisabeth Varin, implementation of the capability to model multiple reflector regions by Brian Phelps and Peter Schwanke, and increase of the maximum number of records/sub-indices in the direct-access file by Dave Jenkins, Wei Shen and Kevin Ho to handle more axial meshes and fuel types, etc.
- Development of new capabilities, such as the implementation of the distributed fixed-source-term in the diffusion analysis by Brian Phelps, implementation of various fuel-temperature calculation options by Wei Shen, and implementation of a refuelling option to model the short-term time dependence of the flux during refuelling by Dave Jenkins.
- Enhancement of the quasi-static bulk-control and spatial-control capability by Peter Schwanke for various types of CANDU reactors, including the ACR-1000.

In addition, a new development is being carried out in RFSP by Julia Mao to develop a generic RRS module *GENRRS to model the RRS action for all CANDU reactors (including CANDU-6, Darlington, Pickering, Bruce, and ACR-1000) under the transient conditions.

18. Ancillary Activities: User Feedback, Documentation, Verification, Validation

For a code like RFSP to be recognized and accepted for design and analysis, including the all-important safety analysis, code documentation, verification and validation must go hand in hand with the code development.

The long history of RFSP and its many versions saw therefore a very large number of people involved as code holders, active users, giving useful feedback, verifiers, validators, etc. – too large a number for any list to do justice to all of them. Some names of people, particularly active in any of these roles, that come to mind to the authors (in no particular order) are Al Wight, Dave Buss, Benoit Arsenault, Marv Gold, Augustine Mao, Azeez Rehman (Ontario Hydro), José Fink (NA-SA), Hank Chow, Jim Donnelly, Eleodor Nichita, M.T. Sissaoui, Peter Schwanke, Brian Phelps, Elisabeth Varin, Julia Mao, R.D. McArthur, Farzad Ardeshiri, Michaela Ovanes, P.S.W. Chan, Ron Davis, Mohamed Younis, P.D. Thompson, Chuck Newman and E.G. Young (New Brunswick Power), André Baudouin, Guy Hotte and Michel Beaudet (Hydro-Québec), Adriaan Buijs, Larry Blake and Iouri Martchouk (AMEC NSS) - and many others.

19. Conclusion

RFSP and its predecessor FMDP have served an important role for several decades in the design and analysis of CANDU reactor cores, as well as in core-follow activities at CANDU stations. RFSP has played a central role in the excellent performance of CANDU reactors both in Canada and abroad.

20. References

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