RFSP-IST, The Industry Standard Tool Computer Program for CANDU® Reactor Core Design and Analysis

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Abstract

In the last few years, the Canadian nuclear industry defined an Industry Standard Toolset (IST) of computer programs for CANDU-reactor design and analysis. These Industry Standard Tools are intended to be adopted as the standard numerical calculation methods for application to the safety analysis of CANDU reactors. While the intent of Industry Standard Tools is primarily safety analysis, they are or can be used also in reactor-design calculations, and even in operations support. RFSP-IST is the Industry Standard Tool for CANDU full-core calculations in three dimensions. This paper describes the functionalities of RFSP-IST important to both current and future CANDU products, and describes the process which was followed for the validation of the reactor-physics IST code suite.

Keywords: CANDU, Reactor Physics, Industry Standard Tool, Core Design, Safety Analysis, Computer Program Validation

1. Introduction

The Canadian Nuclear Industry has in the last few years developed an Industry Standard Toolset (IST) for CANDU-reactor design and analysis. Computer programs in a number of disciplines have been designated as Industry Standard Tools. The intent is that these be adopted by all organizations within the Canadian nuclear industry as their standard numerical calculation methods for application to the safety analysis of CANDU reactors. However, while the primary focus of the Industry Standard Tools is definitely safety analysis, that is certainly not their exclusive application. In fact, many of these computer programs are or can be used also in reactor-design calculations, and even in operations support at the CANDU plants.

Reactor physics is of course one of the major disciplines in reactor analysis. It comprised therefore a central area of activity within the IST initiative. The collaboration in the physics community was particularly strong, and consensus was quickly reached on how to achieve the goal of defining Industry Standard Tools in the three major areas of reactor-physics analysis:

- for calculations of basic lattice properties, WIMS-IST [ref. 1] was adopted, comprising the transport-theory cell code WIMS-AECL [ref. 2] Release 2-5d plus the nuclear data library NDAS ENDF/B-VI 1a
- for reactivity-device calculations, the 3-dimensional-transport-theory code DRAGON [ref. 3] was selected as DRAGON-IST, and

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- in the area of full-core calculations, a process was defined to develop an Industry Standard Tool, RFSP-IST (Reactor Fuelling Simulation Program – Industry Standard Tool).

This paper will discuss mostly RFSP-IST.

2. Development of RFSP-IST

RFSP-IST was developed from the AECL legacy diffusion-theory code RFSP [refs. 4, 5] and a related code version, OHRFSP, which had been ported to Ontario Hydro (now Ontario Power Generation) in the early 1980s. Through the years, these two codes had diverged significantly as a result of independent development: OHRFSP supported the needs of the (then) Ontario Hydro CANDU reactors, and RFSP served AECL and the CANDU-6 utilities, both in Canada and abroad. The separate development had followed logically according to the different needs. For instance, flux-mapping analysis and the capability to perform core-follow based on mapped flux distributions had been built into RFSP. On the other hand, the capability to do asymptotic spatial control (i.e., to calculate the predicted long-term steady-state liquid-zone-controller water fills) using the powers of Fully INstrumented CHannels (FINCHes) instead of zone fluxes from mapping detectors, as calibration for the zone-control detectors, had been added to OHRFSP .

To produce an Industry Standard Tool which would serve the needs of all the CANDU IST partners, RFSP and OHRFSP were remerged, yielding RFSP-IST. This was not a trivial task. Obtaining a single source code which produced no error messages on the different FORTRAN compilers of the two organizations was found to require prolonged effort and several iterations. Also, care had to be taken to preserve all the different functionalities of the two codes, so that no existing application for any of the CANDU stations would be jeopardized. The merging task took significantly more than a calendar year of work to accomplish.

However, the merging of the two codes was not the sole activity in the creation of RFSP-IST. At the same time, new capabilities were introduced to integrate RFSP-IST with the other physics IST components, WIMS-IST and DRAGON-IST. The central feature was to build in a general capability for full-two-energy-group core calculations. While the neutron-diffusion equation solved in RFSP had always been formally a two-energy-group equation, the original equation was of a "customized", simplified form. In this simplified equation fast fission was not represented by a separate cross section, but was instead treated as part of thermal fission, and no up-scattering term was included.

The reason for this idiosyncrasy is that this is the definition of cross sections provided to the core code by POWDERPUFS-V [ref. 6], the original lattice code for CANDU neutronics. POWDERPUFS-V is a semi-empirical cell code for heavy-water-moderated lattices, and is based on the results of experiments in Chalk River research reactors. The scheme of POWDERPUFS-V cross sections, known as the Westcott convention, was also occasionally referred to as a "one-and-a-half-group" formalism. It has been used with great success for operations support at CANDU plants. POWDERPUFS-V is in fact still a module in RFSP-IST.

However, POWDERPUFS-V is not suitable for application to fuels very different from natural uranium at the start of their irradiation. This led to the decision to adopt WIMS-IST as the lattice code of the future for CANDU. With this decision, it became necessary to ensure the "full" two-energy-group set of cross sections could be handled by RFSP-IST in all its applications. The extension to the full two-group formalism better integrates RFSP-IST with WIMS-IST and DRAGON-IST, both firmly founded on neutron-transport theory. It also provides the necessary flexibility for adoption of further refinements in lattice-physics methodology as they become available in the future.

3. Physics-Code Applications

From AECL's perspective, the new IST physics code suite provides reactor analysts with the requisite tools to continue supporting indefinitely all its current products, and in addition to advance CANDU technology with confidence into the future. CANDU reactors have superior neutron economy, which allows the use of natural-uranium fuel but which can also be applied to advantage in advanced fuel cycles. The IST tools are essential in the rigorous physics modelling, investigation and analysis of AECL's new products and future applications. Some of these are listed here:

- advanced fuels, such as CANFLEX, a 43-element fuel-bundle design, with thinner pins in the outer 2 rings of elements, which reduces the peak linear-element rating by ~20% relative to the 37-element bundle
- enriched fuel, such as slightly enriched uranium (SEU) or recovered uranium (RU), typically to 0.9 % enrichment, which can be used to increase achievable burnup and reduce the amounts of used fuel
- advanced fuel cycles, such as the use of mixed-oxide (MOX) fuel, MOX based on weapons-derived plutonium, DUPIC (Direct Use of PWR Fuel in CANDU), and thorium cycles
- the Advanced CANDU Reactor (ACR) design (the Next Generation CANDU), which features enriched fuel, light-water coolant, a much smaller lattice pitch, reduced volumes of heavy-water moderator, and a very significant capital-cost reduction target.

4. Functionalities of RFSP-IST

RFSP-IST is the "workhorse" code for full-core CANDU calculations. It models the entire reactor core and provides to the design analyst or the operations physicist crucial system data, such as reactor multiplication constants, 3-d power and burnup distributions, fuel exit burnup, reactivity worth of devices, device performance, etc.

RFSP-IST is a very large computer program, with more than 1,500 subroutines. It has a modular structure, with different modules performing different functions. The modules exchange information via a direct-access file which includes all model details.

RFSP-IST can handle both static (steady-state) and time-dependent problems. Capabilities of RFSP-IST for the applications listed in the previous section are built equally into the code modules for time-dependent or time-independent calculations. The major modules incorporate the following functionalities:

- Design Support

  The *TIME-AVER module analyses the equilibrium time-average configuration of the CANDU core. With it, one can study the impact that different fuels, different refuelling schemes (e.g., 8-, 4-, or 2-bundle-shift refuelling) and the use of differential radial burnup zones and differential fuelling rates make on the flux and power distributions, the achievable fuel exit burnup and uranium utilization, the reactivity worth of devices, etc.

- Core Follow

  The *SIMULATE module allows the calculation of design and actual reactor operating histories. In these simulations, it models and tracks at intervals of one or several days the channel refuelling operations, the instantaneous irradiation and power distributions, the changes in zone-control-compartment water fills, the amount of moderator poison required for criticality in the early period of reactor operation and through the period of the plutonium peak, etc.

  The "local-parameter history-based" capability is available for calculating nuclear properties of individual fuel bundles consistent with the local conditions at the bundle position (e.g., coolant density, flux level, fuel temperature, pressure-tube creep) as well as the history of these conditions (e.g., the history of changes in moderator-poison concentration). This capability had originally been developed for use with POWDERPUFS-V. As WIMS-IST transport-theory calculations require much greater computational effort than the empirical recipes in POWDERPUFS-V, a high-speed lattice-cell calculation consistent with WIMS-IST results, called the Simple-Cell Model [ref. 7], has been developed for doing local-parameter, history-based-type calculations.

  The tracking of the core at an operating station provides the instantaneous value of the channel-power peaking factor (maximum ratio of instantaneous channel power to reference channel power, in high-power region of the core). This is required daily for calibration of the Regional Overpower Protection System in-core detectors.

  The *SIMULATE module can, if desired, be used equally in predictive mode at the station to study the consequences of specific selections of channels for refuelling.

  Alternatively, one can use the *FLUXMAP module, which performs flux mapping, or reconstruction of the full 3-dimensional flux distribution in the core. Mapping is done using a linear superposition of flux modes (essentially, harmonics of the diffusion equation) and the instantaneous readings of a large number of in-core vanadium detectors (102 in the CANDU 6 core). The mapped flux distribution can then be used instead of the diffusion-theory flux in core tracking. This has the advantage of making use of actual "live" data from the operating reactor in core-follow.

- Operations Support

  Both the *SIMULATE and *TIME-AVER modules can follow saturating-fission-product transients in all fuel bundles through the core, and their effect on the neutron-flux distribution. The most important capability here is that for treating the xenon-iodine ($^{135}Xe/^{135}I$) kinetics, which allows the study of xenon tilts and xenon oscillations, and the performance of reactivity devices in arresting these oscillations. In addition to $^{135}Xe/^{135}I$, several other nuclide pairs can also be analyzed, e.g. $^{149}Sm/^{149}Pm$. The important neptunium-plutonium pair $^{239}Np/^{239}Pu$ is also simulated in the same way.

- Safety Analysis

  The *CERBERUS module provides the 3-dimensional fast-kinetics (time-dependent) capability in RFSP-IST, including delayed-neutron effects. This major module is used to calculate the physics input to safety analysis. *CERBERUS is coupled to various thermalhydraulics codes. Fast neutronic transients, such as occur for instance following a hypothetical loss of coolant, can therefore be simulated in coupled neutronics-thermalhydraulics mode.

  In simulating fast transients for safety analysis, the actuation time of the shutdown system(s) is important. The *TRIP-TIME module simulates the response of in-core detectors and out-of-core ion chambers. It models both prompt and delayed components of detector response, and the associated electronics, and works in conjunction with the *CERBERUS module to calculate the actuation times from the neutronic trips.

  The *CERBRRS module has the same kinetics capability as *CERBERUS, but simulates in addition the action of the CANDU-6 Reactor Regulating System (RRS) in time.

- Random-Snapshot Analysis

  The *INSTANTAN module allows the calculation of instantaneous core snapshots without the need for continuous core tracking. The core irradiation distribution which defines the snapshot is determined by selecting for each fuel channel an "age" (0 to 1) in its refuelling cycle between just-refuelled (age of 0) and ready-to-be-refuelled (age of 1). The channel ages are selected randomly or according to a fixed pattern, which better permits keeping a requisite distance between refuelled channels in space and time, thus reducing "hot spots".

5. Code Validation

One of the requirements of the Industry Standard Toolset initiative was that the computer programs must be formally validated for use. In this context, a general program of formal validation and verification was initiated by the Canadian nuclear industry several years ago. The object was to establish software quality assurance, ensure code-version control, validate the computer programs against available measurements, and derive quantifiable code biases and uncertainties for use in safety analysis. The physics code suite WIMS-IST/DRAGON-

IST/RFSP-IST was recently subjected to this validation process. Since modelling an operating or even research reactor in three dimensions entails the use of all components of the suite: lattice, reactivity-device, and full-core codes, and not a single one of the components, it is not possible to validate RFSP-IST alone; the validation pertains to the entire code suite.

The validation process for the physics code suite began with the identification of relevant physics phenomena which are anticipated to play a role in, and govern, the core behaviour during postulated accident conditions. A list of sixteen physics phenomena was drawn up:

PH1	Coolant-Density-Change Induced Reactivity
PH2	Coolant-Temperature-Change Induced Reactivity
PH3	Moderator-Density-Change Induced Reactivity
PH4	Moderator-Temperature-Change Induced Reactivity
PH5	Moderator-Poison-Concentration-Change Induced Reactivity
PH6	Moderator-Purity-Change Induced Reactivity
PH7	Fuel-Temperature-Change Induced Reactivity
PH8	Fuel-Isotopic-Composition-Change Induced Reactivity
PH9	Refuelling Induced Reactivity
PH10	Fuel-String-Relocation Induced Reactivity
PH11	Device-Movement Induced Reactivity
PH12	Prompt/Delayed Neutron Kinetics
PH13	Flux-Detector Response
PH14	Flux and Power Distribution (Prompt/Decay Heat) in Space and Time
PH15	Lattice-Geometry-Distortion Reactivity Effects
PH16	Coolant-Purity-Change Induced Reactivity

Note that not all of the 16 phenomena enter equally in the calculations of all three computer codes in the physics suite. For example, DRAGON-IST has been used in CANDU safety analysis only to calculate incremental cross sections for reactivity devices. However, these incremental cross sections are ingredients in any full-core model. Some phenomena are primarily within the realm of one IST physics code, with only secondary contribution from the others. A few of the phenomena have roughly equal contributions from all three physics codes.

Following the listing of the phenomena, a Validation Matrix was drafted, which identified the primary and secondary phenomena at play in various postulated accidents. The Validation Matrix also documented experimental or analytical data sets which could be used for validation of the code suite in its modelling of the phenomena.

Individual validation exercises were then performed against the documented data. The approach to validation consisted in comparing calculation results to actual measurements in CANDU reactors and in other reactors, such as the Chalk River research reactor ZED-2. When experimental conditions did not cover the full range of conditions found in operating power reactors, code-to-code comparisons, mostly with the Monte Carlo code MCNP [ref. 8], and other studies of the models were used to supplement the validation.

From these comparisons to measurements and code-to-code results, the ultimate point in the validation was then the derivation of values for the bias (offset) and uncertainty (standard deviation) for the modelling of each phenomenon at CANDU operating conditions. These values of bias and uncertainty can now be used in safety analyses of CANDU reactors with RFSP-IST and the other components of the IST physics code suite.

6. Conclusion

RFSP-IST has been established as a reactor-physics Industry Standard Tool for the Canadian Nuclear Industry. It serves as the standard computer program for full-core physics calculations for CANDU-reactor safety analysis. RFSP-IST will continue to service well the needs of current CANDU plants, and, together with the cell and device codes WIMS-IST and DRAGON-IST, it should be well positioned to serve the needs of advanced CANDU fuel cycles and new reactor designs. The IST physics code suite has been subjected to a thorough validation process with regard to conventional CANDU applications, and offsets and uncertainties have been derived for the physics phenomena listed in the validation matrix, for use in safety analysis.

7. References

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