TECHNOLOGY TRANSFER: CANDU® FUEL-MANAGEMENT CODE RFSP

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ABSTRACT

AECL's main physics tool for performing finite-reactor calculations is the computer program RFSP (Reactor Fuel Simulation Program). This program can be used to perform a large variety of core-design and fuel-management activities for any CANDU® reactor. RFSP is an important component of AECL's technology transfer to new CANDU utilities to assist in the effective operation of their plant. In this paper the main capabilities of the code are explained, with emphasis on their significance to the station physicist or fuelling engineer. AECL's practice and experience in technology transfer in the area of reactor physics is described. This technology transfer consists of courses in reactor physics and in the functional aspects of RFSP. Courses are normally supplemented by hands-on instruction in the use of RFSP. This is especially important for CANDU station physics staff. From the length of the instruction period to its exact content, the training can be customized to meet the user's needs. Technology transfer will continue to play an important role for CANDU utilities.

INTRODUCTION

For a country with a relatively small population, Canada has achieved great technological success with its distinctive CANDU nuclear reactor. The CANDU design has evolved from the initial conception of the small Nuclear Power Demonstration (NPD) reactor and the prototype Douglas Point generating station through successive generations of larger plants. In Canada, the Province of Ontario built multi-unit stations, whereas Québec and New Brunswick favoured the single-unit CANDU 6 design. In the last two decades especially, the CANDU 6 reactor has also enjoyed great favour in the export market. Units have been built in Argentina, South Korea, and Romania, and more units are scheduled to come online in the next few years in South Korea and China.

One of the distinctive characteristics of the CANDU design is, of course, its on-power-refuelling capability. This provides several advantages from the reactor-physics point of view; for example, low excess core reactivity and flexibility to shape the core power distribution. Naturally, on-power refuelling also gives the station reactor physicist special responsibilities, for instance in terms of on-going core monitoring, daily selection of channels for refuelling, and performing various analyses of reactor behaviour. To discharge daily duties, the CANDU station physicist therefore requires a powerful and versatile core-physics and fuel-management tool.

REACTOR FUELLING SIMULATION PROGRAM

To respond to the needs of both core designers and station physicists, AECL has developed the versatile computer program known as RFSP (Reactor Fuelling Simulation Program). This program can be used to perform a large variety of core-design and fuel-management activities for any CANDU reactor. It is a very

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extensive program, consisting of more than 1,000 subroutines. The code structure is modular: different modules perform different functions. It is a "living", evolving, and actively maintained computer code: new features are under development and new capabilities are added on an on-going basis to satisfy new needs and users' requests. For portability, RFSP is written in FORTRAN 77, and it is under strict change control at AECL.

Because of the uniqueness of the CANDU design and the need to support CANDU owners' reactor-physics groups in their responsibilities, RFSP has been and will continue to be a very important component in AECL's technology transfer to CANDU utilities, notwithstanding the fact that some utility owners may have, for historical or other reasons, also developed other codes.

FUNCTIONS PROVIDED BY RFSP

The station reactor physicist will use RFSP as an aid in performing varied duties day to day. The following examples are *some* of the applications that are made of the code.

Core-Follow Calculations

Core-follow calculations are one of the primary responsibilities of the station physicist. It is important to track, on a continuous basis, the core excess reactivity and the three-dimensional fuel irradiation (burnup) and flux and power distributions. This tracking is done with the *SIMULATE module of RFSP. Core-follow simulations are typically performed two or three times per week, but may be done on a shorter "burnup step", because the frequency of code execution is entirely up to the user. Each simulation must take into account all the refuelling operations that are performed during the burnup step, i.e., it must specify the channels refuelled, the exact time of each refuelling, and the refuelling scheme used. The simulation must also use as input the reactor power level, the poison (boron) concentration in the moderator during the burnup step, and the current levels of light water in the zone-control compartments. In the infrequent case where the reactor is being run in "shim mode" (that is, with some adjuster rods withdrawn from the core), the adjuster configuration and the governing reactor power must also be specified.

RFSP provides the station physicist with two different methodologies to perform core-follow simulations:

- The first methodology is traditional diffusion-theory: the 3-dimensional core flux distribution is calculated by solving the neutron diffusion equation (in its finite-difference form) in 2 energy groups.
- The second methodology is flux mapping. This can be used when the reactor is equipped with in-core flux-mapping detectors (usually made of vanadium). Figure 1 shows the location of a small subset of the 102 vanadium detectors in the CANDU-6 reactor. In flux mapping, the three-dimensional flux distribution is reconstructed from the readings of the in-core vanadium detectors by flux synthesis, using a linear combination of various precalculated spatial modes, sometimes loosely called "basis functions". The functions most often used are the first ten to fifteen harmonics of the diffusion equation. See Figure 2. These harmonics physically represent possible gross perturbations in the flux shape (e.g., various orders of azimuthal, axial, and radial perturbations).

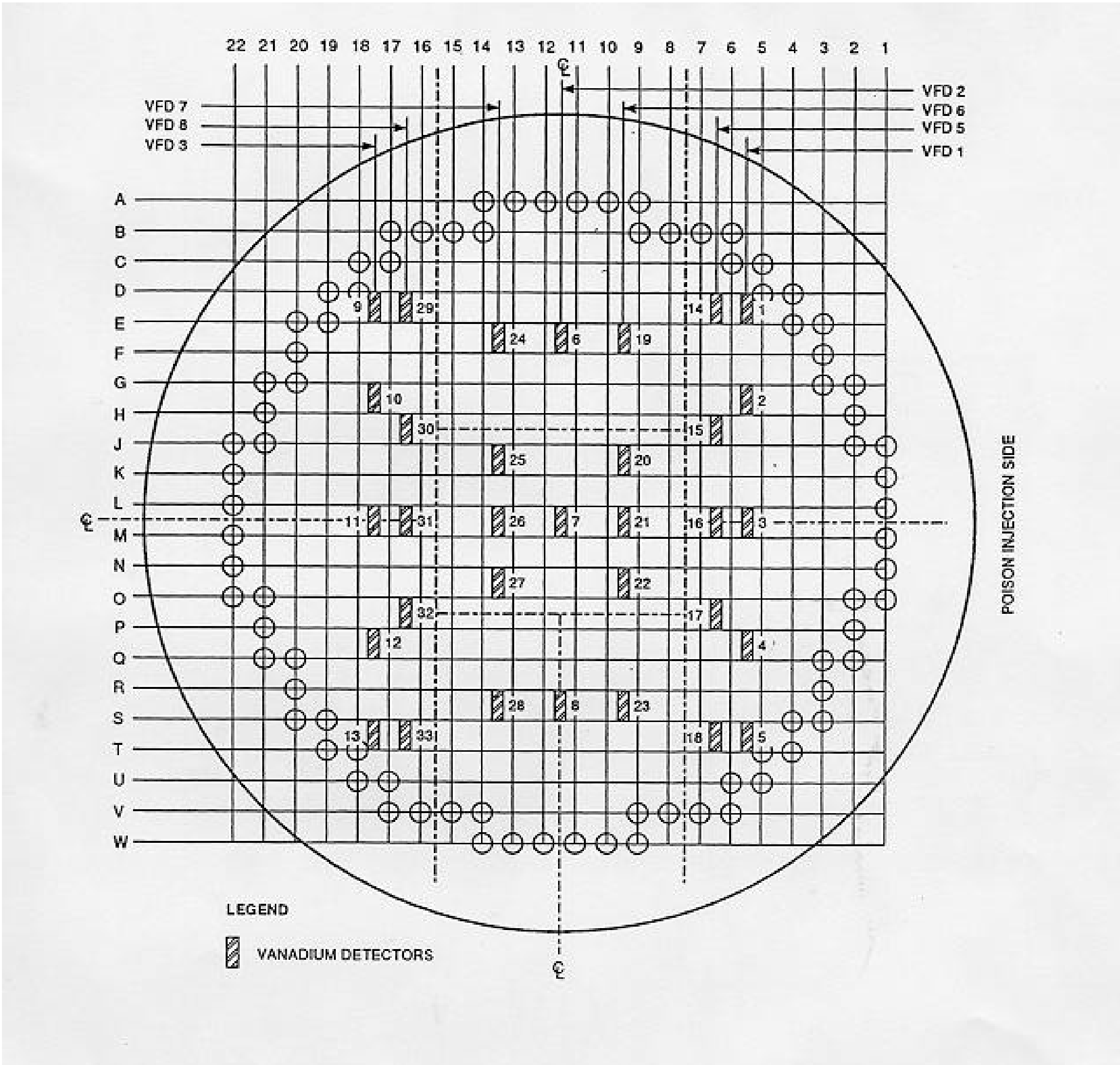


Figure 1 Location of Some of the 102 Vanadium Flux-Mapping Detectors in the CANDU 6 Reactor

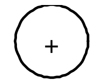
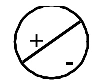
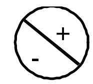
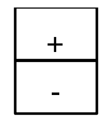
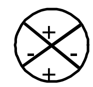
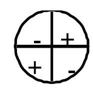
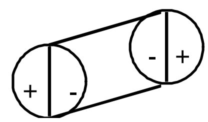
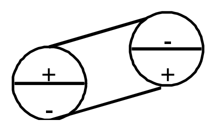
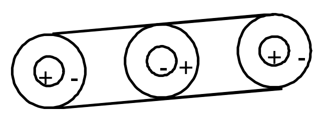
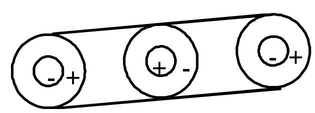
MODE NUMBER	DESIGNATION	SUBCRITICALITY MK	MODE SCHEMATIC (IDEALIZED)
0	**Fundamental**	**0**	
1	**First Azimuthal–A**	**16.2**	
2	**First Azimuthal–B**	**16.9**	
3	**First Axial**	**27.1**	
4	**Second Azimuthal–A**	**44.0**	
5	**Second Azimuthal–B**	**47.0**	
6	**First Azimuthal–A x First Axial**	**46.9**	
7	**First Azimuthal–B x First Axial**	**47.7**	
8	**First Radial x Second Axial–A**	**66.3**	
9	**First Radial x Second Axial–B**	**80.6**	

Figure 2 Flux Modes and Subcriticalities

Core-follow calculations provide important data on the instantaneous state of the core, such as the core burnup distribution and the channel and bundle powers. Another quantity that emerges is the instantaneous channel-power peaking factor (CPPF); the maximum value of the ratio of instantaneous to reference power for channels in a defined high-power region of the core. The CPPF has great operational significance, because it is used in the calibration of the in-core safety-system (ROP) detectors - see further below - and it therefore has a direct effect on operating margin. It is the responsibility of the station fuelling engineer to provide the current value of the CPPF to the control-room operator and shift supervisor to allow timely recalibration of the ROP detectors.

Selection of Channels for Refuelling

The station physics group has the responsibility for selecting channels for refuelling. It usually does this by periodically creating a list of channels that are, at the time, good candidates for refuelling. At the time a refuelling operation is to take place, the reactor operator on shift then selects from the list those channels that are the most appropriate for refuelling, taking into account the instantaneous state of the core (zone-controller fills, etc.).

The station physicist can select good-candidate channels using data provided by the latest RFSP core-follow snapshot: channel irradiations, channel, bundle, and zone powers, CPPF, and predicted change in reactivity should each channel be refuelled individually. The fuelling engineer is responsible for managing and controlling the power distribution in the reactor, avoiding, for example, the creation of power "hot spots", tilts in the power distribution, degradation in the exit fuel burnup, etc.

The station physicist can also use RFSP in *presimulation* mode to test or verify the adequacy of specific channel refuellings. Such presimulations, which must of course use the diffusion-theory methodology, can provide the expected post-refuelling reactivity, power distribution, and levels of water in the zone compartments. These quantities can be assessed against desired criteria.

Calculation of Time-Average Flux Distribution

As for design-type applications, RFSP can be used to design and calculate time-average flux and power distributions. In this type of calculation, the core is subdivided into any desired number of irradiation regions, and the relative values of average exit burnup varied to design a desired target time-average flux shape (e.g., the desired degree of radial flattening of the power distribution). This can be used as the target flux distribution (together with its associated power distribution) once the reactor is operating. The calculation provides the target refuelling rate for each channel in the core, basic data to have on hand when considering channels for refuelling.

Calculation of Flux Distributions Corresponding to Different Core Configurations

RFSP may be used to calculate the flux and power distributions corresponding to any number of core configurations: various reactivity-device positions, perturbations to operating parameters, power manoeuvres, etc. Some of these core configurations may belong to the category of expected flux shapes, others represent off-nominal situations. Also, the cases analyzed may be based on either a time-average or an instantaneous reference configuration.

One specific application of this capability is the generation of the very large number – several hundreds – of flux (and power) distributions used as the basis for designing the in-core regional-overpower protection (ROP) system of detectors, that is, for determining the detector layout and trip setpoints which ensure coverage of accident conditions.

Other types of flux distributions which may be calculated by the code are the harmonic flux shapes used in the flux-mapping function.

Calculation of Xenon Transients

With its "fission-product drivers", RFSP has the capability to solve the spatial ^{135}Xe-^{135}I kinetics equations. The station physicist can therefore investigate the effects of xenon transients on reactivity and on the 3-dimensional flux and power distributions. Xenon transients are important for the physicist to consider under a variety of conditions:

- Reactor-power manoeuvres, such as power deratings, power stepbacks, reactor shutdowns, power recoveries, etc.

- Reactivity-device movements, such as adjuster-bank insertions and withdrawals. In some cases, these movements may accompany power manoeuvres, such as a reactor startup from a configuration with adjuster rods out-of-core, or load following. Device movements may initiate xenon oscillations, which are damped by the zone-control system. Simulations allow assessing the performance of the spatial-control system.
- Following refuelling operations, fresh fuel enters the core with zero concentration of ^{135}Xe or other fission products. The ^{135}Xe typically builds in over a period of 24 to 36 hours. During this interval the power of fresh bundles is somewhat higher than it will be when the saturating fission products have reached their equilibrium concentration.

The code can also solve similar kinetics equations for saturating fission products other than ^{135}Xe, such as ^{130}Rh, ^{149}Sm, and ^{151}Sm.

Spatial-Kinetics Calculations

The spatial-kinetics function of RFSP resides in the *CERBERUS module, which solves the time-dependent diffusion equation, including delayed-neutron effects. The companion *TRIP_TIME module permits the modelling of the safety-detector response (prompt and delayed components), and of the associated electronic circuits (compensators, amplifiers, etc.). These modules allow the simulation and analysis of fast neutronic transients. The safety analyst will use this capability to assess the consequences of hypothetical loss-of-coolant accidents. The resident station physicist responsible for monitoring reactor systems can compare the predicted and measured in-core-detector flux rundown in shutdown-system trip tests, periodically conducted at the station. This validates the modelling and the calculation method, and gives confidence in their use in predicting overall shutdown-system performance. It may also permit the determination of changes in the prompt and delayed parameters of the detector response (or of the electronic hardware) over time.

Bulk- and Spatial-Control-Function Modelling

The code can determine the long-term (asymptotic) values towards which the Reactor Regulating System tends to move the zone-control-compartment fills in response to global or differential reactivity perturbations (such as a poison-concentration change or an asymmetric movement of reactivity devices respectively). This capability allows the code user to model slow transients such as power manoeuvres, taking into account the expected movement of water in the various zone compartments following adjuster-rod insertions into or withdrawals from core.

TRAINING

One extremely important part of any technology-transfer program is training. Since the 1970s, when the first CANDU 6 projects were committed, AECL has been very active in this area of heavy-water-reactor technology transfer. And in no discipline has it been more so than in the core-technology area of reactor physics. Every CANDU reactor project initiated a training program in the science of CANDU physics for a new group of (usually young) reactor physicists. In some cases, training programs were organized even without the prior incentive of a reactor sale.

A central component is always familiarization with the use of RFSP and related computer programs. This is an essential supplement to the physical transfer of the code to a utility. This training provides confidence that new users can make proper and effective use of their new tool.

In terms of reactor physics and RFSP, AECL has over the years prepared and provided various courses on different topics:

- the fundamentals of CANDU reactor physics;
- reactor kinetics, especially as it applies to CANDU reactors;
- the theory underlying calculational methods incorporated in RFSP;
- the varied functions and capabilities of RFSP.

These courses are available and can be offered in various combinations, depending on the particular requirements of the individual utility or trainee. Another practical constraint of course is always the amount of training time available.

Although lecture courses can provide a lot of information on a theoretical level in a relatively short time, training must also take other forms to help the trainee assimilate the material on a deeper level. Thus a very crucial component of the training program is hands-on work with the RFSP computer code. It translates "knowledge on paper" into real practical experience. It is important that hands-on training be offered in a wide variety of applications, as the training period permits.

Trainees have come to AECL from many different points on the globe. Over the years, staff members from the following organizations (listed alphabetically) have been attached to AECL for training periods of various lengths[1]:

- Badan Tenaga Atom Nasional (Indonesia)
- China National Nuclear Corporation (CNNC)
- Comisión Nacional de Energía Atómica (CNEA, Argentina)
- ENEL (Italy)
- Hydro-Québec
- Institute for Advanced Energy (Korea)
- Korea Atomic Energy Research Institute (KAERI)
- Korea Electric Power Corporation (KEPCO)
- New Brunswick Power
- Ontario Hydro
- Pakistan Atomic Energy Commission
- Regia Autonoma de Electricitate - RENEL (Romania)

A typical program of practical training in the use of RFSP would generally consist of exercises in applying the code in the following areas of core design and fuel management:

- lattice-cell calculations with the resident lattice-code module (*POWDERPUF); investigation of the effect of various lattice parameters (e.g., lattice pitch, pressure- and calandria-tube thicknesses, fuel mass per bundle, fuel temperature, etc.);
- calculation of lattice reactivity coefficients (fuel, moderator, and coolant temperatures), moderator poison, coolant density (void reactivity), etc.;
- computation of time-average flux distributions; shaping the power distribution by varying number and size of irradiation regions and regional target values of fuel exit burnup;
- calculation of 3-dimensional flux distributions corresponding to sample core configurations (device positions);
- setup and varied application of model for Phase-B (low-power reactor commissioning) studies;
- core-follow of a sufficiently long period of reactor operating history, modelling changes in moderator poison concentration, practising selections of channel refuellings, keeping track of maximum channel and bundle powers and CPPF, monitoring core power distribution for hot spots

[1] The author apologizes for any omissions, which are attributable to memory lapses.

and power tilts, etc.;
- studying reactor behaviour in fast transients, such as planned shutdown-system trip tests or large loss-of-coolant accidents; modelling and study of in-core detectors.

Anyone with computer experience knows that becoming an expert user, or even merely a knowledgeable user, of a large computer program cannot be accomplished in a few days. For full effectiveness, a program such as the one detailed above normally requires several months of training. When an interval of this length is simply not available, the program is shortened by selecting a fewer number of items from the above listing. Most often, consistent with the trainee's future responsibilities and duties, the true fuel-management capabilities (i.e., core-follow applications) are the ones that are retained in the training, at the expense of others.

It should be noted that in some cases RFSP hands-on training for foreign trainees has been provided on subcontract by organizations other than AECL. This was the case, for instance, on the Cernavoda project, where Romanian trainees were on attachment for several months at the Point Lepreau Nuclear Generating Station in New Brunswick, Canada. Such experience at CANDU operating sites is extremely beneficial, because it provides trainees with a true picture of day-to-day work with the new tool in an environment similar to the one in which they will function.

SUMMARY

Technology transfer often helps achieve success on the international nuclear marketplace. The fuel-management computer code RFSP is AECL's main instrument in the area of reactor physics. RFSP offers extensive capabilities to meet the requirements of both designers and CANDU station staff in core design and analysis as well as core-follow. It is an important component of AECL's technology transfer to new CANDU utilities, to assist in the effective operation of their plant. Code documentation is an integral part of the transfer package. Training in the code is essential for CANDU station physicists and fuelling engineers, and can be customized to meet the user's needs.

KEYWORDS

Technology, Transfer, Physics, Fuel Management, Training, Instruction.