# RFSP-IST SIMULATION OF FUEL TRANSIENT DURING REFUELLING THE ACR – 1000 REACTOR

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**Abstract**

Similar to the CANDU®* reactors, the ACR-1000**™ reactors will use on-power refueling to maintain long-term reactivity control. During the fuelling operation, the power transients, mainly in the channel being refueled, are induced as the fresh and irradiated fuel bundles are shifted in and out of high flux regions in the core. This refueling shift transient has been simulated with the *SIMULATE module of RFSP-IST to derive bundle and channel power transients with spatial flux tilt and bulk reactivity control accounted for. Moreover, to capture possible short-term time-dependent effects, a coupled kinetics-thermal hydraulic dynamic simulation using the *CERBERUS module of RFSP-IST has also been performed. In this paper, the model and methodology of the refueling simulation will be discussed. Results will be presented.

## 1. Introduction

The ACR-1000 is the advanced CANDU reactor using low enriched fuel (LEU), light water ($H_2O$) coolant and heavy water ($D_2O$) moderator. The core is designed to produce 1150 MW(e) of electrical power. The core has 520 fuel channels arranged in a 24.0 cm lattice pitch array. Each channel has 12 fuel bundles. The ACR-1000 reference core fuel load will contain fuel with uniform enriched fuel of 2.4 wt% using a bi-directional 2-bundle shift refuelling sequence.

The main reactor physics design parameters are summarized below in Table 1

In an equilibrium fuelled ACR-1000 reactor, there are small local time-dependent variations in flux associated with refuelling due to the change in fuel burnup locally. During an on-power refuelling operation of a single channel, spatial power transients are induced as the fresh and irradiated fuel bundles are shifted in and out of high axial flux regions in the core. The power ramps occur mostly in the fuel bundles in the channel being fuelled, but also in the surrounding channels.

Various fuelling schemes and fuel types have been studied with RFSP-IST simulations to assess the power transients of the fuelled channel in order to find an optimal fuelling option for the ACR-1000 core.

In this paper, the model and methodology of the refuelling simulation are discussed. Also presented are some results of the fuelling transients in a typical channel, H12, from the following analyses:

- An RFSP-IST steady-state simulation;
- A coupled RFSP-IST and CATHENA dynamic simulation with a more detailed RRS model.

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The steady-state simulation using *SIMULATE module provides distribution of power transients with spatial flux tilt and bulk reactivity control accounted for, and the dynamic simulation using *CERBERUS module shows the short-term time-dependent effects during the fuelling sequence.

**Table 1 ACR 1000 Physics Design Parameters**

| Parameter | Unit | ACR-1000 Reference Core |
|---|---|---|
| Number of Fuel Channels | | 520 |
| Number of Bundles per Channel | | 12 |
| Reflector Average Thickness | cm | 60 |
| Core Length | cm | 594.36 |
| Calandria Shell Inner Diameter | cm | 744 |
| Total Fission Power | MW | 3321 |
| Reactor Thermal Power Output | MW | 3200 |
| Gross Electrical Power Output | MW | 1150 |
| Radial Form Factor | | 0.94 |
| Fuel Type | wt % | 2.4 |
| Fuelling Scheme | | 2 Bundle Shift |
| Core-Average Discharge Fuel Burnup | MWd/kgU | 20 |

## 2. Model and Methodology

In the reference fuelling scheme for the ACR-1000 reference core, two fresh fuel bundles are added one at a time from the upstream fuelling machine under pressure of coolant flow. At the same time the downstream fuelling ram withdraws at a constant rate of about 2 cm/sec to shift most of the fuel string out of core. The removal of two irradiated fuel bundles from the fuel discharge end of the channel requires that the entire fuel string in the channel be shifted 11 bundle length toward the discharge end. Two irradiated bundles are then removed at the downstream end by the fuelling machine, which leaves only three (two fresh plus one irradiated) bundles left in core with the remaining nine irradiated bundles in the liner/pressure tube area outside of core. At this point a water-filled column is left behind in-core of about nine bundles in length. Following removal of the irradiated bundles the remaining twelve bundle fuel string is then pushed back into core at a constant rate. The in-core configuration of fuel bundles during the fuel shifting sequence is schematically depicted in Figure 1, where the sequence is divided into 20 steps. One step represents a shift in the fuel string of one bundle length. Given the fuelling ram speed of 2 cm/sec, each step corresponds to about 25 seconds (49.53 / 2 = ~25 sec. Fuel bundle length is 49.53 cm).

### 2.1. Modelling of Fuelling Transient

The continuous fuelling process described above is approximated in the physics simulations as a sequence of one bundle movement. The bundle movement, however, is discretized, i.e., a bundle stays in one bundle position for about 25 seconds and then immediately appears in the next position. In the dynamic simulation, the time step for the neutron kinetics diffusion equation solution, currently set to 0.5 sec, is significantly shorter than the refuelling steps.

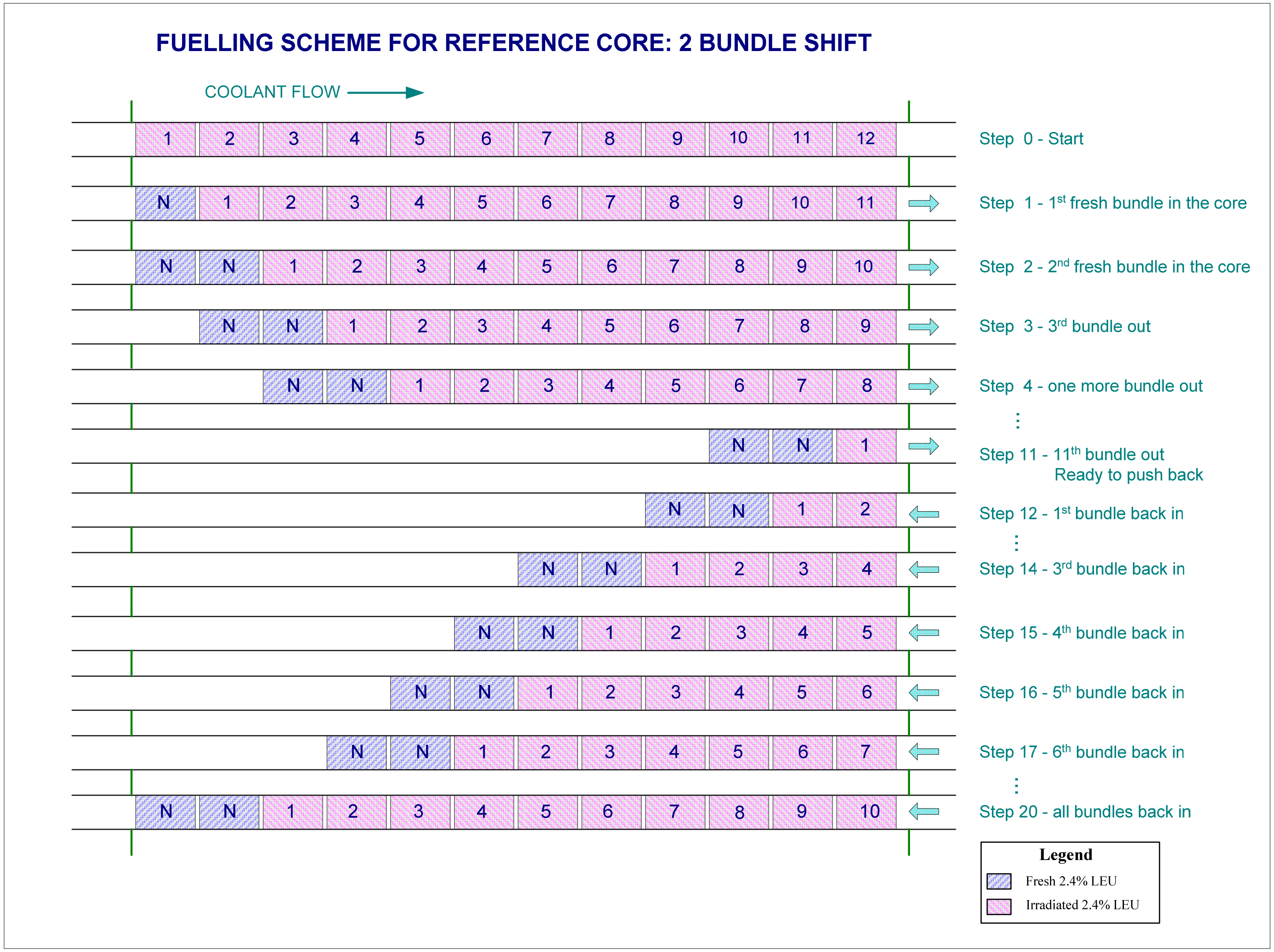


Figure 1 Schematic Plot of Fuelling Sequence for ACR-1000 Reference Core

The 20 steps mentioned above are modelled as below:

| | |
|---|---|
| Step 0 | An instantaneous reactor core for the start of refuelling. Refuelling time t = 0 second. |
| Step 1: | The first fresh 2.4 % enriched bundle is pushed in the first bundle position of refuelled channel. Each step during refuelling simulation is a movement of one bundle position. |
| Step 2 | After 25 seconds the second fresh 2.4 % enriched bundle is pushed in the refuelled channel. |
| Step 3: | After another 25 seconds a “water bundle” is pushed in the refuelled channel. The “water bundle” is used in RFSP-IST to simulate part of the refuelled channel (one bundle length) where only coolant exists. |
| Steps 4 to 11: | Step 3 is repeated 8 times (steps 4 to 11) and at step 11 in the refuelled channel there are 3 bundles remaining in the core*. |
| Step 12: | Back fuelling starts – the bundle string is pushed back into the core. |
| Steps 14 to 20: | Step 12 is repeated 8 times with a time step of 25 seconds between properties retrieval. |

## 2.2. RFSP-IST Model

The RFSP-IST (Reactor Fuelling Simulation Program, Industry Standard Toolset) is a computer program for core-wide neutronics calculations in CANDU reactors (References [1] and [2]). RFSP-IST is also used in the ACR-1000 physics design analysis.

The RFSP-IST core model used in dynamic/steady-state fuelling transient analysis incorporates important information about the fuel bundles, the reflector, the in-core structural materials and the movable reactivity control devices. The model is represented as a grid of lattice cells over the core. In these cells, the nuclear properties are assumed to be homogeneous; the reactivity devices are represented by the corresponding incremental cross sections to be overlaid on the cell fuel properties as well as in the reflector region if applicable. The basis for the core modelling data applicable to the RFSP-IST model used in the present report is given in Table 1.

## 2.3. CATHENA Single Channel Model

In the dynamic fuelling simulation, a coupled RFSP-IST and CATHENA (Reference [3]) analysis is performed to obtain thermal hydraulic transient conditions for the fuel in the reactor core. The components of a single-channel model include a RIH and a ROH, feeders, end fittings, pressure tube, and 12 ACR-1000 fuel bundles inside the pressure tube (Figure 2). To analyze the fuel and fuel channel behaviour, each representative channel is divided into twelve characteristic flow regions (axial nodes) corresponding to the twelve fuel bundles within the channel. The axial nodes are equal in length the fuel bundles. The single channel model represents an individual fuel channel (or a channel group) that defines a thermal hydraulic path from the RIH through the fuel channel to the ROH.

The RFSP-IST *CERBERUS module is coupled to the CATHENA calculation and receives thermal hydraulic data at the beginning of each simulation. The data, consisting of coolant density, coolant temperature and fuel temperature at a specified “node” of the thermal hydraulic model, are written in RFSP-IST records “DENSITY”, “COOL TEMP” and “FUEL TEMP” under index “LOCAL PARM” of the direct-access file and used in the RFSP-IST calculations.

* Actually, the minimum number of bundles remaining in the core will be ~3.6. Since it is hard to simulate a fraction of a bundle in the RFSP-IST simulation, the minimum number of bundles is therefore set to three.

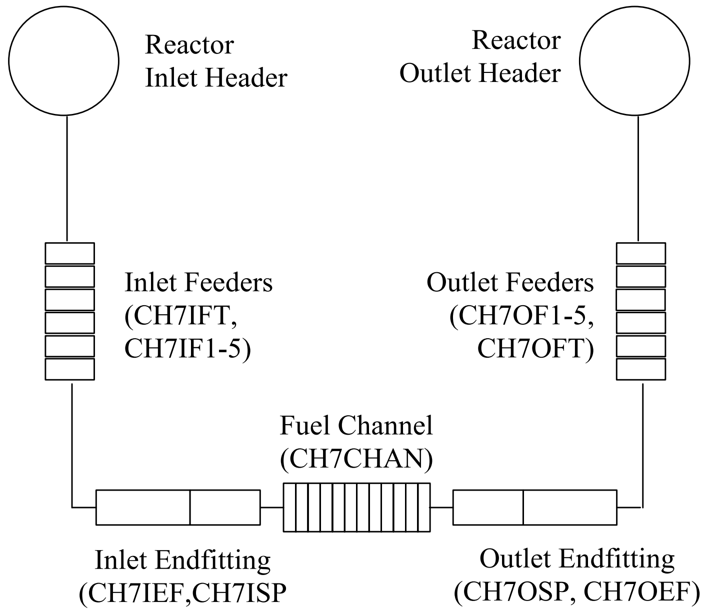


Figure 2 Nodalization of CATHENA Single Channel Model (An example for 7 groups)

The axial power distribution for each channel group are calculated by averaging the bundle powers, provided by RFSP-IST calculation, over all channels in the thermal hydraulic group. Figure 3 shows the thermal hydraulic groups for all 520 fuel channels. Channels in each group share the same channel power and same axial power distribution. The channel grouping is performed according to channel powers predicted by a time-average model of the ACR-1000 equilibrium core. Channel H12, the channel to be refuelled in this study, will have significant variations in the channel power during refuelling; therefore, it is assigned with a single thermal hydraulic group, group 17. Groups 15 and 16 are assigned to the neighbouring channels of H12.

## 2.4. Methodology

The power transients in a refuelled channel H12 are analyzed using RFSP-IST. The steady-state simulation is performed by the *SIMULATE module with both local-parameter effects and the individual nuclide history of each bundle taken into account. The dynamic simulation uses the kinetic *CERBERUS module which solves the time-dependent neutron diffusion equation using the grid-based local-parameter method. Delayed-neutron terms, which are very important in fast-transient calculations, are included in the diffusion equation. As mentioned in Section 2.2, the fuel bundles and reactivity devices in the RFSP-IST model are represented by fuel tables and incremental cross sections, which are generated by WIMS-AECL (Reference [4]) and DRAGON-IST (Reference [5]), respectively. The fuelling transient simulations start from an instantaneous reactor core produced by the *INSTANTAN module of RFSP-IST, based on the “patterned-channel-age” model, to represent the variation of the power about the time-averaged power distribution due to refuelling. The “patterned-channel-age” model assumes that irradiation varies linearly with the time during the cycle between refuelling of a specific channel, so that the current value of irradiation is simply a function of the “age” of the channel. Every channel in the core is assigned an age between 0 and 1, where 0 stands for a recently-fuelled channel, and 1 for a channel that is about to be fuelled. A typical channel-age map is presented in Figure 4, where the age is patterned for an array of 7×7 channels, emulating the fuelling sequence and

| | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | 13 | 14 | 15 | 16 | 17 | 18 | 19 | 20 | 21 | 22 | 23 | 24 | 25 | 26 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| A | | | | | | | | | | | 3 | 2 | 1 | 1 | 2 | 3 | | | | | | | | | | |
| B | | | | | | | | 4 | 3 | 3 | 4 | 4 | 4 | 4 | 4 | 4 | 3 | 3 | 4 | | | | | | | |
| C | | | | | | | 5 | 5 | 6 | 6 | 10 | 11 | 11 | 11 | 11 | 10 | 6 | 6 | 5 | 5 | | | | | | |
| D | | | | | | 7 | 6 | 9 | 9 | 11 | 11 | 12 | 12 | 12 | 12 | 11 | 11 | 9 | 9 | 6 | 7 | | | | | |
| E | | | | 6 | 7 | 8 | 10 | 10 | 11 | 12 | 12 | 12 | 12 | 12 | 12 | 12 | 12 | 11 | 10 | 10 | 8 | 7 | 6 | | | |
| F | | | | 7 | 9 | 12 | 11 | 11 | 12 | 12 | 12 | 12 | 12 | 12 | 12 | 12 | 12 | 12 | 11 | 11 | 12 | 9 | 7 | | | |
| G | | | 8 | 9 | 13 | 13 | 12 | 12 | 12 | 12 | 15 | 15 | 15 | 12 | 12 | 12 | 12 | 12 | 12 | 12 | 13 | 13 | 9 | 8 | | |
| H | | 5 | 8 | 13 | 14 | 14 | 12 | 12 | 12 | 12 | 15 | 17 | 15 | 12 | 12 | 12 | 12 | 12 | 12 | 12 | 14 | 14 | 13 | 8 | 5 | |
| J | | 6 | 9 | 13 | 14 | 14 | 13 | 13 | 12 | 12 | 16 | 16 | 16 | 13 | 13 | 13 | 12 | 12 | 13 | 13 | 14 | 14 | 13 | 9 | 6 | |
| K | | 6 | 10 | 13 | 14 | 14 | 13 | 13 | 12 | 12 | 13 | 13 | 13 | 13 | 13 | 13 | 12 | 12 | 13 | 13 | 14 | 14 | 13 | 10 | 6 | |
| L | 7 | 7 | 13 | 14 | 14 | 14 | 13 | 13 | 12 | 12 | 13 | 13 | 12 | 12 | 13 | 13 | 12 | 12 | 13 | 13 | 14 | 14 | 14 | 13 | 7 | 7 |
| M | 7 | 7 | 13 | 14 | 14 | 14 | 13 | 13 | 12 | 12 | 13 | 13 | 11 | 11 | 13 | 13 | 12 | 12 | 13 | 13 | 14 | 14 | 14 | 13 | 7 | 7 |
| N | 8 | 8 | 14 | 14 | 14 | 14 | 13 | 13 | 12 | 12 | 13 | 13 | 11 | 11 | 13 | 13 | 12 | 12 | 13 | 13 | 14 | 14 | 14 | 14 | 8 | 8 |
| O | 8 | 8 | 14 | 14 | 14 | 14 | 13 | 13 | 12 | 12 | 13 | 13 | 11 | 11 | 13 | 13 | 12 | 12 | 13 | 13 | 14 | 14 | 14 | 14 | 8 | 8 |
| P | 7 | 7 | 13 | 14 | 14 | 14 | 13 | 13 | 12 | 12 | 13 | 13 | 11 | 11 | 13 | 13 | 12 | 12 | 13 | 13 | 14 | 14 | 14 | 13 | 7 | 7 |
| Q | 7 | 7 | 13 | 14 | 14 | 14 | 13 | 13 | 12 | 12 | 13 | 13 | 12 | 12 | 13 | 13 | 12 | 12 | 13 | 13 | 14 | 14 | 14 | 13 | 7 | 7 |
| R | | 6 | 10 | 13 | 14 | 14 | 13 | 13 | 12 | 12 | 13 | 13 | 13 | 13 | 13 | 13 | 12 | 12 | 13 | 13 | 14 | 14 | 13 | 10 | 6 | |
| S | | 6 | 9 | 13 | 14 | 14 | 13 | 13 | 12 | 12 | 13 | 13 | 13 | 13 | 13 | 13 | 12 | 12 | 13 | 13 | 14 | 14 | 13 | 9 | 6 | |
| T | | 5 | 8 | 13 | 14 | 14 | 12 | 12 | 12 | 12 | 12 | 12 | 12 | 12 | 12 | 12 | 12 | 12 | 12 | 12 | 14 | 14 | 13 | 8 | 5 | |
| U | | | 8 | 9 | 13 | 13 | 12 | 12 | 12 | 12 | 12 | 12 | 12 | 12 | 12 | 12 | 12 | 12 | 12 | 12 | 13 | 13 | 9 | 8 | | |
| V | | | | 7 | 9 | 12 | 11 | 11 | 12 | 12 | 12 | 12 | 12 | 12 | 12 | 12 | 12 | 12 | 11 | 11 | 12 | 9 | 7 | | | |
| W | | | | 6 | 7 | 8 | 10 | 10 | 11 | 12 | 12 | 12 | 12 | 12 | 12 | 12 | 12 | 11 | 10 | 10 | 8 | 7 | 6 | | | |
| X | | | | | | 7 | 6 | 9 | 9 | 11 | 11 | 12 | 12 | 12 | 12 | 11 | 11 | 9 | 9 | 6 | 7 | | | | | |
| Y | | | | | | | 5 | 5 | 6 | 6 | 10 | 11 | 11 | 11 | 11 | 10 | 6 | 6 | 5 | 5 | | | | | | |
| Z | | | | | | | | 4 | 3 | 3 | 4 | 4 | 4 | 4 | 4 | 4 | 3 | 3 | 4 | | | | | | | |
| ZZ | | | | | | | | | | | 3 | 2 | 1 | 1 | 2 | 3 | | | | | | | | | | |

Figure 3 CATHENA Channel Group Map

history for a group of 49 channels. In this channel-age map, there are a group of channels, including H12, with an age of 0.98, indicating they are about to be refuelled. Channel H12 is located in a high flux region and close to a zone control rod (ZCR), which makes it a good candidate channel for the fuelling transient study.

The whole reactor core is divided into symmetric octants, each comprising one control zone with a pair of grey (i.e., nominally 50% inserted) ZCRs, the insertion levels of which can be adjusted for spatial control to minimize flux tilts and maintain bulk control to make the reactor core critical. In the steady-state analysis, the reactor regulating system (RRS) is modelled so that in each refuelling step the grey ZCRs' insertion is adjusted based on the total thermal flux in the octant zone. However, the dynamic simulation simulates the ZCRs' response to the RRS in-core detector readings in the control zone for a real-time spatial and bulk reactivity-control. In the ACR-1000 control scheme currently under consideration there are three RRS detectors and two RRS control rods in an octant zone. As shown in Figure 5, where, for the octant zone in which the ZCU01 is located, the RRS is composed of VFD02, VFD04 and VFD06 as detectors and ZCU02, ZCU03 as control rods. The *INTREP module in RFSP-IST was used to interpolate the thermal flux to all the RRS detector locations and the *WROPFILE module was then used to integrate the flux over the length of the detectors. The RRS signal takes the median value of the three RRS detectors associated with a pair of grey ZCRs.

### 2.5. Other Important Assumptions

- For the steady-state simulation, the coolant density and temperature are set to be constant at 0.7213 g/cc and 300°C, respectively. The fuel temperature for each bundle is calculated according to the bundle power and burnup using pre-determined correlations programmed in RFSP-IST. For the dynamic simulation, the coolant density, coolant temperature and fuel temperature are all calculated by a CATHENA single channel model.
- Speed of the grey ZCRs is proportional to the power error, i.e., the difference between the current power and the reference power. There is no time delay applied to the movement of the grey ZCRs and electronics are assumed to respond promptly.
  The time to fully insert or fully withdraw grey ZCRs at its maximum speed is assumed to be 60 seconds.
- The radial power fraction, i.e. the power percentage for the four rings of a fuel bundle, is assumed to be bundle independent.
- The ZCRs are modelled as a "relative" representation in the RFSP-IST model for the steady-state simulation while they are modelled as an "absolute" representation in the dynamic simulation.

### 2.6. Computer Codes

Fuelling transient analyses have been performed on the AECL Linux farm. The RFSP-IST executable is of version 3.04; CATHENA executable is of version MOD-3.5d/Revision 2.

| | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | 13 | 14 | 15 | 16 | 17 | 18 | 19 | 20 | 21 | 22 | 23 | 24 | 25 | 26 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| A | | | | | | | | | | | 0.16 | 0.06 | 0.32 | 0.36 | 0.94 | 0.44 | | | | | | | | | | |
| B | | | | | | | | 0.44 | 0.22 | 0.76 | 0.54 | 0.96 | 0.66 | 0.58 | 0.04 | 0.22 | 0.88 | 0.30 | 0.12 | | | | | | | |
| C | | | | | | | 0.84 | 0.10 | 0.88 | 0.02 | 0.24 | 0.50 | 0.28 | 0.68 | 0.38 | 0.76 | 0.02 | 0.60 | 0.18 | 0.80 | | | | | | |
| D | | | | | | 0.34 | 0.26 | 0.52 | 0.30 | 0.60 | 0.70 | 0.08 | 0.82 | 0.90 | 0.16 | 0.54 | 0.24 | 0.70 | 0.92 | 0.34 | 0.26 | | | | | |
| E | | | | 0.08 | 0.14 | 0.56 | 0.72 | 0.98 | 0.12 | 0.18 | 0.92 | 0.14 | 0.40 | 0.48 | 0.06 | 0.96 | 0.50 | 0.08 | 0.14 | 0.56 | 0.72 | 0.98 | 0.12 | | | |
| F | | | | 0.82 | 0.40 | 0.86 | 0.42 | 0.64 | 0.46 | 0.80 | 0.34 | 0.56 | 0.86 | 0.78 | 0.32 | 0.66 | 0.28 | 0.82 | 0.40 | 0.86 | 0.42 | 0.64 | 0.46 | | | |
| G | | | 0.68 | 0.90 | 0.48 | 0.78 | 0.74 | 0.20 | 0.62 | 0.84 | 0.26 | 0.72 | 0.42 | 0.74 | 0.36 | 0.58 | 0.68 | 0.90 | 0.48 | 0.78 | 0.74 | 0.20 | 0.62 | 0.84 | | |
| H | | 0.04 | 0.38 | 0.16 | 0.06 | 0.32 | 0.36 | 0.94 | 0.44 | 0.10 | 0.52 | 0.98 | 0.64 | 0.20 | 0.94 | 0.04 | 0.38 | 0.16 | 0.06 | 0.32 | 0.36 | 0.94 | 0.44 | 0.10 | 0.52 | |
| J | | 0.22 | 0.76 | 0.54 | 0.96 | 0.66 | 0.58 | 0.04 | 0.22 | 0.88 | 0.30 | 0.12 | 0.46 | 0.62 | 0.44 | 0.22 | 0.76 | 0.54 | 0.96 | 0.66 | 0.58 | 0.04 | 0.22 | 0.88 | 0.30 | |
| K | | 0.88 | 0.02 | 0.24 | 0.50 | 0.28 | 0.68 | 0.38 | 0.76 | 0.02 | 0.60 | 0.18 | 0.80 | 0.84 | 0.10 | 0.88 | 0.02 | 0.24 | 0.50 | 0.28 | 0.68 | 0.38 | 0.76 | 0.02 | 0.60 | |
| L | 0.52 | 0.30 | 0.60 | 0.70 | 0.08 | 0.82 | 0.90 | 0.16 | 0.54 | 0.24 | 0.70 | 0.92 | 0.34 | 0.26 | 0.52 | 0.30 | 0.60 | 0.70 | 0.08 | 0.82 | 0.90 | 0.16 | 0.54 | 0.24 | 0.70 | 0.92 |
| M | 0.98 | 0.12 | 0.18 | 0.92 | 0.14 | 0.40 | 0.48 | 0.06 | 0.96 | 0.50 | 0.08 | 0.14 | 0.56 | 0.72 | 0.98 | 0.12 | 0.18 | 0.92 | 0.14 | 0.40 | 0.48 | 0.06 | 0.96 | 0.50 | 0.08 | 0.14 |
| N | 0.64 | 0.46 | 0.80 | 0.34 | 0.56 | 0.86 | 0.78 | 0.32 | 0.66 | 0.28 | 0.82 | 0.40 | 0.86 | 0.42 | 0.64 | 0.46 | 0.80 | 0.34 | 0.56 | 0.86 | 0.78 | 0.32 | 0.66 | 0.28 | 0.82 | 0.40 |
| O | 0.20 | 0.62 | 0.84 | 0.26 | 0.72 | 0.42 | 0.74 | 0.36 | 0.58 | 0.68 | 0.90 | 0.48 | 0.78 | 0.74 | 0.20 | 0.62 | 0.84 | 0.26 | 0.72 | 0.42 | 0.74 | 0.36 | 0.58 | 0.68 | 0.90 | 0.48 |
| P | 0.94 | 0.44 | 0.10 | 0.52 | 0.98 | 0.64 | 0.20 | 0.94 | 0.04 | 0.38 | 0.16 | 0.06 | 0.32 | 0.36 | 0.94 | 0.44 | 0.10 | 0.52 | 0.98 | 0.64 | 0.20 | 0.94 | 0.04 | 0.38 | 0.16 | 0.06 |
| Q | 0.04 | 0.22 | 0.88 | 0.30 | 0.12 | 0.46 | 0.62 | 0.44 | 0.22 | 0.76 | 0.54 | 0.96 | 0.66 | 0.58 | 0.04 | 0.22 | 0.88 | 0.30 | 0.12 | 0.46 | 0.62 | 0.44 | 0.22 | 0.76 | 0.54 | 0.96 |
| R | | 0.76 | 0.02 | 0.60 | 0.18 | 0.80 | 0.84 | 0.10 | 0.88 | 0.02 | 0.24 | 0.50 | 0.28 | 0.68 | 0.38 | 0.76 | 0.02 | 0.60 | 0.18 | 0.80 | 0.84 | 0.10 | 0.88 | 0.02 | 0.24 | |
| S | | 0.54 | 0.24 | 0.70 | 0.92 | 0.34 | 0.26 | 0.52 | 0.30 | 0.60 | 0.70 | 0.08 | 0.82 | 0.90 | 0.16 | 0.54 | 0.24 | 0.70 | 0.92 | 0.34 | 0.26 | 0.52 | 0.30 | 0.60 | 0.70 | |
| T | | 0.96 | 0.50 | 0.08 | 0.14 | 0.56 | 0.72 | 0.98 | 0.12 | 0.18 | 0.92 | 0.14 | 0.40 | 0.48 | 0.06 | 0.96 | 0.50 | 0.08 | 0.14 | 0.56 | 0.72 | 0.98 | 0.12 | 0.18 | 0.92 | |
| U | | | 0.28 | 0.82 | 0.40 | 0.86 | 0.42 | 0.64 | 0.46 | 0.80 | 0.34 | 0.56 | 0.86 | 0.78 | 0.32 | 0.66 | 0.28 | 0.82 | 0.40 | 0.86 | 0.42 | 0.64 | 0.46 | 0.80 | | |
| V | | | | 0.90 | 0.48 | 0.78 | 0.74 | 0.20 | 0.62 | 0.84 | 0.26 | 0.72 | 0.42 | 0.74 | 0.36 | 0.58 | 0.68 | 0.90 | 0.48 | 0.78 | 0.74 | 0.20 | 0.62 | | | |
| W | | | | 0.16 | 0.06 | 0.32 | 0.36 | 0.94 | 0.44 | 0.10 | 0.52 | 0.98 | 0.64 | 0.20 | 0.94 | 0.04 | 0.38 | 0.16 | 0.06 | 0.32 | 0.36 | 0.94 | 0.44 | | | |
| X | | | | | | 0.66 | 0.58 | 0.04 | 0.22 | 0.88 | 0.30 | 0.12 | 0.46 | 0.62 | 0.44 | 0.22 | 0.76 | 0.54 | 0.96 | 0.66 | 0.58 | | | | | |
| Y | | | | | | | 0.68 | 0.38 | 0.76 | 0.02 | 0.60 | 0.18 | 0.80 | 0.84 | 0.10 | 0.88 | 0.02 | 0.24 | 0.50 | 0.28 | | | | | | |
| Z | | | | | | | | 0.16 | 0.54 | 0.24 | 0.70 | 0.92 | 0.34 | 0.26 | 0.52 | 0.30 | 0.60 | 0.70 | 0.08 | | | | | | | |
| ZZ | | | | | | | | | | | 0.08 | 0.14 | 0.56 | 0.72 | 0.98 | 0.12 | | | | | | | | | | |

Figure 4 A Typical Channel-Age Map

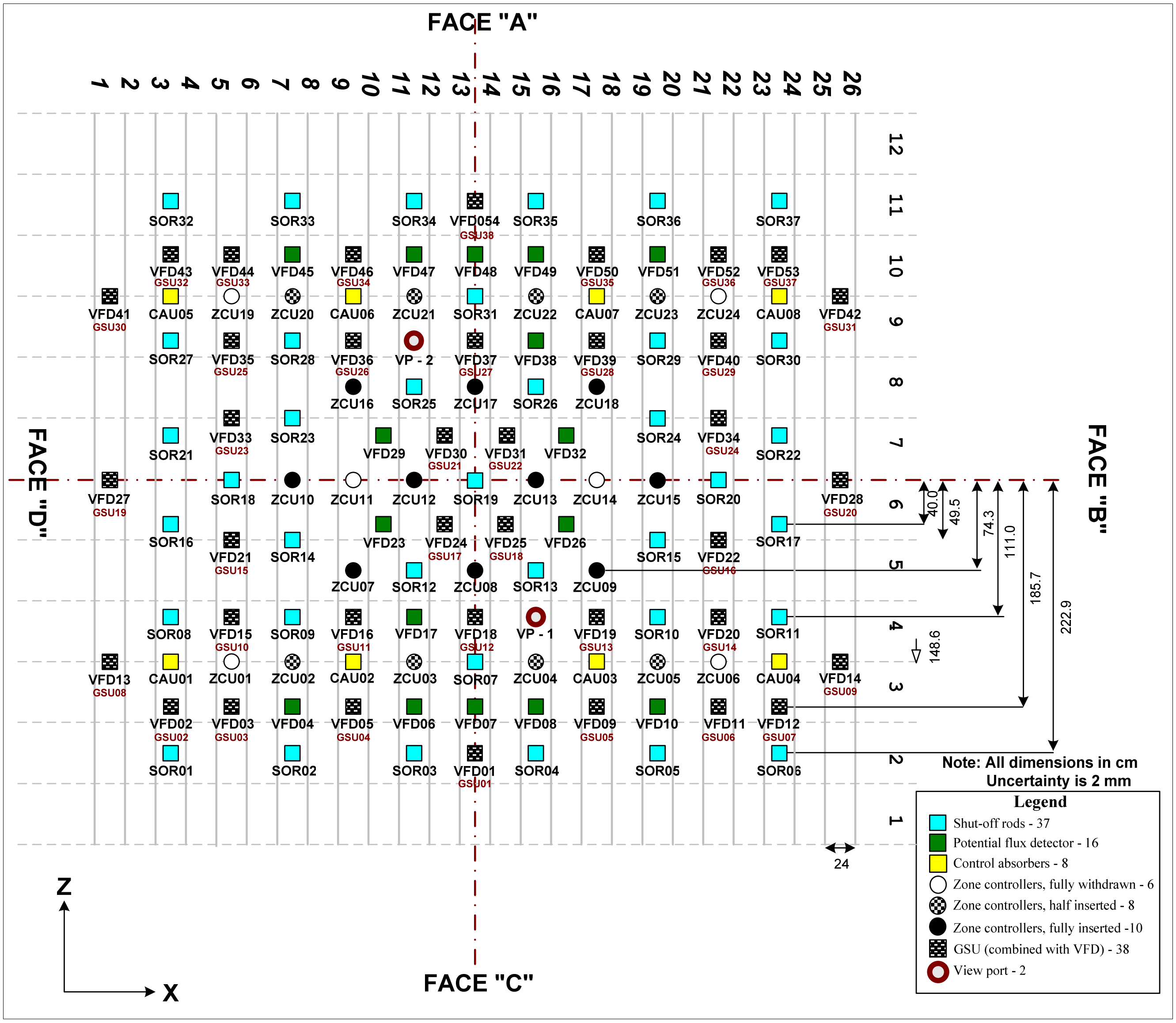


Figure 5 Plan View of Vertical Reactivity Devices and Detector Assemblies for ACR-1000 Reactor

## 3. Results

The refuelling shift transients in channel H12 have been simulated with RFSP-IST. For the ACR-1000 reference core, a 2-bundle shift refuelling scheme, as illustrated in Figure 1, is applied in the analysis.

Table 2 provides the power transient in the refuelled channel H12. While passing through the region of higher flux, the powers of the low-burnup bundles ramp up. It is found that the maximum bundle power, during the shifting of the fuel string, always occurs to the bundle that used to be at bundle position 1 (called "*irradiated bundle 1*" hereafter) before the refuelling. Power peaking in the fresh bundles inserted at the start of fuelling is suppressed by the poison in the fuel*.

* 1 gram of Gadolinium is added in a CANFLEX fuel bundle and uniformly distributed in the outer 42 pins.

**Table 2 Bundle Power Transients in Channel H12 with 2-Bundle Shift Refuelling Scheme**

| Step | Channel Power (kW) | Bundle Power in Channel H12 (kW) | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 |
| 0 | 6122.3 | 243.3 | 568.0 | 682.8 | 688.9 | 652.8 | 591.7 | 562.9 | 565.1 | 537.1 | 488.8 | 382.4 | 158.5 |
| 1 | 6420.8 | 232.6 | 593.5 | 716.1 | 724.8 | 697.1 | 629.0 | 601.3 | 601.1 | 565.4 | 507.8 | 393.6 | 158.5 |
| 2 | 6704.3 | 228.6 | 561.3 | 739.6 | 766.9 | 745.5 | 674.4 | 639.9 | 641.1 | 596.5 | 534.2 | 412.3 | 164.0 |
| 3 | 6742.2 | 0.0 | 551.4 | 700.1 | 799.2 | 796.8 | 723.3 | 686.0 | 680.5 | 631.9 | 563.8 | 436.8 | 172.4 |
| 4 | 6437.4 | 0.0 | 0.0 | 687.3 | 762.5 | 832.7 | 774.0 | 735.9 | 728.9 | 668.9 | 599.0 | 464.6 | 183.6 |
| 5 | 5976.1 | 0.0 | 0.0 | 0.0 | 779.0 | 793.4 | 807.9 | 785.9 | 778.4 | 711.6 | 631.5 | 493.3 | 195.1 |
| 6 | 5346.9 | 0.0 | 0.0 | 0.0 | 0.0 | 767.5 | 760.4 | 817.0 | 830.5 | 760.9 | 676.1 | 525.4 | 209.1 |
| 7 | 4689.5 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 732.6 | 767.9 | 862.7 | 812.1 | 725.3 | 565.2 | 223.7 |
| 8 | 4022.1 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 738.9 | 810.1 | 844.8 | 777.3 | 609.2 | 241.8 |
| 9 | 3310.3 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 781.6 | 798.9 | 813.9 | 654.8 | 261.1 |
| 10 | 2517.4 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 780.9 | 774.8 | 682.9 | 278.8 |
| 11 | 1693.5 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 767.1 | 641.7 | 284.7 |
| 12 | 2517.4 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 780.9 | 774.8 | 682.9 | 278.8 |
| 13 | 3310.3 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 781.6 | 798.9 | 813.9 | 654.8 | 261.1 |
| 14 | 4022.1 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 738.9 | 810.1 | 844.8 | 777.3 | 609.2 | 241.8 |
| 15 | 4689.5 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 732.6 | 767.9 | 862.7 | 812.1 | 725.3 | 565.2 | 223.7 |
| 16 | 5346.9 | 0.0 | 0.0 | 0.0 | 0.0 | 767.5 | 760.4 | 817.0 | 830.5 | 760.9 | 676.1 | 525.4 | 209.1 |
| 17 | 5976.1 | 0.0 | 0.0 | 0.0 | 779.0 | 793.4 | 807.9 | 785.9 | 778.4 | 711.6 | 631.5 | 493.3 | 195.1 |
| 18 | 6437.4 | 0.0 | 0.0 | 687.3 | 762.5 | 832.7 | 774.0 | 735.9 | 728.9 | 668.9 | 599.0 | 464.6 | 183.6 |
| 19 | 6742.2 | 0.0 | 551.4 | 700.1 | 799.2 | 796.8 | 723.3 | 686.0 | 680.5 | 631.9 | 563.8 | 436.8 | 172.4 |
| 20 | 6704.3 | 228.6 | 561.3 | 739.6 | 766.9 | 745.5 | 674.4 | 639.9 | 641.1 | 596.5 | 534.2 | 412.3 | 164.0 |

The average grey ZCRs insertion through the fuelling transient is shown in Figure 6. Both the dynamic and steady-state analyses present the trend in the ZCR movement. The average grey ZCR insertion reaches the minimum at t=280 seconds (step 11) to compensate the reactivity when there are only 3 fuel bundles remaining in the core in the refuelled channel H12.

Figure 7 presents a comparison of the maximum bundle powers obtained from the dynamic and steady-state fuelling transient simulations. In general, the results agree with each other. The peak values appear roughly at t = 180 seconds (step 6) when the "*irradiated bundle 1*" reaches bundle position 8.

The channels neighbouring to the refuelled channel H12 are also investigated. Variations in the channel and bundle powers in those channels are found to be less than 1% during the refuelling transient.

## 4. Summary

To demonstrate that the ACR-1000 reactor can be refueled online while maintaining various reactor physics parameters within prescribed limits, a fuelling transient analysis was performed by using RFSP-IST. In general, the kinetic *CERBERUS simulations indicate that short-term temporal transients induced by refueling are not significant, and that the power transient effects are well captured by the steady-state RFSP-IST simulations.

The simulations show that the expected fuel channel and bundle power transient during refuelling are well controlled, and within the expected design operating envelope.

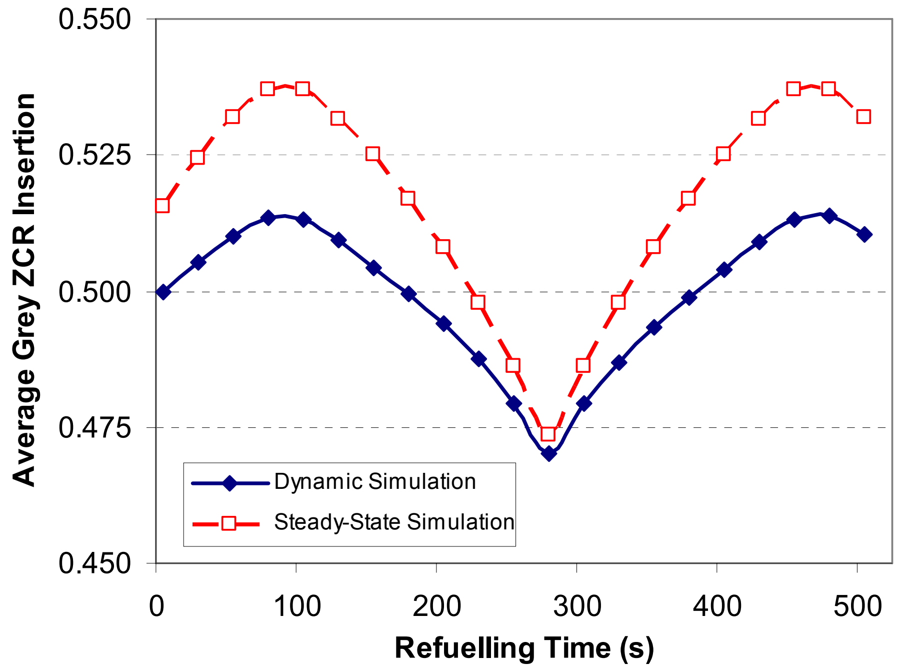


Figure 6 Average Grey ZCRs Insertion during Fuelling Transient

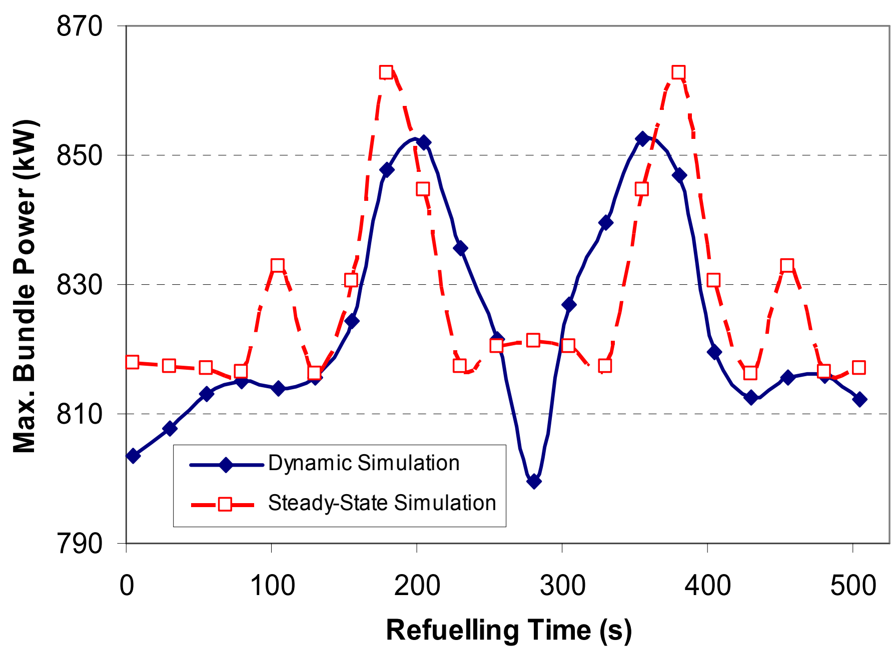


Figure 7 Maximum Bundle Powers during Refuelling Transient

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