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DERMAGA – An alternative tool to generate random patterned-channel-age in CANDU fuel management analyses part II: Robustness against varying basic pattern size

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A B S T R A C T

The instantaneous power distribution in the core can be calculated when the actual bundle-wise burnup distribution is known. In the light water reactor technology where batch fuelling practice is employed, the snapshot of power distribution during the cycle could be easily obtained by monitoring and simulating the core from the beginning to the end of the fuel cycle. Such calculation is more challenging for CANDU reactors. Considering the fact that CANDU utilizes the on-power refuelling to compensate for the reduction in reactivity due to fuel burnup, in CANDU fuel management analyses, snapshots of power and burnup distributions can be obtained by simulating and tracking reactor operation over an extended period using various tools such as the *SIMULATE module of the reactor fuelling simulation program (RFSP) code. However, for some studies, such as an evaluation of a conceptual design of a next generation CANDU reactor, the preferred approach to obtain a snapshot of the power distribution in the core is based on the patterned-channel-age model implemented in the *INSTANTAN module of the RFSP code. The objective of this approach is to obtain a representative snapshot of core conditions quickly and use such snapshot to perform additional reactor-physics related analyses. Presently such patterns could be generated by a program called RANDIS which is implemented within the *INSTANTAN module. An alternative approach called DERMAGA (DistributEd RandoM Age generator using Genetic Algorithm) has been developed to derive the patterned-channel-age model where an optimization algorithm is utilized to find patterns which produce representative power distributions in the core. Within DERMAGA, the genetic algorithm technique has been utilized as the optimization engine to find a *quasi*-optimal patterned-channel-age. It has been demonstrated that DERMAGA is a viable alternative tool to produce representative snapshots of daily core configuration. In the present paper which is Part II of a two-part paper, the robustness of DERMAGA is tested against various different sizes of basic grid used for generating the random patterned-channel-age.

1. Introduction

In light water reactors, the refuelling of the reactor is done in batch fashion every 18–24 months. This practice is possible due to the utilization of enriched fuel elements. In Canada Deuterium Uranium or CANDU reactors, due to the utilization of natural-uranium fuel elements, the batch fuelling practice is not an option and the refuelling is done on-power daily. This means that the inventory in the core is changing daily. Therefore, in order to capture the correct fuel burnup distribution in the core which is required for determining the power distribution in the core, the operation of the reactor needs to be simulated and tracked continuously from the beginning of reactor's life. The information from core tracking will allow the operator to simulate the core condition using a core simulator and, subsequently, obtain the power distribution in the core as well as other pertinent parameters for reactor core physics analysis. While this is a practice for obtaining the in-core power distribution adopted by operating CANDU reactors (since the daily operational information is readily available), a different approach is utilized during a conceptual design of a new CANDU-type reactor. For this purpose, the concept of a time-average core is introduced as a representation of an "equilibrium" core state after the reactor is operating for a long

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Nomenclature

CANDU	Canada Deuterium Uranium
GA	genetic algorithm
RFSP	reactor fuelling simulation program

period of time. To have an example of a daily snapshot of core condition, a patterned-channel-age model is implemented through the *INSTANTAN module of the Reactor Fuelling Simulation Program (RFSP) code (Shen and Schwanke, 2012) to generate a refuelling ripple that is added to the time-average power distribution. The RFSP code is the industry standard tool in the CANDU community used for performing the in-core fuel management (Rouben, 2002; Choi and Roh, 2004; Choi et al., 2005; Song, 2015). Presently, these patterned-channel-ages are generated by a program called RANDIS which has been implemented in the *INSTANTAN module. Unfortunately, there are two known disadvantages of this code. Firstly, it can only create a “limited” number of patterns. At this point, there are only 99,999 possible patterns that can be generated by this module. Secondly, the maximum bundle and channel powers from applying these patterns tend to be on the high side. To address these limitations an alternative approach called DERMAGA (DistributEd RandoM Age generator using Genetic Algorithm) has been developed for generating patterned-channel-ages (Kastanya, 2016). In this approach, the patterned-channel-age is optimized such that either the maximum bundle power or the maximum channel power is minimized. The Genetic Algorithm (GA) technique (Holland, 1975; Goldberg, 1989) is employed to perform the optimization. The GA technique is chosen for this particular implementation of the tool because it has been widely used for fuel management optimization in various reactor types, such as for PWR (Alim et al., 2007; De Lima et al., 2009), BWR (Martin-del-Campo et al., 2009), VVER (Karahroudi et al., 2013; Sustek, 2005), and CANDU (Do et al, 2006a; Do et al., 2006b; Huo and Xie, 2005a; Huo and Xie, 2005b). For CANDU application, the GA has also been utilized for optimization of regional overpower protection detector layout (Kastanya, 2012, 2013).

The objective of the present paper is to evaluate the robustness of DERMAGA against the use of different grid sizes of basic pattern. The sizes of grids evaluated in this study range from 5 × 5 up to 11 × 11. Section 2 provides an overview of the *INSTANTAN module where the patterned-channel-age is incorporated into, an overview of the DERMAGA algorithm, and descriptions of criteria used for evaluating the results. After presenting and discussing the results from this study in Section 3, the paper is concluded with some closing remarks.

2. Methodology

2.1. An overview of the *INSTANTAN module to capture a snapshot of the core condition

While the time-average equilibrium core represents the average core behaviour over a long period of time, it does not characterize the actual core state on any particular day. The effect of daily refuelling is missing. The time-average power distribution does not capture the actual powers with refuelling “ripples”, resulting from the application of a particular fuel management scheme. Since an instantaneous power distribution of any day within the equilibrium stage can be obtained when the current value of burnup is available for each fuel bundle in the core, various approaches have been developed to determine an instantaneous burnup distribution.

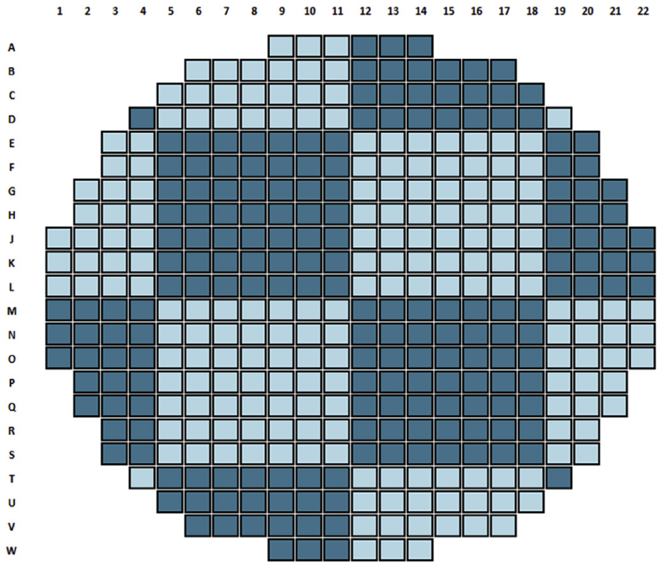

Fig. 1. Distribution of Patterned-Channel-Age for 7 × 7 Grid [Darker-shaded squares represent parts of original age matrix; Lighter-shaded squares represent transposed age matrix].

As indicated earlier, the most realistic approach to obtain instantaneous power distributions is to actually simulate and track reactor operations over an extended period of time using a tool such as the *SIMULATE module of RFSP. However, for some studies such as the conceptual design of a new CANDU reactor, the preferred approach is based on the patterned-channel-age model as implemented in the *INSTANTAN module of RFSP since there is no actual reactor operation to track. This module allocates a specific burnup to individual bundles reflecting a particular channel refuelling sequence.

At the end of each time-average calculation, the fuel irradiations (expressed in the unit of n/kb or neutron per kilo-barn) at the beginning of the fuel cycle, denoted ω_{jk}^{BOC}, and at the end for the fuel cycle, denoted, ω_{jk}^{EOC}, for bundle position k in fuel channel j are calculated. The channel-age model assumes that the fuel irradiation varies linearly as a function of time during the cycle between the refuelling of channel j, so that the current values of fuel irradiation are simply a function of the “age” (denoted as f_j) of the channel. The fuel irradiation for each bundle[1] location at a particular time t can then be written as

$$\omega_{jk}(t) = \omega_{jk}^{BOC} + f_j(t) \cdot \left\{ \omega_{jk}^{EOC} - \omega_{jk}^{BOC} \right\} \tag{1}$$

Provided that the map of channel-dependent values of $f_j(t)$ is available, the burnup distribution can then be determined by applying this equation to each fuel bundle in the core. Having established the burnup distribution, one can calculate the instantaneous power distribution in the core.

Presently, a program called RANDIS is implemented in the *INSTANTAN module of RFSP and could be utilized to create the patterned-channel-age distribution. It creates an age distribution for a 7 × 7 grid in which the channel ages are some fraction of the total dwell time ranging from 0.02 to 0.98.[2] To assign an age for each channel in the core, this age distribution and its transpose are

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[1] It should be noted that in a typical CANDU fuel channel there are 12 fuel bundles.

[2] A low fraction (such as 0.02) represents a channel which has been recently refueled and a high fraction (such as 0.98) represents a channel which is about to be refueled.