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Evaluating the effect of cross-over length and mutation rate variations on the performance of DERMAGA

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ABSTRACT

In the CANDU fuel management analysis, snapshots of power and burnup distributions in the core could be obtained by simulating and tracking reactor operation over 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 quickest 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. Recently an alternative algorithm, called DERMAGA, has been developed for generating patterned-channel-ages to be used by the *INSTANTAN module. It has been demonstrated that the DERMAGA algorithm has been used successfully to produce patterned-channel-ages where the maximum channel and bundle powers are close to the values observed during operation. The heart of the DERMAGA algorithm is the Genetic Algorithm (GA) technique. Since there are many user-defined parameters that could be varied for an optimization using the GA technique, the performance of the algorithm could be affected by the choices of these parameters. Some numerical simulations have been conducted to evaluate the robustness of the DERMAGA algorithm against the variations in some of these parameters. The results from evaluating the performance of DERMAGA against the variation in the mutation rates per generation and the cross-over length are presented in this paper.

1. Introduction

Unlike the light water reactors, the CANDU reactors have to perform on-power refueling on a daily basis in order to sustain the long-term criticality of the reactor. This is due to the fact that CANDU reactor utilizes natural-uranium fuel elements, instead of enriched fuel elements. The daily refueling practice results in a continuously changing core inventory. Therefore, in order to be able to get an accurate power distribution in the core, which requires an accurate fuel burnup distribution in the core, the operation of the reactor needs to be simulated and tracked continuously from the beginning of the reactor's life. The information from core tracking will allow the operator to simulate the core condition using a core simulator and, subsequently, produce the power distribution in the core as well as other important parameters for reactor core physics analysis, such as the worth of various reactivity control devices and the reactivity coefficients.

The practice of simulating and tracking the core conditions can be easily done by an operating CANDU reactor. However, a different approach is needed when designing a new CANDU-type reactor, since the daily operational information is not readily available. In this alternate approach, 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 period of time. Being an "average" representation of the core configuration, the time average core does not necessarily represent any specific core configuration at any particular day. To have an example of a daily snapshot of the core configuration, 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 refueling 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).

Up to this point, the RANDIS program implemented as an option in the *INSTANTAN module of the RFSP code has the capability of generating these patterned-channel-ages. 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. To assign an age for each channel in the core, this age distribution and its transpose are applied throughout the core as shown in Fig. 1. In this figure,

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Nomenclature

BP	bundle power
BWR	boiling water reactor
CANDU	Canada deuterium uranium
CP	Channel power
EFPD	effective full power day
GA	Genetic Algorithm
PWR	pressurized water reactor
RFSP	reactor fuelling simulation program
VVER	Vodo-Vodyanoi Energetichesky Reaktor (Water-Water Energetic Reactor)

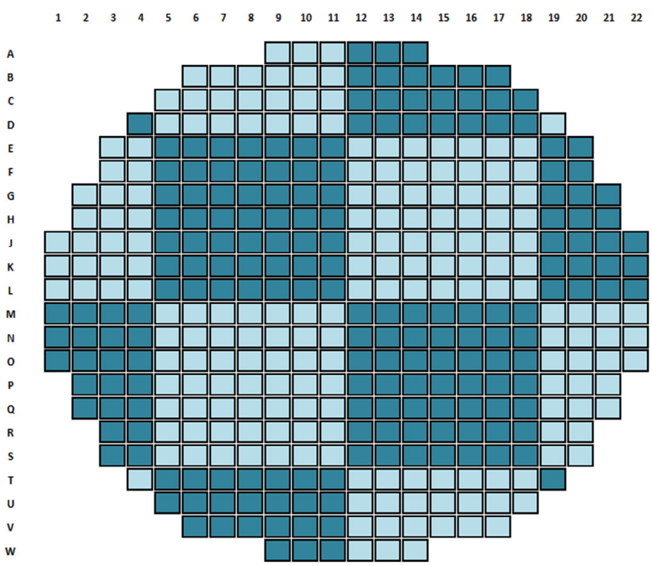

Fig. 1. Distribution of patterned-channel-age for 7 × 7 Grid [darker-shaded squares represent parts of original age matrix; lighter-shaded squares represent transposed age matrix].

the channel locations marked by the darker shade use the basic age distribution (*i.e.*, the one produced by RANDIS) and the channel locations marked by the lighter shade use the transpose of the age distribution. Some examples of 7 × 7 age distribution are given in Fig. 2.

Unfortunately, there are two disadvantages of the RANDIS program. 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. While it is true that these possible patterns should be sufficient for practical purpose, it is only a very small sub-set of the overall possible patterns that can be generated on a 7 × 7 grid. Secondly, the maximum bundle and channel powers from applying these patterns tend to be on the high side. From an operational point of view, this is not a desirable behaviour since a reactor physicist or a fuel engineer, while planning the fueling activities, does not want to run into maximum bundle power or channel power compliance issue. Therefore, it is important that these values are maintained at a reasonable margin from the corresponding limits. To address these limitations an alternative approach called DERMAGA (DistributEd RandoM Age generator using Genetic Algorithm) has been developed recently as an alternative tool for generating patterned-channel-ages (Kastanya, 2016). In this approach, the patterned-channel-age is optimized such that either the maximum bundle power (BP) or the maximum channel power (CP) is minimized. Within DERMAGA, 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, 2006b; Huo and Xie, 2005a, 2005b). For CANDU application, the GA has also been utilized for optimization of regional overpower protection detector layout (Kastanya, 2012, 2013).

2. Methodology

2.1. A brief overview of CANDU fuel management analysis

Due to the fact that the CANDU reactor employs an on-power refueling strategy, with respect to its fuel management, the life of a CANDU reactor can be divided up into three different stages, namely pre-fueling, pre-equilibrium, and equilibrium stages. Fuel management practices related to each of these stages are presented below.

The first stage (*i.e.*, the pre-fueling stage) commences at first criticality and lasts until the first fuel channel is refueled. With respect to the overall life of the reactor, the first stage spans a relatively short period which extends around 100–150 effective full power days (EFPD). The CANDU reactors are designed to utilize natural-uranium fuel elements throughout its lifetime, except during the pre-fueling stage. The initial core of a CANDU reactor is loaded with natural-uranium fuel elements ubiquitously except for a small number of depleted-fuel bundles strategically placed within the core to flatten the power distribution. This is necessary since the power distribution inside a CANDU reactor with all fresh natural-uranium fuel elements is very peaked toward the centre of the core. Without the presence of depleted-fuel bundles, the maximum bundle and channel power compliances could be jeopardized. Despite the fact that the overall core reactivity is slightly reduced due to the presence of the depleted-fuel bundles, a significant excess reactivity still exists in the core. To compensate for this excess reactivity, soluble boron poison is added to the moderator. This too is a practice which is unique to this stage.

As the reactor operates, the depletion of ^{235}U, the production of plutonium due to neutron capture in ^{238}U, and the creation of various fission products begin. In the beginning of the pre-fuelling stage, the rate of plutonium production is higher than the combined rate of ^{235}U depletion and fission-product concentration build-up. These competing rates reach equilibrium at around 40–50 EFPDs and the phenomenon leads to what is known as "plutonium peak", at which the core reactivity culminates. Beyond the plutonium peak, the negative reactivity introduced by fission-product build-up and ^{235}U depletion becomes more dominant. As time progresses the excess reactivity in the core continues to decrease, up to a point where refueling is required to maintain the reactor critical. This marks the end of the pre-fuelling stage and the beginning of the pre-equilibrium stage.

The pre-equilibrium stage is essentially a transitional period leading to the equilibrium stage. On-power refueling begins during the pre-equilibrium stage. At this end of this second stage, all of the depleted-fuel bundles are supposed to be discharged from the core. During this stage, especially in the beginning, a higher fueling rate is sometimes required to compensate for a drastic decrease in core