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Original Article

A Study on the Optimal Position for the Secondary Neutron Source in Pressurized Water Reactors

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ABSTRACT

This paper presents a new and efficient scheme to determine the optimal neutron source position in a model near-equilibrium pressurized water reactor, which is based on the OPR1000 Hanul Unit 3 Cycle 7 configuration. The proposed scheme particularly assigns importance of source positions according to the local adjoint flux distribution. In this research, detailed pin-by-pin reactor adjoint fluxes are determined by using the Monte Carlo KENO-VI code from solutions of the reactor homogeneous critical adjoint transport equations. The adjoint fluxes at each allowable source position are subsequently ranked to yield four candidate positions with the four highest adjoint fluxes. The study next simulates ex-core detector responses using the Monte Carlo MAVRIC code by assuming a neutron source is installed in one of the four candidate positions. The calculation is repeated for all positions. These detector responses are later converted into an inverse count rate ratio curve for each candidate source position. The study confirms that the optimal source position is the one with very high adjoint fluxes and detector responses, which is interestingly the original source position in the OPR1000 core, as it yields an inverse count rate ratio curve closest to the traditional 1/*M* line. The current work also clearly demonstrates that the proposed adjoint flux-based approach can be used to efficiently determine the optimal geometry for a neutron source and a detector in a modern pressurized water reactor core.

1. Introduction

Excore neutron detectors are used to monitor reactivity states of commercial pressurized water reactors (PWRs) with the aid of the inverse count rate ratio (ICRR) curve. In the ICRR curve, the normalized ratio of the source range detector count rates to the reference signals is calculated and extrapolated to zero at criticality. The detector signals must exceed a specified

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minimum count rate, which necessitates the use of secondary neutron sources to ensure neutron levels are high enough to be detected by nuclear instruments at all times, especially during subcritical startup operation of the PWR. For example, californium-252 (^{252}Cf) is used to supply source neutrons in initial cores while antimony–beryllium (Sb-Be) is used in reload cores. In near-equilibrium cycles, however, neutrons from spontaneous fissions of actinides such as those of curium-242 (^{242}Cm) and curium-244 (^{244}Cm) are sufficiently high to yield the minimum detector count rates. In this regard, secondary neutron sources are unnecessary and, therefore, removed from the near-equilibrium PWR cores. Removal of these highly radioactive non-nuclear materials is also advantageous since it reduces the risk of accidental coolant activation from any probable breach in the neutron source assemblies [1]. Secondary neutron sources are, in fact, only used up to Cycle 5 or 6 in standard Korean OPR1000 core designs [2].

However, one must note that modern PWR cores normally load highly-burned fuel assemblies on their periphery in pursuit of high neutron economy. In a highly subcritical near-equilibrium core, such as during all-rod-in (ARI) startup operation, this low-leakage core in tandem with the absence of secondary neutron sources significantly suppresses the ex-core detector count rates and, therefore, severely limits the detector sensitivity. As a result, reactivity monitoring with the ICRR curve can be misleading [3–5]. This is because the measured ICRR curve in the core can actually be highly nonlinear while the theoretical ICRR curve used in the core reactivity warning system, such as the boron dilution alarm setpoint (BDAS), is linear. The discrepancy between the actual nonlinear ICRR curve and the ideal ICRR curve is illustrated in Fig. 1 [3]. This possibly results in a noticeable time delay in the boron dilution alarm system, which adversely affects the core reactivity monitoring and compromises the overall reactor safety. This safety concern is highlighted in the United States Nuclear Regulatory Commission's information notice 93-32 that warns of the possible loss of shutdown margin at the Comanche Peak Steam Electric Station due to its nonconservative BDAS determination [6]. In particular, the predetermined BDAS, which is based on the traditional subcritical multiplication theory, may only be triggered after an appreciable amount of boron dilution has occurred in the core. This unmitigated boron dilution event is regarded by the United States Nuclear Regulatory Commission as a serious breakdown which requires adequate protection action [7]. Similar concern over the nonconservative ICRR curve behavior was also observed during a postulated boron dilution event at shutdown with all rods inserted at the Diablo Canyon nuclear power station [3].

One possible solution is to install secondary neutron sources in the near-equilibrium PWR cores so as to “make” its ICRR curve linear again. Note that the efficiency and functionality of the secondary neutron source depends greatly on its location in the core. As such, an optimal position exists where the source efficiency is optimized in terms of the neutron source importance, ex-core detector responses, and linearity of the corresponding ICRR curve.

The simplest method to determine such an optimal source position is by performing a direct exhaustive search, i.e., evaluating detector responses for each allowable neutron source location separately. This is, however, very time consuming. Moreover, all of the calculations must be painstakingly repeated should there be any design change in the ex-core detector system. A more efficient methodology is thereby needed.

This paper proposes a unique adjoint flux-based approach to efficiently determine the optimal source-detector geometry in a modern PWR core. In this research, the source position is evaluated by taking into account its contribution to the fission reaction in the core instead of evaluating the conventional neutron importance to the ex-core detector signal. As such,

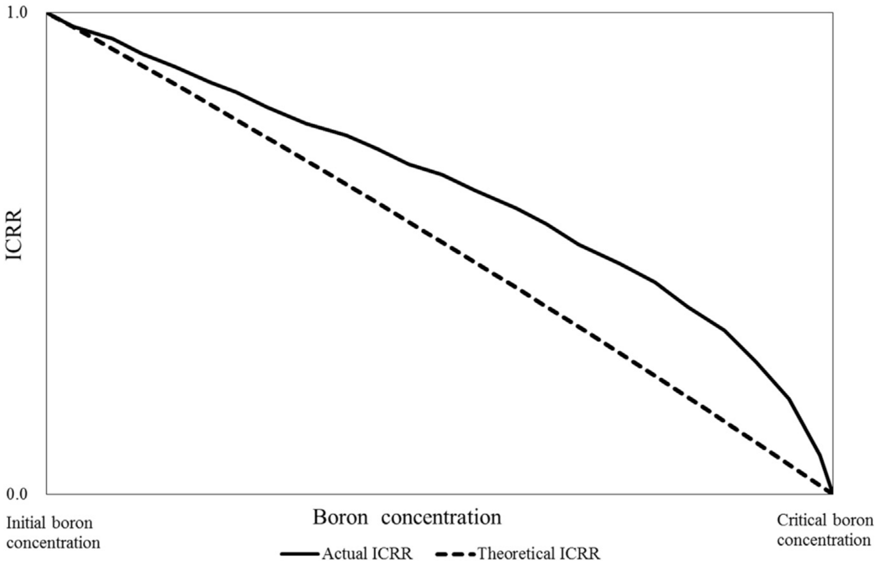

Fig. 1 – Illustrative discrepancy between the actual inverse count rate ratio (ICRR) curve and the theoretical 1/*M* line against boron concentration in the core.

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