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Application of the modified neutron source multiplication method to the prototype FBR Monju

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ABSTRACT

The Modified Neutron Source Method (MNSM) is applied to the prototype FBR Monju. This static method to estimate the reactivity in sub-critical conditions has already given good results on commercial pressurized water reactors. The MNSM consists both in the extraction of the fundamental mode seen by a detector to avoid the effect of higher modes near sources, and the correction of flux distortion effects due to control rod movement between different reactor states. Among Monju's particularities that have a big influence on the MNSM factors are: the presence of two californium sources near the core and the position of the detector, which is located far from the core outside of the reactor vessel. The importance of spontaneous fission and (α, n) reactions, which have increased during the shutdown period of 15 years, will also be discussed. In order to evaluate the detector count rate, a propagation calculation has been conducted from the reactor vessel to the external detector. For two sub-critical states, an estimation of the reactivity has been made and compared to experimental data obtained in the restart experiments at Monju (2010). Results indicate a good agreement between the MNSM reactivity and the reactivity measured with other methods. The reactivity dependence of the correction to apply to the point kinetic equation is discussed.

1. Introduction

A fundamental problem exists when trying to estimate the reactivity of a nuclear reactor if one uses a static method, with a constant neutron source in the reactor. Indeed, the well-known relation to calculate the reactivities of different states of the reactor, associating the reactivity ratio to the inverse of a measured count rate ratio, does not take into account the effects due to the change of the flux shape between the different reactor states. The Modified Neutron Source Multiplication Method (MNSM) can be used to reconstruct the link between the reactivity defined with the *eigenvalue* of the critical system and the count rate observed by a detector placed in a *source driven* system. It is shown that the correction comes from three physical effects:

1. a spatial effect due to the distortion of the critical flux shape between different states of the reactor (for instance due to control rod movement),
2. an extraction effect due to the difference between the critical flux shape and the actual source driven flux shape,
3. an importance effect due to the distortion of the adjoint flux: a neutron released by a source may not have the same importance in the fission chain depending on the reactivity of the reactor.

These three correction factors are mathematically introduced in Section 2 of this paper. In Section 3, the method is applied to the prototype FBR Monju. The MNSM correction factors mainly depend on the source and detector positions, and thus the sources and detectors must be characterized with proper accuracy. In order to precisely estimate the intensity of the independent sources coming from californium, spontaneous fission in the fuel and (α, n) reactions, a calculation has been done taking into account the roughly 15 years of aging of the fuel, corresponding to the shutdown period of Monju between December 1995 and May 2010.

The necessity to calculate the flux both in the core and at the detector position causes a computer memory problem if one desires to make a model which takes into account the whole geometry. In Monju, the detector is located far away from the core, outside of the vessel, in a nitrogen atmosphere. It has been chosen to treat this problem in two steps: first, a model of the core limited to the primary vessel has been created, and second, a propagation

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of the flux from the boundary of the vessel to the detector position is done. Two ways of propagating the flux are explored:

1. an analytical way considering nitrogen as void,
2. a propagation based on the adjoint source-detector problem, from the detector to the vessel.

The last section presents the results obtained for a detector placed anywhere in the primary vessel, as well as for the actual position of the detector after propagation of the flux. These results are compared with results of dynamic measurements done by JAEA. In general, the MNSM results are different but within the error margin of the measured reactivities. The reactivity dependence of the MNSM correction is also analyzed in order to provide a direct expression of reactivity.

2. The modified neutron source multiplication method

Before we start our discussion, a note about definitions. A nuclear reactor is deemed to be *critical* if, in the absence of an independent source of neutrons, there is a steady state neutron population in the reactor. This implies a balance between the number of neutrons produced by fissions and the number of neutrons lost by leakage and absorption. In calculations one usually does not deal with a critical reactor, and an artificial parameter is introduced into the neutron balance equation so that an *artificial* steady state is obtained. Mathematically the neutron balance equation is transformed into an eigenvalue equation. The most common choice is to apply the correction factor (the eigenvalue) to the fission term in the neutron balance equation. In such a case, one often speaks of the λ*-eigenvalue* and the corresponding eigenmodes are called λ*-modes*. Related to the λ-eigenvalue is the *multiplication factor k*:

$$\lambda \equiv \frac{1}{k} \tag{1}$$

In the framework of the *Point Kinetics Equations* (PKEs), there is yet another parameter in use: the *reactivity* ρ, which is related as follows:

$$\rho \equiv \frac{k-1}{k} \equiv 1-\lambda \tag{2}$$

Note here that technically one can only speak of a *reactivity* in the framework of the point kinetics equations. However, in the present paper we will find expressions similar to Eq. (2) and we will loosely use the term *reactivity* for these.

This section presents the three correction factors of the modified neutron source multiplication method using the approach of Tsuji et al. (2003). When a reactor is sub-critical and if there is a constant source of neutrons, the neutron population in the reactor is constant. Such a steady state of the reactor, with a constant reactivity, leads to a constant neutron population in the reactor and this yields a constant count rate in a detector. This paper refers to such a situation as a *reactivity state*. Let us start with the classic static point kinetic relation in Eq. (3) where ρ is the reactivity, and $\mathscr{M}$ is the count rate. Suppose there are two distinct reactivity states for the reactor (e.g. two different control rod patterns are present in the reactor, to create two distinct reactivity states). The detector count rates are observed in the two reactivity states. Let one of the reactivity states be defined as the *reference state* (indexed as *ref*). The other state is an arbitrary reactivity state of the reactor different from the reference state. $\mathbf{r}_d$ is the detector position. If the reactivity of the reference state is known (for instance by performing a measurement), then the reactivity ρ of any other state can be calculated from the observed count rate in that other state, as follows:

$$\rho = \frac{\mathscr{M}_{\text{ref}}(\mathbf{r}_d)}{\mathscr{M}(\mathbf{r}_d)}\rho_{\text{ref}} \tag{3}$$

Such a reactivity is called the *estimated reactivity*. The spatial distortion of the flux as a function of the reactivity is not taken into account in Eq. (3), which is defined for a point reactor model. The MNSM Method will introduce three coefficients to correct this equation. The MNSM equation is given in Eq. (4), with C^{im} the *importance correction*, C^{sp} the *spatial correction* and C^{ext} the *extraction correction*.

$$\rho = C^{\text{im}}C^{\text{sp}}C^{\text{ext}}\frac{\mathscr{M}_{\text{ref}}(\mathbf{r}_d)}{\mathscr{M}(\mathbf{r}_d)}\rho_{\text{ref}} \tag{4}$$

- The importance correction C^{im} reflects the difference of the importance between a source neutron in state *ref* and the state presently under consideration. For example, in a deeply sub-critical state the source neutrons are relatively more important than in a nearly critical state.
- C^{sp} reflects the change of the flux distribution due to the physical change in the reactor between the reference state and the state under observation, e.g. the insertion of one or more control rods.
- C^{ext} is necessary to extract the *fundamental mode* component from the actual (source driven) flux distribution in the reactor. The fundamental mode depends on the state of the reactor, and thus the fundamental mode will change (slightly) between the reference state and the state under observation.

Note that the reactivity in the MNSM approach is not the same concept as the reactivity in the PKE, as will be demonstrated later. The task at hand is now to estimate, given some arbitrary sub-critical state of the reactor, the multiplication factor, which is defined using the eigenvalue $\lambda = 1/k$ of the criticality equation (Eq. (5)), given that the reactor is source-driven, i.e. the flux corresponds to the solution of the source-driven equation (Eq. (7)). Introduce the forward criticality equation:

$$\mathbf{L}\boldsymbol{\phi}^c(\mathbf{r}) = \frac{1}{k}\mathbf{F}\boldsymbol{\phi}^c(\mathbf{r}) \tag{5}$$

It is adjoint equation:

$$\mathbf{L}^\dagger\boldsymbol{\phi}^{c\dagger}(\mathbf{r}) = \left(\frac{1}{k}\right)^\dagger\mathbf{F}^\dagger\boldsymbol{\phi}^{c\dagger}(\mathbf{r}) \tag{6}$$

and the source-driven equation:

$$\mathbf{L}\boldsymbol{\phi}^s(\mathbf{r}) = \mathbf{F}\boldsymbol{\phi}^s(\mathbf{r}) + \mathbf{s}(\mathbf{r}) \tag{7}$$

In these equations, $\mathbf{L}$ is defined as the destruction and scatter operator, $\mathbf{F}$ as the production (fission) operator and $\mathbf{s}$ as the independent source. We use the multi-group formalism, i.e. the operators $\mathbf{L}$ and $\mathbf{F}$ are matrices, and the source $\mathbf{s}$ and flux $\boldsymbol{\phi}^{c,s}$ are vectors. The superscript *c* indicates *critical*, i.e. Eq. (5) and the superscript *s* indicates *source-driven*, i.e. Eq. (7). It is known that Eq. (5) has a spectrum of eigenvalues $\lambda_i = \frac{1}{k_i}$ and corresponding eigenfunctions $\boldsymbol{\phi}_i^c$. The smallest (in magnitude) eigenvalue λ_1 is the *fundamental eigenvalue*, the corresponding $1/k_1$ is the *multiplication factor*, and the corresponding eigenvector $\boldsymbol{\phi}_1^c$ is the *fundamental mode*. All discussions of the multiplication factor of the (sub-critical) reactor deal with k_1 and $\boldsymbol{\phi}_1^c$. We now introduce the assumption that the eigenfunctions form a complete, orthogonal basis (there are some non-trivial technicalities involved with this assumption, see Section 2.1 for more details). Then, we can write:

$$\boldsymbol{\phi}^s(\mathbf{r}) = A_1\boldsymbol{\phi}_1^c(\mathbf{r}) + \sum_{i=2}^{\infty}A_i\boldsymbol{\phi}_i^c(\mathbf{r}) \tag{8}$$