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Original Article

COMPOUND EFFECTS OF OPERATING PARAMETERS ON BURNUP CREDIT CRITICALITY ANALYSIS IN BOILING WATER REACTOR SPENT FUEL ASSEMBLIES

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A B S T R A C T

This study proposes a new method of analyzing the burnup credit in boiling water reactor spent fuel assemblies against various operating parameters. The operating parameters under investigation include fuel temperature, axial burnup profile, axial moderator density profile, and control blade usage. In particular, the effects of variations in one and two operating parameters on the curve of effective multiplication factor (k_{eff}) versus burnup (B) are, respectively, the so-called single and compound effects. All the calculations were performed using SCALE 6.1 together with the Evaluated Nuclear Data Files, part B (ENDF/B)-VII238-neutron energy group data library. Furthermore, two geometrical models were established based on the General Electric (GE)14 10 $\times$ 10 boiling water reactor fuel assembly and the Generic Burnup-Credit (GBC)-68 storage cask. The results revealed that the curves of k_{eff} versus B, due to single and compound effects, can be approximated using a first degree polynomial of B. However, the reactivity deviation (or changes of k_{eff}, Δk) in some compound effects was not a summation of the all Δk resulting from the two associated single effects. This phenomenon is undesirable because it may to some extent affect the precise assessment of burnup credit. In this study, a general formula was thus proposed to express the curves of k_{eff} versus B for both single and compound effects.

1. Introduction

Nuclear criticality safety analysis is essential for ensuring the safe storage, transportation, reprocessing, and disposition of spent fuel. Traditionally, the analysis is based on the most conservative condition in which all the spent fuel assemblies have the most reactive nuclide inventories. For example, both pressurized water reactors and boiling water reactors (BWRs) use the condition of fresh fuel assemblies. BWRs especially use the condition of reactivity peak if the fuel assemblies contain gadolinium (Gd) rods. The advantages of such assumptions simplify nuclear criticality safety analysis while reducing computation time. However, one disadvantage of such assumptions is that, to maintain nuclear criticality safety, there is less spent fuel storage capacity, which subsequently creates an economic issue [1–6]. Therefore, the usage of burnup credit to minimize this problem is an appealing option.

When performing nuclear criticality safety analysis, the concept of burnup credit involves using credit to reduce the reactivity caused by the irradiation of nuclear fuel during power operation [4]. The reactivity reduction includes the consumption of fissile materials as well as the production of strong neutron-absorbed materials, such as actinides and fission products. As a whole, the motivation for considering burnup credit can be summarized as follows [4]: (1) capacity improvement in spent fuel storage facilities can avoid or minimize adverse environmental damage associated with new storage pools, dry storage facilities, and reprocessing facilities; (2) use of higher capacity casks can lead to fewer shipments, less exposure to workers and public, and lower risk possibility of radiological accidents; and (3) for the disposal of spent fuel assemblies, the utilization of higher capacity casks can enhance the efficiency of spent fuel storage, thus implying that a smaller repository footprint is possible. Therefore, an inclusion of burnup credit in nuclear criticality safety analysis is of vital importance.

In reality, reactor operating history affects spent fuel composition by changing the depletion rate of uranium and the generation rates of plutonium, fission products, or other actinides [2]. In

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examining the effects of such reactor operating history on burnup credit criticality analysis in BWR spent fuel assemblies, this study considers the most important operating parameters in reactor operating history, namely, fuel temperature (FT), axial burnup profile (AB), axial moderator density profile (AM), and control blade usage (CB) [2]. Furthermore, to our knowledge, there has been a lack of studies that have analyzed compound effects in regard to the characteristics of effective multiplication factor (k_{eff}) versus burnup (B) resulting from simultaneous variations of two operating parameters. Therefore, such analysis is the objective of this study. The relative importance of both major and minor actinides as well as fission products in the characteristics of k_{eff} versus B due to both single and compound effects are also investigated in detail.

2. Calculation models and method

In this study, all the calculations were performed using the SCALE 6.1 computer code together with the Evaluated Nuclear Data Files, part B (ENDF/B)-VII 238-neutron energy group data library [7]. The SCALE computer code was developed by the Oak Ridge National Laboratory (ORNL) and has been widely used for decades to perform nuclear criticality safety analyses. The SCALE 6.1 computer code comprises various multipurpose control modules. In the calculation procedures conducted in this study, TRITON was first used to perform two-dimensional depletion calculations to generate ORIGEN-ARP libraries. These ORIGEN-ARP libraries contain the atomic densities of spent fuel inventories under prescribed levels of initial fuel enrichment and moderator density. Subsequently, the STARBUCS control module utilized these ORIGEN-ARP libraries along with the requested operating parameters to quickly calculate burned fuel composition. In addition, if the axial burnup or moderator density profile was considered in the calculation, the ORIGEN-ARP libraries were used 25 times to generate burned fuel composition for each axial zones in the fuel assembly, and thus a three-dimensional model of the fuel assembly was established. Finally, the burned fuel was inserted into the CSAS5 control module to calculate k_{eff} by means of a 3-D Monte Carlo criticality calculation model.

Two geometrical models representing the typical General Electric (GE)14 10 × 10 BWR fuel assembly and General Burnup Credit (GBC)-68 storage cask (including 68 BWR spent fuel assemblies) [1,2] were adopted in this study and are shown in Fig. 1A and B, respectively. The fuel assembly is composed of two water rods and 92 fuel rods. A total of 68 fuel assemblies are placed in the cask. The fuel rod pitch, active fuel length, and outer dimension of the fuel channel are 1.295, 381, and 13.914 cm, respectively. The fuel rods, with a height of 381 cm, were divided into 25 axial zones if nonuniform axial burnup or moderator density profile was considered in the calculations, but otherwise only one axial zone was applied. Notably, this study followed the approaches by Nuclear Regulatory Commission (NRC)/ORNL for using BWR fuel assemblies that did not contain Gd [2]. The initial enrichment of the fuel rods in all the fuel assemblies was 5 w/o. The fuel, cladding, and moderator temperatures were 840, 567, and 512 K, respectively. The power density (or specific power) during the power operation was maintained at 30 MW/MTU, and the cooling time was 5 years. A total of 28 nuclides were tracked and included: (1) 9 major actinides (i.e., ^{234}U, ^{235}U, ^{238}U, ^{238}Pu, ^{239}Pu, ^{240}Pu, ^{241}Pu, ^{242}Pu, and ^{241}Am); (2) 3 minor actinides (i.e., ^{236}U, ^{237}Np, ^{243}Am); and (3) 16 major fission products (i.e., ^{95}Mo, ^{99}Tc, ^{101}Ru, ^{103}Rh, ^{109}Ag, ^{133}Cs, ^{147}Sm, ^{149}Sm, ^{150}Sm, ^{151}Sm, ^{152}Sm, ^{143}Nd, ^{145}Nd, ^{151}Eu, ^{153}Eu, ^{155}Gd). The selection of these nuclides followed the recommendations of the US NRC [1,2]. The standard deviation of k_{eff} is approximately 10 pcm for all the calculations performed in this study.

Four important operating parameters were considered in this study, including FT, AM, AB, and CB. Only two variations in all the operating parameters were considered in this study and are shown in Table 1. In addition, for simplicity, certain approaches were used to assume these operating conditions, which will be described in detail in the following section. Furthermore, six combinations resulted when any two out of four operating parameters were selected simultaneously. These are listed in Table 2. Notably, the reference conditions employed in this study for the reactivity deviation (or change of k_{eff}, Δk) calculations consisted of FT = 840 K, AM = uniform, AB = uniform, and CB = full withdrawal. The uniform and nonuniform profiles of axial burnup and moderator density employed are shown in Fig. 2A and B, respectively. These profiles were adopted from assembly B2 of the LaSalle Unit 1 Commercial Reactor Critical (CRC) data and NRC/ORNL document and have been widely accepted for burnup credit calculations [2,8].

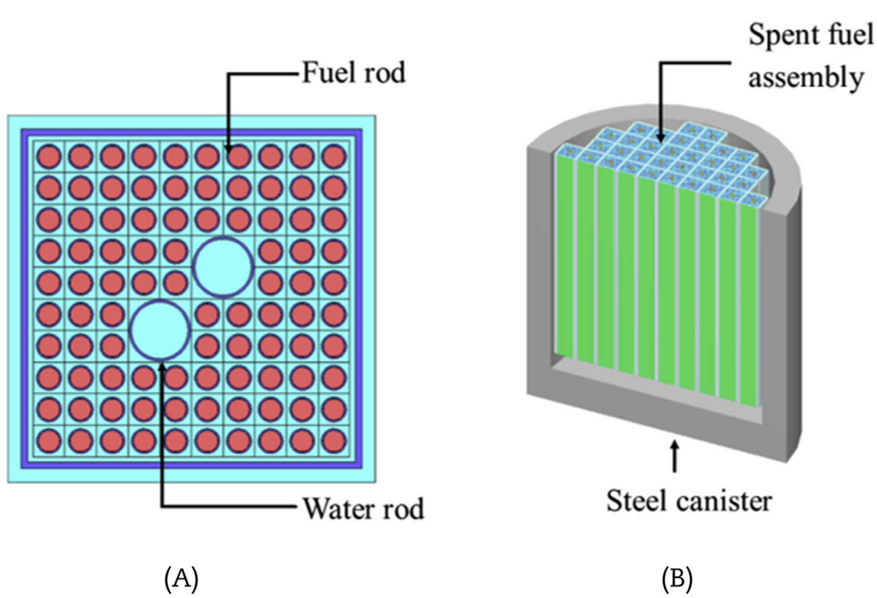

Fig. 1. Geometrical models. (A) GE 10 × 10 fuel assembly model. (B) GBC-68 cask model.

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