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Effect of Control Blade History, and Axial Coolant Density and Burnup Profiles on BWR Burnup Credit

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1. Introduction

Oak Ridge National Laboratory (ORNL) and the US Nuclear Regulatory Commission (NRC) have initiated a multiyear project to investigate the application of burnup credit (BUC) for boiling water reactor (BWR) fuel in storage and transportation systems (often referred to as casks) and spent fuel pools (SFPs). This work is divided into two main phases. The first phase investigated the applicability of peak reactivity methods currently used in SFPs to transportation and storage casks and the validation of reactivity calculations and spent fuel compositions within these methods [1, 2]. The second phase focuses on extending BUC beyond peak reactivity. This paper documents the analysis of the effects of control blade insertion history, and moderator density and burnup axial profiles for extended BWR BUC.

Extended BUC has been applied for pressurized water reactor (PWR) SFPs and storage and transportation casks for a number of years. Peak reactivity analyses have been performed for storage of BWR fuel in SFPs over the last 20 years. In this context, "extended BUC" refers to BWR fuel beyond peak reactivity burnup values, typically greater than 15 to 20 GWd/MTU. (The exact burnup point at which a licensee would use peak reactivity methods or extended BUC methods has yet to be defined.) The existence of two separate methods of BUC in BWRs is associated with the gadolinia burnable absorber used in BWRs. Because of the burnable absorber, the reactivity of the fuel assembly increases from the beginning of irradiation until the gadolinium has been depleted and the reactivity peaks. After the peak, the reactivity of the fuel decreases for the remainder of operation.

To apply full BUC to BWRs, a number of effects need to be analyzed. The operation of BWRs is significantly different from that of PWRs. This paper analyzes three major operational effects in BWRs: the coolant density axial distribution, the use of control blades during operation, and the axial burnup profile. Although some results originally published in [3] will be discussed, the main focus of this paper will be additional studies performed for axial coolant density profile and control blade history, and recent results for the study of the axial burnup profile.

BWR fuel assemblies undergo a significant change in axial moderator density from the bottom to the top of the fuel assembly as a result of boiling of the water coolant. Low moderator density leads to increased plutonium production for the same exposure, leading to effects on cask reactivity. Additionally, BWRs operate using control blades (inserted from the bottom of the core) to control excess reactivity. The use of control blades significantly shifts the power distribution in the reactor and leads to increased plutonium production due to the spectral hardening. The application of a real axial burnup profile has a significant effect on cask reactivity because of the relatively low-burnup at the axial extremities of the fuel.

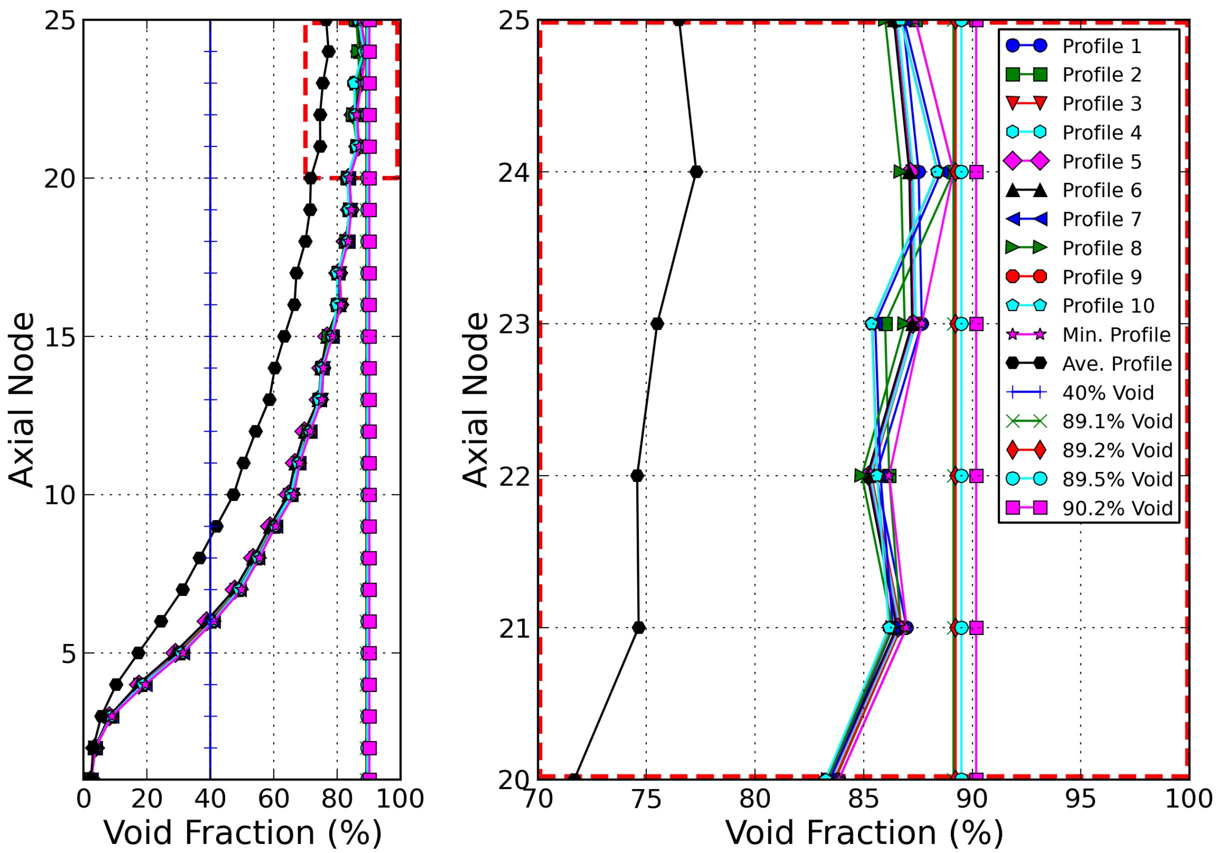
2. Methodology

The SCALE code system [4] was used for all calculations. Either SCALE/TRITON or STARBUCS was used for depletion calculations, whereas SCALE/KENO-Va was used for spent fuel cask criticality calculations. In the study of the axial coolant density profile and axial burnup profile, STARCBUCS was used extensively to generate depleted fuel isotopics. However, for the control blade history studies, SCALE/TRITON was required for depletion calculations because of current limitations in the STARBUCS methodology.

3. Results

3.1. Axial Coolant Density (Void Fraction) Profile

A plot of the axial void profiles can be found in Figure 1. In this figure, the axial void profiles have been expanded for the top six nodes of the 25 in the assembly to show the slight variations that cause differences in reactivity. After initial axial coolant density (or void fraction) profile studies were performed in [3], additional calculations were completed using a number of different uniform coolant density axial profiles. These profiles were modeled to ascertain the level of penalty/conservatism that would result from using a uniform low-density coolant profile over the entire irradiation. Previous studies simulated different axial profiles, including those taken from the core operating data [3]. The "Min" profile corresponds to the minimum void fraction in each axial node of ten real profiles. The "Ave" profile is the average over all fuel assemblies in the core and over the whole cycle of operating time. The uniform profiles (40%, 89.1%, 89.2%, 89.5% and 90.2% void fraction) use the same moderator density in every axial node; however, that density corresponds to a very high void fraction.



(a) Void fraction profiles

(b) Void fraction profiles, expanded for the top six axial nodes

Figure 1. Void fraction profiles used in the axial coolant density profile study.

The cask reactivity values for the actinide and fission product isotope sets can be found in Table I for assembly–average burnup values of 30, 40, and 50 GWd/MTHM. The difference between the most limiting realistic axial void profile (Profile 1) and every other profile has been calculated and included in Table I. The uniform 40% void profile, which is commonly used as a core-average void fraction value, results in nonconservative cask reactivities from -4.8 to -7.3 % Δk_{eff} for assembly average burnup between 30 and 50 GWd/MTHM. For this reason, it is not recommended that the uniform 40% void profile be used for BWR BUC analysis. The core-average moderator density profile results in nonconservative cask reactivities from -2.0 to -2.9 % Δk_{eff} for assembly average burnup between 30 and 50 GWd/MTHM. The "Min" profile is less than 0.1% Δk_{eff} conservative for assembly average burnup between 30 and 50 GWd/MTHM. The uniform high-void profiles from 89.1% to 90.2% void are all conservative by 0.6–1.1 % Δk_{eff} , depending on the profile and burnup point.

Table I. Calculated cask k_{eff} values for the each axial void profile at selected burnup points

	30 GWd/MTU		40 GWd/MTU		50 GWd/MTU	
Profile Name	k_{eff}	$\Delta^{\dagger}$	k_{eff}	$\Delta^{\dagger}$	k_{eff}	$\Delta^{\dagger}$
Profile 1	0.86367	–	0.84389	–	0.82709	–
Profile 2	0.86335	−0.00032	0.84344	−0.00045	0.82645	−0.00064
Profile 3	0.86336	−0.00031	0.84304	−0.00085	0.82614	−0.00095
Profile 4	0.86329	−0.00038	0.84299	−0.00090	0.82639	−0.00070
Profile 5	0.86304	−0.00063	0.84285	−0.00104	0.82614	−0.00095
Profile 6	0.86293	−0.00074	0.84260	−0.00129	0.82583	−0.00126
Profile 7	0.86230	−0.00137	0.84211	−0.00178	0.82528	−0.00181
Profile 8	0.86207	−0.00160	0.84178	−0.00211	0.82485	−0.00224
Profile 9	0.86196	−0.00171	0.84157	−0.00232	0.82476	−0.00233
Profile 10	0.86206	−0.00161	0.84158	−0.00231	0.82473	−0.00236
Min.	0.86438	0.00071	0.84478	0.00089	0.82848	0.00139
Avg.	0.84364	−0.02003	0.81910	−0.02479	0.79799	−0.02910
40% Void	0.81541	−0.04826	0.78298	−0.06091	0.75351	−0.07358
89.1% Void	0.86993	0.00626	0.85040	0.00651	0.83412	0.00703
89.2% Void	0.86998	0.00631	0.85067	0.00678	0.83451	0.00742
89.5% Void	0.87066	0.00699	0.85166	0.00766	0.83549	0.00840
90.2% Void	0.87235	0.00868	0.85341	0.00952	0.83766	0.01057

† Δk_{eff} calculated with respect to the most reactive real profile, Profile 1.

The aforementioned studies all use the same burnup profile for three consecutive operating cycles. This assumption is clearly nonphysical; near the end of the assembly life, the axial void fraction profile is likely to have a relatively low average void fraction because of the limited amount of power produced by the assembly. However, the logic behind this assumption is that any limiting axial void fraction profile repeated for three consecutive cycles will be more limiting than the void fraction profile experienced by a single assembly for any three real cycles.

3.2. Control Blade Histories

Previous work [3] analyzed a number of hypothetical control blade histories, which contain very simplistic control blade patterns. These included control blade histories such as blades inserted for the entire irradiation, blades removed for the entire irradiation, blades inserted for the first half of irradiation, and so on. Through analysis of the hypothetical histories, key k_{eff} sensitivities—such as control blade insertion depth (or elevation), control blade insertion time (early or late in life), and control blade insertion duration— were analyzed.

This study revealed that the fuel cask reactivity is highly sensitive to control blade insertion depth. This sensitivity was further analyzed by running a number of calculations with the control blades inserted to depths between 50 and 100%—inserted for all three consecutive cycles. They showed that the sensitivity to control blade insertion becomes very high when the control blade reaches to the top four nodes in the fuel assembly. That is, the cask reactivity increases nonlinearly as a function of control blade insertion depth in the top four nodes of the fuel assembly. This result highlights the ”end effect” in which the vast majority of fissions in the cask geometry occur in the uppermost nodes of the assembly. This occurs because of the relatively low-burnup fuel in the upper portion of the fuel assembly, combined with the relatively low moderator density in these regions during depletion, and the increased moderation in the axial ends of spent fuel storage and transportation casks.

With the knowledge from the hypothetical history cases and the knowledge that the upper nodes have a disproportionate effect on cask reactivity compared to lower nodes, ten realistic control blade histories expected to be more limiting than others were selected from the operating data. As expected from previous results, control blade histories that contain control blade insertion for any amount of time into the top four axial nodes lead to much higher reactivity than control blade histories with significant control blade insertion at a lesser depth.

3.3. Axial Burnup Profile

All burnup profiles in the operating data are being analyzed as part of this work. These calculations and data analysis are under way but remain to be completed and will be documented in the full paper.

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