Criticality Evaluation of Control Component Credited Mixed Zone Spent and Fresh Fuel Storage In High Density PWR Racks

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Abstract

To expand the set of assemblies that qualify for storage in high-density racks, a mixed zone analysis may be performed where repeating pattern configurations within the rack are prescribed. In a mixed zone analysis, assemblies that are more reactive (low burnup) are stored adjacent to less reactive (highly burned) assemblies, thereby meeting the same overall criticality requirements as with the uniform burnup/enrichment analysis. The Arkansas Nuclear One (ANO) Plant has faced several challenges with respect to their spent fuel storage that reach beyond simply the number of spent fuel assemblies and available storage cells. These issues have resulted in the need for ANO to use an advanced storage strategy. In addition to using the mixed zone burnup approach in the high-density racks, ANO also proposed a new solution involving credit for control components in the spent fuel pool. ANO submitted an amendment of their spent fuel pool technical specifications to the Nuclear Regulatory Commission (NRC) based on the evaluation performed by Holtec International that was subsequently approved. This paper presents a description of the overall methodology used for supporting the submittal, and provides further discussion regarding the reactivity effect of control rods in a PWR spent fuel pool.

KEYWORDS: Burnup Credit, Storage Racks, Spent Fuel, CASMO, MCNP

INTRODUCTION

To accommodate the limited available space in the nuclear plant spent fuel storage pools, several high density, or so-called Region 2, storage racks are currently being used. Since these racks are not capable, from a criticality safety perspective, of storing fresh fuel, it is necessary to take credit for the fuel burnup. In the burnup credit methodology, a criticality analysis is performed in which acceptable minimum burnup requirements are determined to ensure compliance with the regulations [1] for the specific rack and its corresponding stored assembly. The minimum burnup requirements are calculated as a function of initial enrichment such that an acceptable burnup/enrichment curve is concluded in the analysis. While a uniform burnup/enrichment requirement curve for all cells in a given rack would provide operational simplicity, a uniform requirement may not be suitable for a plant's entire spent fuel inventory. To expand the set of assemblies that qualify for storage in high-density racks, a mixed zone analysis may be performed where repeating pattern configurations within the rack are prescribed. In a mixed zone analysis, assemblies that are more reactive (low burnup) are stored adjacent to less reactive (highly burned) assemblies, thereby meeting the same overall criticality requirements as with the uniform burnup/enrichment analysis.

The Arkansas Nuclear One (ANO) Plant has faced several challenges with respect to their spent fuel storage that reach beyond simply the number of spent fuel assemblies and available storage cells. First, their racks contain the Boraflex^{TM} neutron poison material, which was found to degrade over time. Because of this degradation, credit for the absorber is no longer allowed thus increasing the burnup requirements within the racks in order to compensate for this loss of criticality control. Second, ANO has a diverse spent fuel inventory in terms of burnup/enrichment combinations. Of most significance are the several prematurely discharged (highly reactive) assemblies that do not meet a typical burnup/enrichment requirement for a high-density rack, especially considering the loss of Boraflex^{TM} credit. Third, many of the assemblies that have been selected for dry fuel storage are not the highly reactive assemblies that would provide criticality relief in the racks. This is due to one of two reasons, assembly selections resulting from cask-related storage restrictions, or from optimization of the dry storage campaigns based on thermal and dose considerations. Fourth, cells in the spent fuel pool racks are used to temporarily store fresh fuel during refueling outages. These issues have resulted in the need for ANO to use an advanced storage strategy.

In addition to using the mixed zone burnup approach in the high-density racks, ANO also proposed a new solution involving credit for control components in the spent fuel pool. ANO submitted an amendment of their spent fuel pool technical specifications to the Nuclear Regulatory Commission (NRC) based on the evaluation performed by Holtec International that was subsequently approved [2]. This paper presents a description of the overall methodology used for supporting the submittal, and provides further discussion regarding the reactivity effect of control rods in a PWR spent fuel pool.

DESCRIPTION OF THE ACTUAL WORK

The objective of this work is to ensure that the effective neutron multiplication factor (k_{eff}) for the evaluated spent fuel storage configurations is less than or equal to 0.95 with the racks loaded with Combustion Engineering 16 x 16 assemblies and the pool flooded with borated water at a temperature corresponding to the highest reactivity. In addition, it is demonstrated that k_{eff} is less than 1.0 under the assumed accident of the loss of soluble boron in the pool water, i.e. assuming unborated water in the spent fuel pool. The maximum calculated reactivities include a margin for uncertainty in reactivity calculations, including manufacturing tolerances, and are calculated with a 95% probability at a 95% confidence level [3]. The overall methodology for performing this work is adapted from the guidance provided in [4, 5]. This analysis is used to qualify the existing ANO racks for the spent fuel inventory in the pool and in the core, as well as fresh assemblies during re-load. In the evaluation, credit is taken for the presence of soluble boron in the spent fuel pool, fuel burnup, cooling time and for the presence of control element assemblies (CEAs) from the core placed in selected fuel assemblies. In order to successfully store the diverse inventory, it is necessary to establish different checkerboard patterns for assemblies with different reactivities. Five fuel configurations (patterns) were established based on reactivity studies, which are shown in Figure 1, and a description of the assemblies and their reactivity rank (by k_{inf}) is provided in Table 1. All assembly types are pre-defined with the exception of the "C" assembly. Through an iterative process, these evaluations determine the definition of the "C" assembly in terms of burnup, enrichment, and cooling time curves. Each configuration containing a "C" assembly, namely patterns 3, 4, and 5, are analyzed such that a "C" assembly definition can be established that will satisfy the criticality acceptance criteria for all desired loading patterns.

The principal method for the criticality analysis of the storage racks is the three-dimensional Monte Carlo code MCNP [6]. MCNP, a continuous energy code developed at the Los Alamos National Laboratory, was selected because it has been previously validated for use in spent fuel criticality analyses and has all of the necessary features for this evaluation. The MCNP calculations used continuous energy cross-section data based on ENDF/B-V and ENDF/B-VI.

Fuel depletion analyses during core operation were performed with CASMO-4 (using the 70-group cross-section library), a two-dimensional multi-group transport theory code based on collision probabilities [7]. CASMO-4 is also used to determine the isotopic composition of the spent fuel, which is subsequently used in the MCNP criticality calculations. In addition, the CASMO-4 calculations are restarted in the storage rack geometry yielding the two-dimensional infinite multiplication factor (k_{inf}) for the storage rack to determine the reactivity effect of fuel and rack tolerances. In addition to achieving the objective of determining acceptable storage configurations, several studies are also performed such as pattern-to-pattern interfaces, burnout of CEAs, effect of CEA worth as a function of assembly burnup, and postulated accident scenarios.

RESULTS AND SUMMARY OF CONCLUSIONS

Each of the patterns was evaluated in a 3-D MCNP criticality calculation and effects of temperature variations and manufacturing tolerances were considered to determine an upper subcritical limit (USL). A summary of the results is provided in Table 2, showing each of the proposed pattern USL values that meet the acceptance criteria. The minimum burnup/enrichment/cooling time requirements for the "C" assembly type are provided in Table 3. An analysis of all possible adjacent pattern-to-pattern interfaces was performed and determined that not all interfaces were found to meet the acceptance criteria. Subsequently, restrictions were imposed prohibiting certain interfaces. A study of reactivity effects of CEA burnout shows that ^{10}B depletion within the CEAs does not have a significant effect on the calculated multiplication factor in the spent fuel configurations. However, it was determined that the CEA worth decreases as a function of burnup in fuel assemblies that contain CEAs. This is shown in the plot in Figure 2 of burnup vs Δk_{inf} , where Δk_{inf} is the difference in reactivity between assemblies with and without CEAs. A missing CEA and fresh assembly miss-load accident was analyzed to conclude that a minimum soluble boron level of 825 ppm was necessary to prevent a criticality accident under either of these scenarios.

Figure 1: Loading Patterns for ANO-2 Spent Fuel Pool

Bc or A	BC or A
BC or A	Bc or A

Pattern 1

F	X
X	F

Pattern2

F	Cc
Cc	Cc

Pattern 3

Fc	C
C	Fc

Pattern 4

B	C
C	C

Pattern 5

Table 1: Assembly Types, Rank and Description

Rank	Assembly	Description	k-inf
1	F	Fresh Fuel, 4.55 ± 0.05 wt% U-235	1.2413
2	B	4.1% maximum enrichment, 11.3 GWD/MTU minimum burnup, 0 years cooling time, low burnup, typically one cycle	1.1191
3	Fc	Fresh 4.55± 0.05 wt% fuel with a current CEA inserted	1.0520
4	A	An assembly that meets the uniform Region 2 minimum burnup curve requirements	0.9666
5	Bc	A “B” type assembly with a CEA inserted	0.9511
6	C	High burnup, defined by burnup/enrichment/cooling time requirements developed (iteratively) in this work	0.9253
7	Ac	An “A” type assembly with a CEA inserted	0.8516
8	Cc	A “C” type assembly with a CEA inserted	0.8103
9	X	Water cell, no fuel	0.0000

Table 2: Summary of Results for Patterns

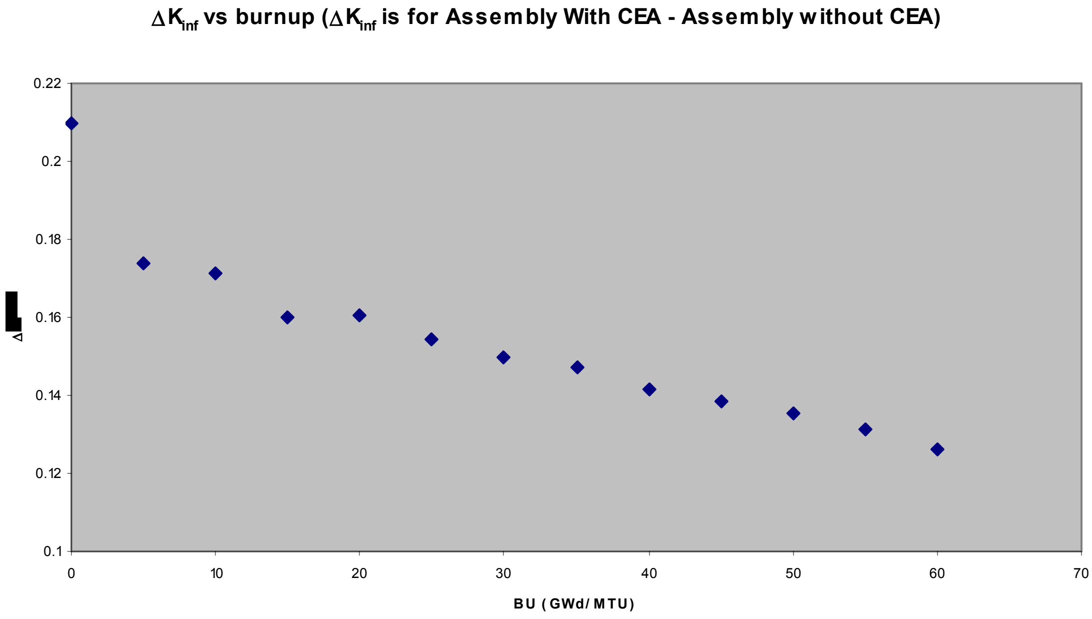
	Pattern 1	Pattern 2	Pattern 3	Pattern 4	Pattern 5
Burnup (GWD/MTU)	43.0	0	49.75	49.75	49.75
Reference* k_{eff}	0.9706	0.9151	0.9758	0.9742	0.9706
MCNP4a Bias	0.0009	0.0009	0.0009	0.0009	0.0009
Temperature Effect	0.0092	0.0101	0.0094	0.0094	0.0094
MCNP Bias Uncertainty	0.0011	0.0011	0.0011	0.0011	0.0011
MCNP Statistics (95/95) Uncertainty	0.0007	0.0007	0.0007	0.0007	0.0007
Manufacturing Tolerance Uncertainty	0.0097	0.0129	0.0096	0.0096	0.0096
Enrichment Tolerance Uncertainty	0.0033	0.0019	0.0033	0.0033	0.0033
Depletion Uncertainty	0.0136	N/A	0.0070	0.0092	0.0136
Fuel Eccentric Positioning Uncertainty	0.0021	0.0002	0.0010	0.0010	0.0022
Statistical Combination of Uncertainties	0.0172	0.0131	0.0124	0.0138	0.0171
USL (For k<1)	**0.9727**	**0.9759**	**0.9773**	**0.9759**	**0.9725**
USL (For k<0.95)**	**0.9227**	**0.9259**	**0.9273**	**0.9259**	**0.9225**

* Calculated with unborated water ** An acceptable level of soluble boron allowed to meet this level

Table 3: "C" Assembly Requirements

	BURNUP, GWD/MTU				
Enrichment, wt% U^{235}	**0 Years Cooling Time**	**5 Years Cooling Time**	**10 Years Cooling Time**	**15 Years Cooling Time**	**20 Years Cooling Time**
2	17	15	14	13.3	13
2.5	25	22	21	20.3	20
3	32	29	27	26	25
3.5	37	35	32.5	31	30
4	43	40	39	38	37
4.5	49.75	46	45	44	43

Figure 2: Effect of Assembly Burnup vs Difference in Reactivity Between Assemblies With and Without CEAs



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