Abstract
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Development of a Comprehensive Fuel Assembly Criticality Safety Model that Groups Multiple Fuel Assembly Designs as One Content Type for Type AF Packages

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1. Abstract

Traditionally, fresh fuel assembly shipments in Type A, fissile packaging require analyzing and licensing specific individual fuel assembly designs as separate contents. This method is cumbersome and can reveal proprietary data. In addition, any minor change in the dimensions of a design could require a new analysis to demonstrate continued compliance. To mitigate this issue, a new criticality analysis method was developed to arrange fuel assembly designs with similar parameters into bounding groups that represent a single comprehensive fuel assembly (CFA). Fuel assembly designs are then grouped by the primary parameters that contribute a large part to the criticality of the system, which include lattice size (i.e. 17x17), fuel rod pattern (i.e. the number and location of fuel rods and non-fuel holes), and nominal fuel rod pitch. The bounding CFA is developed through analysis by modeling all combinations of the fuel designs' most reactive secondary parameters, which consist of fuel pellet diameter and radial cladding dimensions. The CFA is then analyzed in the single package and package array analyses to demonstrate compliance with the transport regulations. For a fuel assembly to be shipped in the package, it must match the primary parameters of a CFA and be bounded by the secondary parameters specified for the CFA. This method has been licensed for a Type AF, PWR fresh fuel package. Application of the criticality method has reduced the number of fuel assemblies specified in the certificate of compliance by approximately half. In future analyses, this method may be improved further by collecting a larger number of fuel assemblies into a grouping with one representative CFA, for example, based on lattice size (i.e. 17x17).

2. Introduction

Shipping fresh, unirradiated fuel assemblies often requires very detailed, long certificates of compliance (CoC) that describe the dimensions of each fuel assembly design relevant to criticality safety in extreme detail. This is necessary because traditional criticality safety analyses for fresh fuel assemblies credit the exact dimensions of each fuel assembly to demonstrate compliance. While these exacting analyses are perfectly suitable for transporting current fuel assembly designs, the method is not acceptable with respect to exposure of proprietary fuel information; defining strict limits on contents, such that a slight change to a dimension requires a new analysis; and the sheer amount of information presented in a CoC.

To address these issues, a categorized fuel assembly (CFA) method has been developed to reduce the number of fuel assembly designs specified, increase the robustness of the CoC with respect to accommodating slight design changes in fuel assembly designs, and shield the fuel designers against proprietary information exposure. This paper describes the CFA method, including how fuel assembly designs are grouped together for analysis and how bounding CFAs are determined.

3. Method

Fuel assembly designs are grouped together into bins based on the primary parameters of lattice size, fuel rod pattern, and nominal fuel rod pitch. A bounding configuration, the categorized fuel assembly

(CFA), was determined for each bin of fuel assemblies based on the most reactive secondary parameters, consisting of fuel pellet diameter, fuel-clad gap, and cladding thickness. The CFA was determined by comparing the infinite neutron multiplication factors of infinite arrays of fuel assemblies. To determine the most reactive configurations with as few variables as possible, packaging was not modeled in the determination of the CFA. This analysis was performed with the SCALE 6.1.2 code package.

3.1. Grouping Fuel Assembly Designs into Bins

Fuel assembly designs are organized into bins based on three primary parameters: lattice size (e.g., a 17x17 fuel rod lattice), fuel rod pattern (i.e., the locations of fuel rods and non-fuel holes), and nominal fuel rod pitch. Consider the four fuel assembly designs in Table 1. There are two parts to a bin name: the “16” indicates a 16x16 fuel rod lattice and the “1” indicates this is the first bin with this lattice size, and there can be multiple bins with the same lattice size, for example, “16 Bin 2.” Based on all three primary parameters, the 16B1A fuel assembly design was put in “16 Bin 1.” The 16B2A, 16B2B, 16B2C fuel assembly designs were put in “16 Bin 2” because they all share lattice size, fuel rod pattern, and fuel rod pitch. Although the 16B1A fuel assembly design shares the same number of fuel rods and non-fuel holes with the 16B2A, 16B2B, and 16B2C fuel assembly designs, 16B1A was grouped separately into 16 Bin 1 because it has a different fuel rod pattern (i.e., the fuel rods and non-fuel holes are not in the same location, Figure 1) and fuel rod pitch compared to the three other fuel assembly designs.

Table 1: Bin Organization EXAMPLE

Parameter	16 Bin 1	16 Bin 2		
Primary Parameters of Fuel Assembly Designs				
Fuel Assembly Design	16B1A	16B2A	16B2B	16B2C
Lattice Size	16 x 16	16 x 16	16 x 16	16 x 16
No. of Fuel Rods	236	236	236	236
No. of Non-Fuel Holes	20	20	20	20
Nominal Fuel Rod Pitch (in.)	0.56	0.51	0.51	0.51
Secondary Parameters of Fuel Assembly Designs				
Nominal Fuel Pellet Diameter (in.)	0.36	0.32	0.33	0.32
Nominal Clad Inner Diameter (in.)	0.37	0.33	0.34	0.34
Nominal Clad Outer Diameter (in.)	0.42	0.37	0.38	0.38

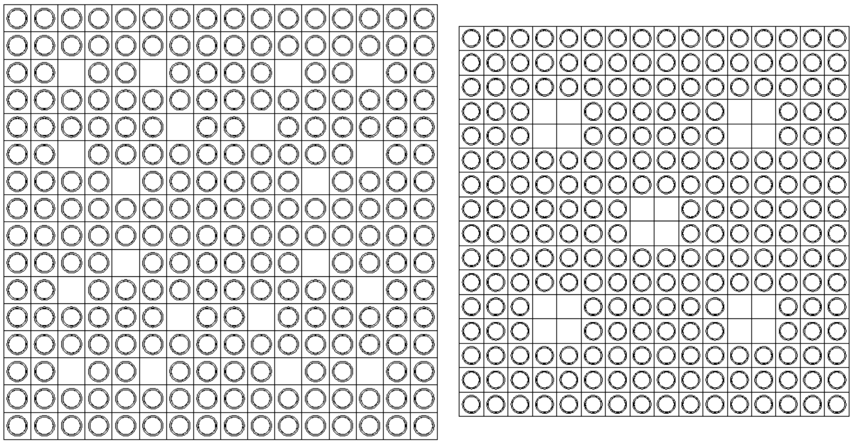

Figure 1: Fuel Rod Patterns of 16B1A (left) and 16B2A, 16B2B, and 16B2C (right). Not to scale.

3.2. Creating Generic Fuel Assemblies

To create a bounding CFA, first, many generic fuel assemblies were made and analyzed that encompassed the complete range of secondary parameters of a bin. The ranges for each secondary parameter, consisting of fuel pellet diameter, fuel-clad gap, and cladding thickness, were determined based on the nominal dimensions and tolerances of each fuel assembly design in a bin. Tolerances were included to provide a margin based on a real dimension in the secondary parameter ranges.

3.2.1. Fuel Pellet Radius Range

The fuel pellet radius range of a bin was determined using the nominal fuel pellet diameters of the fuel assemblies of that bin and their tolerances. If a bin had only one nominal fuel assembly design, the fuel pellet diameter range consisted of the nominal fuel pellet diameter of that fuel assembly design plus or minus one tolerance (e.g., 17 Bin 2 in Table 2). If there was more than one fuel assembly design in a bin, upper and lower limits were defined in the following way: the upper limit of the range was the largest nominal fuel pellet diameter of the bin plus the largest tolerance and the lower limit was the smallest nominal fuel pellet diameter of the bin minus the largest tolerance. The range then consisted of the upper and lower limits and two additional, equally spaced intervals between the upper and lower limits (e.g., 16 Bin 2 in Table 2).

Table 2: Fuel Pellet Radius Range Determination EXAMPLE

	16 Bin 2			**17 Bin 2**
Dimensions	**16B2A**	**16B2B**	**16B2C**	**17B2A**
Fuel Diameter Example (in.)	0.32	0.33	0.32	0.32
Fuel Diameter Tolerance Example (in.)	0.001	0.001	0.001	0.0015
Minus Radius (in.)	0.1595	0.1645	0.1595	0.1585
Nominal Radius (in.)	0.16	0.165	0.16	0.16
Plus Radius (in.)	0.1605	0.1655	0.1605	0.1615
Lower Limit (in.)	0.1595			0.1585
Interval 1 (in.)	0.1615			0.16

	16 Bin 2			**17 Bin 2**
Dimensions	**16B2A**	**16B2B**	**16B2C**	**17B2A**
Interval 2 (in.)	0.1635			-
Upper Limit (in.)	0.1655			0.1615

3.2.2. Fuel-Clad Gap Range

Although cladding inner diameter (ID) and cladding outer diameter (OD) are the dimensions reported for fuel assembly designs, these secondary parameters were examined as *fuel-clad gap* (cladding inner radius – fuel pellet radius) and *cladding thickness* (cladding outer radius – cladding inner radius). Evaluating the cladding ID and OD as a gap and thickness produced several benefits, such as model simplification through dimension stacking, easily observable trends in k_∞, and did not result in unrealistic modeling, i.e., generic fuel assemblies with a fuel-clad gap five times larger than any nominal fuel-clad gap.

The fuel-clad gap range of a bin was determined using the nominal fuel pellet diameters and cladding IDs of the fuel assembly designs of that bin and their respective tolerances. The nominal fuel-clad gap is half the difference of the cladding ID and the fuel pellet diameter. The fuel-clad gap tolerance is equivalent to the average of the fuel diameter tolerance and the cladding ID tolerance.

If a bin contained a single fuel assembly design, the fuel-clad gap range was the nominal fuel-clad gap plus or minus one tolerance (e.g., 17 Bin 2 in Table 3). If a bin contained multiple fuel assembly designs, the lower limit of the fuel-clad gap range was the smallest fuel-clad gap minus its tolerance and the upper limit was the largest fuel-clad gap plus its tolerance, with two equally spaced intervals in between (e.g., 16 Bin 2 in Table 3).

Table 3: Fuel-Clad Gap Range Determination EXAMPLE

	16 Bin 2			**17 Bin 2**
Dimensions	**16B2A**	**16B2B**	**16B2C**	**17B2A**
Fuel Diameter (in.)	0.32	0.33	0.32	0.32
Cladding ID (in.)	0.33	0.34	0.34	0.33
Fuel Diameter Tolerance (in.)	0.0010	0.0010	0.0010	0.0015
Cladding ID Tolerance (in.)	0.0020	0.0020	0.0020	0.0030
Fuel-Clad Gap Tolerance (in.)	0.0015	0.0015	0.0015	0.00225
Minus Gap (in.)	0.0035	0.0035	0.0085	0.00275
Nominal Gap (in.)	0.0050	0.0050	0.0100	0.00500
Plus Gap (in.)	0.0065	0.0065	0.0115	0.00725
Lower Limit (in.)	0.00350			0.00275
Interval 1 (in.)	0.00617			0.005
Interval 2 (in.)	0.00883			-
Upper Limit (in.)	0.01150			0.00725

3.2.3. Cladding Thickness Range

The cladding thickness range of a bin was determined using the nominal cladding IDs and ODs of the fuel assembly designs of that bin and their respective tolerances. The nominal cladding thickness of a fuel assembly is half the difference of the cladding OD and the cladding ID. Like the fuel-clad gap, cladding thickness also does not have an explicitly defined tolerance. Instead, its tolerance is the average of the cladding OD and ID tolerances.

If a bin contained a single fuel assembly design, the cladding thickness range was the nominal cladding thickness plus or minus one tolerance (e.g., 17 Bin 2 in Table 4). If a bin contained multiple fuel assembly designs, the lower limit of the cladding thickness range was the smallest cladding thickness minus its tolerance and the upper limit was the largest cladding thickness plus its tolerance, with two equally spaced intervals in between (e.g., 16 Bin 2 in Table 4).

Table 4: Cladding Thickness Range Determination EXAMPLE

	16 Bin 2			**17 Bin 2**
Dimensions	**16B2A**	**16B2B**	**16B2C**	**17B2A**
Cladding ID (in.)	0.33	0.34	0.34	0.33
Cladding OD (in.)	0.37	0.38	0.38	0.38
Cladding ID Tolerance (in.)	0.0020	0.0020	0.0020	0.0030
Cladding OD Tolerance (in.)		0.0030	0.0030	
Cladding Thickness Tolerance (in.)		0.0025	0.0025	
Minus Thickness (in.)	0.0180	0.0175	0.0175	0.022
Nominal Thickness (in.)	0.0200	0.0200	0.0200	0.025
Plus Thickness (in.)	0.0220	0.0225	0.0225	0.028
Lower Limit (in.)	0.01750			0.022
Interval 1 (in.)	0.01917			0.025
Interval 2 (in.)	0.02083			-
Upper Limit (in.)	0.02250			0.028

3.3. Generic Fuel Assembly Model

Generic fuel assemblies (GFAs) were modeled in a hexagonally-pitched array that was infinite in the X-Y-plane by modeling white boundary conditions on the lateral faces of the hexagonal prism, with 30.48 cm of full-density, light water reflection in the Z direction (the long axis of the fuel assembly) and void between the flooded fuel assembly envelope and the boundaries of the model (Figure 2). The pitch of the fuel assemblies in the infinite array takes credit for the spacing afforded by standard PWR packaging designs (X-Y cross-section in Figure 2).

Several modeling conditions were chosen for this analysis that are bounding of actual conditions:

1. UO_2 was modeled at theoretical density (10.96 g/cm^3) and at an enrichment of 5-wt% ^{235}U, with the remaining uranium modeled solely as ^{238}U.
2. All water was modeled as full-density light water at room temperature.

3. No credit was taken for fuel pellet dishing or chamfering in this analysis, as no individual fuel pellets are modeled. Instead, the fuel was modeled as one continuous cylinder of UO_2.
4. The entire fuel assembly envelope was modeled as flooded with light water, including all fuel-clad gaps. The fuel-clad gaps were flooded as a bounding conservatism.

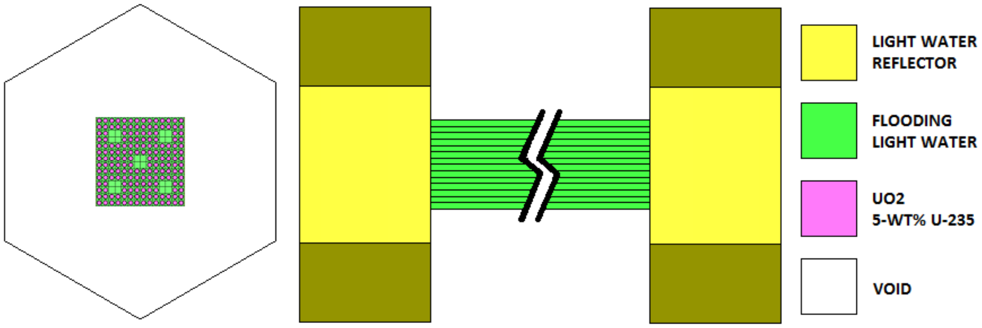

Figure 2: X-Y (left) and X-Z (right) cross-sections of the generic fuel assembly array model. Not to scale.

3.4. Determination of Categorized Fuel Assemblies

The CFA is the most reactive combination of primary and secondary parameters of a bin. To determine the CFA, three comparative studies were performed with the GFAs of a bin that examined the individual effect on k_∞ of secondary parameters (i.e., fuel pellet radius, fuel-clad gap, and cladding thickness). Each GFA modeled a unique combination of all three secondary parameters. To examine the effect of each secondary parameter on k_∞, one secondary parameter was varied while the other secondary parameters were held constant.

3.4.1. Fuel-Clad Gap Study

The fuel-clad gap ranges examined were very small, which made it hard to clearly determine a trend indistinguishable from statistical noise. Therefore, additional cases were added to all fuel-clad gap studies; represented by "Extra" cases in Table 5 and light blue points in Figure 3. Linear regression curves and R^2 values were added to the fuel-clad gap study plots to better highlight the trends involved and prove the effect from fuel-clad gap on k_∞.

For example, the most reactive GFA of 15 Bin 1 was case 15bin1_1_1_1_in. To determine the effect of fuel-clad gap on k_∞, the other GFAs that modeled the same fuel pellet radius and cladding thickness as the most reactive GFA, but which modeled varying fuel-clad gaps (i.e., cases 1_2_1, 1_3_1, and 1_4_1), were compared to the most reactive GFA, case 1_1_1 (see Table 5).

Table 5: Fuel-Clad Gap Effect EXAMPLE - 15 Bin 1

Case	Delta from Minimum (cm)	$k_\infty + 2\sigma$
Extra1	-0.00508	1.42685
Extra2	-0.00254	1.42628
15bin1_1_1_1_in	0.0	1.42630
15bin1_1_2_1_in	0.00170	1.42608

Case	Delta from Minimum (cm)	$k_\infty + 2\sigma$
15bin1_1_3_1_in	0.00340	1.42601
15bin1_1_4_1_in	0.00511	1.42589
Extra3	0.00765	1.42577
Extra4	0.01019	1.42510

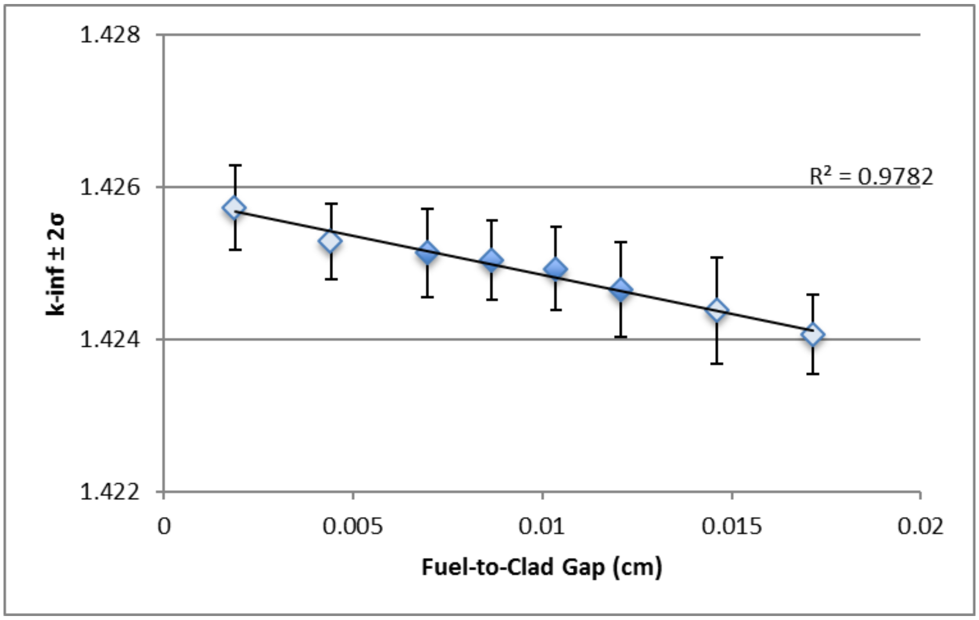

Figure 3: Trend Plot of Fuel-Clad Gap Effect EXAMPLE - 15 Bin 1

3.4.2. Fuel Pellet Radius Study

The fuel pellet radius range of each bin was analyzed to determine the bounding fuel pellet radius. The method here is identical to the fuel-clad gap study: the most reactive GFA is the starting point of the study. From there, the fuel-clad gap and cladding thickness of that case are held constant as the fuel pellet radius is varied to determine the effect of fuel pellet radius on k_∞. For bins with fuel pellet radius ranges that were too small to produce trends indistinguishable from statistical noise, extra cases were added to extend the range.

3.4.3. Cladding Thickness Study

The cladding thickness range of each bin was analyzed to determine the bounding cladding thickness. The method here is identical to the fuel-clad gap study: the most reactive GFA is the starting point of the study. From there, the fuel pellet radius and fuel-clad gap of that case are held constant as the cladding thickness is varied to determine the effect of cladding thickness on k_∞. All bins had cladding thickness ranges that were sufficiently large enough to see a meaningful trend distinguishable from statistical noise, therefore, no additional cases were added.

4. Results and Discussion

4.1. Categorized Fuel Assemblies

For each bin, the minimums of all secondary parameters analyzed produced the bounding CFA by maximizing k_∞. Because fuel assemblies are under-moderated by design, reducing the volume of any non-water components allows more water to be present, thus allowing more moderation and an increase in neutron multiplication.

Reducing the fuel pellet diameter and the cladding thickness have nearly identical effects on increasing the reactivity of the system (see Table 6 and Figure 4). Reducing the fuel-clad gap does not have as pronounced an effect on increasing the reactivity of the system due to the competing effects of reducing the volume of water in the fuel-clad gap while simultaneously reducing the ID and OD of the cladding, which increases the volume of water in the fuel assembly.

Table 6: Effect of Secondary Parameters on Reactivity for 15 Bin 1 EXAMPLE

Case	Delta from Minimum (cm)	$k_\infty + 2\sigma$
Fuel Pellet Radius		
15bin1_1_1_1_in	0.0	1.42572
15bin1_2_1_1_in	0.00348	1.42433
15bin1_3_1_1_in	0.00697	1.42232
15bin1_4_1_1_in	0.01046	1.42101
Fuel Clad Gap		
15bin1gp_1_in	-0.00508	1.42629
15bin1gp_2_in	-0.00254	1.42578
15bin1_1_1_1_in	0.0	1.42572
15bin1_1_2_1_in	0.00170	1.42556
15bin1_1_3_1_in	0.00340	1.42547
15bin1_1_4_1_in	0.00511	1.42527
15bin1gp_3_in	0.00765	1.42507
15bin1gp_4_in	0.01019	1.42458
Cladding Thickness		
15bin1_1_1_1_in	0.0	1.42572
15bin1_1_1_2_in	0.00613	1.42342
15bin1_1_1_3_in	0.01227	1.42033
15bin1_1_1_4_in	0.01840	1.41667

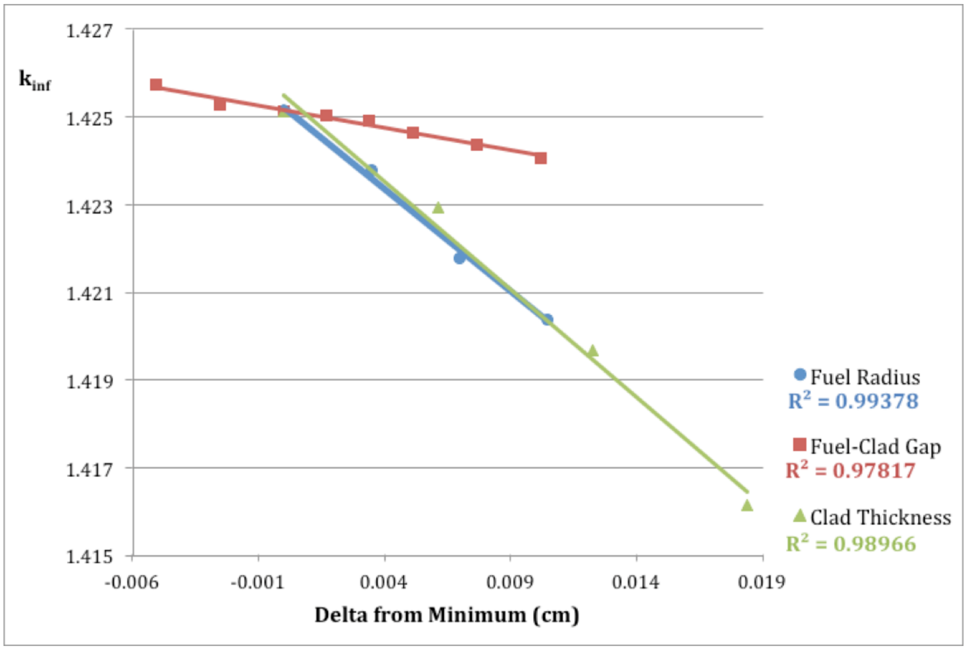

Figure 4: Trend Plot of Effect of Secondary Parameters on k-inf – 15 Bin 1

Analyzing CFAs that are bounding of several fuel assembly designs has a trade-off. Analyzing CFAs that are bounding of more and more fuel assembly designs means the reactivity will increase and the consignment size may have to be restricted accordingly. However, the CFA method produces gains in simplicity in the CoC and robustness in accepting future fuel designs with the potential for no further criticality safety analyses.

4.2. Future Improvements to the CFA Method

Taking the CFA method presented in this paper forward to its logical conclusion results in a single CFA to represent all fuel assembly designs of a package. What would it take to get to that point?

Of the primary parameters used to define a bin, the easiest variable to incorporate into the CFA method would be fuel rod pitch, as it is a simple variable like fuel pellet radius and cladding diameter that does not have a lot of variance among designs. The consequence of including fuel rod pitch would be that the addition of another variable could greatly increase the number of cases analyzed. In addition, adding fuel rod pitch alone may have minimal gains, as it may only reduce the number of fuel assembly designs in the CoC by a small amount. It is not common for separate fuel assembly designs with the same fuel rod pattern to have different fuel rod pitches.

The next variable to incorporate would be fuel rod pattern, i.e., the number and location of fuel rods and non-fuel holes. Analyzing this variable by itself with traditional methods would require an immense number of cases. Considering the sensitivity of the number of non-fuel holes and their location in the fuel lattice alone would be a very large analysis. Perhaps a ¼ model geometry should be considered. Newer analytical codes, such as the SCALE code TSUNAMI, seem to be purpose-built for such a sensitivity analysis. However, once the CFA method is reintroduced, it is not clear what effect that would have on the non-fuel hole sensitivity analysis, specifically, the effect between non-fuel holes and secondary parameters such as cladding thickness and how many cases would have to be analyzed. With respect to value for the customer, the effort necessary to do the fuel rod pattern sensitivity seems worthwhile because this change has the potential to greatly reduce the number of assemblies in the CoC, as it is quite common for several, separate fuel assembly designs to share a given lattice size (e.g., 17x17). Combining fuel assembly designs on the basis of fuel rod pattern would further reduce the complexity of the CoC.

The final variable is fuel lattice size (e.g., 17x17). The result of incorporating this variable into the CFA method would be to have one CFA that represents all fuel assemblies that could be shipped in the package. The level of effort required to collapse all lattice sizes into a single, bounding CFA for all fuel assembly designs of a package seems as if it may not be worth it or even necessary. Deciding to have several, separate CFAs in the CoC instead of completely reducing all fuel assembly designs to one CFA may in fact be more advantageous. In the instance where a new fuel assembly design is not covered by the single CFA, the entire analysis may have to be redone to include the new design. With a CoC that has several, separate CFAs, only one of those CFA analyses would have to be reevaluated. The importance of this cannot be understated, as one of the major bases for developing the CFA method was to reduce or eliminate the impact of adding new fuel assembly designs to a package license. Thus, completely reducing the CoC to one CFA may have the counter-intuitive effect of increasing the work required to add a new fuel assembly design to a package license compared to some more work up front to specify separate, nominal fuel assembly designs in the CoC. Therefore, it may be practical to stop expanding the CFA method at fuel lattice size and have a CoC with a CFA for 14x14 fuel assemblies, a CFA for 15x15 fuel assemblies, etc.

5. Conclusions

The categorized fuel assembly (CFA) method reduces the number of fuel assembly designs specified in a certificate of compliance (CoC), reduces the exposure of proprietary information, and adds a degree of robustness to allow for small changes in existing fuel assembly designs and, to a certain degree, new fuel assembly designs with no additional analyses.

This first application of the CFA method had good results by reducing the fuel assembly designs specified by one third. Future reductions in the number of fuel assembly designs specified in the CoC could be realized by considering the fuel rod pitch and fuel rod pattern as variables in grouping fuel assembly designs into bins.