# *Insert Modeling in UNF ST&NDARDS*

**Spent Fuel and Waste Disposition**

***Prepared for***
***US Department of Energy***
***Spent Fuel and Waste Science and Technology***

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# 1. INTRODUCTION

The Used Nuclear Fuel-Storage, Transportation & Disposal Analysis Resource and Data System (UNF-ST&DARDS) is a software tool that integrates a used nuclear fuel (UNF) or spent nuclear fuel (SNF) relational database and key analysis capabilities to simplify and automate numerous UNF management and fuel cycle–related activities [1]. UNF-ST&DARDS is being developed for the US Department of Energy's Office of Nuclear Energy Spent Fuel and Waste Disposition program. UNF-ST&DARDS provides an integrated framework that uses advanced modeling and simulation to predict the behavior of SNF over the timescales associated with permanent disposal in a geologic repository. After leaving the spent fuel pool, SNF is transferred to dry storage in a dual-purpose canister (DPC). DPCs are considered "dual purpose" because they are designed for both storage and transportation, removing the need to transfer the fuel to a separate transportation cask. However, much research has been conducted investigating the feasibility of directly disposing of DPCs in geologic repositories [2], [3], [4]. Direct disposal of DPCs could reduce worker exposure during repackaging, reducing the amount of low-level waste from the discarded DPCs and potentially saving billions of dollars [2]. Therefore, direct disposal of as-loaded DPCs is desirable if it can be done safely.

However, DPC designs could achieve criticality under certain circumstances over the timescales associated with permanent disposal. For this to occur, a moderator must be introduced to the DPCs. Using a conservative, worst–case-scenario approach, all air in the DPC models is replaced with pure water. This postulated water ingress increases the canister reactivity and can also degrade neutron poison materials, further increasing reactivity.

Of the UNF-ST&DARDS DPC direct disposal analyses to date, none have accounted for the effects of inserts that are often placed in the canisters along with the fuel. Control rods, also called *rod cluster control assemblies (RCCAs)*, can be left in the guide tubes of an assembly that is then placed into a DPC. Additionally, discrete burnable poisons, such as Pyrex (borosilicate glass) or wet annular burnable absorbers (WABAs), can also be placed in the guide tubes of select assemblies before being placed in the canister. Although Pyrex and WABA no longer contain substantial neutron poisons after one cycle, they displace water in the flooded DPC scenario, reducing the overall eigenvalue.

The purpose of this work is to incorporate the ability to model these inserts in UNF-ST&DARDS. This proof-of-concept work analyzed the 61 DPCs at the Zion Nuclear Power Station. Zion is a shutdown reactor site in Illinois, and many of its assemblies have high enrichments and low burnup, making them more reactive than typical SNF placed in DPCs. Additionally, Zion was chosen because of the detailed insert data available in the UNF-ST&DARDS database; not all sites have these data readily available.

Section 2 describes the implementation of these inserts and the DPCs. Then, Section 3 details the results from these models. Finally, Section 4 presents the conclusions drawn from these results and plans for future work.

# 2. MODELS

## 2.1 INSERT MODELS

Six types of inserts, or nonfuel components, are placed in the Zion DPCs along with the fuel: WABA, Pyrex, RCCAs, thimble plugs, neutron source assemblies (NSAs), and hafnium flux reduction assemblies (HFRAs). However, this work models only WABA, Pyrex, and RCCAs. Thimble plugs were neglected because of their relatively short length and because they are located at the top of the plenum, far away from the fuel. The NSAs and HFRAs were omitted because of a lack of information about their compositions and dimensions. These omissions are conservative because not including them in these models displaces less water, thus increasing reactivity slightly. Descriptions of the included inserts are given in the following sections.

### 2.1.1 WABA

WABA is a discrete burnable absorber that is used in loading strategies to reduce excess reactivity at the start of a cycle to improve fuel performance and fuel cycle economics. A WABA rod consists of two concentric Zircaloy-4 tubes that contain annular $B_4C$ burnable absorber material. The central annulus is allowed to fill with flowing coolant to enable increased thermalization near the absorber, resulting in a more complete burnup of the poison during the cycle. This leads to a small residual effect near the end of the cycle. The WABA dimensions used in this work were taken from Table 4-3 of Bishop and Clarity [5] which is recreated in Table 1. A depiction of a WABA rod is shown in Figure 1 in which the blue regions represent the water that has flooded the pin, the green regions represent the Zircaloy-4 cladding for the guide tube and the WABA, and orange represents the $B_4C$ burnable absorber material. Because WABAs are assumed to be completely depleted after one cycle, the $^{10}B$ concentration was set to zero for all cases in this work.

**Table 1. Pyrex and WABA specifications**

| Parameter | Pyrex | WABA |
|---|---|---|
| Burnable Absorber Material | Borosilicate Glass | $B_4C$ |
| Inner Diameter, inch | 0.2440 | 0.2780 |
| Outer Diameter, inch | 0.3890 | 0.3180 |
| Clad Material | SS | Zr |
| Inner Clad Thickness, inch | 0.0065 | 0.0210 |
| Inner Clad Outer Diameter, inch | 0.2360 | 0.2670 |
| Outer Clad Thickness, inch | 0.0188 | 0.0260 |
| Outer Clad Outer Diameter, inch | 0.4310 | 0.3810 |

### 2.1.2 PYREX

Pyrex is a discrete burnable absorber that is used similarly to WABA. However, instead of using a $B_4C$ burnable absorber material, Pyrex consists of a borosilicate glass. Although WABA rods are intended to be wet, Pyrex rods are sealed at the bottom, and the annulus is filled by an inert gas. Additionally, the rod cladding is made of stainless steel instead of Zircaloy-4. The dimensions of the Pyrex rods were taken from Table 4-3 of Bishop and Clarity [5] and are shown in Table 1. A cross-sectional representation of a Pyrex rod is shown in Figure 2; the black region is the borosilicate glass material, the yellow region is the stainless-steel cladding, and the white region is He. To be as conservative as possible, a flooded case was also tested in which the He was replaced with water. A depiction of this flooded Pyrex rod is shown in Figure 3. Because Pyrex are assumed to be completely depleted after one cycle, the $^{10}B$ concentration was set to zero for all cases in this work.

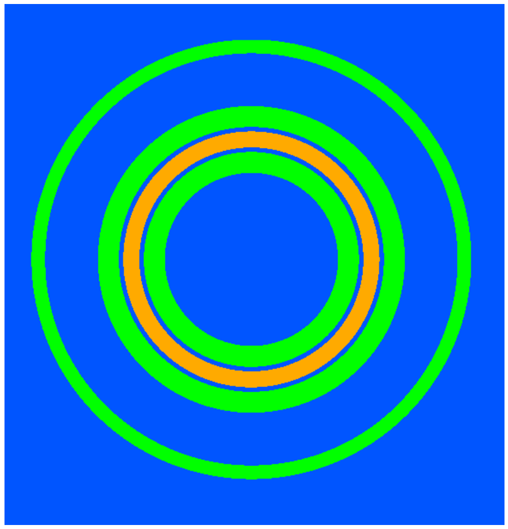


**Figure 1. Radial material distribution of a WABA rod.**

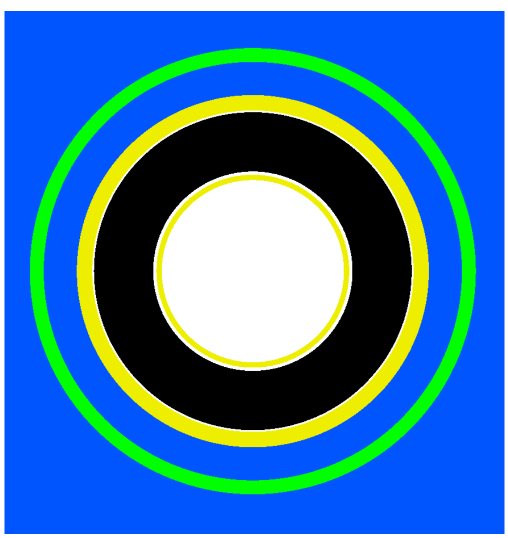


**Figure 2. Radial material distribution of a Pyrex rod.**

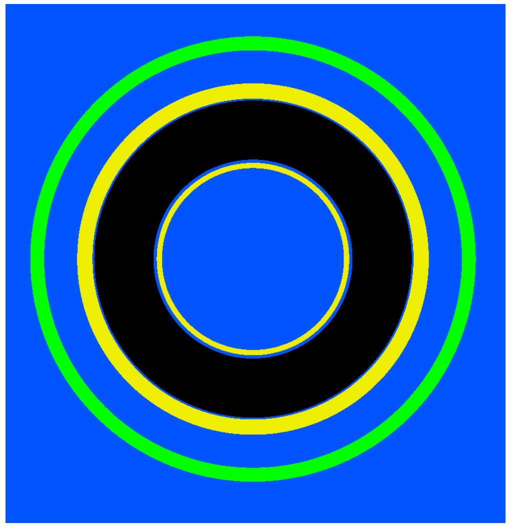


**Figure 3. Radial material distribution of a flooded Pyrex rod.**

### 2.1.3 RCCA

RCCAs are the primary source of reactivity control in a reactor and are used to control the power at startup and shutdown in addition to other power maneuvers. They also are an important component of the emergency shutdown system. The RCCA dimensions that were used in this work were taken from Table 4-2 of Bishop and Clarity [5] which is reproduced in Table 2. The absorber material modeled was Ag-In-Cd (AIC), an alloy consisting of 80% Ag, 15% In, and 5% Cd by weight. The AIC absorber is contained within a stainless-steel outer cladding and is inserted into the assembly guide tubes. A depiction of the RCCA geometry is shown in Figure 4 in which gray is the AIC absorber and yellow is the stainless-steel cladding. For conservatism, the gap between the AIC and the clad is assumed to be flooded, although it will have a negligible effect on the overall reactivity.

**Table 2. RCCA specifications**

| Parameter | Value |
|---|---|
| Material | Silver-Indium-Cadmium |
| Silver content, wt% | 80 |
| Indium content, wt% | 15 |
| Cadmium content, wt% | 5 |
| Poison outer diameter, inch | 0.3900 |
| Clad inner diameter, inch | 0.4005 |
| Clad outer diameter, inch | 0.4390 |
| Clad material | SS |
| Poison density, g/cc | 10.17 |

Unlike the discrete burnable absorbers described in the preceding sections, RCCAs are designed to be extremely potent and to not burn away by the end of a cycle. Additionally, when at hot full power, the control rods spend most of the cycle withdrawn from the core and do not accumulate much burnup. However, to err on the side of conservatism, a study was performed to examine the depletion of an RCCA in which one 2D lattice model was depleted at hot full power for over 3 years with the control rods inserted.

All three elements that constitute the AIC absorber contain isotopes that have thermal neutron absorption

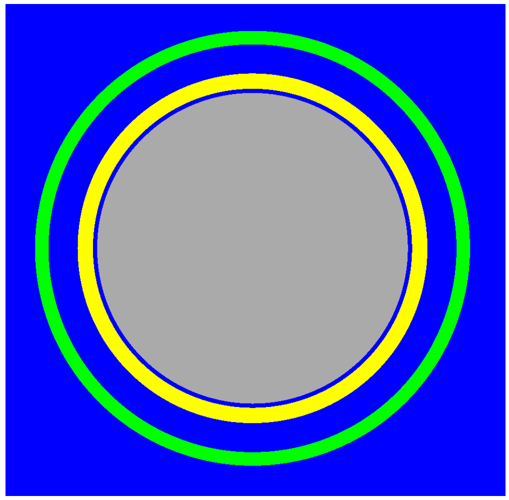


**Figure 4. Radial material distribution RCCA control rod.**

cross sections: $^{109}$Ag, $^{115}$In, and $^{113}$Cd [6]. However, as shown in Figure 5, the $^{113}$Cd thermal cross section is roughly 100 times larger than the other isotopes. Therefore, the depletion of $^{113}$Cd was used to determine the remaining potency of the RCCA after depletion.

Silver has two stable, naturally occurring isotopes; In has two; and Cd has eight. The changes in these 12 AIC isotope concentrations over the course of the depletion are shown in Figure 6 as a percent of the initial loading. As shown in Figure 6, all isotopes either increase or remain largely unchanged, except $^{113}$Cd. The increases in $^{108}$Cd, $^{110}$Cd, and $^{114}$Cd are products of neutron captures of $^{107}$Ag, $^{109}$Ag, and $^{113}$Cd, respectively. By the end of the depletion, $^{113}$Cd was reduced to 56% of its initial enrichment. Therefore, a conservative 50% concentration was used to model the AIC absorber material in each RCCA in this work.

To estimate the effect of this assumption on the reactivity, each Zion DPC that contains an RCCA was modeled with seven different AIC densities: 0, 10, 30, 50, 70, 90, and 100% of the nominal density. Of the 61 DPCs at the Zion site, 39 are loaded with discarded RCCAs. A plot of each canister's eigenvalue as a function of RCCA density is shown in Figure 7. The DPCs that contain only a few RCCAs show very little difference in eigenvalue, regardless of the concentration of AIC. The DPCs with the most RCCAs only begin to exhibit significantly higher eigenvalues with concentrations less that 30%. At 50%, all canisters have relative differences of less than 1% compared with the 100% full-strength eigenvalue. Therefore, the conservative 50% AIC concentration will not have a significant effect compared with modeling full-strength RCCAs, but it will be significantly different from not modeling the RCCAs at all.

### 2.1.4 INSERT PATTERNS

The number of inserts in a given assembly within a DPC are assumed by the component ID name associated with that assembly. There are four, eight, 12, 16, and 20 insert configurations. However, the exact pattern of these configurations is unknown. Therefore, insert patterns were created and used for both WABA and Pyrex. These patterns are shown in Figure 8. RCCAs always use the 20 insert configuration. A small number of component IDs did not contain a number and thus were assumed to consist of eight inserts. This assumption is more conservative than assuming the 12, 16, or 20 insert patterns because less water is displaced, and the four inset patterns are much rarer than the eight insert patterns.

## 2.2 DPC MODELS

Two types of DPCs are used at the Zion facility: 32 transportable storage canisters (TSC-37s) and 29 transportable storage canisters for damaged fuel (TSCDF-37s). The "37" indicates that each DPC has 37

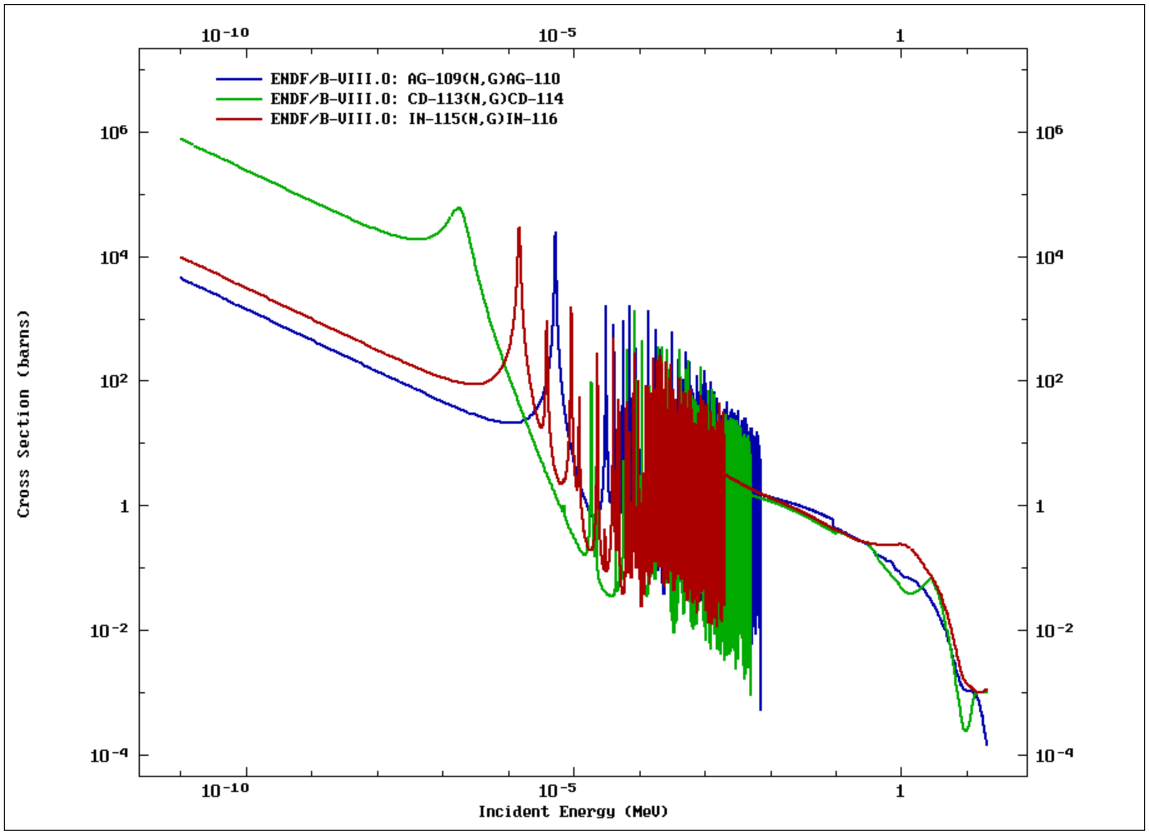



**Figure 5. Capture cross sections for the three prominent isotopes in AIC.**

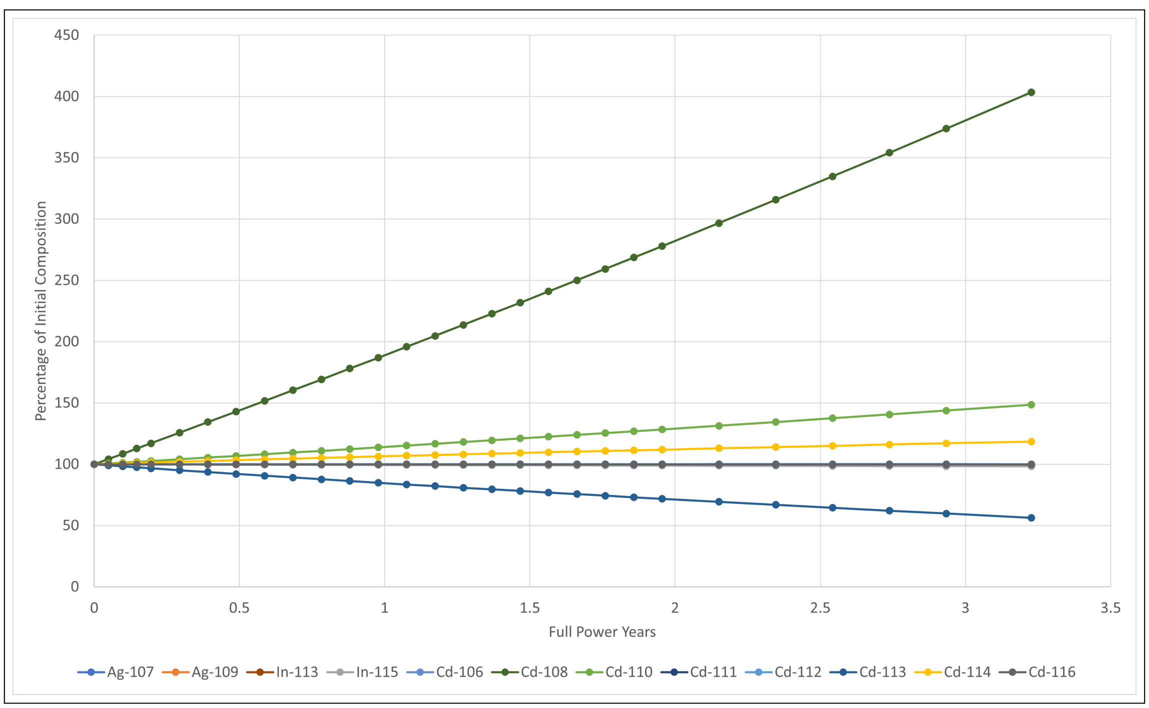



**Figure 6. Changes in AIC isotopics at hot full power with control rods inserted.**

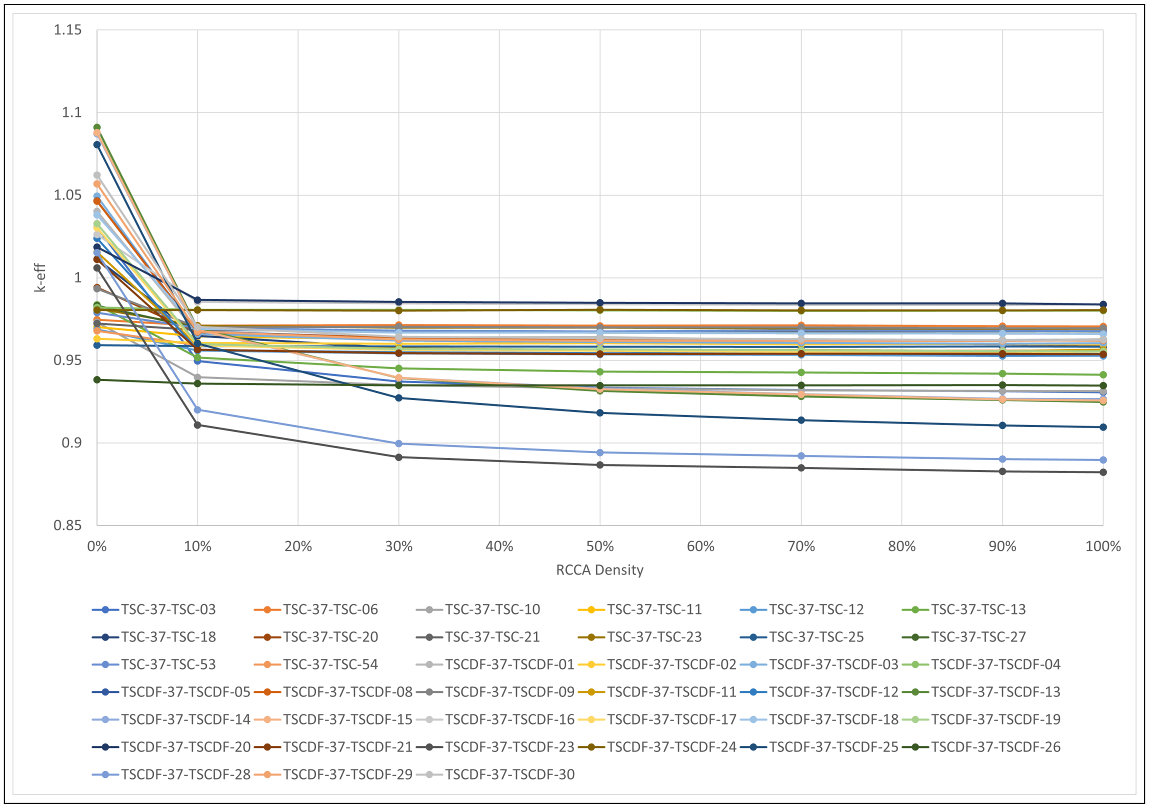


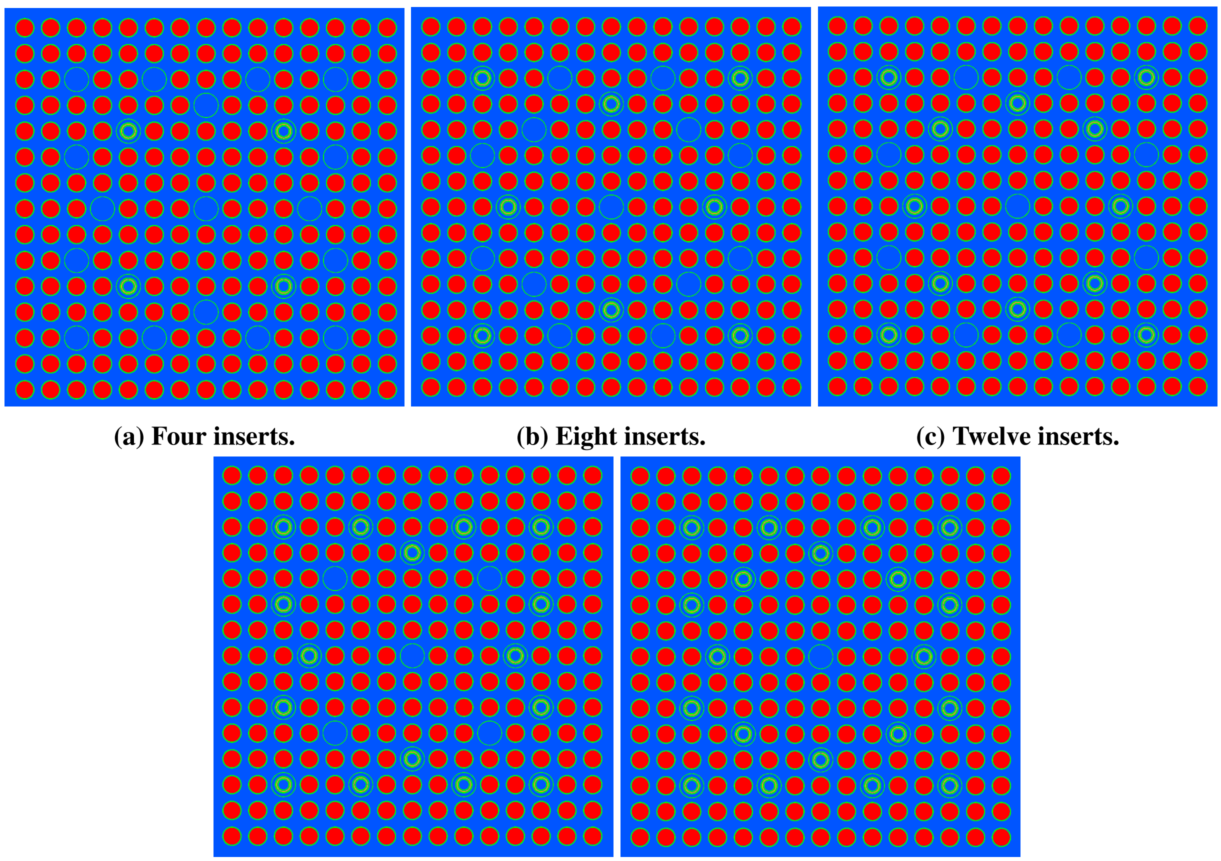

**Figure 7. Eigenvalue as a function of AIC density for the 39 Zion DPCs that contain RCCAs.**

slots and can hold up to 37 fuel assemblies. The TSCDF-37s are licensed to contain both intact and damaged fuel, although each TSCDF-37 can support only up to four damaged assemblies. The radial layouts of a representative TSC-37 and TSCDF-37 are shown in Figure 9 and Figure 10, respectively. Zion DPCs consist exclusively of Westinghouse 15 × 15 assemblies. In Figures 9 and 10, the dark green grid is the internal basket structure composed of carbon steel. Both sets of models are assumed to be completely flooded and a 50 cm water reflector surrounds the canister on all sides. In Figure 10, the four corners are the locations where four damaged assemblies could be placed.

### 2.2.1 DEGRADATION SCENARIOS

When analyzing DPCs for permanent disposal, some assumptions about their degradation over these long timescales must be considered. Because it is assumed that water intrusion will occur, material degradation is also assumed and leads to the two scenarios considered in this work. First, a complete and total loss of the neutron absorber material, or *no absorber (NA)*, is assumed. When the DPCs are first loaded, borated Al alloy sheets are mechanically attached to the basket to serve as a thermal neutron absorber. Figure 11 depicts these neutron absorbers (shown as magenta). To model the NA scenario, all neutron absorber material is removed and replaced with water, as shown in Figure 12. This NA scenario significantly increases the reactivity of the canister and is the primary scenario used in this work.

The second material degradation scenario considered is the complete and total loss of the internal basket structure, including the absorber material. Therefore, this degraded basket (DB) scenario is another step beyond the NA case. The basket and neutron absorbers are removed from the model and replaced with water, as shown in Figure 13. Removing the carbon steel basket further reduces neutron absorption and increases canister reactivity.



**(a) Four inserts.** **(b) Eight inserts.** **(c) Twelve inserts.**

**(d) Sixteen inserts.** **(e) Twenty inserts.**

**Figure 8. Hypothesized insert patterns used for Zion analysis. These images depict WABA, but Pyrex use the same patterns.**

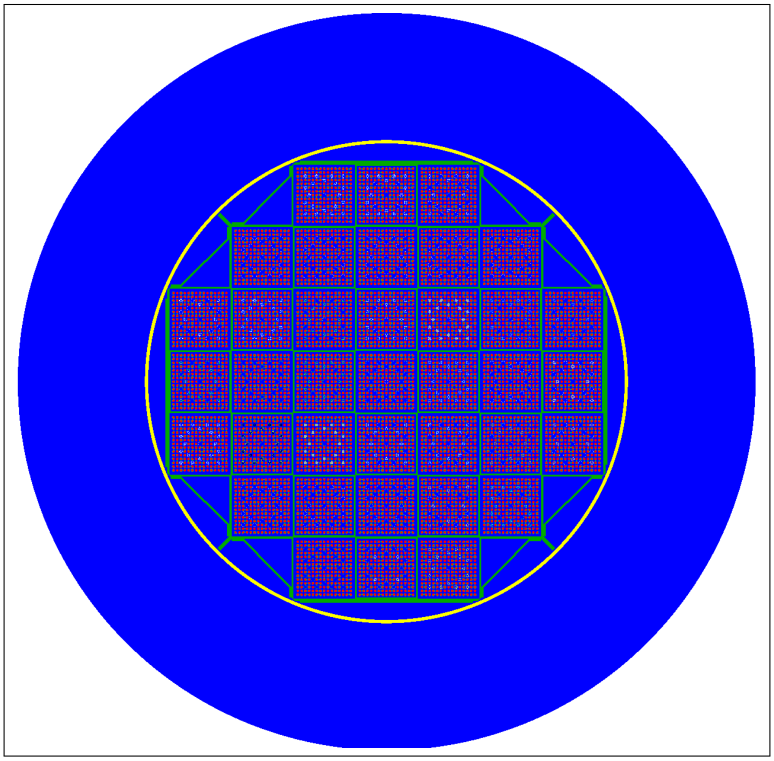


**Figure 9. DPC model layout for ZION TSC-37-TSC-54.**

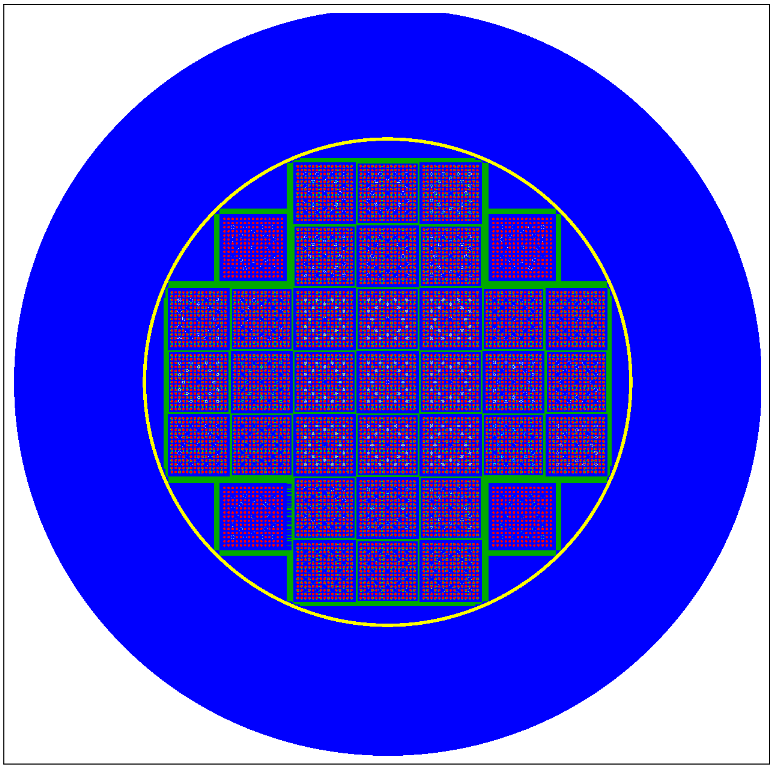


**Figure 10. DPC model layout for ZION TSCDF-37-TSCDF-30.**

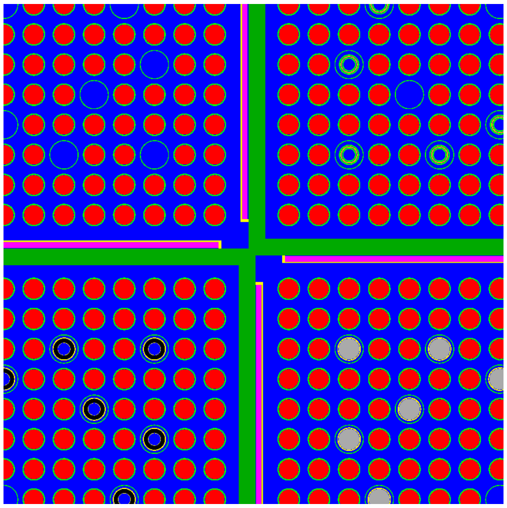


**Figure 11. Nominal DPC configuration with neutron absorbers.**

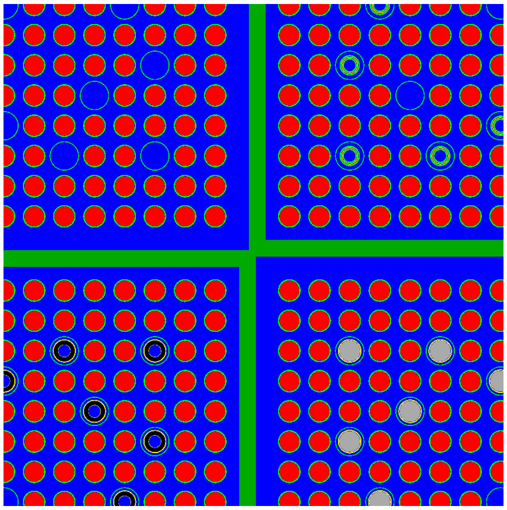


**Figure 12. NA DPC configuration with neutron absorbers removed and replaced with water.**

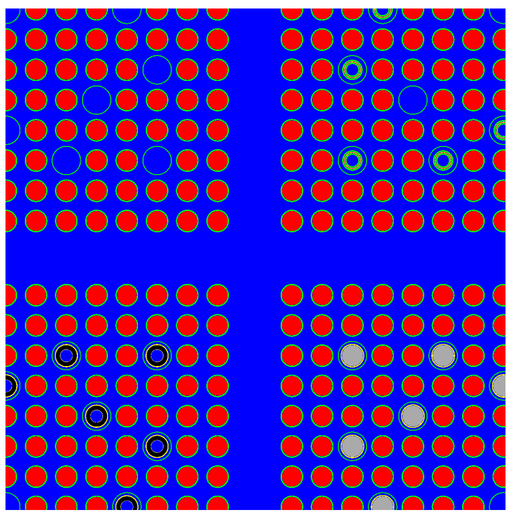


**Figure 13. NA DPC configuration with neutron absorbers removed and replaced with water.**

# 3. RESULTS

Using the models described in Section 2, UNF-ST&DARDS automatically generated the as-loaded DPC inputs for each of the 61 Zion canisters using the SCALE code system [7]. The criticality analysis sequence CSAS6 was used to perform eigenvalue calculations using the KENO-VI Monte Carlo code using the continuous-energy ENDF/B-VII.1 cross section library. Using the integrated work flow in UNF-ST&DARDS, each assembly was depleted to the assembly average burnup stated in the database and was given a bounding axial burnup profile using 18 axial zones. These depletion calculations include each cycle the assembly experienced, and the associated decay time between cycles. After the last cycle, each assembly was decayed out to the analysis date of this work, which was the year 22,000 [8].

The year 22,000 was chosen because of an increase in reactivity that occurs after 100 years of cooling time. This increase in reactivity is driven by the decay of two primary neutron absorbers: $^{241}$Am, which has a half-life of 432.7 years, and $^{240}$Pu, which has a half-life of 6,560 years [9]. Choosing an analysis date with the largest expected eigenvalue over repository time frames maximizes conservatism.

Once depleted and decayed, each assembly was then individually loaded into its corresponding location within each DPC. Each DPC model was then analyzed with KENO to calculate the eigenvalue or effective multiplication constant, $k_{eff}$. Maintaining subcriticality ($k_{eff} < 1.0$) is a primary goal of long-term DPCs disposal. However, because this work does not consider computational biases and uncertainties, they were estimated to be 2% of $k_{eff}$. Therefore, the subcritical limit used in this work is $k_{eff} < 0.98$.

The following sections discuss the results of different permutations of the insert modeling performed. These cases were converged to standard deviations of 25 pcm or lower.

## 3.1 EFFECT OF WABA AND PYREX MODELING

Two sets of Zion DPC models were simulated to determine the effect of WABA and Pyrex modeling on the eigenvalue. The first set contained no inserts; every guide tube was empty and filled with water. The second set models the as-loaded WABA and Pyrex configurations for each DPC, but no RCCAs were modeled. For conservatism, the Pyrex are assumed to be flooded. Both sets of models used the NA degradation scenario. The eigenvalues for each set of models are shown in Figure 14. The numbers above each DPC pairing are the total number of WABA and Pyrex bearing assemblies in that canister. Though it may be difficult to see, error bars are shown at the top of each bar graph that display the calculated standard deviation. Although the number of fingers and their placement within the DPC will have affect the overall effect, there is an average 6.4 pcm decrease in eigenvalue per insert assembly across all 61 Zion DPCs. Therefore, water displacement within the guide tubes has a very small effect on the overall reactivity of the canister.

With relation to the 0.98 subcriticality limit, the set with no inserts has 37 DPCs that exceed this limit. Once the WABA and Pyrex are modeled, this number decreases to 35. However, both canisters had eigenvalues barely above the 0.98 limit, and the slight decrease in reactivity reduced the eigenvalue to below the limit.

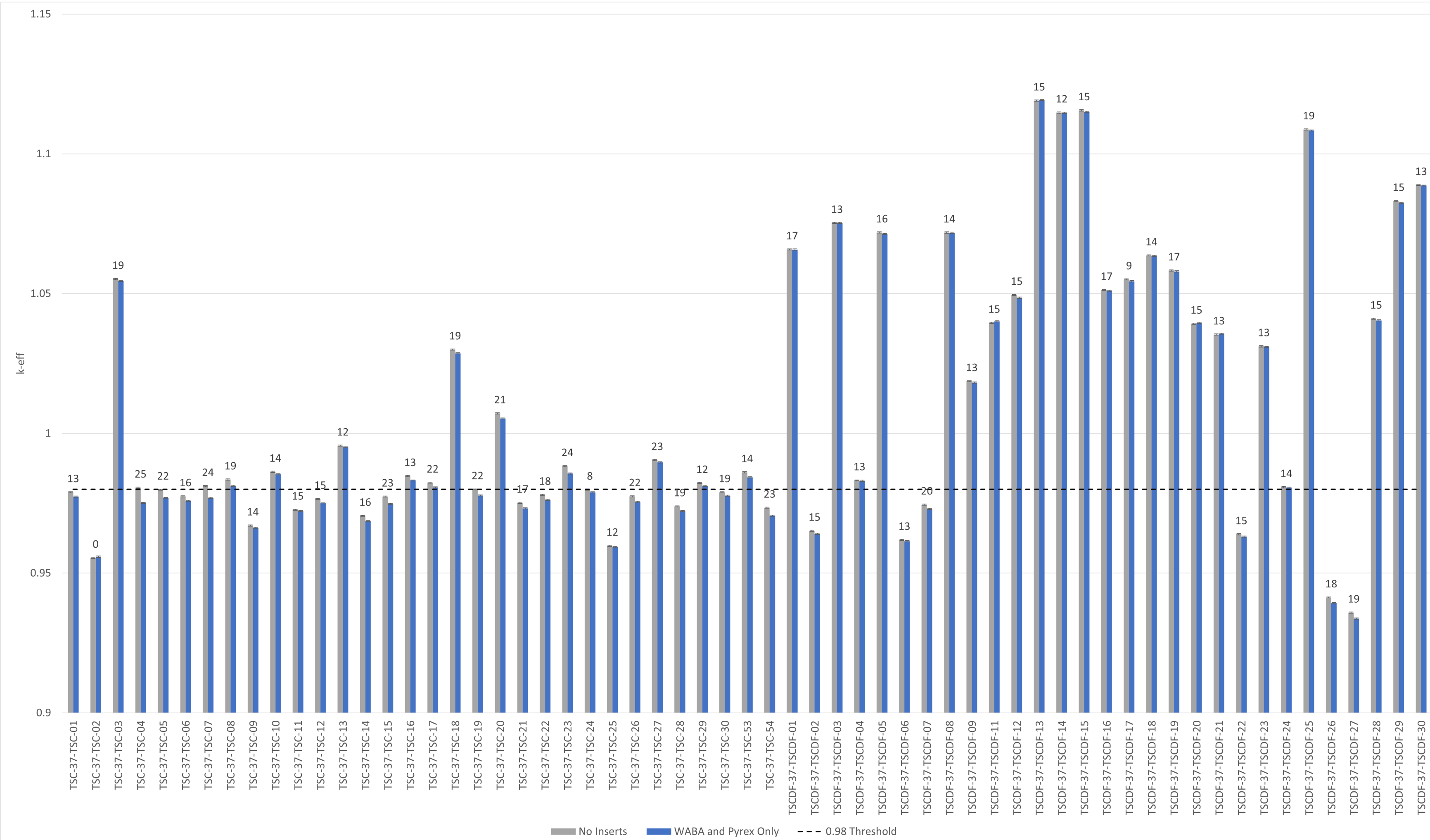



**Figure 14. Effect of WABA and Pyrex water displacement on the eigenvalue for all 61 Zion DPCs for the NA degradation scenario.**

### 3.2 EFFECT OF DRY VS. FLOODED PYREX

The effect of assuming that the Pyrex would flood was tested. Two sets of cases were modeled: one in which every Pyrex assembly was dry and one in which every Pyrex assembly was flooded. The models of each of these cases are described in Section 2.1.2. Each set of models includes WABA and Pyrex, but no RCCAs are modeled. Both sets of models used the NA degradation scenario. The results of these simulations show almost no difference in the eigenvalues. The average eigenvalue difference across each of the 61 canisters is a 2 pcm eigenvalue reduction achieved by drying the Pyrex. However, with an average standard deviation of 21 pcm, there is no statistically significant difference in the eigenvalues as a result of displacing slightly more water than the inserts themselves. However, to maximize conservatism, all Pyrex discussed in the remainder of this document was flooded.

### 3.3 EFFECT OF RCCA MODELING

With the effects of modeling WABA and Pyrex having been sufficiently analyzed in the previous sections, the effect of modeling RCCAs was then determined. Two sets of cases were modeled. In the first set, no inserts were modeled, and every guide tube was empty and filled with water. In the second set, all inserts were modeled: WABA, Pyrex, and RCCAs. As described in Section 2.1.3, all RCCAs were modeled assuming that only 50% of the AIC burnable absorber remained. Both sets of models used the NA degradation scenario. The eigenvalues for each set of models are shown in Figure 15. The numbers above each DPC pairing are the total number of RCCAs in that canister. Error bars at the top of each bar graph display the calculated standard deviation; the average standard deviation is approximately 21 pcm. As shown in Figure 15, including the RCCAs greatly affected canister reactivity. The effect is proportional to the number of RCCAs in a given canister. The most RCCAs in any one Zion DPC is nine, most of which are in the TSCDF-37 canisters. On average, each RCCA decreases the eigenvalue by roughly 1260 pcm.

When no inserts are modeled, 37 DPCs exceed the 0.98 subcriticality limit. When all inserts are modeled, that number is reduced to eight canisters that exceed the 0.98 subcriticality limit, four of which do not contain any RCCAs.

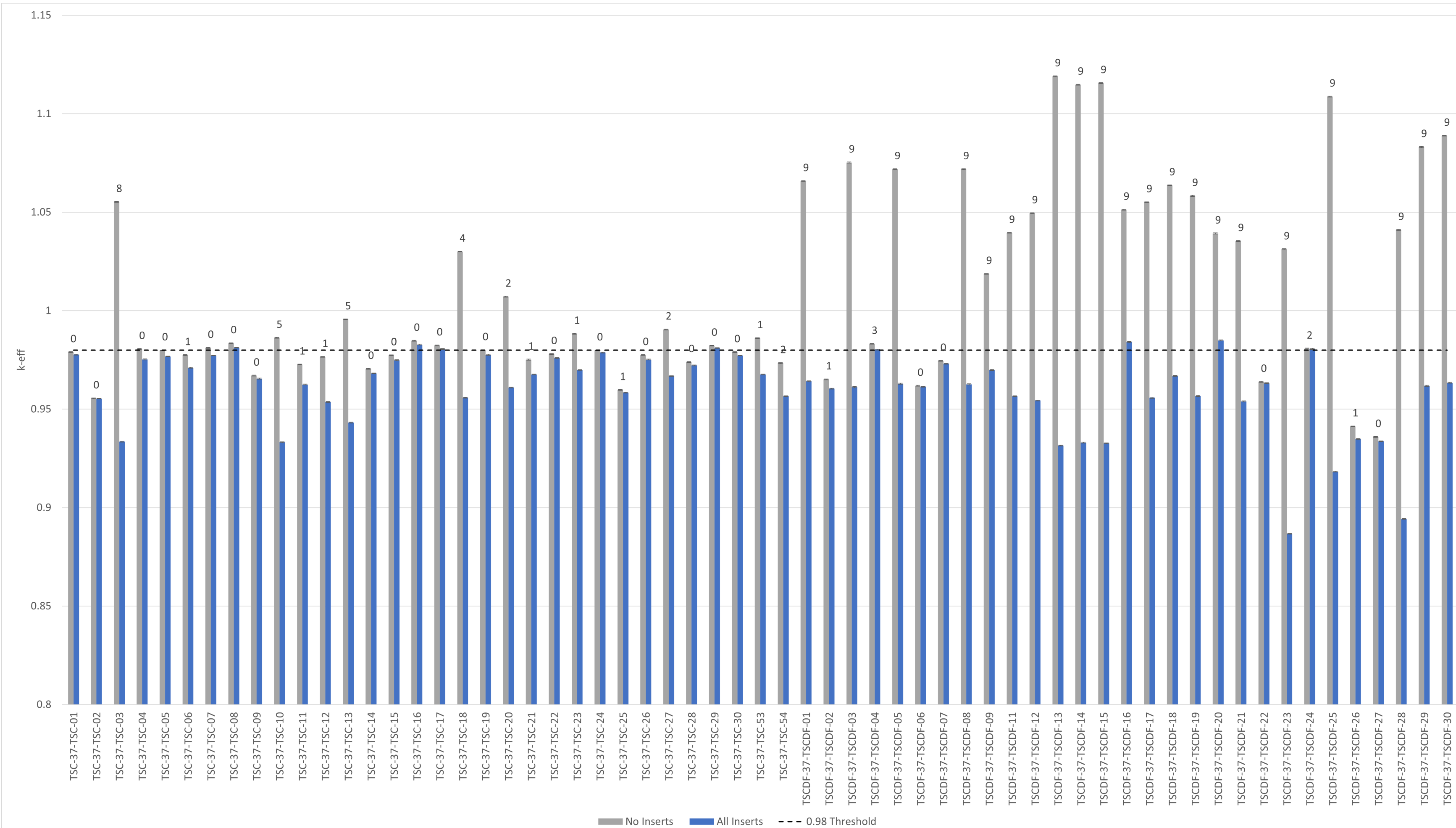



**Figure 15. Effect of modeling all inserts on eigenvalue for all 61 Zion DPCs for the NA degradation scenario.**

### 3.4 EFFECT OF INSERT MODELING ON DB SCENARIO

As discussed in Section 2.2.1, the DB scenario is one step of degradation beyond the NA scenario. As a result, the DB canisters are much more reactive than the NA canisters. To examine how modeling the inserts affects the eigenvalue, two sets of cases were modeled. The first set contains no inserts, and all guide tube are left empty and filled with water. The second set models WABA, Pyrex, and RCCAs and assumed that only 50% of the AIC burnable absorber remained, as discussed in Section 2.1.3. The eigenvalues for each set of models are shown in Figure 16. The numbers above each DPC pair represent the total number of RCCAs that canister contains. Error bars on each dataset represent the standard deviation for that eigenvalue. The average standard deviation is roughly 21 pcm.

Like the results shown in Figure 15, Figure 16 demonstrates a large reactivity effect for canisters that have multiple RCCAs. This effect is proportional with the total number of RCCAs in a given canister. The primary difference between the DB and NA scenarios is that the DB eigenvalues are much higher than those for the NA cases, although the overall effect of the insert modeling is the same. Without modeling any inserts, all 61 of the Zion DPC exceed the 0.98 subcriticality limit. If the effect of the modeled inserts is included, this number is reduced to 59. Although including inserts, primarily RCCAs, decreases the canister eigenvalue, it is not enough to offset the total loss of the neutron absorber and the internal basket.

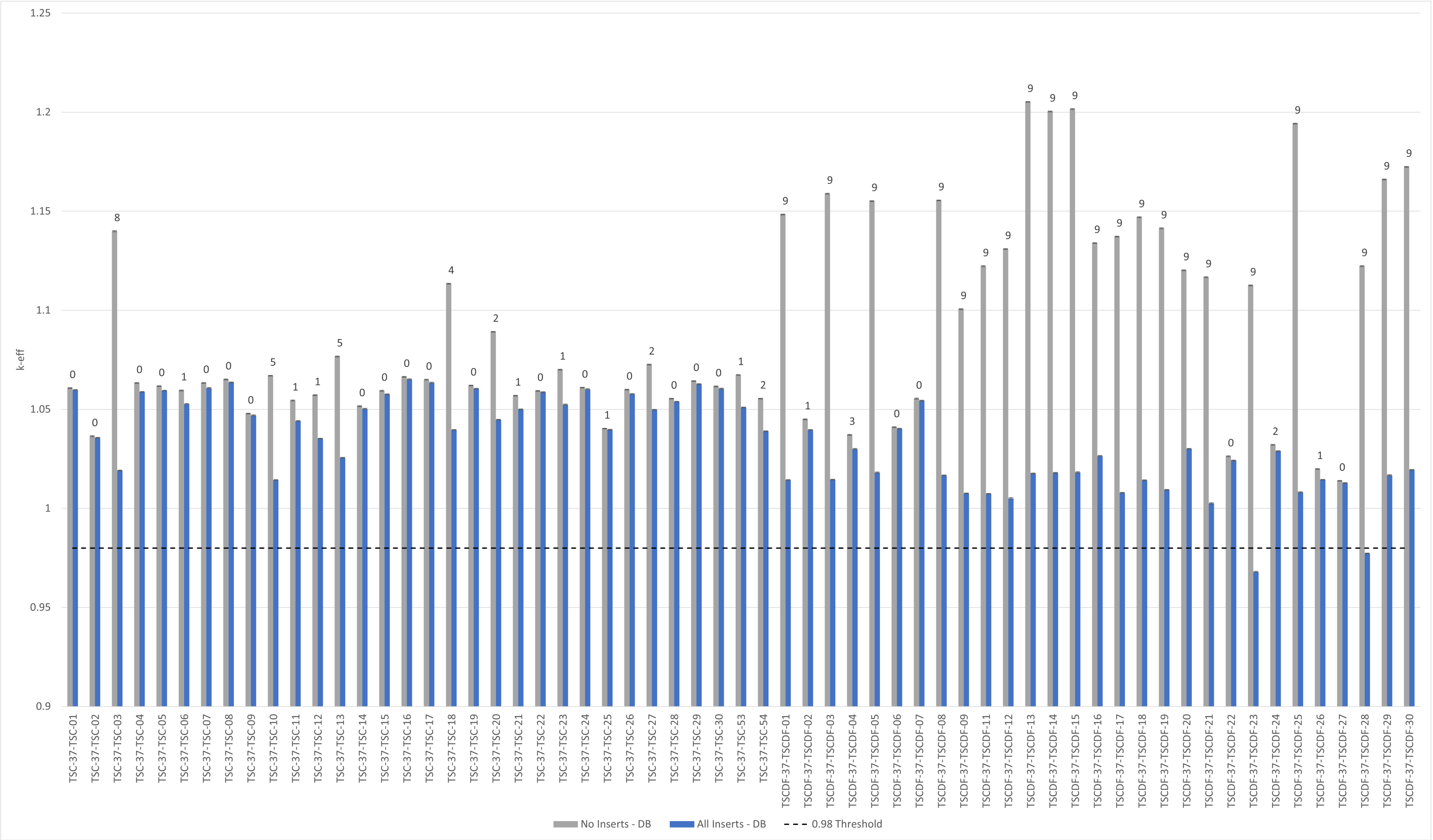



**Figure 16. Effect of modeling all inserts on eigenvalue for all 61 Zion DPCs for the DB degradation scenario.**

# 4. CONCLUSION

The work described in this report examined the effects of modeling inserts on the eigenvalue for DPCs intended for geologic disposal. The canisters studied in this work were as-loaded DPCs from the shuttered Zion Nuclear Power Station. Zion represents a worst-case scenario because some of the assemblies in its DPCs have the high enrichment and low burnup. Therefore, analyzing this site served as a conservative situation compared with other sites. Zion has 61 DPCs, 32 of which are TSC-37s and 29 of which are TSCDF-37s. The inserts considered in the work were WABA, Pyrex, and RCCA.

When examining the effects of modeling WABA and Pyrex, their overall effect was very minor. On average, each insert assembly decreases the eigenvalue by only 6 pcm because of water displacement. Additionally, this work examined whether having dry or flooded Pyrex inserts greatly affects the overall eigenvalue. Flooding the Pyrex rods was found to not significantly affect overall canister reactivity.

Finally, the effect of modeling RCCAs on the overall canister eigenvalue was determined. The overall neutron absorber content of the RCCAs was conservatively assumed to be only 50% of its initial value. Even with this reduction taken into account, the Zion RCCAs significantly affected the overall eigenvalue for the NA and DB degradation scenarios. On average, each RCCA reduces the canister eigenvalue by approximately 1260 pcm. For the NA scenario, the inclusion of inserts reduces the number of DPCs that exceed the 0.98 subcriticality limit from 37 to 8, and for the DB scenario from 61 to 59.

Future work will extend this methodology to other sites beyond Zion. The first step will be to examine the UNF-ST&DARDS database and identify any potential sites that have similar data available. Potential identified sites could store their data in a format different from what is currently expected in UNF-ST&DARDS. These insert data must first be converted before any useful analysis can begin. Additionally, future work will look at determining the effect of using low density water as the moderator because decay heat will reduce the overall water density.

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