

# Impacts of LEU+ and ATF on Fresh Fuel Storage Criticality Safety

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Alex Shaw  
Oak Ridge National Laboratory  
Justin Clarity  
Pacific Northwest National Laboratory

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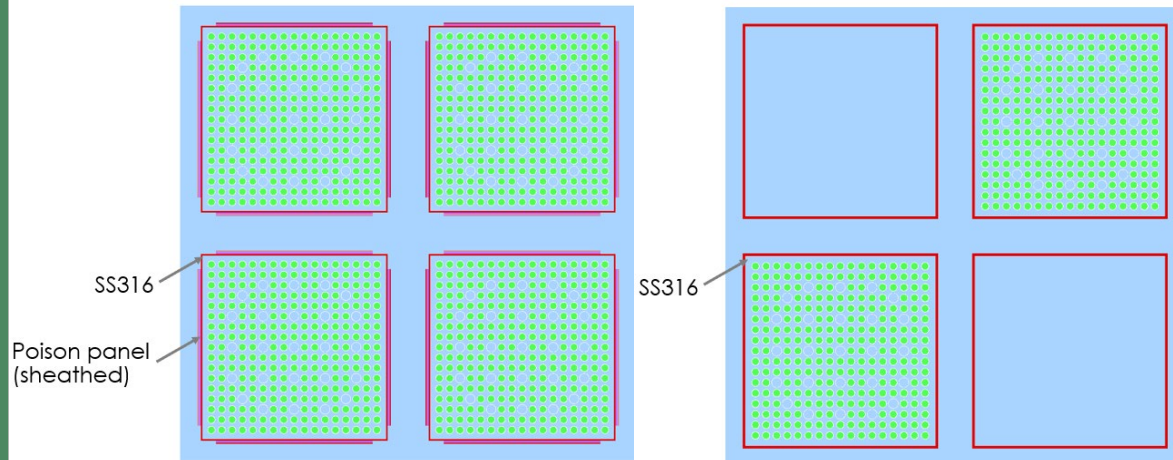
# Overview

- Racks in the New Fuel Vault (NFV) and Spent Fuel Pool (SFP) and accompanying fuel handling procedures are currently designed with a maximum enrichment of 5.0 wt. %.
- Publicly available source documents were used to develop baseline models of fresh fuel storage configurations
  - PWR SFP: Low density array, intact absorber (IA)
  - PWR SFP: Low density array, degraded absorber (DA)
  - PWR NFV
  - BWR NFV
- How do LEU+ enrichments fare with current regulation?

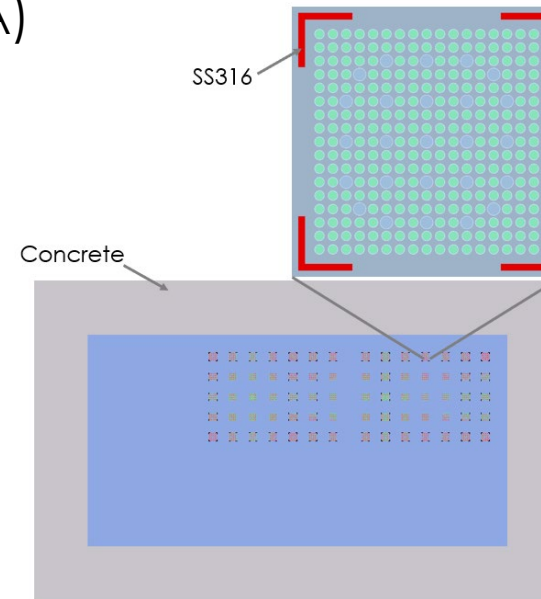
# Baseline Models

PWR SFP

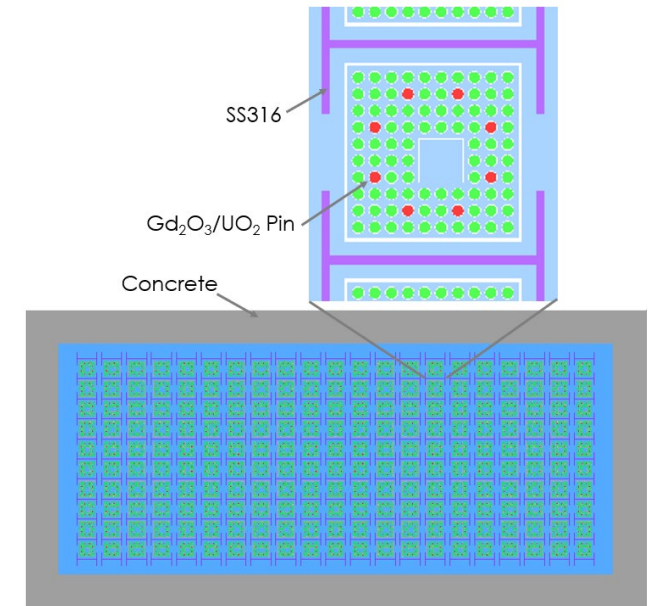
Intact Absorber (IA)    Degraded Absorber (DA)



PWR NFV



BWR NFV



| $k_{\text{eff}}$ limit (10 CFR 50.68) | PWR IA SFP | PWR DA SFP | PWR NFV | BWR NFV |
|---------------------------------------|------------|------------|---------|---------|
| Fully Flooded                         | 1.0        | 1.0        | 0.95    | 0.95    |
| Optimum Moderation                    | N/A        | N/A        | 0.98    | N/A     |

# LEU+ and ATF

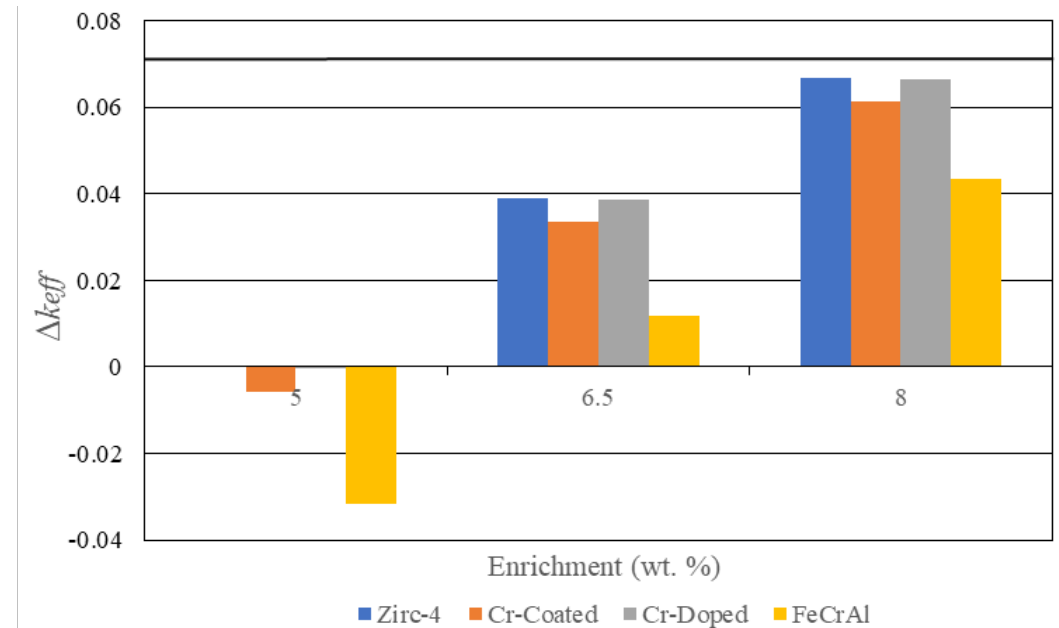
- Nominal enrichments were increased to 6.5 and 8 wt % as potential LEU+ enrichments
- The following ATF concepts were investigated, with technical specification guidance from Hall et al.
  - Cr-coated: 20  $\mu\text{m}$  thick Cr-coated cladding of the conventional Zirc-4 cladding
  - Cr-doped: 1000 ppm  $\text{Cr}_2\text{O}_3$  dopant of  $\text{UO}_2$  fuel
  - FeCrAl: C26M variant of FeCrAl alloy with composition of 12% by weight Cr, 6% Al, 2% Mo, 0.2% Si, 0.003% Y, and the remainder Fe

R. Hall et al. 2021. *Extended-Enrichment Accident-Tolerant LWR Fuel Isotopic and Lattice Parameter Trends*. ORNL/TM-2021/1961. Oak Ridge: Oak Ridge National Laboratory.

# LEU+&ATF Change from Baseline: IA SFP

- $K_{eff}$  differential relative to nominal condition: 5% Zirc-4
  - 6.5 wt. %  $\sim 0.039 \Delta k_{eff}$  increase
  - 8.0 wt. %  $\sim 0.066 \Delta k_{eff}$  increase
- ATF
  - Cr-coating  $0.005 \Delta k_{eff}$  decrease
  - Cr-dopant  $\sim 0.0$
  - FeCrAl  $\sim 0.023$  (8 wt.%) –  $0.031$  (5 wt. %)

Margin to unborated 1.0 Limit



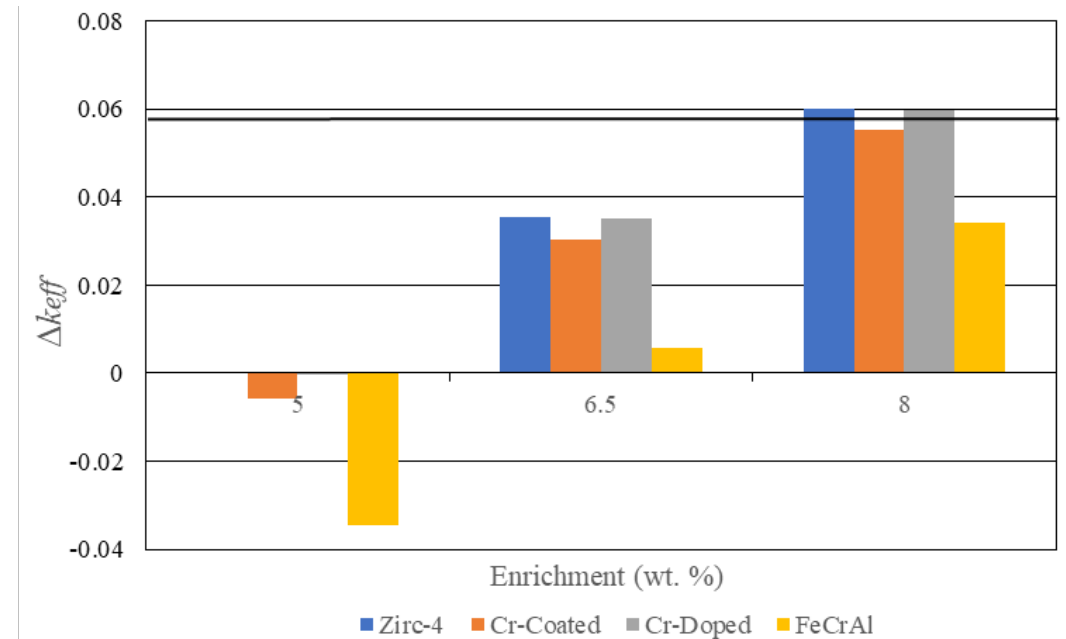
Maximum  $k_{eff}$

|                 | ATF Cladding Material |           |          |        |
|-----------------|-----------------------|-----------|----------|--------|
| Fuel Enrichment | Zirc-4                | Cr-Coated | Cr-Doped | FeCrAl |
| 5.0             | 0.9278                | 0.9219    | 0.9275   | 0.8962 |
| 6.5             | 0.9667                | 0.9612    | 0.9665   | 0.9397 |
| 8.0             | 0.9945                | 0.9893    | 0.9942   | 0.9711 |

# LEU+&ATF Change from Baseline: DA SFP

- $K_{eff}$  differential relative to nominal condition: 5% Zirc-4
  - 6.5 wt. %  $\sim 0.035 \Delta k_{eff}$  increase
  - 8.0 wt. %  $\sim 0.060 \Delta k_{eff}$  increase
- ATF
  - Cr-coating  $0.005 \Delta k_{eff}$  decrease
  - Cr-dopant  $\sim 0.0$
  - FeCrAl  $\sim 0.025$  (8 wt.%) –  $0.035$  (5 wt. %)

Margin to unborated 1.0 Limit



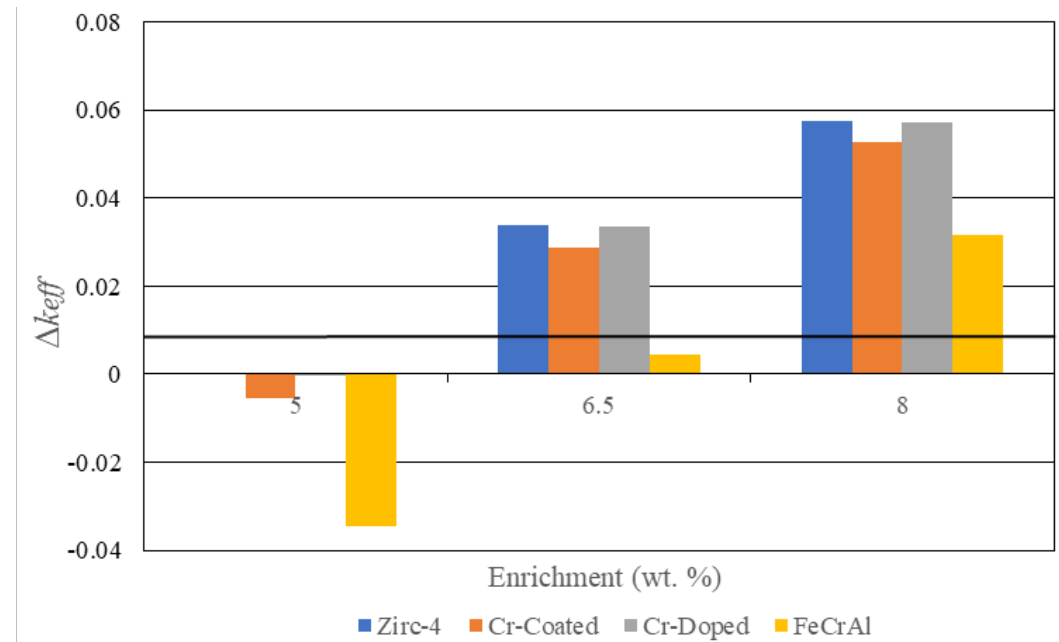
Maximum  $k_{eff}$

| Fuel Enrichment | ATF Cladding Material |           |          |        |
|-----------------|-----------------------|-----------|----------|--------|
|                 | Zirc-4                | Cr-Coated | Cr-Doped | FeCrAl |
| 5.0             | 0.9412                | 0.9355    | 0.9409   | 0.9065 |
| 6.5             | 0.9766                | 0.9714    | 0.9763   | 0.9469 |
| 8.0             | 1.0012                | 0.9966    | 1.0009   | 0.9754 |

# LEU+&ATF Change from Baseline: PWR NFV (Flooded)

- $K_{eff}$  differential relative to nominal condition: 5% Zirc-4
  - 6.5 wt. %  $\sim 0.034 \Delta k_{eff}$  increase
  - 8.0 wt. %  $\sim 0.057 \Delta k_{eff}$  increase
- ATF
  - Cr-coating  $0.005 \Delta k_{eff}$  decrease
  - Cr-dopant  $\sim 0.0$
  - FeCrAl  $\sim 0.026$  (8 wt.%) –  $0.034$  (5 wt. %)

Margin to fully flooded 0.95 Limit



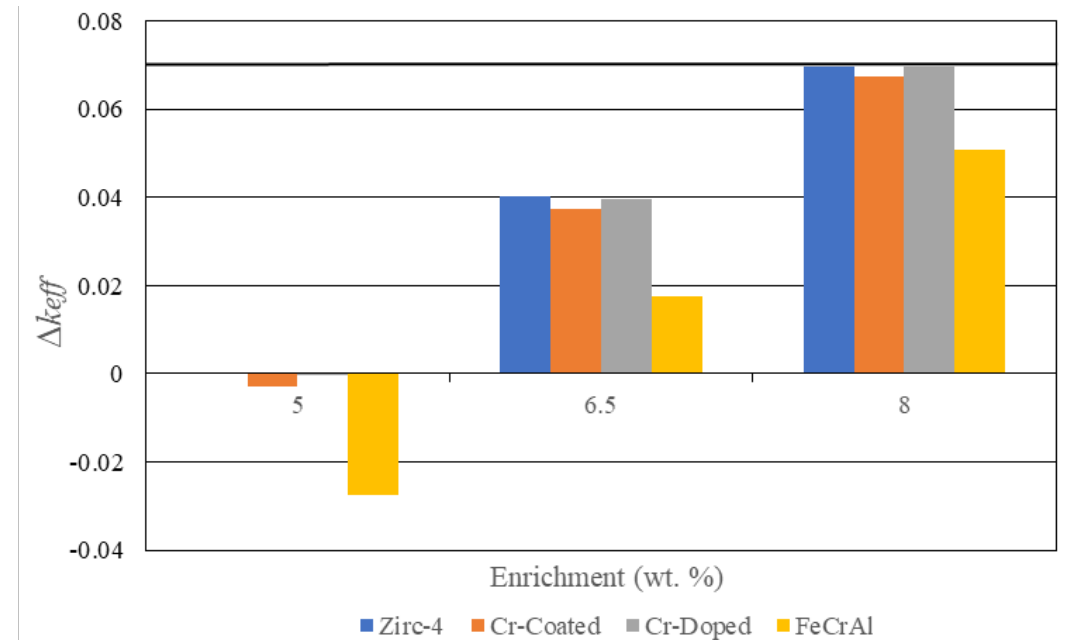
Maximum  $k_{eff}$

|                 | ATF Cladding Material |           |          |        |
|-----------------|-----------------------|-----------|----------|--------|
| Fuel Enrichment | Zirc-4                | Cr-Coated | Cr-Doped | FeCrAl |
| 5.0             | 0.9429                | 0.9373    | 0.9426   | 0.9085 |
| 6.5             | 0.9767                | 0.9716    | 0.9766   | 0.9473 |
| 8.0             | 1.0003                | 0.9955    | 1.0001   | 0.9746 |

# LEU+&ATF Change from Baseline: PWR NFV (Opt. Mod.)

- $K_{eff}$  differential relative to nominal condition: 5% Zirc-4
  - 6.5 wt. %  $\sim 0.04 \Delta k_{eff}$  increase
  - 8.0 wt. %  $\sim 0.07 \Delta k_{eff}$  increase
- ATF
  - Cr-coating  $0.003 \Delta k_{eff}$  decrease
  - Cr-dopant  $\sim 0.0$
  - FeCrAl  $\sim 0.019$  (8 wt.%) –  $0.028$  (5 wt. %)

Margin to optimum moderation 0.98 Limit



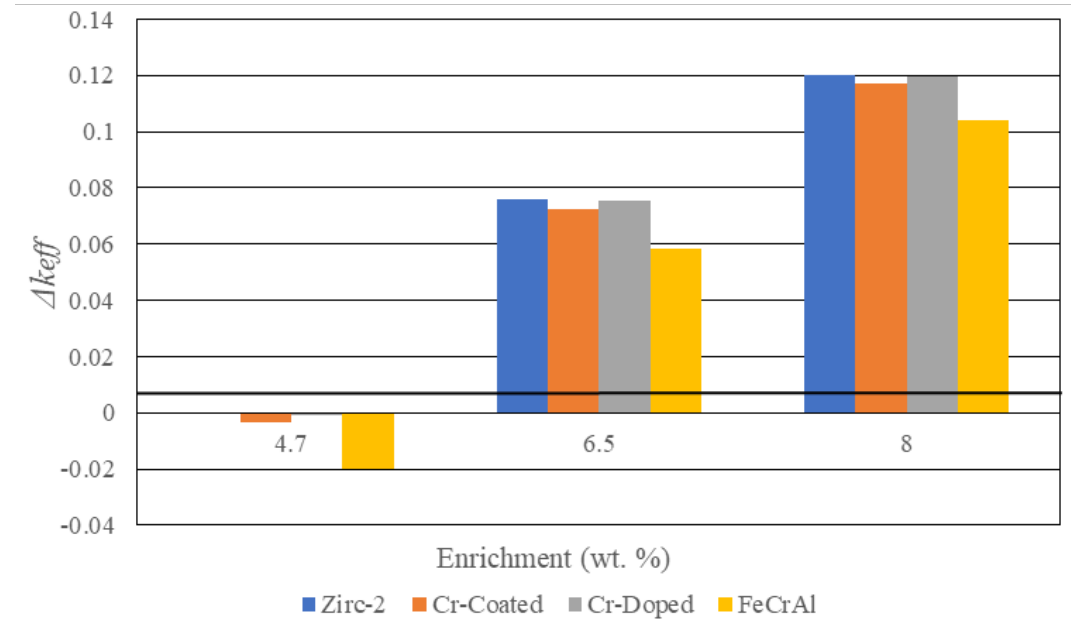
Maximum  $k_{eff}$

| Fuel Enrichment | ATF Cladding Material |           |          |        |
|-----------------|-----------------------|-----------|----------|--------|
|                 | Zirc-4                | Cr-Coated | Cr-Doped | FeCrAl |
| 5.0             | 0.9101                | 0.9071    | 0.9098   | 0.8826 |
| 6.5             | 0.9502                | 0.9475    | 0.9496   | 0.9277 |
| 8.0             | 0.9798                | 0.9776    | 0.9796   | 0.9610 |

# LEU+&ATF Change from Baseline: BWR NFV

- $K_{eff}$  differential relative to nominal condition: 5% Zirc-2
  - 6.5 wt. %  $\sim 0.078 \Delta k_{eff}$  increase
  - 8.0 wt. %  $\sim 0.12 \Delta k_{eff}$  increase
- ATF
  - Cr-coating  $0.003 \Delta k_{eff}$  decrease
  - Cr-dopant  $\sim 0.0$
  - FeCrAl  $\sim 0.016$  (8 wt.%) –  $0.020$  (5 wt. %)

Margin to fully flooded 0.95 Limit

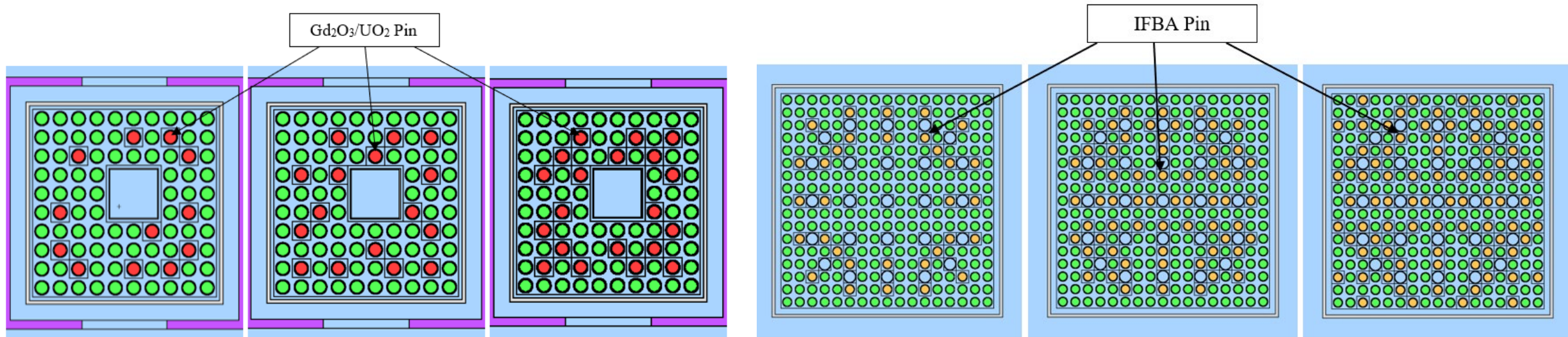


Maximum  $k_{eff}$

| Fuel Enrichment | ATF Cladding Material |           |          |        |
|-----------------|-----------------------|-----------|----------|--------|
|                 | Zirc-2                | Cr-Coated | Cr-Doped | FeCrAl |
| 4.7             | 0.9451                | 0.9416    | 0.9443   | 0.9252 |
| 6.5             | 1.0209                | 1.0177    | 1.0205   | 1.0035 |
| 8.0             | 1.0651                | 1.0623    | 1.0645   | 1.0490 |

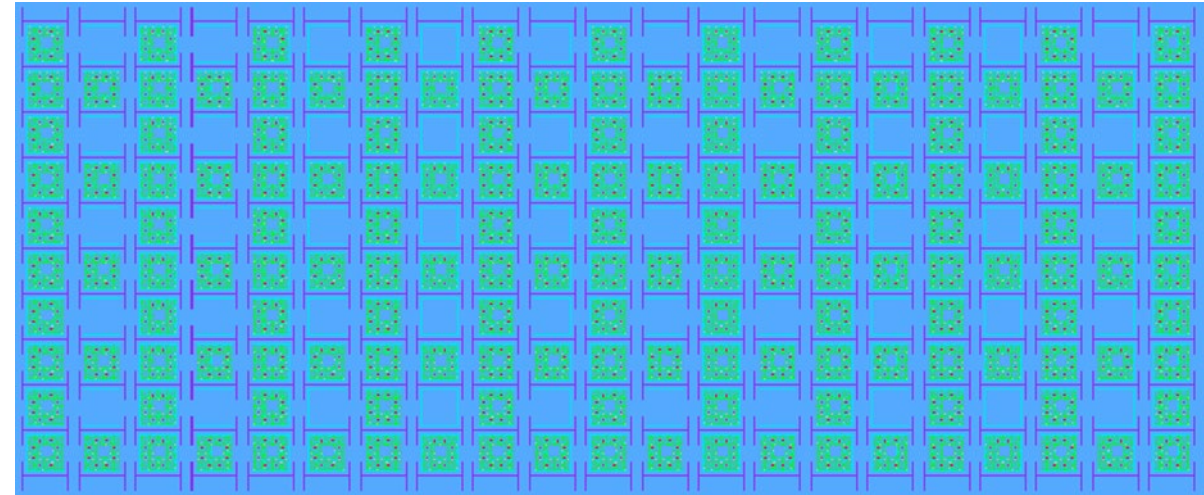
# Reactivity Credits

- Looked at offsetting increases in reactivity with
  - Absorber credit
    - IFBA for PWRs
    - Gd for PWRs and BWRs
  - Addition of empty rack cell locations



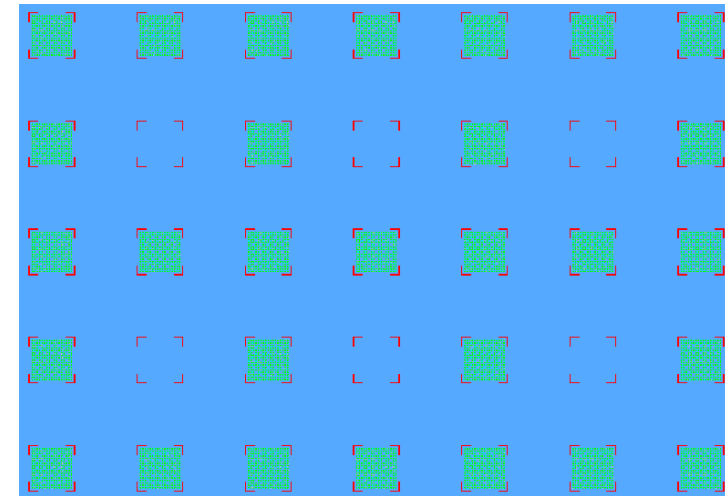
# BWR NFV Reactivity Credits

| Configuration       | Array Loading | Gd wt. % | Gd Rods | Absorber $\Delta k_{eff}$ |         | Maximum Reactivity ( $k_{eff}$ ) |              |
|---------------------|---------------|----------|---------|---------------------------|---------|----------------------------------|--------------|
|                     |               |          |         | 6.5%                      | 8%      | 6.5% $k_{eff}$                   | 8% $k_{eff}$ |
| Base                | 100%          | 2%       | 8       | 0                         | 0       | 1.0209                           | 1.0651       |
| +1% Gd              | 100%          | 3%       | 8       | -0.0058                   | -0.0059 | 1.0151                           | 1.0592       |
| +2% Gd              | 100%          | 4%       | 8       | -0.0099                   | -0.0099 | 1.0110                           | 1.0552       |
| +4 Rods             | 100%          | 2%       | 12      | -0.0455                   | -0.0415 | 0.9754                           | 1.0236       |
| +1% Gd, +4 Rods     | 100%          | 3%       | 12      | -0.0539                   | -0.0499 | 0.9670                           | 1.0152       |
| +2% Gd, +4 Rods     | 100%          | 4%       | 12      | -0.0595                   | -0.0556 | 0.9614                           | 1.0095       |
| +8 Rods             | 100%          | 2%       | 16      | -0.0997                   | -0.0922 | 0.9212                           | 0.9729       |
| +1% Gd, +8 Rods     | 100%          | 3%       | 16      | -0.1106                   | -0.1030 | 0.9103                           | 0.9621       |
| +2% Gd, +8 Rods     | 100%          | 4%       | 16      | -0.1181                   | -0.1109 | 0.9028                           | 0.9542       |
| +12 Rods            | 100%          | 2%       | 20      | -0.1318                   | -0.1218 | 0.8891                           | 0.9433       |
| +1% Gd, +12 Rods    | 100%          | 3%       | 20      | -0.1440                   | -0.1343 | 0.8769                           | 0.9308       |
| +2% Gd, +12 Rods    | 100%          | 4%       | 20      | -0.1526                   | -0.1429 | 0.8683                           | 0.9222       |
| -1 Assembly         | 76%           | 2%       | 8       | -0.1166                   | -0.1216 | 0.9043                           | 0.9435       |
| -1 Assembly, +1% Gd | 76%           | 3%       | 8       | -0.1221                   | -0.1269 | 0.8988                           | 0.9382       |
| -1 Assembly, +2% Gd | 76%           | 4%       | 8       | -0.1256                   | -0.1305 | 0.8953                           | 0.9346       |



# PWR NFV Reactivity Credits

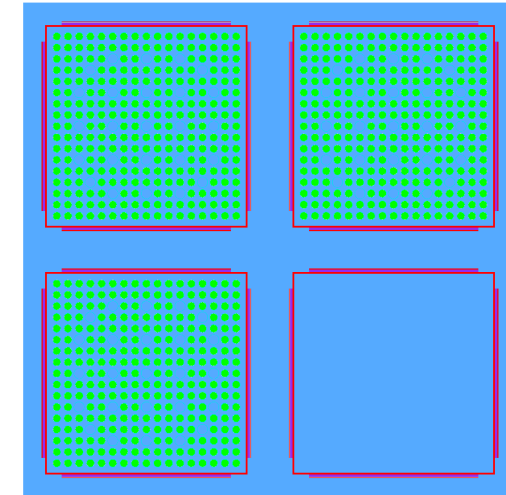
| Configuration         | Array Loading | Gd wt.% | Gd Rods | IFBA Rods | Absorber $\Delta k_{eff}$ |         | Maximum Reactivity ( $k_{eff}$ ) |              |
|-----------------------|---------------|---------|---------|-----------|---------------------------|---------|----------------------------------|--------------|
|                       |               |         |         |           | 6.5%                      | 8%      | 6.5% $k_{eff}$                   | 8% $k_{eff}$ |
| Base                  | 100%          | 0       | 0       | 0         | 0.0000                    | 0.0000  | 0.9767                           | 1.0003       |
| +32 Rods              | 100%          | 0       | 0       | 32        | -0.0330                   | -0.0290 | 0.9437                           | 0.9713       |
| +64 Rods              | 100%          | 0       | 0       | 64        | -0.0720                   | -0.0637 | 0.9047                           | 0.9366       |
| -1 Assembly           | 83%           | 0       | 0       | 0         | -0.0003                   | -0.0003 | 0.9764                           | 1.0000       |
| -1 Assembly, +32 Rods | 83%           | 0       | 0       | 32        | -0.0335                   | -0.0295 | 0.9432                           | 0.9708       |
| -1 Assembly, +64 Rods | 83%           | 0       | 0       | 64        | -0.0724                   | -0.0641 | 0.9043                           | 0.9362       |
| +4 Gd Rods (2% wt.)   | 100%          | 2%      | 4       | 0         | -0.0195                   | -0.0174 | 0.9572                           | 0.9829       |
| +4 Gd Rods (3% wt.)   | 100%          | 3%      | 4       | 0         | -0.0207                   | -0.0187 | 0.9560                           | 0.9816       |
| +4 Gd Rods (4% wt.)   | 100%          | 4%      | 4       | 0         | -0.0218                   | -0.0196 | 0.9549                           | 0.9807       |



# PWR SFP Reactivity Credits

## Intact Absorber

| Configuration         | Array Loading | Gd wt.% | Gd Rods | IFBA Rods | Absorber $\Delta k_{eff}$ |         | Maximum Reactivity ( $k_{eff}$ ) |        |
|-----------------------|---------------|---------|---------|-----------|---------------------------|---------|----------------------------------|--------|
|                       |               |         |         |           | 6.5%                      | 8%      |                                  |        |
| Base                  | 100%          | 0       | 0       | 0         | 0                         | 0       | 0.9667                           | 0.9945 |
| +32 Rods              | 100%          | 0       | 0       | 32        | -0.0335                   | -0.0298 | 0.9332                           | 0.9647 |
| +64 Rods              | 100%          | 0       | 0       | 64        | -0.0763                   | -0.0676 | 0.8904                           | 0.9269 |
| -1 Assembly           | 75%           | 0       | 0       | 0         | -0.0418                   | -0.0434 | 0.9249                           | 0.9511 |
| -1 Assembly, +32 Rods | 75%           | 0       | 0       | 32        | -0.0733                   | -0.0715 | 0.8934                           | 0.9230 |
| -1 Assembly, +64 Rods | 75%           | 0       | 0       | 64        | -0.1153                   | -0.1086 | 0.8514                           | 0.8859 |
| +4 Gd Rods (2% wt.)   | 100%          | 2%      | 4       | 0         | -0.0220                   | -0.0192 | 0.9447                           | 0.9753 |
| +4 Gd Rods (3% wt.)   | 100%          | 3%      | 4       | 0         | -0.0232                   | -0.0209 | 0.9435                           | 0.9736 |
| +4 Gd Rods (4% wt.)   | 100%          | 4%      | 4       | 0         | -0.0243                   | -0.0219 | 0.9424                           | 0.9726 |



## Degraded Absorber

| Configuration       | Array Loading | Gd wt.% | Gd Rods | IFBA Rods | Absorber $\Delta k_{eff}$ |         | Maximum Reactivity ( $k_{eff}$ ) |        |
|---------------------|---------------|---------|---------|-----------|---------------------------|---------|----------------------------------|--------|
|                     |               |         |         |           | 6.5%                      | 8%      |                                  |        |
| Base                | 50%           | 0       | 0       | 0         | 0                         | 0       | 0.9766                           | 1.0012 |
| +32 Rods            | 50%           | 0       | 0       | 32        | -0.0330                   | -0.0290 | 0.9436                           | 0.9722 |
| +64 Rods            | 50%           | 0       | 0       | 64        | -0.0717                   | -0.0638 | 0.9049                           | 0.9374 |
| +80 Rods            | 50%           | 0       | 0       | 80        | -0.0847                   | -0.0756 | 0.8919                           | 0.9256 |
| +4 Gd Rods (2% wt.) | 50%           | 2%      | 4       | 0         | -0.0198                   | -0.0175 | 0.9568                           | 0.9837 |
| +4 Gd Rods (3% wt.) | 50%           | 3%      | 4       | 0         | -0.0211                   | -0.0187 | 0.9555                           | 0.9825 |
| +4 Gd Rods (4% wt.) | 50%           | 4%      | 4       | 0         | -0.0221                   | -0.0198 | 0.9545                           | 0.9814 |

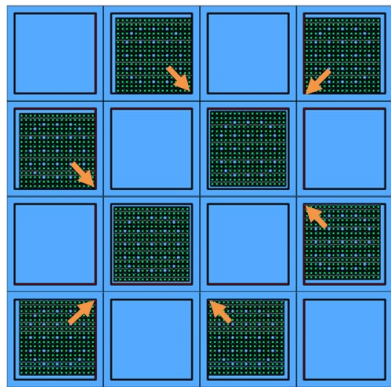
- NFVs as examined have less initial margin than SFPs as examined, resulting in unallowable configurations at 6.5+ wt %
  - The observed flooded conditions have about the same  $\Delta k_{\text{eff}}$
- While required in several conditions, burnable absorber credit requirements are reasonable
  - Particularly given increased absorber loading in LEU+ fuel cycles
- HALEU approaching 20 wt % will require burnable absorber crediting or soluble boron content beyond practicality

# Questions?

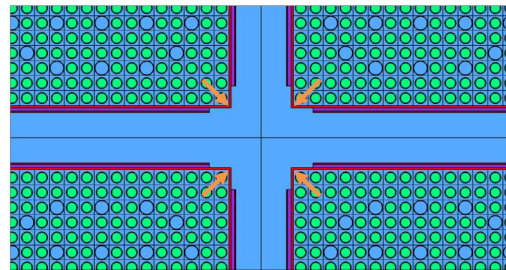


# Eccentric Positioning

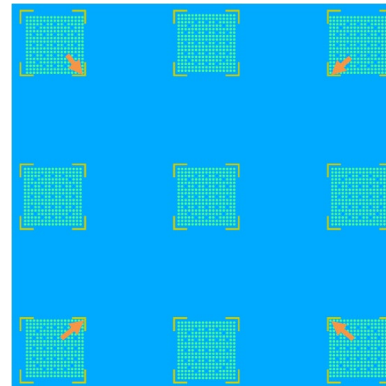
- NFV and SFP models were offset in a clustered manner to observe any reactivity deviations
- The chosen positioning is believed to be reasonable to determine whether there is an enrichment-dependent effect



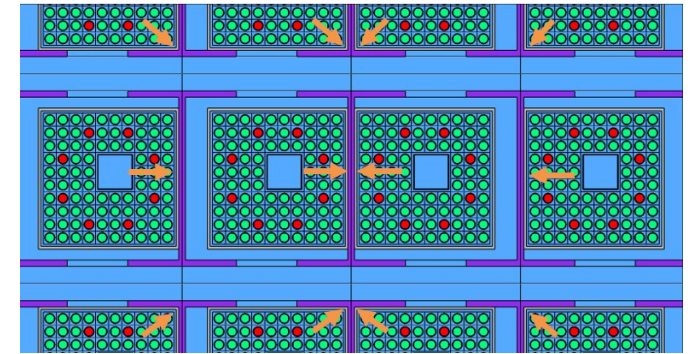
DA PWR SFP



IA PWR SFP



PWR NFV

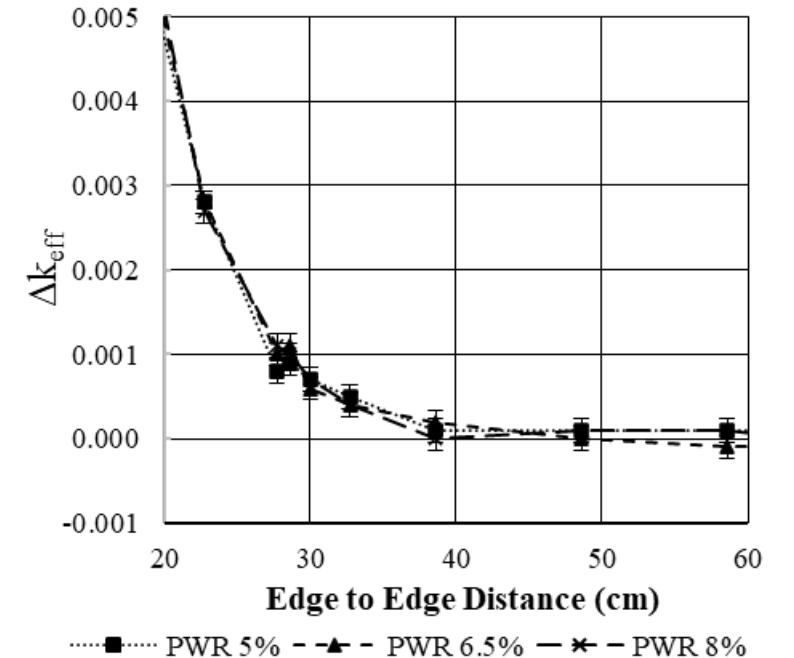
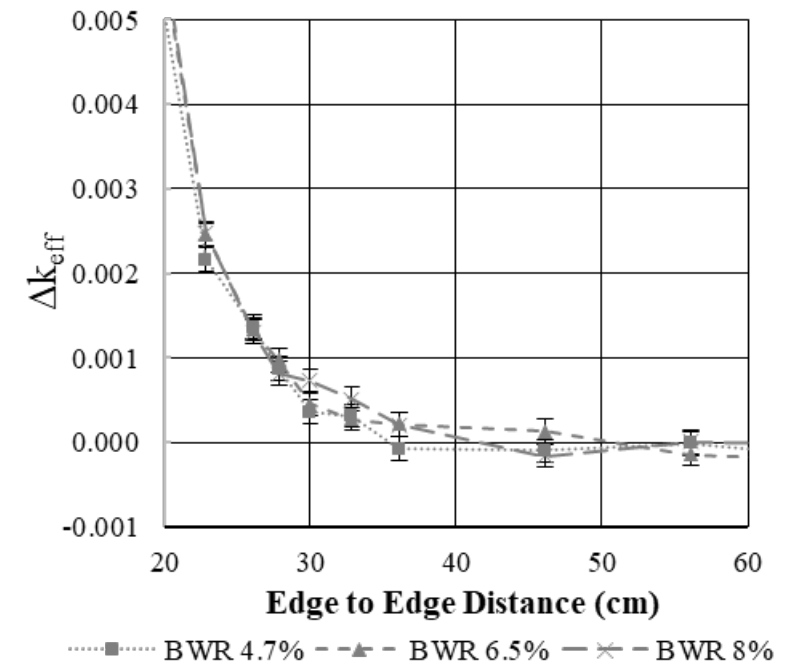


BWR NFV

| Fuel Enrichment (wt. %) | $\Delta k_{eff}$ |            |         |         |
|-------------------------|------------------|------------|---------|---------|
|                         | PWR DA SFP       | PWR IA SFP | PWR NFV | BWR NFV |
| 5.0                     | 0.0019           | -0.0008    | 0.0002  | 0.0200  |
| 6.5                     | 0.0019           | -0.0003    | 0.0005  | 0.0223  |
| 8.0                     | 0.0024           | 0.0000     | 0.0003  | 0.0235  |

# Neutronic decoupling

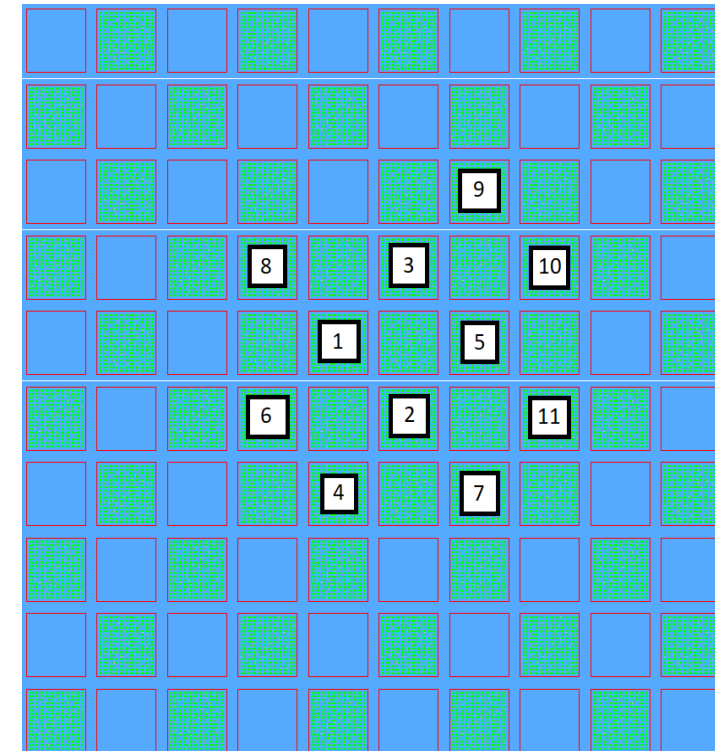
- Neutronic decoupling distance was evaluated for the W 17 × 17 STD and ATRIUM 10 fuel assemblies
- Nominal enrichment assemblies at 30 cm separation have less than 0.00075 difference in  $k_{\text{eff}}$  from the maximum separation
- This is replicated with LEU+ enrichments



# Soluble boron credit (SBC) and accident analysis

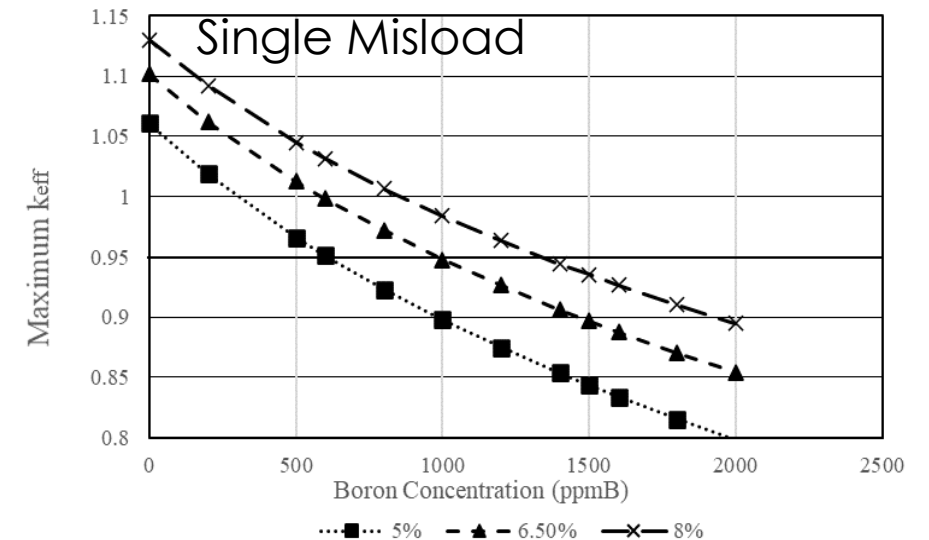
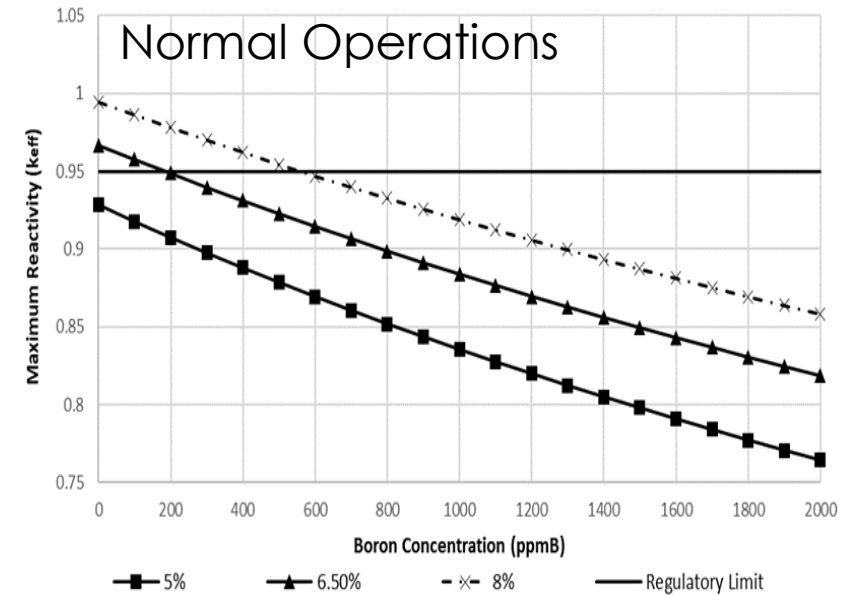
- PWR pools have bifurcated limit
  - Less than 1.0 with no credit for boron in pool water
  - Less than 0.95 with SBC
  - Accidents typically considered in SBC analysis
- Looked at
  - Boron concentration to get 0.95 under normal conditions
  - Misload into DA SFP model
    - 1, 5, and 11 misloads considered
    - 5.0, 6.5, and 8 wt. %
    - Zirc-4 cladding

Expanded Misload Analysis Model



# Normal operations and misload results

- Normal conditions boron requirements
  - 0 for 5.0 wt. %, 200 ppm for 6.5 wt. %, and 600 for 8.0 wt. %
- Single misload result
  - 600 ppm for 5 wt. %, 1000 ppm for 6.5 wt. %, and 1400 ppm for 8.0 wt. %



# 5- and 11-misload cases

- 5-misload case requires
  - 5 wt. % - 1000 ppm, 6.5 wt. % - 1500 ppm, 8.0 wt. % - 2000 ppm
- 11-misload case
  - 5 wt. % - 1200 ppm, 6.5 wt. % - 1600 ppm, 8 wt. % - >2000 ppm

