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Pressurized Water Reactor Gadolinia Pin Location Optimization

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Nuclear Energy and Fuel Cycle Division

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ABBREVIATIONS

BA burnable absorber

BOC beginning of cycle

IFBA Integral Fuel Burnable Absorber

LWR light-water reactor

MOT metaheuristic optimization tool

NRC US Nuclear Regulatory Commission

PPF pin peaking factor

PWR pressurized water reactor

ABSTRACT

This report presents the results of lattice optimization studies performed to find optimum locations for gadolinia burnable absorber (BA) rods in pressurized water reactor (PWR) lattice fuel designs. Initial excess reactivity suppression allows core designers to further improve operational economics by extending cycle length. Gadolinia BAs are commonly used in boiling water reactor assembly designs for this purpose. In recent years, gadolinia absorbers have been used in PWR designs owing to their longer effectiveness for reactivity suppression compared with common BAs used in PWR assemblies. This report examines the optimum gadolinia pin placement in 17 × 17 PWR lattices at different fuel and gadolinia concentrations for optimized lattice performance, using the `SCALE/Polaris` lattice physics code. The completed work is continuation of the Light Water Reactor LEU+ Lattice Optimization (ORNL/TM-2021/2366) project. An optimization driver called the metaheuristic optimization tool (MOT) is used to automate domain space exploration and optimization of the lattice designs. Heuristics from previous light-water reactor (LWR) lattice optimization studies were used to construct the objective function and define the domain space for optimization. This work successfully demonstrated that the optimization algorithms of MOT can generate feasible, nonproprietary PWR lattice designs with gadolinia.

1. INTRODUCTION

Suppression of initial core excess reactivity using BAs is a common practice in LWR assembly design. The reactivity suppression allows core designers to increase batch size and fuel enrichment to further improve operational economics by extending cycle length. Gadolinia-loaded fuel rods are commonly used in boiling water reactor assembly designs for this purpose. In recent years, gadolinia absorbers have been used in PWR designs, especially those with increasing fuel enrichment. Gadolinia absorbers have extended effectiveness for reactivity suppression compared with Integral Fuel Burnable Absorber (IFBA) and operational convenience compared with wet annular burnable absorbers and Pyrex rods that are commonly used in PWR assemblies [1]. Gadolinia-loaded fuel rod locations in 17 × 17 PWR lattices with dominant fuel enrichment ranging from 4.4% to 4.95% and carrier fuel enrichment (fuel enrichment in the gadolinia rod) ranging from 2.6% to 4.7% were investigated for 6–11 wt % gadolinia. Lattice design performance metrics, such as excess reactivity at BOC, reactivity at end-of-cycle reactivity, and pin peaking factors were calculated using the `SCALE/Polaris` lattice physics code for each tested configuration. Based on the results, a simple linear correlation can map target gadolinia pin peaking factor, dominant fuel enrichment, and ratio of gadolinia concentration to carrier fuel enrichment to provide a starting point to help core designers with approximate lattice designs.

An optimization driver called the MOT is used to automate domain-space exploration and optimization of the lattice designs. Heuristics from previous LWR lattice optimization studies were used to construct the objective function and define the domain space for optimization. The objective function includes important metrics such as the number of gadolinia pins in the lattice and maximum PPF. This work successfully demonstrated that the optimization algorithms of MOT can generate feasible, nonproprietary PWR lattice designs using gadolinia that meets the provided set of constraints. The presented study is a continuation of the Light Water Reactor LEU+ Lattice Optimization project, and implementation details of MOT can be found elsewhere [2].

2. OPTIMIZATION PROBLEM DEFINITION

The objective of this optimization problem is to design a PWR lattice with a certain number of gadolinia pins, with the lowest pin peaking factor (PPF). Gadolinia pins herein denote gadolinia-loaded fuel pins, and gadolinia pin enrichment denotes the ^{235}U enrichment of gadolinia-loaded fuel pins. Furthermore, an additional constraint is enforced such that gadolinia pin PPF values cannot exceed 0.95 because gadolinia pins have lower thermal conductivity, which can be a limiting factor in lattice performance.

Thus the lattice optimization includes two constraints:

1. The number of gadolinia pins in the assemblies should match the user-defined number.
2. The PPF of gadolinia pins must be less than 0.95.

And the optimization objective is to minimize the maximum PPF in time and location. The k_{inf} value does not need to be considered in the optimization function because the amount of gadolinia pin loading enforces the amount of BA loading. In other words, for the same amount of BA loading, the k_{inf} curve is almost identical, with minor differences with respect to gadolinia pin location.

The objective function for the PWR assembly optimization is shown in Eq. (1). The weighting coefficients heavily enforce against violations of the gadolinia pin numbers and the gadolinia pin PPF constraint. The weighting coefficients are chosen so that the algorithm optimizes the number of gadolinia pins first, and then fine-tunes the PPF distribution.

$$\begin{aligned} \text{Minimize} \quad F = {} & PPF_{\mathrm{max}} \\ & 2 \cdot |N_{\mathrm{gp,lattice}} - N_{\mathrm{gp,goal}}| \\ & 5 \cdot \max(0, PPF_{\mathrm{gp,max}} - 0.95) \end{aligned} \tag{1}$$

where

PPF_{max} = maximum PPF during lattice lifetime (i.e., max(PPF(x,BU))

$N_{\mathrm{gp,lattice}}$ = number of gadolinia pins in the lattice

$N_{\mathrm{gp,goal}}$ = desired number of gadolinia pins

$PPF_{\mathrm{gd,max}}$ = maximum gadolinia pin PPF during lattice lifetime

3. NOMINAL MODEL

The nominal model is a representative Westinghouse 17 × 17 PWR lattice. An assumed uniform fuel pin enrichment of 4.8 wt % is used for the nominal design. From that design, the fuel pins are replaced with gadolinia pins that are enriched to 3.5 wt %. The reduction of the gadolinia pin enrichment reduces the PPF on the gadolinia pins because the pins have a lower thermal conductivity with gadolinia. The 3.5 wt % enrichment value is provided by the US Nuclear Regulatory Commission (NRC) and has been confirmed by a separate sensitivity analysis (presented in the report) to be the highest gadolinia pin enrichment that ensures low enough PPF in most designs.

The gadolinia concentration in the fuel is fixed to 8%, and the pin density is adjusted from 10.376 g/cm^3 for fuel pins to 10.138 g/cm^3 for gadolinia pins.

4. RESULTS

The optimization results are organized in two parts: an explanation of the evolutionary process of lattice designs from the design scope and an in-depth explanation of the selected design for each optimization study.

To efficiently scope the design dimensions, the study was executed as follows to reduce the number of optimization runs:

1. A gadolinia pin location optimization was performed for 4.8% fuel pin enrichment and 8% gadolinia concentration configuration for 16, 20, and 24 gadolinia pin configurations.
2. The optimized lattice designs with optimized gadolinia pin positions were then perturbed in enrichment and gadolinia concentration.

4.1 Gadolinia Pin Location Optimization Results

Three optimization studies were performed. Assuming 4.8% enrichment for fuel pins, 3.5% enrichment for gadolinia pins, and 8% gadolinia concentration for gadolinia pins, the optimization driver was tasked to find optimal lattice designs for 16, 20, and 24 gadolinia pins. In other words, the $N_{\mathrm{gp,goal}}$ in Eq. (1) was set to 16, 20, and 24 for each optimization case.

The optimization run had 64 samples per iteration (generation) and ran for 30 iterations. Figures 1, 2, and 3 show how the lattice design metrics evolved with iteration. It shows that the optimization driver successfully guides the design to match the user-defined number of gadolinia pins while also reducing PPF.

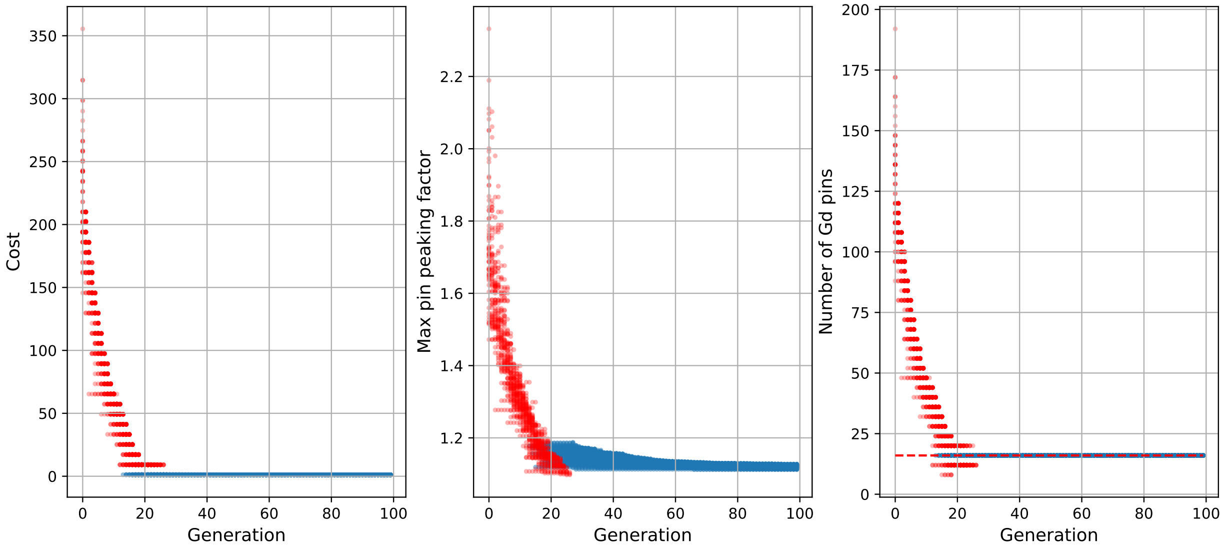


Figure 1. Evolution of gadolinia pin location optimization designs for lattices with 4.8% fuel enrichment and 16 gadolinia pins with 8% gadolinia concentration and 3.5% enrichment. The cost in the leftmost panel is the objective function result from Eq. (1). The red points denote designs that did not satisfy the constraint on the number of gadolinia pins.

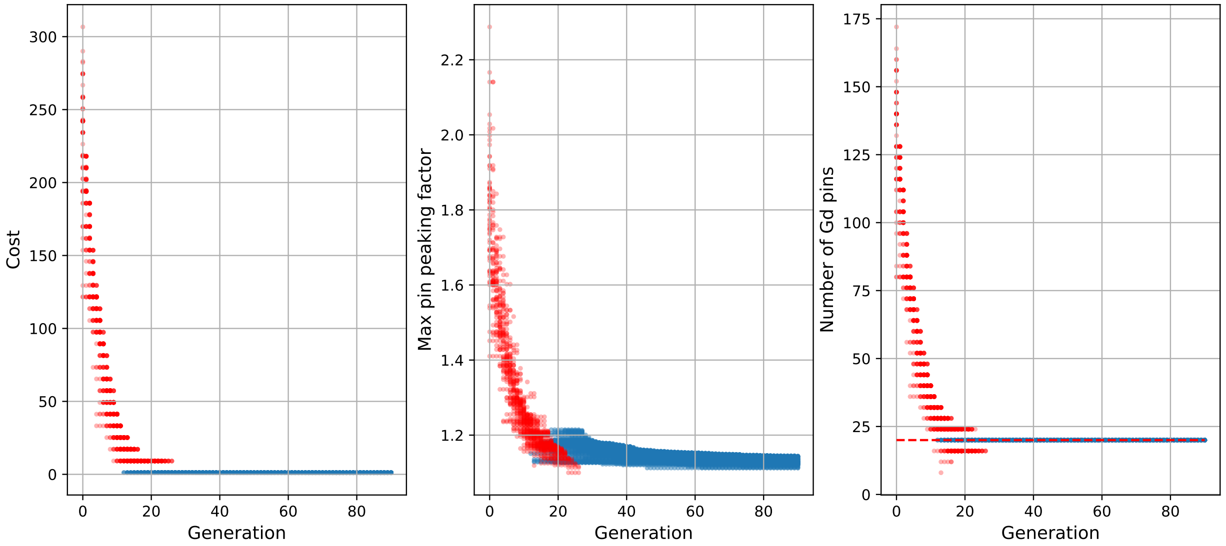


Figure 2. Evolution of gadolinia pin location optimization designs for lattices with 4.8% fuel enrichment and 20 gadolinia pins with 8% gadolinia concentration and 3.5% enrichment. The cost in the leftmost panel is the objective function result from Eq. (1). The red points denote designs that did not satisfy the constraint on the number of gadolinia pins.

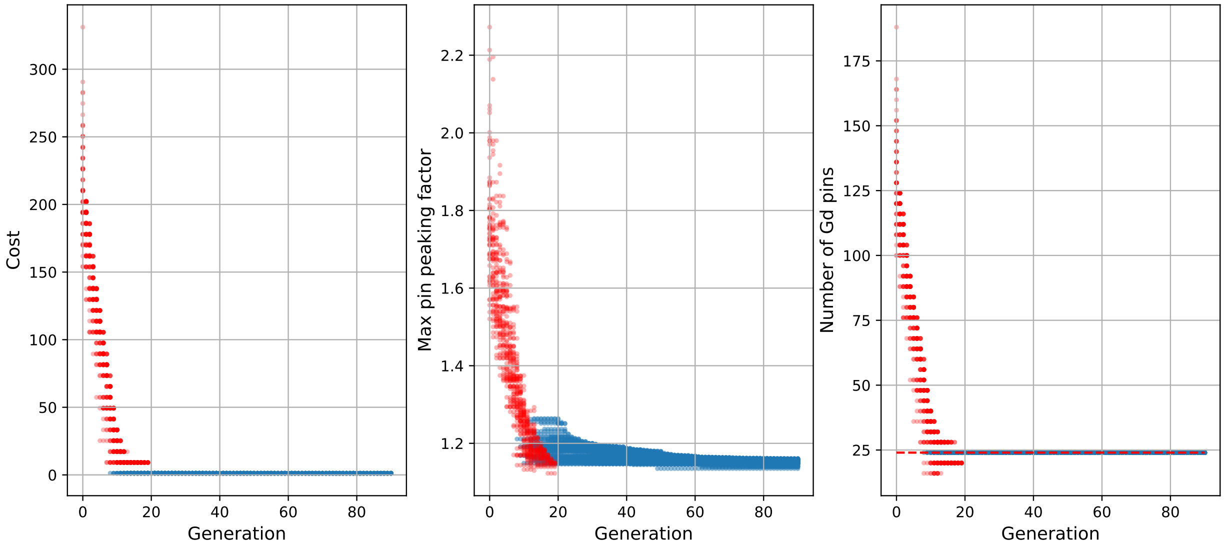
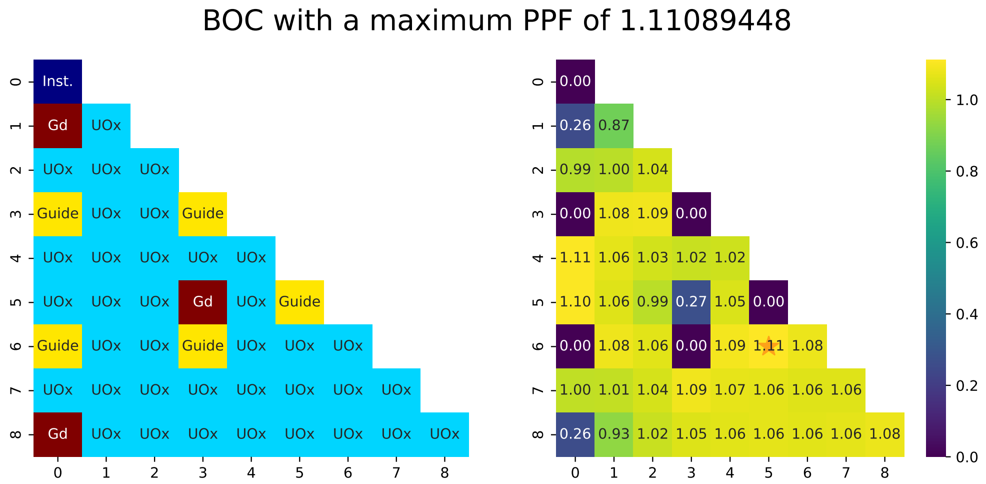


Figure 3. Evolution of gadolinia pin location optimization designs for lattices with 4.8% fuel enrichment and 24 gadolinia pins with 8% gadolinia concentration and 3.5% enrichment. The cost in the leftmost panel is the objective function result from Eq. (1). The red points denote designs that did not satisfy the constraint on the number of gadolinia pins.

For each optimization run, $30 \times 64 = 1920$ lattice designs were sampled. Among them, the lattice design that did not meet the gadolinia pin number and gadolinia pin PPF limit of 0.95 were filtered out. From the remaining designs, the design with the lowest PPF was selected.

Because the assembly pin location is defined as a 1/8 symmetry, the number of pins per location differs throughout the assembly. For example, if a pin is placed in the edges of the 1/8 assembly, then the entire assembly will contain four pins. Similarly, if the pins fall within the bounds of the assembly, then the entire assembly will contain eight pins. This constraint makes it difficult for the algorithm to find the right combination of gadolinia pin locations that matches the exact number of user-defined gadolinia pins, possibly limiting its optimization.

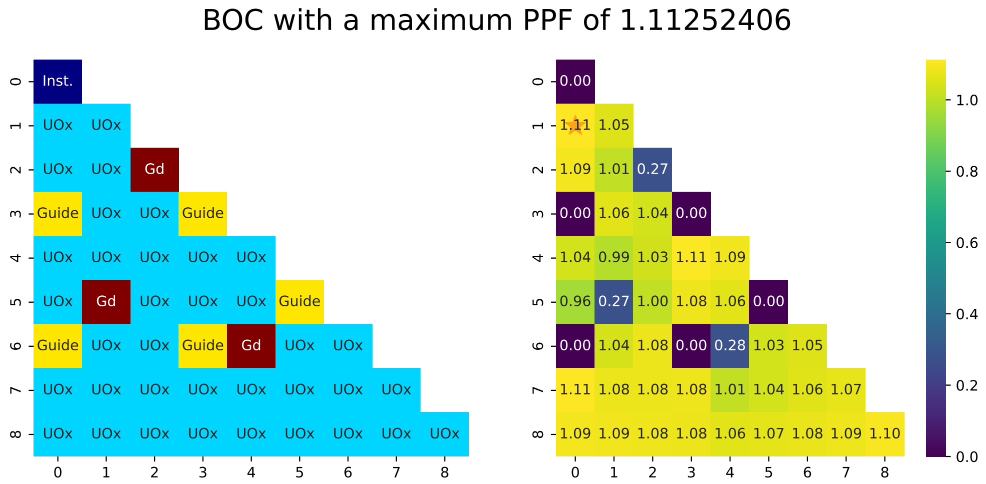
The optimized lattice designs are shown in Figures 4 through 6. All the maximum PPF occurs in BOC, usually near the gadolinia pin, and next to a guide tube or instrumentation location. Due to the significantly lower enrichment—4.8% for the fuel pin and 3.5% for the gadolinia pins—the maximum PPF of the gadolinia pins does not exceed 0.95 at any depletion step.


BOC with a maximum PPF of 1.11089448

	0	1	2	3	4	5	6	7	8
0	Inst.								
1	Gd	UOx							
2	UOx	UOx	UOx						
3	Guide	UOx	UOx	Guide					
4	UOx	UOx	UOx	UOx	UOx				
5	UOx	UOx	UOx	Gd	UOx	Guide			
6	Guide	UOx	UOx	Guide	UOx	UOx	UOx		
7	UOx	UOx	UOx	UOx	UOx	UOx	UOx	UOx	
8	Gd	UOx	UOx	UOx	UOx	UOx	UOx	UOx	UOx

	0	1	2	3	4	5	6	7	8
0	0.00								
1	0.26	0.87							
2	0.99	1.00	1.04						
3	0.00	1.08	1.09	0.00					
4	1.11	1.06	1.03	1.02	1.02				
5	1.10	1.06	0.99	0.27	1.05	0.00			
6	0.00	1.08	1.06	0.00	1.09	1.11	1.08		
7	1.00	1.01	1.04	1.09	1.07	1.06	1.06	1.06	
8	0.26	0.93	1.02	1.05	1.06	1.06	1.06	1.06	1.08

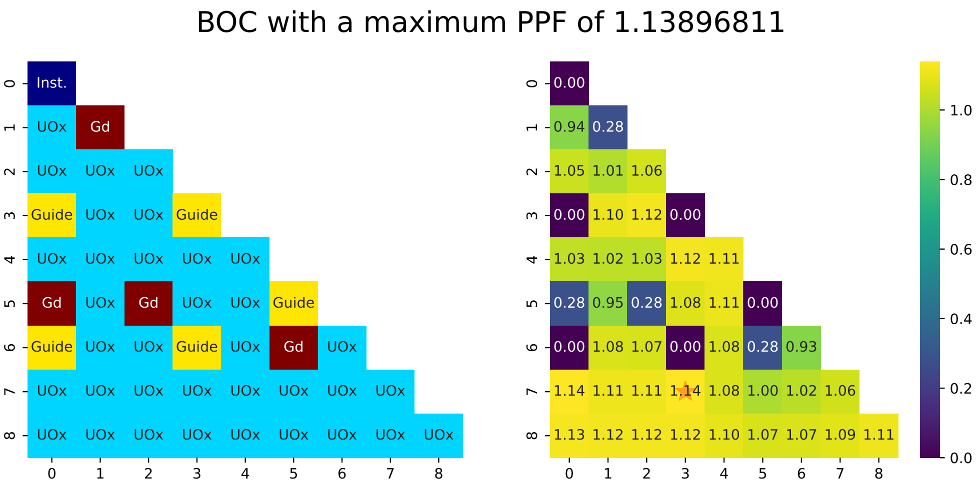
Figure 4. Pin map and BOC PPF distribution for the 16 gadolinia pin configuration.


BOC with a maximum PPF of 1.11252406

	0	1	2	3	4	5	6	7	8
0	Inst.								
1	UOx	UOx							
2	UOx	UOx	Gd						
3	Guide	UOx	UOx	Guide					
4	UOx	UOx	UOx	UOx	UOx				
5	UOx	Gd	UOx	UOx	UOx	Guide			
6	Guide	UOx	UOx	Guide	Gd	UOx	UOx		
7	UOx	UOx	UOx	UOx	UOx	UOx	UOx	UOx	
8	UOx	UOx	UOx	UOx	UOx	UOx	UOx	UOx	UOx

	0	1	2	3	4	5	6	7	8
0	0.00								
1	1.11	1.05							
2	1.09	1.01	0.27						
3	0.00	1.06	1.04	0.00					
4	1.04	0.99	1.03	1.11	1.09				
5	0.96	0.27	1.00	1.08	1.06	0.00			
6	0.00	1.04	1.08	0.00	0.28	1.03	1.05		
7	1.11	1.08	1.08	1.08	1.01	1.04	1.06	1.07	
8	1.09	1.09	1.08	1.08	1.06	1.07	1.08	1.09	1.10

Figure 5. Pin map and BOC PPF distribution for the 20 gadolinia pin configuration.



BOC with a maximum PPF of 1.13896811

	0	1	2	3	4	5	6	7	8
0	Inst.								
1	UOx	Gd							
2	UOx	UOx	UOx						
3	Guide	UOx	UOx	Guide					
4	UOx	UOx	UOx	UOx	UOx				
5	Gd	UOx	Gd	UOx	UOx	Guide			
6	Guide	UOx	UOx	Guide	UOx	Gd	UOx		
7	UOx	UOx	UOx	UOx	UOx	UOx	UOx	UOx	
8	UOx	UOx	UOx	UOx	UOx	UOx	UOx	UOx	UOx

	0	1	2	3	4	5	6	7	8
0	0.00								
1	0.94	0.28							
2	1.05	1.01	1.06						
3	0.00	1.10	1.12	0.00					
4	1.03	1.02	1.03	1.12	1.11				
5	0.28	0.95	0.28	1.08	1.11	0.00			
6	0.00	1.08	1.07	0.00	1.08	0.28	0.93		
7	1.14	1.11	1.11	1.14	1.08	1.00	1.02	1.06	
8	1.13	1.12	1.12	1.12	1.10	1.07	1.07	1.09	1.11

Figure 6. Pin map and BOC PPF distribution for the 24 gadolinia pin configuration.

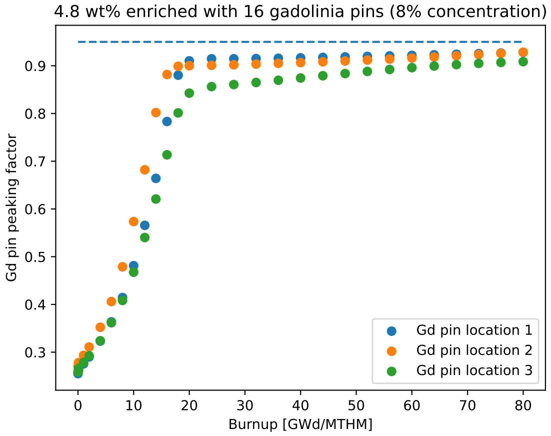


Figure 7. Gadolinia pin PPF with depletion for the 16 gadolinia pin configuration.

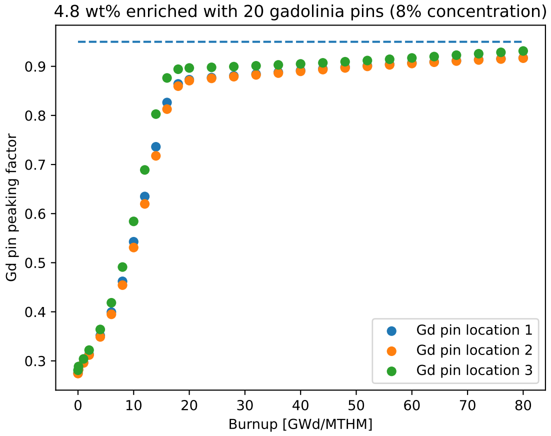


Figure 8. Gadolinia pin PPF with depletion for the 20 gadolinia pin configuration.

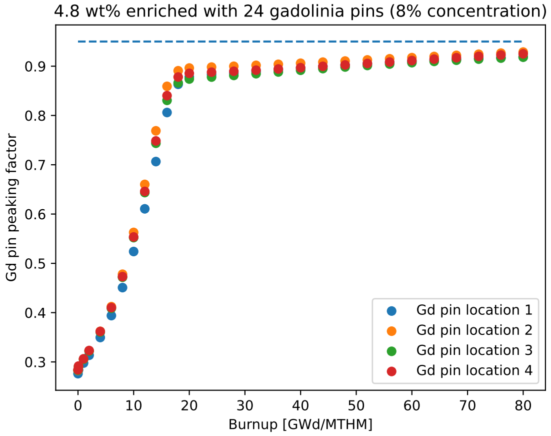


Figure 9. Gadolinia pin PPF with depletion for the 24 gadolinia pin configuration.

4.2 Lattice Design Perturbation Study

The obtained pin map designs for the 16, 20, and 24 gadolinia pin configurations were perturbed in fuel pin enrichment, gadolinia concentration, and gadolinia pin enrichment to explore the sensitivity of the lattice k_{inf} curve and the PPF distribution.

The fuel pin, gadolinia pin enrichment, and gadolinia concentration sample values are listed in Table 1.

The 300 sampled cases (100 enrichment–gadolinia concentration combinations and three different numbers of gadolinia pins) were then analysed to visualize their distribution of pertinent metrics. The gadolinia concentration [%]and number of gadolinia pins are aggregated to a single metric of 'gadolinia loading,' which is the gadolinia concentration times the number of gadolinia pins in the assembly.

Figure 10 shows the distribution of the maximum gadolinia pin PPF. The markers labeled 'X' have maximum gadolinia pin PPF values greater than 0.95. The plot shows that the maximum gadolinia pin PPF strongly correlates with the difference in fuel pin enrichment and gadolinia pin enrichment, especially for small differences (Figure 11). The plot also shows that the maximum gadolinia pin PPF is not strongly affected by gadolinia loading (approximately 0.02).

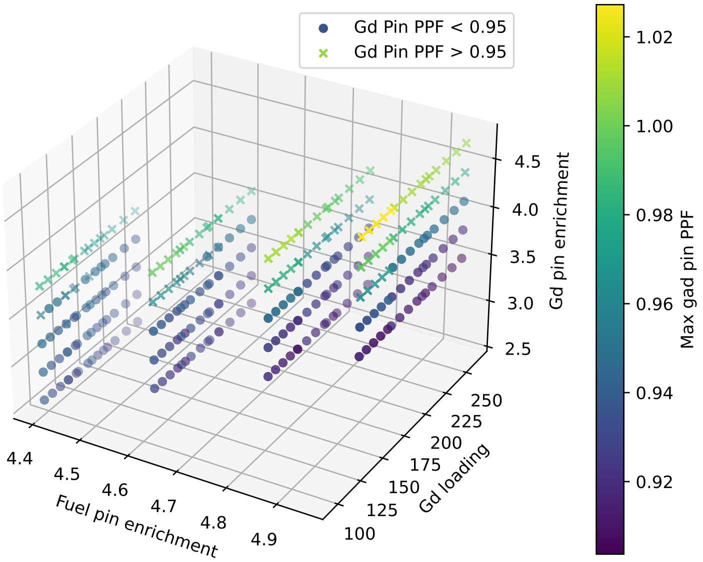


Figure 10. Gadolinia pin PPF distribution for perturbed assembly configurations.

Table 1. Fuel pin enrichment and corresponding gadolinia concentration and gadolinia pin enrichment values sampled for the perturbation study.

Fuel pin enrichment (wt %)	Gadolinia pin enrichment (%)					Gadolinia concentration (%)				
4.4	2.6	2.9	3.2	3.5	3.8	6	6.5	7	7.5	8
4.6	2.9	3.2	3.5	3.8	4.1	7	7.5	8	8.5	9
4.8	3.2	3.5	3.8	4.1	4.4	8	8.5	9	9.5	10
4.95	3.5	3.8	4.1	4.4	4.7	9	9.5	10	10.5	11

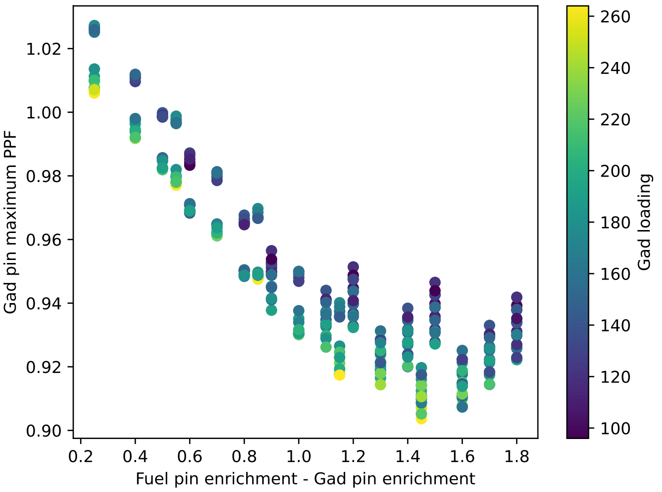


Figure 11. Relationship between difference in fuel pin enrichment and gadolinia pin enrichment and gadolinia pin maximum PPF.

Figure 12 shows the assembly-wide (across all pins) maximum PPF in the assembly design. As expected, the PPF positively correlates with gadolinia loading. Similarly, Figure 13 shows the BOC k_{inf} distribution, indicating that higher gadolinia loading leads to a lower BOC k_{inf} .

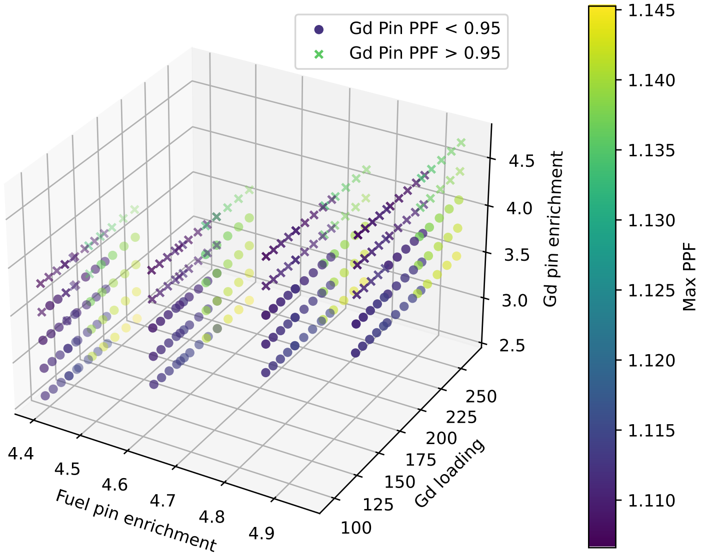


Figure 12. Maximum PPF distribution for perturbed assembly configurations.

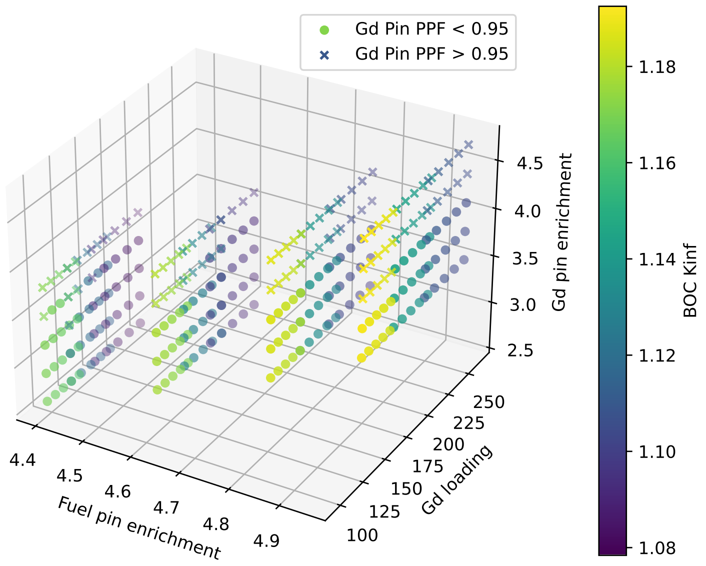


Figure 13. BOC $k_{\mathbf{inf}}$ distribution for perturbed assembly configurations.

The generated data can be used to develop a simple regression function to predict the gadolinia pin enrichment necessary to meet target gadolinia pin maximum PPF (Eq. [2]). A Python multidimensional linear fit function was used to obtain the linear coefficients for the fit (Eq. [3]).

$$E_{Gd} = f(E_F, GdLoad, PPF_{Gd,target}) \tag{2}$$

$$E_{Gd} = 1.130 \cdot (E_F) + 0.00204 \cdot (GdLoad) + 13.280 \cdot (PPF_{Gd,target}) - 14.611 \tag{3}$$

where

E_{Gd} = gadolinia pin ^{235}U enrichment
E_F = Fuel pin ^{235}U enrichment
$GdLoad$ = Gadolinia concentration times the number of gadolinia pins in the assembly
$PPF_{Gd,target}$ = Target gadolinia pin maximum PPF

The linear fit can be used to predict the samples' gadolinia pin enrichment. The difference between prediction and data is shown in Figure 14. The plot shows that if the gadolinia pin enrichment is set to 0.5 wt % less than the predicted value, then a gadolinia pin maximum PPF is guaranteed to be less than the target PPF value. For example, for fuel pin enrichment of 4.95% and gadolinia concentration of 11% with 20 gadolinia pins and a gadolinia pin maximum PPF constraint of 0.95, Eq. 3 returns 4.047. Thus, a gadolinia pin enrichment of 3.54% guarantees that the gadolinia pin PPF remains less than 0.95.

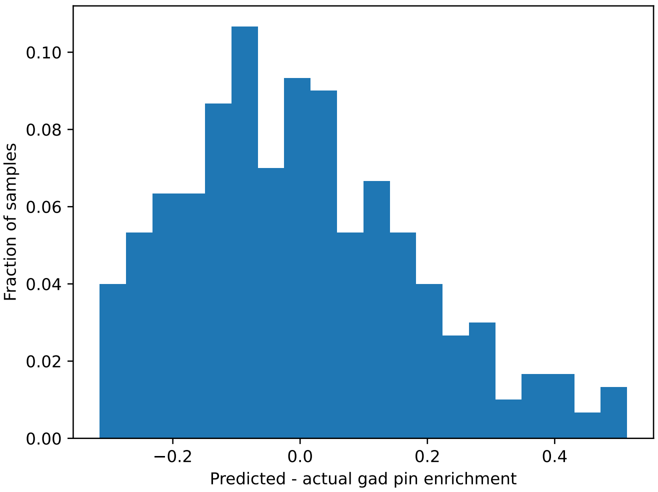


Figure 14. BOC k_{inf} distribution for perturbed assembly configurations.

5. CONCLUSION

This work presents an optimization study and exploration of the design space for a PWR lattice with gadolinia pins. The optimization study aimed to minimize maximum PPF in the assembly while keeping gadolinia pin maximum PPF under 0.95. The optimization workflow found designs with 16, 20, and 24 gadolinia pins that had acceptable PPF.

The design perturbation study shows that the maximum gadolinia pin PPF strongly correlates with the difference between fuel pin and ^{235}U enrichment in the gadolinia pin and is less correlated with total gadolinia loading. However, higher gadolinia loading causes a higher assembly-wide PPF and a lower BOC k_{inf} , as expected.

The primary goal of this study was to provide a representative lattice design for a given set of constraints. The optimization workflow demonstrated the capability to provide a guideline for lattice designs from a set of constraints and a target metric. This workflow can be extended to different configurations and target metrics.

6. REFERENCES

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