Management of Thermal Peaking Factors in CONFU-B PWR Assemblies Using Neutron Poisons and Tailored Enrichment

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Abstract

CONFU-B assemblies are PWR assemblies containing standard Uranium fuel rods and TRU bearing inert material fuel rods and are designed to achieve net TRU destruction over a 4.5-year irradiation. These highly heterogeneous assemblies tend to exhibit large intra-assembly power peaking factors (IAPPF). Neutronic strategies to reduce IAPPF are developed. The IAPPF are calculated at the assembly level using CASMO4, and these are used to calculate the most restrictive thermal margin (the Minimum Departure from Nucleate Boiling Ratio, MDNBR) using a whole-core VIPRE-01 model.

This paper examines two strategies to manage the thermal margin of a CONFU-B assembly while retaining the TRU destruction performance: use of neutron poisons and tailored enrichment schemes. Burnable poisons can be used to suppress BOL reactivity of fresh CONFU-B assemblies with only minor impact on MDNBR and TRU destruction performance. Tailored enrichment, along with the use of soluble boron, can achieve significant improvements in MDNBR, but at some cost to TRU destruction performance.

KEYWORDS: Plutonium Burning, Transuranic transmutation, Heterogeneous Nuclear Assemblies, Advanced PWR Fuels, Inert Matrix Fuel, Power Peaking.

1. Introduction

<u>Co</u>mbined <u>N</u>on-<u>F</u>ertile and <u>U</u>O_2 (CONFU) assemblies are designed to manage the trans-uranic isotopes (TRU) from spent nuclear fuel (SNF). These PWR assemblies are based on a standard Westinghouse 17x17 fuel assembly geometry, and are designed to have neutronic and thermal-hydraulic performance similar to an all UO_2 assembly. They use a mix of standard UO_2 pins along with inert matrix fuel (IMF) pins made of TRU microspheres in an inert matrix [1,2]. CONFU-Burndown (CONFU-B) fuel assemblies have been designed that fission more TRU in the IMF pins than is produced in the UO_2 pins, resulting in a net TRU destruction over a 3-batch, 18-month fuel cycle. The first cycle CONFU-B assembly is shown in Fig. 1.

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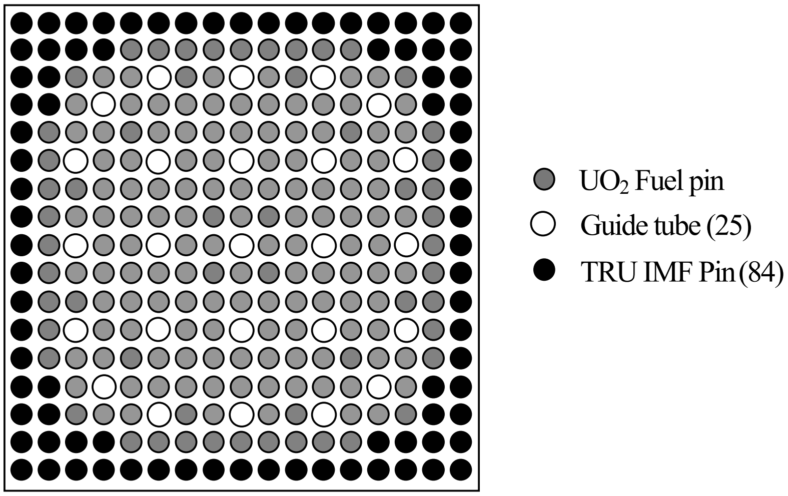
Figure 1: CONFU-B assembly



After an appropriate cooling period, the remaining TRU in the IMF pins is reprocessed and is mixed with the TRU separated from the UO$_2$ pins to make the majority of the TRU for the next CONFU-B batch. Additional TRU from either legacy spent fuel or other discharged CONFU assemblies is needed to fully load the next CONFU batch. In this way, the TRU is multi-recycled, only fission products and separation/reprocessing losses are sent to the repository, and the legacy inventory of TRU is reduced over time. The net destruction rate achieved in CONFU-B assemblies is 0.3 to 3.52 kg per assembly, depending on the mixing scheme, cooling time, and the number of times the TRU has been recycled [3].

However, the highly heterogeneous nature of these assemblies can result in fairly high intra-assembly pin power peaking factors (IAPPF). This can result in a reduction of the minimum departure from nucleate boiling ratio (MDNBR) compared to an all UO$_2$ assembly. This reduces thermal margins, and can restrict where these assemblies are loaded in a reactor core and hence reduce the flexibility available to fuel managers. This paper studies methods to improve the MDNBR of CONFU-B assemblies.

In this work, we generate IAPPF for an assembly using CASMO4 [4] and the JEF2.2 nuclear data library. These IAPPF are then used to conduct a whole-core thermal hydraulic analysis using VIPRE-01 [5]. The core operating parameters used in the VIPRE model are listed in Tab. 1. All calculations were performed at steady state assuming 118% core average power to account for Condition I and II events. The inlet coolant temperature used was 2 ^{o}C higher than nominal to account for uncertainties in inlet temperature distribution. The total coolant mass flux was reduced by 5% to account for bypass flow and uncertainty associated with the core wide flow distribution. In addition, a comparative analysis with an all UO$_2$ core was conducted using the same approach and assumptions.

Table 1: Core Parameters used in VIPRE whole core calculations

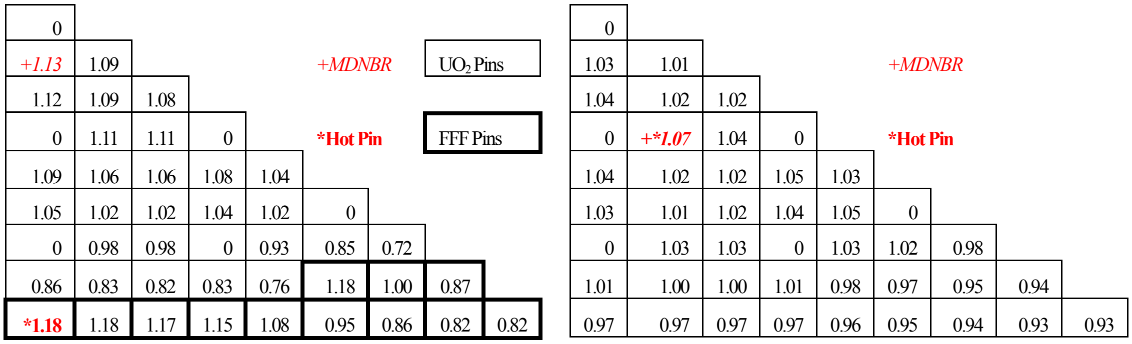
Parameter	**Specification**
Axial Power Profile	Chopped Cosine, peak-to-average ratio=1.55
Reactor Power	Overpower at 118% (4025 MW_{th})
Power Deposited Directly in coolant	2.6%
Core Mass Flux	Reduced by 5% (3549 kg/s-m^2)
Core Inlet Temp	Increased by 2 ^oC (294.7 ^oC)

2. Intra-Assembly Pin Power Peaking Factors and MDNBR

2.1 CONFU-B vs UO_2

By design, an IMF pin in a CONFU-B assembly carries the highest power. This helps the assembly to maximize the TRU destruction. For the first CONFU-B recycle, the highest IAPPF in an IMF pin is 1.18. This high pin peaking is somewhat compensated by having cooler pins in the immediate vicinity. The result is that the hottest pin is *not* the location of the most limiting MDNBR in the assembly. Fig. 2 shows that IAPPF and MDNBR location for the initial load CONFU-B assembly and an all-UO_2 assembly.

Figure 2: IAPPF and MDNBR location for CONFU-B and UO_2 assemblies, 0 MWd/kg



0								
+1.13	1.09							
1.12	1.09	1.08						
0	1.11	1.11	0					
1.09	1.06	1.06	1.08	1.04				
1.05	1.02	1.02	1.04	1.02	0			
0	0.98	0.98	0	0.93	0.85	0.72		
0.86	0.83	0.82	0.83	0.76	1.18	1.00	0.87	
*1.18	1.18	1.17	1.15	1.08	0.95	0.86	0.82	0.82

CONFU –B Assembly

0								
1.03	1.01							
1.04	1.02	1.02						
0	+*1.07	1.04	0					
1.04	1.02	1.02	1.05	1.03				
1.03	1.01	1.02	1.04	1.05	0			
0	1.03	1.03	0	1.03	1.02	0.98		
1.01	1.00	1.00	1.01	0.98	0.97	0.95	0.94	
0.97	0.97	0.97	0.97	0.96	0.95	0.94	0.93	0.93

UO_2 Assembly

Even so, the pin peaking in other parts of the assembly can result in reduced thermal margins compared to an all-UO_2 assembly. However, since the CONFU-B assembly has a more uneven power distribution than the all-UO_2 assembly, it can benefit more from increased turbulent mixing. The VIPRE analysis conducted utilizes the following turbulent mixing correlation:

$$w' = \beta s \overline{G} \tag{1}$$

where:

- w' = turbulent crossflow
- β = turbulent mixing factor
- s = gap width
- $\overline{G}$ = average of the mass flux in adjacent channels

A conservative value for β is 0.038, although mixing vanes in current PWRs can achieve higher values. To test the sensitivity of MDNBR to turbulent mixing, values of 0.038 and 0.072 were used for β.

Additionally, a typical value of 1.587 was used for the peak-to-average radial power peaking. However, previous studies on CONFU-E conducted a whole core neutronic analysis using CASMO-SIMULATE and calculated the peak-to-average radial power peaking of 1.47 [6]. For this analysis, we used values of 1.587 and 1.50 for the peak-to-average radial power profile. Tab. 2 gives the MDNBR attained for combinations of turbulent mixing and radial power distribution.

Table 2: MDNBRs

Assembly Type	Mixing Coefficient	Radial Peaking Factor	Pin Peak	MDNBR
All UO_2	0.038	1.587	1.072	1.440
	0.072	1.587		1.441
	0.072	1.500		1.618
CONFU-B, Recycle 01	0.038	1.587	1.183	1.255
	0.072	1.587		1.283
	0.072	1.500		1.443
CONFU-B, Recycle 03	0.038	1.587	1.233	1.282
	0.072	1.587		1.300
	0.072	1.500		1.499

Note that the heterogeneous CONFU-B assemblies benefit more from improved turbulent mixing than the all-UO_2 assembly does. Also note that a core loaded with CONFU-B assemblies would be limited to a radial power peaking factor of 1.50 in order to attain the minimum goal of MDNBR = 1.40 or better. The ultimate goal would be to exactly match the MDNBR of an all-UO_2 assembly. In other words, for $\beta = 0.072$ and radial peaking = 1.50, we would like to achieve an MDNBR = 1.62.

2.2 CONFU-B vs MOX-UE, CORAIL

As the assembly accumulates burnup, the pin peaking flattens naturally, and thermal-hydraulic margins increase. In addition, as the TRU is multirecycled, it accumulates a larger fraction of fertile isotopes and a smaller fraction of fissile isotopes. This reduces the reactivity of the TRU, and helps improve thermal-hydraulic margins. Note that the discharge burnup of these CONFU-B assemblies is 1350 EFPD. At discharge of cycle 01, the largest IAPPF is 1.07, so the peaking flattens significantly over the course of irradiation.

It is valuable to compare the thermal-hydraulic performance of CONFU-B with other strategies for multi-recycling TRU. Other cycles compared are MOX-UE [7], CORAIL-Pu [8] and CORAIL-TRU [9]. These assemblies use combinations of UO_2, MOX, and IMF pins to multi-recycle Pu-only or the entire TRU vector. Tab. 3

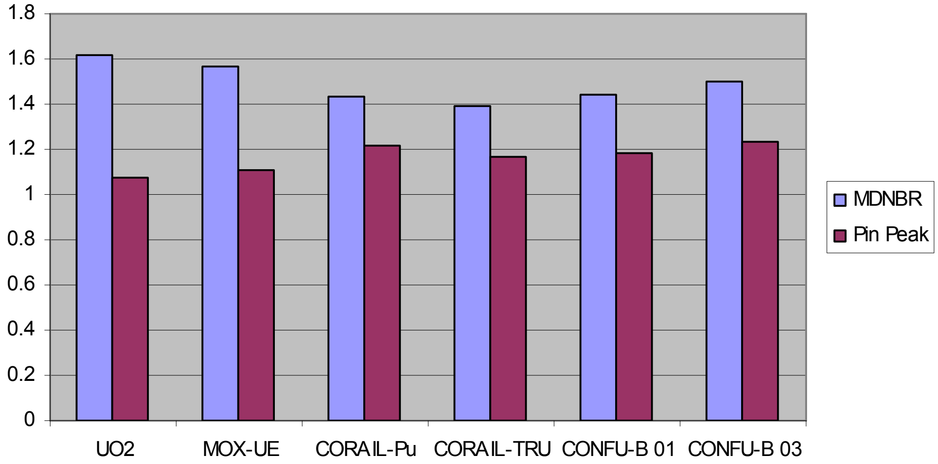
summarizes the key features of each design for the first cycle.

Table 3: Summary of key parameters, cycle 1

	MOX-UE	**CORAIL-Pu**	**CORAIL-TRU**	**CONFU-B**
TRU Recycled	Pu	Pu	TRU	TRU
TRU Host Matrix	MOX	MOX	MOX	IMF
Assembly pins	264 MOX	180 UO_2 / 84 MOX	180 UO_2 / 84 MOX	180 UO_2 / 84 IMF
UO_2 enrichment	0.25 wt %	4.15 wt %	4.72 wt %	4.2 wt %
TRU Loading	9.3 wt %	6.5 wt %	6.57 wt %	10 vol %

We used CASMO to calculate the IAPPF for each of these strategies using their previously published TRU (or Pu) vectors. These IAPPF were then used in the VIPRE whole-core model to determine the MDNBR for each strategy. The results are given in Fig. 3.

Figure 3: VIPRE-01 Results for MOX-UE, CORAIL, CONFU-B, and UO_2 assemblies



Note that homogeneous assembly designs (UO_2 and MOX-UE) exhibit the lowest IAPPF and the best MDNBR, while the heterogeneous designs (CORAIL and CONFU) exhibit higher IAPPF and lower MDNBR. Also note that the MDNBR improves for CONFU-B from cycle 01 to cycle 03. Since the first cycle is the most challenging thermal-hydraulically, it will be the focus of the MDNBR improvement strategies studied in the remainder of this paper.

3. Use of neutron poisons

3.1 General effects of poisons

The first strategy studied to improve thermal-hydraulic margins was the use of neutron poisons. Poisons are used to reduce the reactivity of a fresh CONFU-B assembly when it is first loaded into a reactor. This is necessary for reactivity management at startup, but it also helps to reduce the average power of the assembly when the pin peaking is the greatest. As the assembly accumulates burnup, the pin peaking flattens naturally, and thermal-hydraulic margins increase.

3.2 Soluble Boron

Soluble boron is the first poison considered. Since the TRU in the IMF pins has stronger neutron absorption cross-sections than the UO_2 pins, the boron is worth less near the IMF pins. As a result, power peaking is increased in the IMF pins, which are the hottest pins in the un-poisoned assembly. For 1000-ppm boron, the hottest IMF pin peaking goes from 1.183 to 1.194. Tab. 4 shows the effects of increasing the boron concentration on MDNBR. Note that the MDNBR improves with 1000 ppm boron. This is due to the fact that power is pushed away from the UO_2 pin where the MDNBR is located in the unpoisoned assembly. However, increasing the boron concentration above that pushes more power to the hottest IMF pin, which is now the location of the most restrictive MDNBR location, and pushing more power to it only reduces thermal margins.

Table 4: Impact of increasing boron concentration, CONFU-B cycle 01

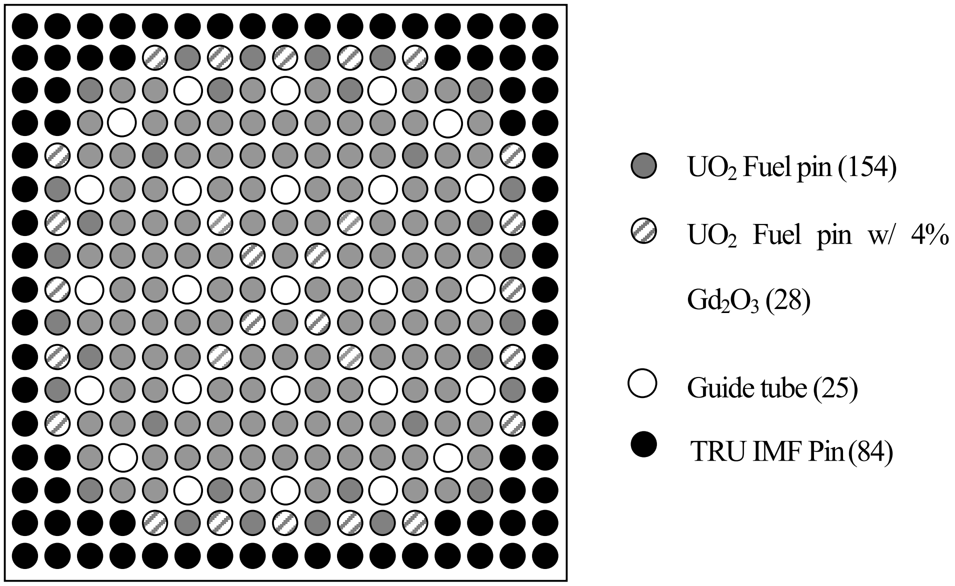
Boron Concentration	Pin Peaking / Type of pin	MDNBR/ Location	Assembly k-inf (BOL)	Net TRU (kg/Assy)	Assembly average BW (pcm/ppm)
0	1.183/IMF	1.433/UO_2	1.333	-3.52	-4.8
1000	1.194/IMF	1.475/IMF	1.251	-3.42	
2000	1.205/IMF	1.458/IMF	1.181	-3.32	

3.3 Gadolinium

Use of gadolinium as a burnable poison proves even more challenging. First, the use of gadolinium in the IMF pins is to be avoided since the gadolinium competes with the TRU for neutrons, and thus degrades the TRU burning performance of the assembly. Second, the number of UO_2 pins poisoned with gadolinium and the amount used must be optimized. The power in each poisoned pin is reduced, and that power is pushed to other parts of the assembly. If too few pins are poisoned, then there is insufficient flexibility to flatten the assembly power, and the pin peaking becomes much worse. If more pins are loaded with slightly less gadolinium (to keep the total gadolinium fixed), this increases the flexibility. However, if too many pins are loaded, then the power pushed to other parts of the assembly is excessive, and the pin peaking becomes much worse.

An optimum poison loading scheme of 4 w/o gadolinium in 28 pins has been developed. This increases the pin peaking in the assembly from 1.183 to 1.241, but since this hottest pin is surrounded by much cooler pins, the MDNBR for the assembly only degrades slightly from 1.443 to 1.432. Fig. 4 shows the loading pattern for this scheme.

Figure 4: Loading pattern for 4% Gd_2O_3 poison



Again, these MDNBR results come from the hottest assembly in a core wide calculation that uses a 1.50 radial power factor. Additionally, the TRU destruction performance of the poisoned assembly actually increases slightly, as the power is shifted from the poisoned UO_2 pins to other pins in the assembly.

Table 5: Best Case Gd Results

Gd Loading	Pin Peaking	MDNBR	Assembly k-inf	Net TRU (kg/Assy)
None	1.183	1.433	1.333	-3.52
4 wt% - 28 pins	1.241	1.432	1.119	-3.53

4. Tailored Enrichment

The second strategy studied to improve thermal-hydraulic margins was tailored enrichment. In this strategy, the loading of the IMF pins was varied along with the enrichment of the UO_2 pins, while retaining sufficient fissile material in the assembly to attain a discharge burnup of 1350 effective full power days (EFPD) using 3-batch management.

The first recycle unpoisoned assembly design (pin peak=1.183, MDNBR=1.443) was loaded with 10 vol % TRU in the IMF and 4.2 w/o enriched UO_2. By reducing the TRU loading, and increasing the UO_2 enrichment, it is possible to flatten the power peaking in the assembly. However, with less TRU loaded, the net TRU destruction of the assembly was reduced.

The CONFU-B design can achieve a net TRU destruction because it maximizes the amount of TRU that can be loaded with each recycle. The net fraction of TRU destroyed in the first recycle is 22.8%. This fraction declines with each succeeding recycle as the TRU vector degrades, but with each recycle, the hottest pin in the assembly is maintained as a FFF pin. And again, the thermal margins improve with each recycle. So, since the first recycle has the highest TRU destruction efficiency, but also the lowest thermal-hydraulic margin, a reasonable strategy would be to reduce the TRU loading, and thereby trade some TRU destruction for additional thermal margin. This is what we call the Tailored Enrichment strategy.

The approach here was to vary the TRU loading from 8-10 vol% and the UO_2 enrichment from 4.2-5.0 wt %. The same number of FFF pins was used and the pins were kept in the same arrangement in the assembly. All assemblies were unpoisoned and achieved a 3-batch lifetime of approximately 1350 EFPD. Another important consideration was whether the hot pin was a FFF pin or a UO_2 pin, since this is a general indicator of TRU destruction efficiency. The results of these calculations are given in Tab. 6. Recall that the original recycle 01 used 10 vol% TRU in 84 FFF pins with 4.2 wt% enriched UO_2.

Table 6: Effects of reducing TRU loading on MDNBR, unpoisoned assemblies

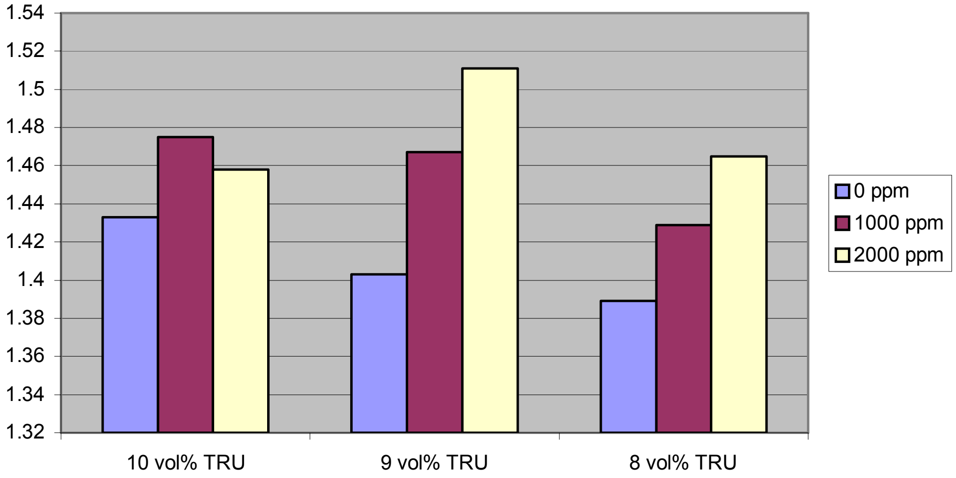
TRU loading (v/o)	UO_2 Enrich (w/o)	Pin Peaking/ type of pin	MDNBR/ Location	TRU loaded (kg)	TRU @EOL + 6-years (kg)	Net TRU (kg)	% TRU burned
10	4.2	1.183/IMF	1.433/UO_2	15.39	11.87	-3.52	22.8%
9	4.5	1.140/UO_2	1.403/UO_2	13.85	10.75	-3.10	22.4%
8	4.8	1.145/UO_2	1.389/UO_2	12.31	9.67	-2.64	21.4%

The trend to note here is that the MDNBR location is at a UO_2 pin in the assembly with 10 v/o TRU and 4.2 w/o enriched UO_2. As we increase the UO_2 enrichment and decrease the TRU loading, we push even more power to the UO_2 pins, and hence make the MDNBR worse. However, we can reverse this trend when soluble boron is added to the core.

5. Synergy between Tailored Enrichment and Chemical Shim

Finally, since we know that soluble boron tends to push power from the UO_2 pins to the FFF pins, we can take advantage of this in the assemblies where the MDNBR location is at a UO_2 pin. In addition, pushing power to the FFF pins can aid the TRU burning performance by partially overcoming the loss due to the presence of poisons. Fig. 5 shows the effect of increasing boron concentration on TRU burning and MDNBR for the three tailored enrichments shown above. The effects on TRU burning were calculated using boron concentrations at the maximum listed value for the first third of the assembly burnup, 50% of max boron concentration for the next third, and 0 ppm for the final third.

Figure 5: Impact of varying boron concentration and TRU loading, CONFU-B cycle 01



6. Conclusion

CONFU-B fuel assemblies can transmute more TRU than they generate, resulting in a net TRU destruction. Excess reactivity at startup can be managed with the use of burnable neutron poisons, which can help manage thermal margins, while not impeding TRU destruction performance. Tailored enrichment, along with soluble boron, can improve thermal margins, but at some cost to TRU destruction performance. Tab. 7 provides a summary of the best case results from the strategies studied.

Table 7: Summary of best case results

Strategy	MDNBR	% Improvement	k-inf	Reactivity Suppression	TRU Destruction fraction	Change in efficiency
Base Case	1.433	n/a	1.333	n/a	22.8%	n/a
Soluble Boron	1.475	+2.9%	1.251	-6.2%	22.2%	-0.6%
Gd_2O_3 burnable poison	1.432	-0.0	1.119	-16.1%	22.9%	+0.1%
Boron and Tailored Enrichment	1.511	+5.4%	1.193	-10.5%	20.8%	-2.0%

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