WINDSOR POND UNIT 1 RELOAD CORE DESIGN

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Background

- Windsor Pond Unit 1 has a CE 2 loop core
- RTP 2700 MWth
- Core Temperature Ranges from 532℉ to 549℉ (0% to 100% power)
- Control Rods move from 0 to 137 steps.
- Target cycle length is 468.2 EFPD
- Core Loading of 8686.236 MTU

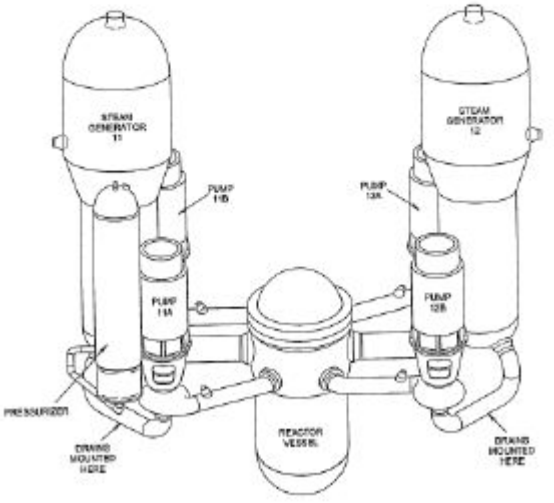


Figure: CE 2 Loop PWR

Objectives

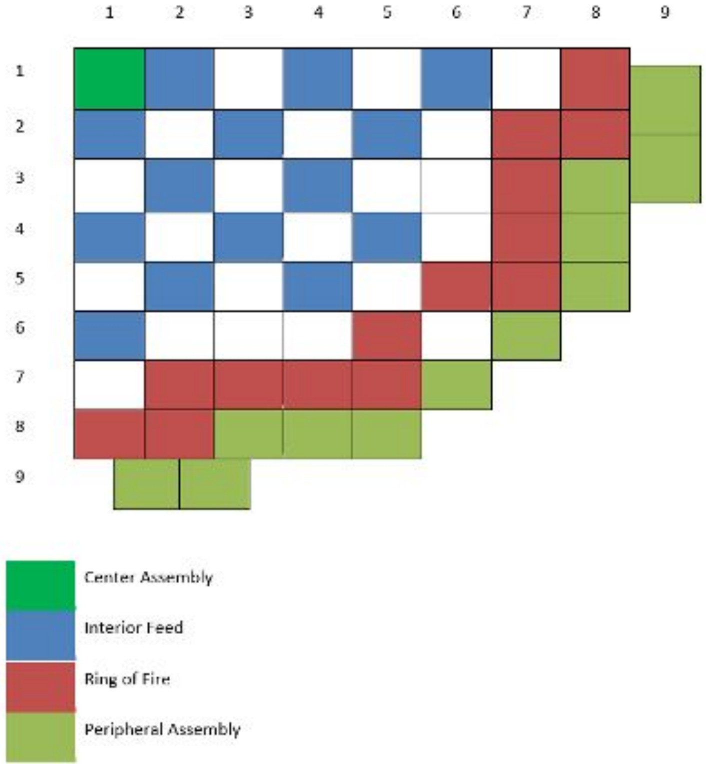
- For Windsor Pond Unit 1 Cycle 13:
    - Design a LP that adheres to the limits set by Westinghouse
    - Perform the Safety Calculations
    - Perform Operational Data Calculations

LP Design Requirements

Criteria	Requirement
Energy [EFPD]	≥ 468.2
ARO FDH	≤ 1.645
MTC [pcm/℉]	≤ 0.50
Feeds	≤ 68 feeds

Figure: LP Design Requirements

Basics of Fuel Management



- Least reactive (twice burned) fuel assemblies are placed on the center and peripheral assembly
- Most reactive feed fuel assemblies are placed on the ring of fire
- Interior region of core is a checkerboard of more reactive and less reactive assemblies

Figure: Fuel Management Tips for Windsor Pond. Courtesy of Mr. Corey Prumo of Westinghouse

Designing the LP

- After creating the Ring of Fire and Periphery, the FDH is still too high.
- C-FDH and C-BU edits were used.
- C-FDH edit shows the FDH of each individual assembly.
- C-BU edit shows the burnup of each individual assembly.

Strategy Used

- Instead of trying to lower the FDH of the “hotspots”, we moved highly reactive assemblies into “coldspots”.
- Did not place highly reactive fuel assemblies in the periphery as there would be high neutron leakage.

Designing the LP

- Another edit used was the C-FM and E-GRP edits.
- The E-GRP lists the IDs of the sister assemblies in the sister quadrants.
- The C-FM edit lists the burnup of all four corners of each assembly
- When the LP is close to meeting the FDH limit, those two edits are used to lower it.

Meeting the FDH Requirement

- The team replaced one R45_04 (4.420 w/o U-235 with 4 gad rods) with an R45_12 (4.365 w/o U-235 with 12 gad rods) in FUELPAT(6,6).

Final Loading Pattern

FUELPAT(1,1)=	K404.007	P45_08X.065	R41_12	N45_16.064	R41_12	P41_16.007	N43_4X.031	R45_12	N43_16.048
FUELPAT(1,2)=	P45_08X.065	P45_12.074	K312.003	R41_12	P43_12.048	N45_16.059	R41_12	R45_04	N41_12.007
FUELPAT(1,3)=	R41_12	K312.021	R41_12	P43_12.047	P45_08.064	P41_20.022	R41_12	N43_16.049	
FUELPAT(1,4)=	N45_16.064	R41_12	P43_12.035	P45_12.076X	P41_20.015	P41_20X.029	R45_12	N43_16.040	
FUELPAT(1,5)=	R41_12	P43_12.033	P45_08.051	P41_20.028	P41_12.003	P45_08.062	R45_04	N43_4.013	
FUELPAT(1,6)=	P41_16.007	N45_16.060	P41_20.020	P41_20.010	P45_08.057	R45_12	N43_4.026		
FUELPAT(1,7)=	N43_4X.031	R41_12	R41_12	R45_12	R45_04	N43_4.021			
FUELPAT(1,8)=	R45_12	R45_04	N41_16.012	N43_16.036	N43_4.016				
FUELPAT(1,9)=	N43_16.043	N41_12.004							

Twice Burned (N/K)	
Once Burned (P)	
Fresh Fuel (R)	

Figure: Fuel Loading Pattern

FDH in LP

	1	2	3	4	5	6	7	8	9
1	0.891	1.229	1.537	1.105	1.609	1.159	1.097	1.613	0.751
2	1.229	1.216	1	1.62	1.274	1.037	1.643	1.62	0.658
3	1.537	1.002	1.589	1.343	1.305	1.184	1.594	0.964	
4	1.105	1.62	1.341	1.22	1.076	1.159	1.547	0.79	
5	1.609	1.321	1.303	1.078	1.062	1.205	1.404	0.671	
6	1.159	1.038	1.188	1.166	1.204	1.361	0.797		
7	1.097	1.644	1.597	1.553	1.408	0.795			
8	1.613	1.62	0.981	0.801	0.675				
9	0.752	0.66							

Figure: FDH of Final LP

E-SUM of LP

NO	BU	POWER	EIGEN	BORON CON		TIN		XE	SM	FQ	FDH	FZ
				PPM	G/KG	DEG-F	DEG-C					
1	0	1.000	0.999997	1434	8.204	549.0	287.2	DS	DS	2.056	1.676	1.201
2	150	1.000	1.000006	1090	6.231	549.0	287.2	DP	DP	1.928	1.634	1.142
3	500	1.000	0.999995	1045	5.976	549.0	287.2	DP	DP	1.887	1.631	1.129
4	1000	1.000	0.999996	997	5.701	549.0	287.2	DP	DP	1.860	1.633	1.122
5	2000	1.000	0.999999	921	5.266	549.0	287.2	DP	DP	1.832	1.630	1.117
6	3000	1.000	1.000010	844	4.826	549.0	287.2	DP	DP	1.804	1.620	1.110
7	4000	1.000	1.000007	768	4.394	549.0	287.2	DP	DP	1.802	1.613	1.109
8	5000	1.000	1.000000	698	3.993	549.0	287.2	DP	DP	1.834	1.608	1.113
9	6000	1.000	0.999999	634	3.624	549.0	287.2	DP	DP	1.866	1.606	1.118
10	7000	1.000	0.999991	575	3.286	549.0	287.2	DP	DP	1.890	1.610	1.124
11	8000	1.000	1.000000	521	2.977	549.0	287.2	DP	DP	1.910	1.621	1.132
12	10000	1.000	0.999997	408	2.335	549.0	287.2	DP	DP	1.937	1.644	1.123
13	12000	1.000	1.000006	249	1.422	549.0	287.2	DP	DP	1.842	1.634	1.093
14	14000	1.000	0.999998	68	0.391	549.0	287.2	DP	DP	1.770	1.581	1.096
15	14660	1.000	0.999993	8	0.047	549.0	287.2	DP	DP	1.753	1.564	1.100

Figure: E-SUM of Final LP

Moderator Temperature Coefficient

- Water and boron have competing effects on MTC
  - Water has a negative MTC
  - Boron has a positive MTC
- As the temperature of the coolant increases, the density of water decreases. Therefore, neutron moderation decreases which decreases the amount of fission.
- As the temperature of the coolant increases, the density of boron decreases. Therefore, neutron absorption decreases which increases the amount of fission.

MTC Calculations

PPM	DEG-F	GWD/MTU	PCM/DEG-F
1589.491	532.009	0.000	0.049
1568.180	532.009	0.150	0.102
1522.949	532.009	0.500	-0.176
1476.343	532.009	1.000	-0.560
1397.677	532.009	2.000	-1.309
1321.476	532.009	3.000	-2.102
1249.354	532.009	4.000	-2.963
1182.646	532.009	5.000	-3.798
1121.453	532.009	6.000	-4.562
1065.625	532.009	7.000	-5.292
1014.956	532.009	8.000	-5.982
911.505	532.009	10.000	-7.583
765.170	532.009	12.000	-9.857
591.852	532.009	14.000	-12.281
532.764	532.009	14.660	-13.080

Figure: MTC Calculations (E-SEQ edit)

MTC Calculations

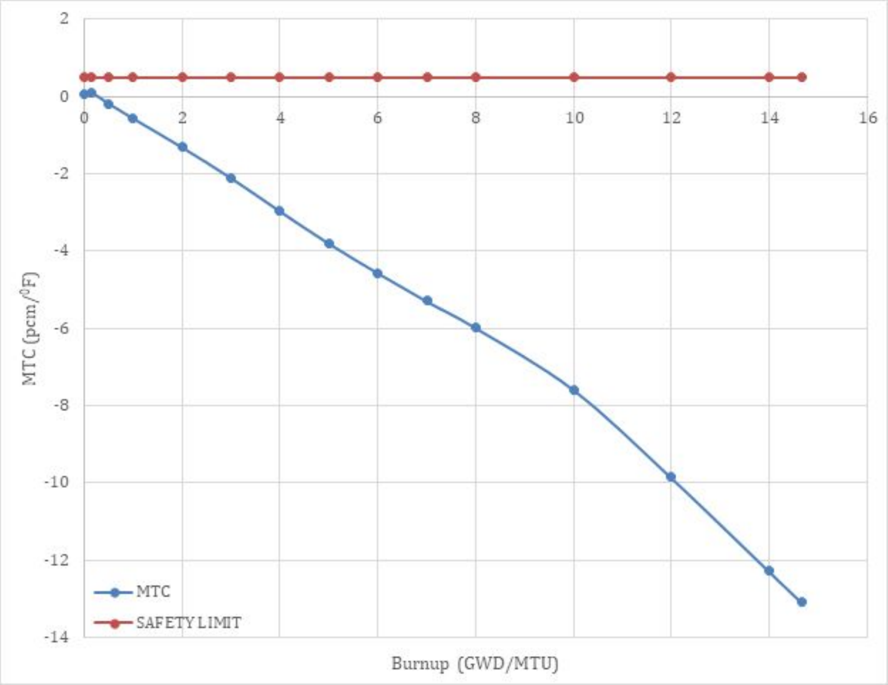


Figure: MTC Calculations

LP Results

Table: LP Requirements & Results

Criteria	Requirement	Result
Energy [EFPD]	≥ 468.2	467.6
ARO FDH	≤ 1.645	1.644
MTC [pcm/℉]	≤ 0.50	0.049
Feed	≤ 68 feeds	68

Safety Analysis Calculations

- To model what would damage the core or release radioactive material in the environment, transient analysts make calculations based on assumed nuclear parameters.
- As the core designers, we must ensure that the nuclear parameters of the newly designed LP is within the range of the assumed parameters
- RSAC itself is the list of values our transient analyst colleagues have assumed and includes:
  1. Rodded FDH
  2. Rod Ejection
  3. Shutdown Margins

Rodded and Unrodded FDH

- While ARO FDH was already calculated, when inserting control banks to their operational insertion limit, the reactor power profile is changed, causing the FDH to possibly increase
- To ensure that the FDH limit is met, the FDH must be calculated with rods inserted at RIL for each depletion step
- To further exaggerate the effect of control rods on the power profile, the axial offset is to be set to the maximum positive value
- In a Westinghouse RSAC, the Rodded FDH would be calculated at different power levels, but for the purpose of this course it will only be calculated at HFP

Rodded and Unrodded FDH Results

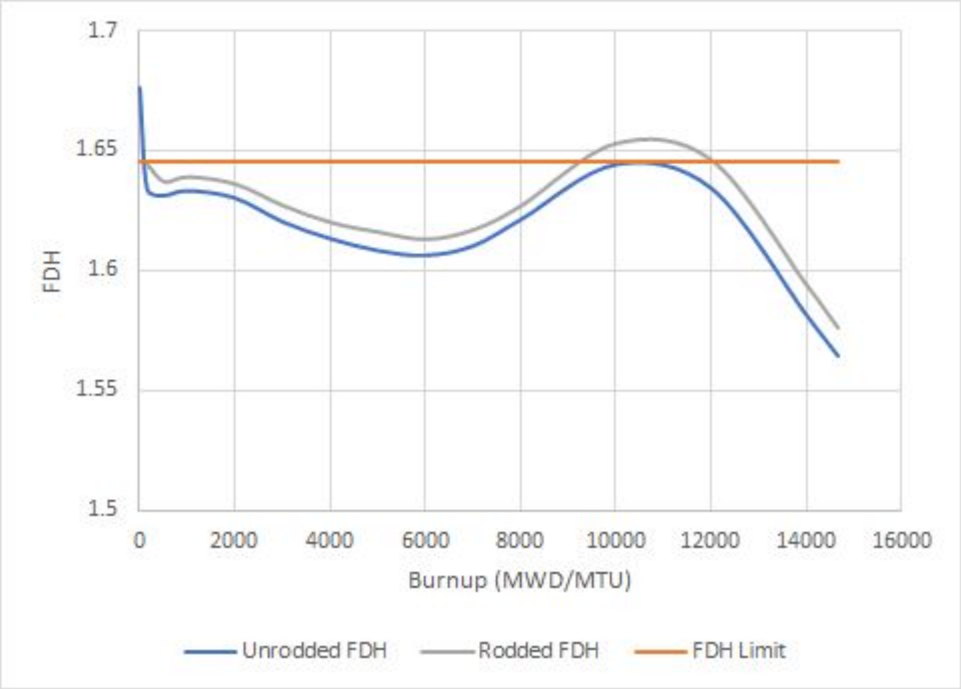


Figure : Rodded and Unrodded FDH Compared to the Limit

Rodded and Unrodded FDH Results

Table : Rodded and Unrodded FDH LP Results

Criteria	Condition(s)	Design Requirements	BU Steps (MWD/MTU)	LP Results
Unrodded FDH	HFP, ARO, any BU	1.645	10000	1.644
Rodded FDH	HFP. 5 at RIL, any BU	1.645	10000	1.653

Rod Ejection

Rod ejection is a serious accident in which, due to a mechanical failure of a control rod pressure housing, a single rod is ejected out of the core leading to a massive insertion of reactivity.

To ensure that the transient analyst calculations are valid, we need to ensure that the ejected rod worth $\Delta\rho(E)$ and ejected rod channel peaking factor $F_Q(E)$ do not exceed values used in safety calculations.

Rod Ejection Results

Table : Max Ejected Rod Worths and Respective Fq Values

Criteria	Condition(s)	Design Requirements	BU Steps (MWD/MTU)	LP Results
Rod Ejection Worth FQ	HZP, BOC	0.60%Δρ 15	0	0.2477%Δρ 7.2791
	HFP, BOC	0.25%Δρ 5.25	150	0.0161%Δρ 2.3515
	HZP,EOC	0.60%Δρ 26.25	14640	0.3277%Δρ 12.1573
	HFP, EOC	0.25%Δρ 5.25	14640	0.02%Δρ 2.2385

Shutdown Margins

Shutdown margins (SDM) are the amount of the core that would be subcritical following a reactor trip, in which the worst control rod is stuck and there are no changes in boron or xenon in the system.

To shutdown the reactor, the operator thus inserts all the control rods, fighting against the total power defect reactivity insertion caused by the trip to HZP.

SDM is then calculated using 6 cases

Shutdown Margins

The six cases used to calculate shutdown margins are:

1. Base case at burnup of interest (BOC and EOC) ARO
2. Rods at RILs
3. Over power at 105% and power skewed to top
4. Trip to zero power
5. ARI
6. Worst rod stuck out

Worst Stuck Rod

Before starting SDM calculations, it is important to determine the worst possible rod to be stuck in a reactor trip. For BOC and EOC respectively, the worst rods were at locations:

BOC: (3,5)

EOC: (6,15)

Shutdown Margin Calculation Results

Table : Conservative and Unconservative SDM and Rod Uncertainty at BOC/EOC

Plant Configuration	SDN Unconservative % Δρ	Rod Uncertainty % Δρ	SDM Conservative %Δρ	Safety Limit %Δρ
BOC	5.4963	0.7024	4.7439	1.6
EOC	5.4711	0.804	4.6171	1.6

Operational Calculations

- Rod Worths
- Xenon Worth
- Boron Worth
- ITC
- HZP Boron Concentration

Purpose of Operational Calculations

- Operational data calculations are performed to provide operators with nuclear parameters necessary for daily operations.
- Additionally, operators validate the model by comparing empirically attained data with the theoretically predicted values.

Rod Worths

- Rod Worth is the reactivity change due to the insertion of a control rod bank into the core from full out to the full in condition (Westinghouse, 2017)
- The different methods used to calculate rod worth are:
  - Boron dilution
  - Rodswap
  - Dynamic rod worth measurement
  - Subcritical rod worth measurement
- Boron dilution method is used in this model

Rod Worths

- Boron dilution consists of inserting control banks one at the time and diluting the boron until the system is critical again.
- The difference in boron concentrations represents the boron worth.
- This method is very time consuming, and expensive. It has since been replaced by more advanced methods utilizing powerful computers.

Rod Worths Results

Table : Predicted Boron for Each Configurations

Configuration	Critical Boron (ppm)	Inserted Bank Worth (ppm)
ARO	1589	---
5	1482	107
5+4	1440	42
5+4+3	1353	87
5+4+3+2	1264	89
5+4+3+2+1	1225	39

Xe Worth

- Xenon worth is the negative reactivity insertion due to the absorption of neutrons by xenon-135 in a core
- Xenon is produced mainly through the decay of iodine-135 and partly directly from fission
- Xenon is removed from the core by:
  - Decaying into cesium
  - Neutron absorption

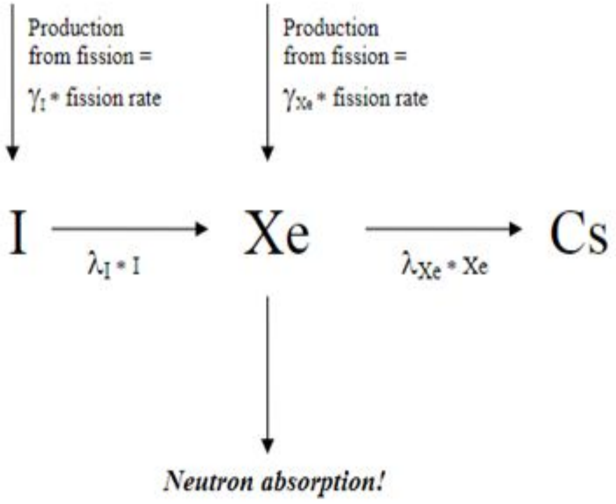


Figure : Xe Production and Removal

Xe Worth Results

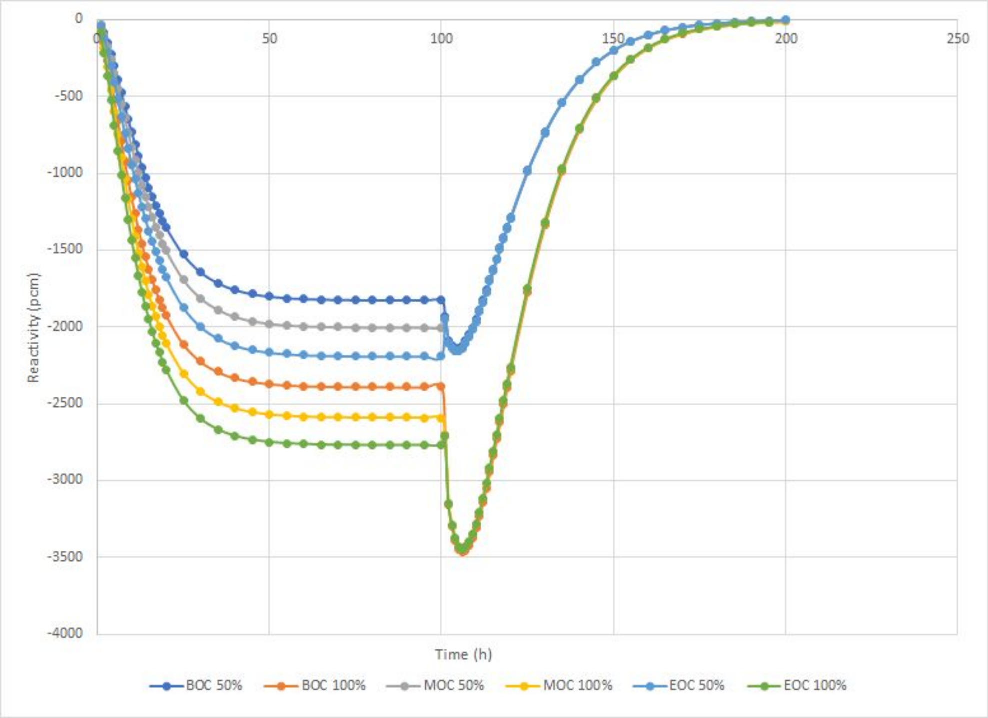


Figure : Xenon Worth at BOC, MOC, EOC at 50% and 100% Over Time

Boron Worth

- Differential boron worth (DBW) is the change in reactivity due to a unit change in boron concentration (Westinghouse, 2017)
- DBW is calculated at both HZP and HFP

DBW at HFP Results

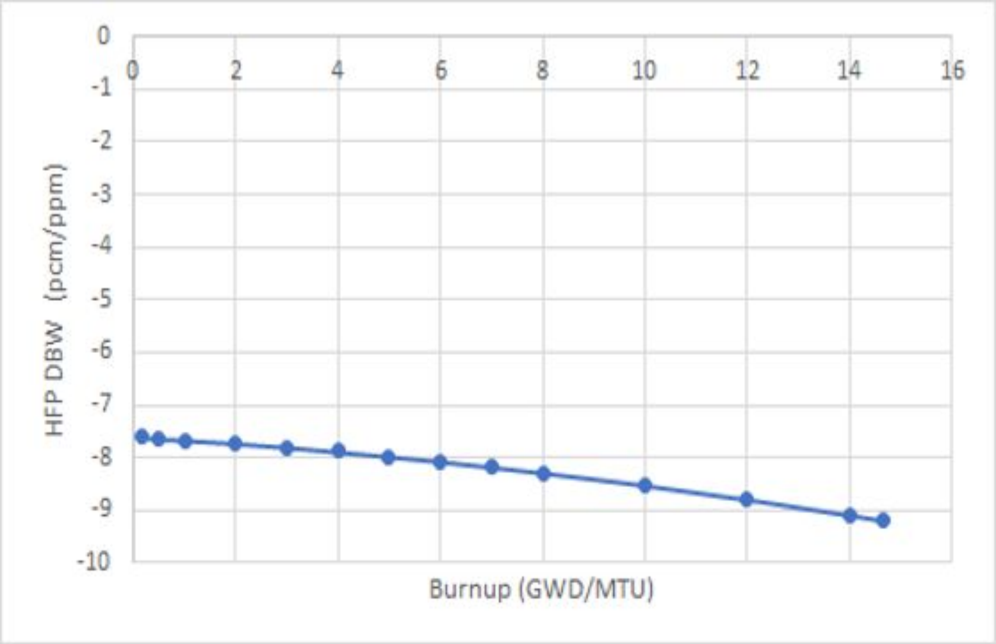


Figure : Boron Worth at HFP vs. Burnup

DBW at HZP Results

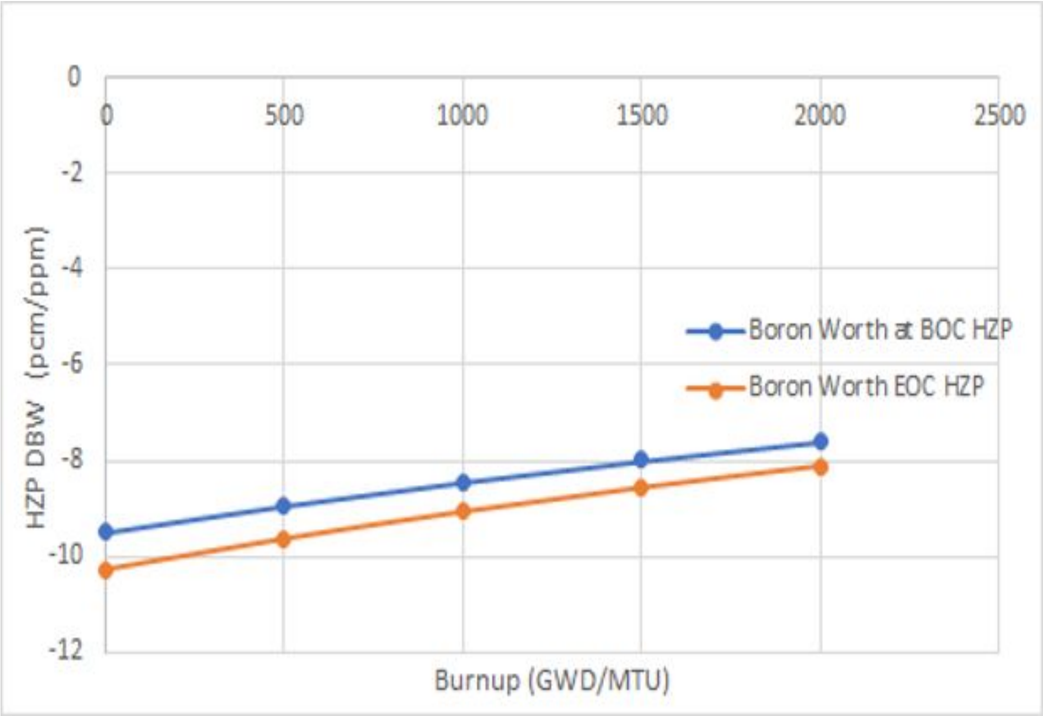


Figure : Boron Worth at HZP vs. Burnup

Isothermal Temperature Coefficient

- Isothermal temperature coefficient (ITC) is the reactivity change per one-degree change in the core temperature (Westinghouse, 2017)
- ITC = MTC + DTC
- ITC is used to predict the temperature feedback behavior of the core.
- Because in a real reactor one cannot freeze one of the feedback mechanisms, operators can use the ITC to determine the MTC by subtracting the known DTC effects

Temperature Coefficient Calculations

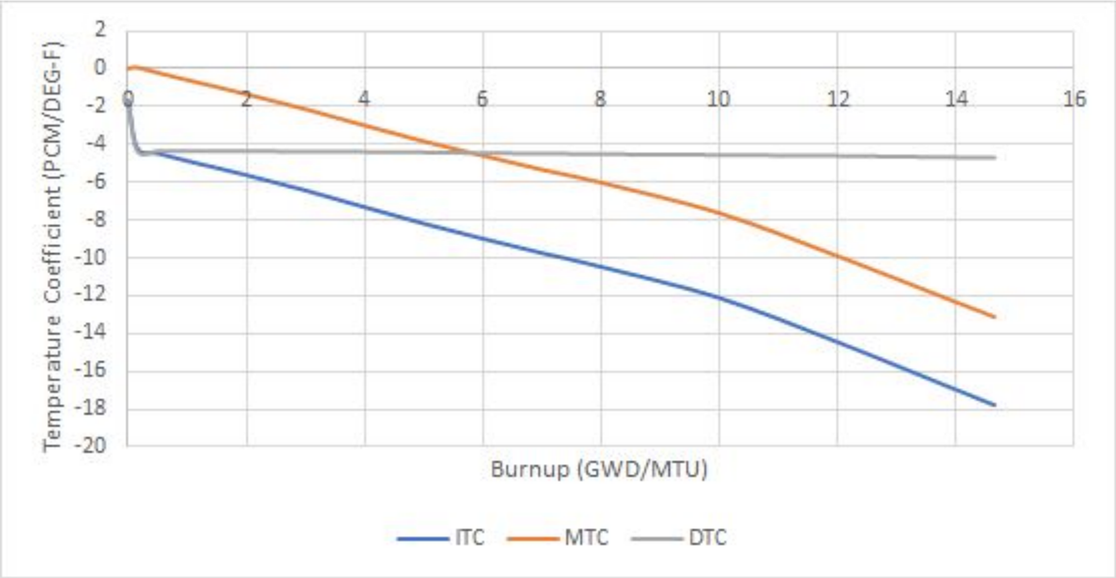


Figure : Temperature Coefficients vs. Burnup

HZP Critical Boron Concentration

- Critical boron concentration has already been determined at HFP, ARO plant configuration.
- Critical boron concentration must be measured at ARO, HZP, and no xenon at BOC conditions.

HZP Boron Concentration

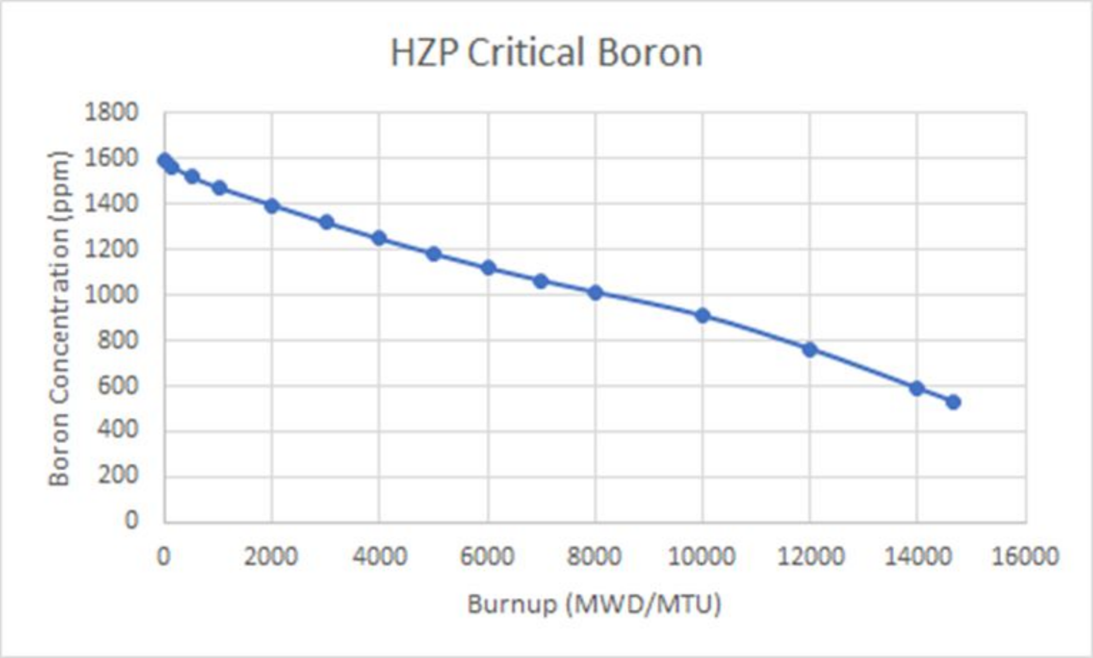


Figure : HZP Critical Boron Concentration

Conclusion

- Due to the failure of energy and rodded FDH requirements, the LP would require a redesign
- Recommendations: Moving a 4.420 w/o assembly to the interior might decrease the FDH and possibly increase EFPD

References

- Group 6. (2020). ANC. Westinghouse
- NUC E 431W Lectures on Loading Patterns
- Penn State Core Design Project. Westinghouse. 2017