INTERMEDIATE REPORT

Windsor Pond Unit 1 Safety Analysis

For the period of

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Submitted to

Dr. William Walters

As a part of

NucE431

by

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NOMENCLATURE

ENGLISH

LP – Loading Pattern

RSAC - Reload Safety Analysis Checklist

HZP- Hot Zero Power

HFP- Hot Full Power

BOC- Beginning of Cycle

EOC- End of Cycle

MTC – Moderator Temperature Coefficient

DTC – Doppler Temperature Coefficient

RILs – Rod Insertion Limits

ARO – All Rods Out

F_Q- Peak Nodal Power Over Average Nodal Power

k – Neutron Multiplication Factor/Eigenvalue

GREEK SYMBOLS

ρ - reactivity
$\Delta\rho$ -change in reactivity

CHAPTER 1: INTRODUCTION

The report deals with the results from the safety analysis for Windsor Pond Unit 1's cycle 13 LP. To perform the safety analysis calculations, ANC software provided by Westinghouse was utilized, utilizing macroscopic parameters given to the group from Phoenix code outputs. It was found that the rodded Fdh was above the safety limit of 1.645, as the insertion of control bank 5 caused a suppression of the power profile in the major diagonal and a subsequent increase of the peaking factor in the periphery. MTC values at each burnup step throughout the cycle were all below the limit of 0.50 pcm/$^{\circ}$F. The rod ejection worth and ejection subchannel peak power were below the limits in each core power level and cycle time tested. Shutdown margins were found to meet and exceed the limiting 1600 pcm both at BOC and EOC.

Following the design of the final LP, it is necessary to test the reload design's safety prior to any physical fuel transportation. Transient analysts perform a comprehensive analysis covering the entire spectrum of nuclear accidents, making many assumptions. Due to the time intensiveness of such calculations, this analysis cannot be repeated for every reload cycle. Westinghouse's RSAC method is thus employed to ensure that the transient analysts' calculations are bounding for the current LP. The method consists of confirming values assumed by transient analysisists are within the prescribed limits. This both ensures that the analysis is bounding and that the core meets

NRC safety requirements. For the purpose of this course, it is required that the LP developed by the group be tested for maximum rodded Fdh peaking factor, MTC limits, rod ejection worth, and shutdown margins. During the calculations, the values will be tested at the most limiting core conditions, to ensure that the RSAC values are conservative and true even in the worst-case scenario.

The first safety check performed was the rodded Fdh. While the Fdh peaking factor, representing the enthalpy rise in a subchannel, had been determined at each ARO burnup step during the LP development step of this project, control rod insertions affect the neutron flux within the core. This shift in neutron flux will shift the power distribution in the core, and thus a Fdh higher than the ARO one can be attained with rods at their RILs. Fdh calculations are essential for the safe operation of a reactor, as values above the limits can cause increases in temperature and subsequent damage to fuel and cladding. For this calculation, the Fdh will be tested throughout the cycle with control rods at the RILs for HFP. The RILs are the maximum allowable insertion of control banks as a function of reactor power. The plot of RIL vs the fraction of reactor power is shown in figure x in appendix A, along with the RILs for HFP and HZP and control rod configuration for the core. For Windsor Pond Unit 1, the RILs for HFP consists of all control banks completely withdrawn, except for the lead control bank, number 5, which is inserted 25% (or 103 steps inserted for the purpose of ANC inputs). The limiting value for the rodded Fdh is the same as the un-rodded one: it must be less than 1.645.

The MTC values throughout the cycle were calculated during the previous step of LP development. Defined as the reactivity change of the core in pcm per $^{\circ}$F change in moderator temperature, the MTC must be below 0.50 pcm/$^{\circ}$F. The limit is allowed to be slightly positive, as the DTC

The rod ejection worth and ejected rod hot channel factor, F_Q, are the next calculations on the RSAC. These calculations deal with the Condition IV accident in which a mechanical failure of the pressure housing of a control rod leads to the ejection of the rod out of the core. This very low probability accident leads to a large positive reactivity insertion into the core, which can cause rapid power increases, DNB, and fuel and clad temperature increases. To confirm the core RILs, pre-calculated by the transient analysts, the worth of the ejected rod, $\Delta\rho(E)$, and the peak power caused by the ejection, the F_Q peaking factor, must be within the RSAC limits. To ensure conformity to the RSAC limits, the rod ejection calculations must be performed at HZP and HFP, for both BOC and EOC. Additionally, to ensure conservative values are provided, the worst possible rod must be selected for ejection in this calculation. The limiting values for these calculations are given in table 1 below. Additionally, at HFP the attained F_Q value is given a 13% uncertainty due to transient xenon effects, and a 10% uncertainty is added to the maximum ejected rod worth, due to inherent rod worth uncertainty. At HZP, the F_Q uncertainty increases to 23% and the rod worth uncertainty to 12%, in order to consider part power effects.

Table 1: Windsor Pond Unit 1 Rod Ejection Worth and F_Q Limits for HZP and HFP, at BOC and EOC

Core Status	Rod Ejection Worth	F_Q
BOC, HFP	0.25%$\Delta\rho$	5.25
BOC, HZP	0.60%$\Delta\rho$	15.0
EOC, HFP	0.25%$\Delta\rho$	5.25
EOC, HZP	0.60%$\Delta\rho$	26.25

Finally, the SDM need to be calculated to ensure that the operators always have enough negative reactivity insertions, in the form of control rods, to trip the reactor. The SDMs are particularly important in the eventuality of reactor casualties that lead to short-term positive reactivity insertions in the core, such as steam-line break and boron dilution accidents. SDMs are calculated using a worst-case, but possible, scenario for reactor trips, to be discussed in depth in the appropriate section. For the purpose of this course, the SDMs are calculated at EOC and BOC, and must be greater than 1.600%$\Delta\rho$.

CHAPTER 2: RESULTS AND DISCUSSION

In this section, the results from LP's safety analysis will be shared and discussed. For each calculation sample inputs and other relevant information can be found in Appendix B. The calculations to be discussed in this section are rodded and un-rodded Fdh, MTC, Rod Ejection Worth, and SDM.

2.1: Rodded and Un-rodded FDH

As discussed above, it is necessary to ensure compliance of Fdh limits both in the rodded and un-rodded core configuration. It is expected that the Fdh be below 1.645 for every core configuration and throughout the entirety of the cycle. For this purpose, the Fdh was calculated for both rodded and un-rodded configuration at each burnup step (consider only 150 MWD/MTU through EOC) with an HFP core configuration. Input file samples for both rodded and un-rodded ANC calculations are present in Appendix B. The results for the un-rodded calculations are given in figure 1, utilizing the E-SUM edit from ANC output. The most limiting Fdh value of 1.644 was found to occur at the 10000 MWD/MTU burnup step. As a means of better envisioning the Fdh value variations throughout the cycle, figure 2 showcases the un-rodded Fdh as a function of burnup. The location of this most limiting Fdh value in the core is shown in figure 3 below, by utilizing the C-FDH edit at the 10000 MWD/MTU step. It is thus found that the limiting Fdh value occurs in the assembly at 7,2 position. The rodded Fdh values are instead displayed in figure 4. The graphical representation in figure 5 showcases the rodded Fdh as a function of burnup. The most limiting value exceeds the 1.645 limit and also occurs during the 10000MWD/MTU step. Figure 6, showcases the assembly where the highest Fdh value occurs and it was found that the value also took place at 7,2 assembly. The explanation for this increase with RIL insertion can be found by analyzing the effect that the control banks have on the entire power profile. Looking at Appendix A, it can be seen that control bank 5 (using quarter core notation) has control rods at positions: 1,7; 3,3; 6,6; and 7,1. By analyzing the divergence points between figures 2 and 6, it is noticed that the rod insertions cause a marked suppression of the power profile along the main diagonal (looking at assembly 3,3 in both cases one notices the rodded Fdh is lessened by 0.122, with an overall decrease also in surrounding assemblies), whereas the effects due to the main axes control rods are less pronounced (only a decrease of 0.60 was found at assembly 7,1, while surrounding assemblies exhibited an increase in Fdh). Thus, the suppression of the power profile along the main diagonal caused an increase in power in the lower and upper octants of the core, increasing the power of the 7,1 assembly to the point that the Fdh surpassed the limits.

```
E-SUM    SUMMARY OF  ANC  RUNS                                         END OF RUN

 NO   BU  POWER   EIGEN   BORON CON      TIN     XE SM   FQ    FDH    FZ    AO/ASI S 5   4   3   2   1
                          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  5.41 0 Y 137 137 137 137 137
  2   150 1.000 1.000006 1090  6.231 549.0 287.2 DP DP 1.928 1.634 1.142  0.58 0 Y 137 137 137 137 137
  3   500 1.000 0.999995 1045  5.976 549.0 287.2 DP DP 1.887 1.631 1.129 -0.12 0 Y 137 137 137 137 137
  4  1000 1.000 0.999996  997  5.701 549.0 287.2 DP DP 1.860 1.633 1.122 -0.50 0 Y 137 137 137 137 137
  5  2000 1.000 0.999999  921  5.266 549.0 287.2 DP DP 1.832 1.630 1.117 -1.15 0 Y 137 137 137 137 137
  6  3000 1.000 1.000010  844  4.826 549.0 287.2 DP DP 1.804 1.620 1.110 -1.55 0 Y 137 137 137 137 137
  7  4000 1.000 1.000007  768  4.394 549.0 287.2 DP DP 1.802 1.613 1.109 -1.97 0 Y 137 137 137 137 137
  8  5000 1.000 1.000000  698  3.993 549.0 287.2 DP DP 1.834 1.608 1.113 -2.39 0 Y 137 137 137 137 137
  9  6000 1.000 0.999999  634  3.624 549.0 287.2 DP DP 1.866 1.606 1.118 -2.75 0 Y 137 137 137 137 137
 10  7000 1.000 0.999991  575  3.286 549.0 287.2 DP DP 1.890 1.610 1.124 -3.14 0 Y 137 137 137 137 137
 11  8000 1.000 1.000000  521  2.977 549.0 287.2 DP DP 1.910 1.621 1.132 -3.61 0 Y 137 137 137 137 137
 12 10000 1.000 0.999997  408  2.335 549.0 287.2 DP DP 1.937 1.644 1.123 -2.93 0 Y 137 137 137 137 137
 13 12000 1.000 1.000006  249  1.422 549.0 287.2 DP DP 1.842 1.634 1.093 -0.57 0 Y 137 137 137 137 137
 14 14000 1.000 0.999998   68  0.391 549.0 287.2 DP DP 1.770 1.581 1.096 -0.68 0 Y 137 137 137 137 137
 15 14660 1.000 0.999993    8  0.047 549.0 287.2 DP DP 1.753 1.564 1.100 -1.04 0 Y 137 137 137 137 137
```

Figure 1: Windsor Pond Unit 1 E-SUM Edit from ANC Output Showcasing the Un-rodded Fdh Values Throughout Cycle 13 and Most Limiting Value

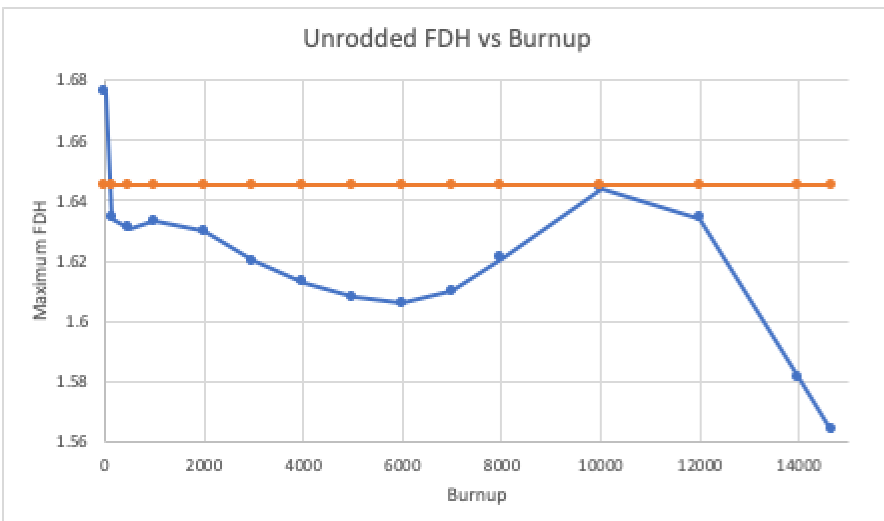

Figure 2: Windsor Pond Unit 1 Cycle 13 Un-rodded Fdh Values Displayed as a Function of Burnup

Unrodded FDH	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 3: Windsor Pond Unit 1 Cycle 13 Un-rodded 10000 MWD/MTU Burnup Step Color Coded Fdh Map of Core.

```
E-SUM    SUMMARY OF  ANC  RUNS                                         END OF RUN

 NO   BU  POWER   EIGEN    BORON CON      TIN      XE SM   FQ    FDH    FZ    AO/ASI S 5   4   3   2   1
                           PPM   G/KG  DEG-F DEG-C                                  *
  1   150 1.000 0.999995 1073   6.135 549.0 287.2 RC HD 2.154 1.644 1.294  7.91 0 Y 103 137 137 137 137
  2   500 1.000 1.000005 1028   5.877 549.0 287.2 RC HD 2.113 1.637 1.287  7.88 0 Y 103 137 137 137 137
  3  1000 1.000 0.999996  980   5.604 549.0 287.2 RC HD 2.096 1.639 1.286  8.08 0 Y 103 137 137 137 137
  4  2000 1.000 0.999994  904   5.169 549.0 287.2 RC HD 2.085 1.636 1.282  7.81 0 Y 103 137 137 137 137
  5  3000 1.000 0.999995  827   4.730 549.0 287.2 RC HD 2.072 1.627 1.281  8.10 0 Y 103 137 137 137 137
  6  4000 1.000 0.999995  752   4.299 549.0 287.2 RC HD 2.063 1.620 1.281  8.28 0 Y 103 137 137 137 137
  7  5000 1.000 1.000003  681   3.898 549.0 287.2 RC HD 2.055 1.616 1.279  8.03 0 Y 103 137 137 137 137
  8  6000 1.000 1.000000  617   3.528 549.0 287.2 RC HD 2.078 1.613 1.287  8.28 0 Y 103 137 137 137 137
  9  7000 1.000 1.000002  558   3.190 549.0 287.2 RC HD 2.096 1.617 1.288  8.00 0 Y 103 137 137 137 137
 10  8000 1.000 0.999999  504   2.884 549.0 287.2 RC HD 2.107 1.627 1.289  7.67 0 Y 103 137 137 137 137
 11 10000 1.000 1.000006  392   2.243 549.0 287.2 RC HD 2.163 1.653 1.298  8.40 0 Y 103 137 137 137 137
 12 12000 1.000 0.999996  230   1.313 549.0 287.2 RC HD 2.102 1.646 1.269  8.00 0 Y 103 137 137 137 137
 13 14000 1.000 0.999995   48   0.277 549.0 287.2 RC HD 2.001 1.594 1.251  7.97 0 Y 103 137 137 137 137
 14 14660 1.000 0.999999  -12  -0.067 549.0 287.2 RC HD 1.970 1.576 1.246  7.75 0 Y 103 137 137 137 137
 15 14660 1.000 0.999998  -12  -0.066 549.0 287.2 RC HD 1.977 1.576 1.250  8.08 0 Y 103 137 137 137 137
```

Figure 4: Windsor Pond Unit 1 E-SUM Edit from ANC Output Showcasing the Rodded Fdh Values Throughout Cycle 13 and Most Limiting Value.

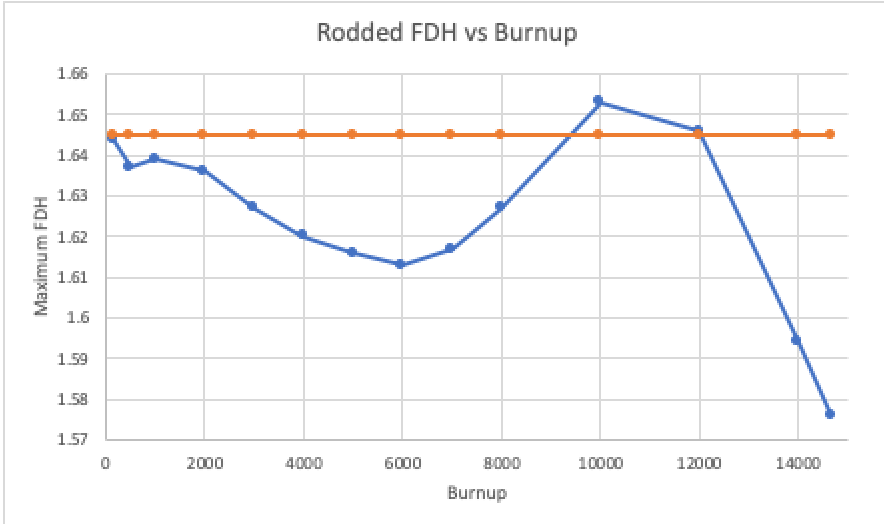

Figure 5: Windsor Pond Unit 1 Cycle 13 Rodded Fdh Values Displayed as a Function of Burnup

Rodded Fdh	1	2	3	4	5	6	7	8	9
1	0.898	1.235	1.544	1.117	1.631	1.168	1.037	1.595	0.751
2	1.235	1.217	0.994	1.629	1.289	1.044	1.651	1.615	0.661
3	1.544	0.993	1.467	1.318	1.312	1.202	1.616	0.971	
4	1.117	1.631	1.316	1.204	1.086	1.178	1.575	0.803	
5	1.631	1.337	1.308	1.088	1.055	1.185	1.415	0.679	
6	1.168	1.045	1.207	1.186	1.184	1.268	0.77		
7	1.037	1.653	1.619	1.581	1.419	0.768			
8	1.595	1.616	0.988	0.813	0.683				
9	0.751	0.663							

Figure 6: Windsor Pond Unit 1 Cycle 13 Rodded 10000 MWD/MTU Burnup Step Color Coded Fdh Map of Core.

2.2 MTC Calculations

As discussed in the introduction, the MTC coefficient determines the reactor's reactivity response to a change in temperature. The most conservative values will be attained at HZP ARO, as the increased reactivity due to lower temperatures at this configuration entails larger ppms of diluted boron in the system. While water has an inherent negative MTC, boron is a poison that absorbs neutrons, therefore its presence in the coolant will cause the MTC to be more positive. This is due to boron being diluted in water and sharing its host's variations in density (higher T → density of B decreases → less parasitic absorption → increase in reactivity). To calculate the MTC, the change in reactivity between two different moderator temperatures must be calculated and divided by the difference between the moderator temperatures. A sample of the input ANC file utilized for the MTC job is showcased in Appendix B. The attained MTC values from this calculation are shown in figure 7 below through the E-SEQ edit of the ANC output file for the MTC job. Figure 8 contains the eigenvalues of the least negative MTC value, using the E-SUM edit of the above-mentioned job, which will be utilized to showcase the MTC calculation method shown in equation 1. Finally, figure 9 displays the MTC in graphical representation vs burnup and in juxtaposition to its safety limit of 0.50 pcm/ $^{\circ}$F. As seen in figure's 7 and 9, all the MTC values meet the safety limit. The least negative value occurs at the 150 MWD/MTU burnup step, with a value of 0.102 pcm/ $^{\circ}$F. This value is more negative than the limit by 0.398 pcm/ $^{\circ}$F. To calculate this least negative MTC, the eigenvalues of the core must first be calculated through ANC at 537 $^{\circ}$F and 527 $^{\circ}$F. Then the change in reactivity can be calculated through the Westinghouse change in reactivity equation $\rho = \ln(k_2/k_1) * 100000$ pcm. Finally, by dividing the attained change in reactivity by the change in temperature (537 $^{\circ}$F - 527 $^{\circ}$F = 10 $^{\circ}$F), one attains the MTC value. In equation 1 below, utilizing the eigenvalues for cases 2 and 3 shown in figure 8, this calculation method is put into practice for the least negative MTC. The result is in accordance (with a negligible degree of reasonable error due to rounding) with the values attained in figure 7, showcasing the validity of the MTC job.

E-SEQ   SUMMARY DATA FOR SEQUENCES

MTC CALCULATION

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 7: Windsor Pond Unit 1 Cycle 13 E-SEQ Edit Showcasing MTC Values Throughout Cycle and Highlighting Least Negative Value.

E-SUM SUMMARY OF ANC RUNS

NO	BU	POWER	EIGEN	BORON CON PPM	G/KG	TIN DEG-F	DEG-C
1	0	0.000	1.000004	1589	9.091	532.0	277.8
2	0	0.000	1.000034	1589	9.091	537.0	280.6
3	0	0.000	1.000029	1589	9.091	527.0	275.0
4	150	0.000	1.000005	1568	8.969	532.0	277.8
5	150	0.000	1.000035	1568	8.969	537.0	280.6
6	150	0.000	1.000025	1568	8.969	527.0	275.0

Figure 8: Windsor Pond Unit 1 Cycle 13 E-SUM Edit Highlighting the Least Negative MTC's Eigenvalues at 527 $^{\circ}$F and 537 $^{\circ}$F.

$$MTC = \frac{\ln ln\left(\frac{k_5}{k_6}\right)*100000}{\Delta T} = \frac{\ln ln\left(\frac{1.000035}{1.000025}\right)*100000\ pcm}{10°F} = 0.1\frac{pcm}{°F} \quad (1)$$

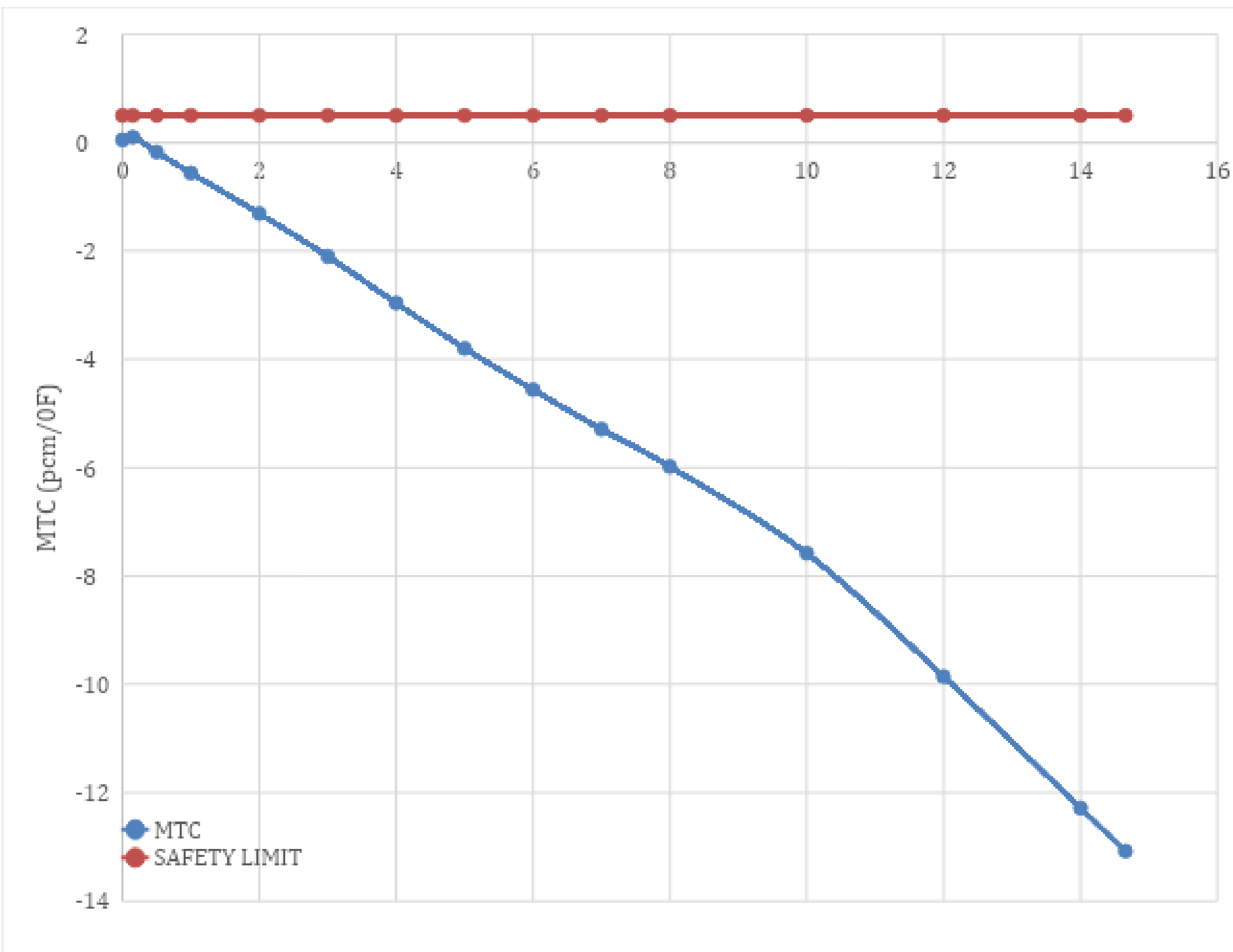

Figure 9: Windsor Pond Unit 1 Cycle 13 Graph of MTC Values Throughout Cycle as a Function of Burnup and Juxtaposed to Safety Limit.

2.3 Rod Ejection Worth

As discussed in the introduction, rod ejection is a serious accident and must be modeled to ensure operational safety of the reactor. What core designers must confirm that in the unlikely eventuality that a control rod initially placed at its RIL, the resulting ejected rod worth and hot channel factor F_Q do not exceed the limits placed by the transient analysts. Confirming that the analysts' calculations are bounding also confirms the RILs for the reactor. To attain conservative values for these two parameters and determine the most limiting value, they are calculated in four cases: at HZP-BOC, HFP-BOC, HZP-EOC, HFP-EOC. To perform the calculations, first base cases are calculated for the four instances in which the rod ejection values are to be calculated. In these base cases the HZP values will have no Xe in the system, whereas HFP cases will have equilibrium Xe. Next the model is unfolded to full core geometry, and, due to the milli-second to second range in which the accident takes place, adiabatic assumptions are assumed and moderator and doppler feedback are frozen during the transient. Next the control rods are set to the appropriate RILs, as shown in Appendix A. For HFP the RILs are all control banks completely withdrawn bar the lead control bank, number 5, which is inserted 25% (or 103 steps withdrawn). For HFP, control banks 5 and 4 are completely inserted (0 steps withdrawn), and control bank 3 is 60% inserted (54 steps withdrawn), while the remaining control banks are completely withdrawn. Finally, the control rods that are inserted at the RILs, found using the C-BNK edit in the output files, are checked for ejected worth using the STUCKROD command. The control rods checked at HFP are the ones at locations (in full core notation): 4,4; 7,7; and 9,3. For HZP more control banks are inserted and thus more control rods need to be checked. At this configuration, the rods checked are: 3,7; 4,4; 7,3; 7,7; 9,3; 9,5; and 9,9. The highest rod worth is then assumed to be the worst-case scenario and compared to the limit along with the highest F_Q values. Figures 10-13 showcase the maximum rod worth for each plant configuration tested through the E-SRW edit in the output files for the rod-ejection ANC job. The input ANC jobs are showcased in Appendix B.3. Table 2 showcases these values, comparing them to their respective limits and adding the appropriate uncertainties. As shown in the aforementioned table, every value is within the safety limits for rod ejection worth and F_Q values. The highest rod worth occurs at EOC-HZP, and is control rod 4,4. The highest F_Q also occurs in this configuration.

```
1   STUCK ROD    ( 9, 9)              **  ANC    8.11.8  **    REF BU=       0.  REF TIME=      0.0
   DATE: 04/01/20  USER: group6    JOB: HZP_Rod_  JOB NUMBER: HZP_0742  MACHINE: Linux
    EJECT RODS IN FULL CORE                                             CASE-0009   PAGE-0065

 E-SRW    STUCK ROD WORTH

          STUCK ROD   EIGENVALUE   WORTH     FDH    FDH*U    LOCATION       FQ      LOCATION    BU-FQ       FXY     LOCATION

          BASE CASE    1.00000
               ( 3, 7) 1.00072      71.7    2.932   3.167    ( 3, 5)     3.776   ( 3, 5,16)      0.      3.391   ( 3, 5,18)
               ( 4, 4) 1.00222     221.2    4.657   5.029    ( 3, 5)     5.918   ( 3, 5, 9)      0.      4.974   ( 4, 4,15)
               ( 7, 3) 1.00070      69.8    2.890   3.121    ( 5, 3)     3.717   ( 5, 3,17)      0.      3.349   ( 5, 3,18)
               ( 7, 7) 1.00138     137.2    2.684   2.899    ( 3, 5)     3.392   ( 3, 5, 9)      0.      3.280   ( 7, 7,23)
               ( 9, 3) 1.00088      87.2    2.526   2.729    (10, 2)     3.616   (10, 2, 7)      0.      2.850   (10, 2, 3)
               ( 9, 5) 1.00117     116.7    2.422   2.616    (13, 3)     3.148   (13, 3, 8)      0.      2.760   ( 9, 5,23)
               ( 9, 9) 1.00035      34.9    1.986   2.145    (13, 3)     2.532   (13, 3, 9)      0.      2.071   (13, 3,12)

          HIGHEST WORTH STUCK ROD   IS         ( 4, 4), WITH WORTH OF     221.2 PCM

          IF MORE THAN TWO CONTROL RODS ARE DROPPED OR STUCK WITHIN A GIVEN CALCULATION, ADDITIONAL
          LOCATIONS DO NOT APPEAR IN THE ABOVE EDIT. THE USER SHOULD CONFIRM THIS VIA THE E-BNK EDIT.

          CORE RELATIVE POWER IS  0.00

          BORON CONCENTRATION IS 1379.1 PPM, 7.888 G/KG


          NUCLEAR UNCERTAINTY =  1.08

          CALCULATIONAL UNCERTAINTY =  1.00
```

Figure 10: Windsor Pond Unit 1 E-SRW Edit Showcasing BOC-HZP Max Ejected Rod Worth and Respective F_Q Value

```
1   STUCK ROD    ( 9, 3)              **  ANC    8.11.8  **    REF BU=     150.  REF TIME=    115.0
   DATE: 04/01/20  USER: group6    JOB: HFP_Rod_  JOB NUMBER: HFP_0740  MACHINE: Linux
    EJECT RODS IN FULL CORE                                             CASE-0005   PAGE-0029

 E-SRW    STUCK ROD WORTH

          STUCK ROD   EIGENVALUE   WORTH     FDH    FDH*U    LOCATION       FQ      LOCATION    BU-FQ       FXY     LOCATION

          BASE CASE    0.99999
               ( 4, 4) 1.00009       9.8    1.755   1.895    ( 3, 5)     2.081   ( 3, 5,10)    250.      2.030   ( 4, 4,23)
               ( 7, 7) 1.00014      14.6    1.706   1.843    ( 7, 7)     2.062   ( 3, 5,10)    250.      2.160   ( 7, 7,23)
               ( 9, 3) 1.00010      10.5    1.684   1.819    (13, 3)     2.062   (13, 3,10)    250.      1.990   ( 8, 3,23)

          HIGHEST WORTH STUCK ROD   IS         ( 7, 7), WITH WORTH OF      14.6 PCM

          IF MORE THAN TWO CONTROL RODS ARE DROPPED OR STUCK WITHIN A GIVEN CALCULATION, ADDITIONAL
          LOCATIONS DO NOT APPEAR IN THE ABOVE EDIT. THE USER SHOULD CONFIRM THIS VIA THE E-BNK EDIT.

          CORE RELATIVE POWER IS  1.00

          BORON CONCENTRATION IS 1067.2 PPM, 6.104 G/KG


          NUCLEAR UNCERTAINTY =  1.08

          CALCULATIONAL UNCERTAINTY =  1.00
```

Figure 11: Windsor Pond Unit 1 E-SRW Edit Showcasing BOC-HFP Max Ejected Rod Worth and Respective F_Q Value

```
1   STUCK ROD    ( 9, 9)              **  ANC   8.11.8  **    REF BU=   14660.  REF TIME=  11236.8
   DATE: 04/01/20  USER: group6    JOB: HZP_Rod_  JOB NUMBER: HZP_0742  MACHINE: Linux
    EJECT RODS IN FULL CORE                                             CASE-0018   PAGE-0065

 E-SRW    STUCK ROD WORTH

          STUCK ROD   EIGENVALUE   WORTH     FDH    FDH*U   LOCATION       FQ      LOCATION     BU-FQ       FXY     LOCATION

          BASE CASE    1.00001
               ( 3, 7) 1.00261     259.5    4.834   5.220    ( 3, 6)     9.884   ( 3, 6,21)   18971.     5.783   ( 3, 6,20)
               ( 4, 4) 1.00294     292.6    4.989   5.388    ( 4, 4)     6.479   ( 4, 4,21)   17861.     5.630   ( 4, 4,17)
               ( 7, 3) 1.00260     258.7    4.823   5.208    ( 6, 3)     9.856   ( 6, 3,21)   18951.     5.770   ( 6, 3,19)
               ( 7, 7) 1.00207     206.0    2.829   3.055    ( 7, 7)     4.209   ( 7, 7,21)   20284.     3.325   ( 7, 7,22)
               ( 9, 3) 1.00231     229.4    4.314   4.660    ( 9, 2)     6.612   ( 9, 2, 4)   21070.     4.560   ( 9, 2, 6)
               ( 9, 5) 1.00191     189.6    2.714   2.931    ( 9, 5)     3.540   ( 9, 5,21)   19923.     3.064   ( 9, 5,21)
               ( 9, 9) 1.00065      64.3    1.800   1.944    ( 9, 7)     2.771   ( 7, 9,21)   18991.     2.180   ( 7, 9,22)

          HIGHEST WORTH STUCK ROD   IS         ( 4, 4), WITH WORTH OF     292.6 PCM

          IF MORE THAN TWO CONTROL RODS ARE DROPPED OR STUCK WITHIN A GIVEN CALCULATION, ADDITIONAL
          LOCATIONS DO NOT APPEAR IN THE ABOVE EDIT. THE USER SHOULD CONFIRM THIS VIA THE E-BNK EDIT.

          CORE RELATIVE POWER IS  0.00

          BORON CONCENTRATION IS  -15.0 PPM,-0.086 G/KG


          NUCLEAR UNCERTAINTY =  1.08

          CALCULATIONAL UNCERTAINTY =  1.00
```

Figure 12: Windsor Pond Unit 1 E-SRW Edit Showcasing EOC-HZP Max Ejected Rod Worth and Respective F_Q Value

```
1   STUCK ROD    ( 9, 3)              **  ANC   8.11.8  **    REF BU=   14660.  REF TIME=  11236.8
   DATE: 04/01/20  USER: group6    JOB: HFP_Rod_  JOB NUMBER: HFP_0740  MACHINE: Linux
    EJECT RODS IN FULL CORE                                             CASE-0010   PAGE-0029

 E-SRW    STUCK ROD WORTH

          STUCK ROD   EIGENVALUE   WORTH     FDH    FDH*U   LOCATION       FQ      LOCATION     BU-FQ       FXY     LOCATION

          BASE CASE    1.00001
               ( 4, 4) 1.00013      12.7    1.663   1.796    ( 6, 3)     1.981   ( 8, 3, 4)   21399.     2.070   ( 4, 4,22)
               ( 7, 7) 1.00019      18.2    1.613   1.742    ( 8, 6)     1.951   ( 8, 3, 4)   21399.     1.980   ( 7, 7,22)
               ( 9, 3) 1.00018      17.2    1.758   1.899    ( 9, 2)     1.968   ( 9, 2,20)   19707.     2.330   ( 9, 2,22)

          HIGHEST WORTH STUCK ROD   IS         ( 7, 7), WITH WORTH OF      18.2 PCM

          IF MORE THAN TWO CONTROL RODS ARE DROPPED OR STUCK WITHIN A GIVEN CALCULATION, ADDITIONAL
          LOCATIONS DO NOT APPEAR IN THE ABOVE EDIT. THE USER SHOULD CONFIRM THIS VIA THE E-BNK EDIT.

          CORE RELATIVE POWER IS  1.00

          BORON CONCENTRATION IS  -22.0 PPM,-0.126 G/KG


          NUCLEAR UNCERTAINTY =  1.08

          CALCULATIONAL UNCERTAINTY =  1.00
```

Figure 13: Windsor Pond Unit 1 E-SRW Edit Showcasing EOC-HFP Max Ejected Rod Worth and Respective F_Q Value

Table 2: Windsor Pond Unit 1 Max Ejected Rod Worths and Respective F_Q Values with Added Uncertainty and Compared to Safety Limits for Each Plant Configuration

Core Status	Rod Ejection Worth Limit (%Δρ)	F_Q Limit	Attained Rod Ejection Worth (%Δρ)	Attained F_Q Values
BOC, HZP	0.60	15.0	0.2477 (rod 4,4)	7.2791(@ 3,5,9)
BOC, HFP	0.25	5.25	0.0161 (rod 7,7)	2.3515 (@ 3,5,10)
EOC, HZP	0.60	26.25	0.3277 (rod 4,4)	12.1573 (@ 3,6,21)
EOC, HFP	0.25	5.25	0.0200 (rod 7,7)	2.2385 (@8, 3, 4)

2.4 Shutdown Margins

As described in the introduction, SDM is the amount of reactivity by which the core would be subcritical at HZP after a reactor trip, while assuming no changes in boron or xenon concentrations, and that the highest worth rod is unable to be inserted. It is essential to have a shutdown margin to ensure that the core can be shut down even in the eventuality of a steam line rupture or boron dilution accident. The SDM can thus be defined as the available control rod worth minus the total power defect assuming core was overpowered and with rods at RILs during standard operation, which is the worst-case situation for a power trip. The power defect is defined as the amount of positive reactivity inserted into the core by the trip to HZP. The phenomena that contribute to the power defect are: MTC, DTC, and flux redistribution effect. During the reactor trip, the moderator experiences a rapid decrease in temperature. Due to the negative MTC, the decrease in temperature leads to a positive reactivity insertion. A similar phenomenon takes place within the fuel, as a decrease in fuel temperature (fuel temperature is a function of power) leads to a sharpening of the U-238 and Pu-240 resonance absorption peaks, and thus a positive reactivity insertion (this is accounted by the DTC). Finally, the trip causes a change in the axial flux shape. During steady operations, the flux peak is driven to the bottom of the core by the enthalpy rise in the subchannels (higher reactivity in colder bottom). At HZP, this enthalpy rise disappears and thus the flux peak moves to the top of the core as it is less depleted than the bottom. This change in flux shape, called the flux redistribution effect, also adds a positive reactivity insertion to the system. Having defined the phenomena that contribute to power defect, it is also worth noting that, following the trip to HZP, the void effects of bubbles in the boiling moderator can disappear due to the temperature change. Thus 50 pcm are removed to account for coolant void disappearance. Another variable to be calculated is the control rod worth, which is to be reduced by 10% for a more conservative value.

Prior to beginning SDM calculations the control rod with the highest worth must be determined and utilized for the 5th eigenvalue, in which all rods are inserted except for the worst stuck rod determined in this step.
Thus, in order to calculate the SDM, which will be calculated at BOC and EOC, 6 eigenvalues are necessary:

1. k_1, the first eigenvalue, is calculated based on the ARO base case at the appropriate burnup (either BOC or EOC)
2. k_2 is calculated after inserting the control rods at the appropriate HFP RILs
3. k_3 is attained after setting the relative core power to 105%, which causes a decrease in core reactivity, thus lessening the SDM. Additionally, the power is skewed to the top while Xe is skewed to the bottom. This accentuates the afore-described flux redistribution effect on the power defect, increasing its positive reactivity insertion at the next step.
4. k_4 is determined after stopping the Xe and B concentrations from changing and changing the plant configuration to HZP. This is the first step in simulating the reactor trip.
5. k_5 is calculated at ARI.
6. k_6 removes the afore-calculated worst stuck rod.

The unconservative SDM can then be calculated by calculating the change in reactivity between k_3 and k_6 using the same Westinghouse equation used to determine the MTC in section 2.2. Then the rod worth uncertainty is attained by multiplying the rod worth, which is the change in reactivity between k_4 and k_6, by 10%. Finally, the conservative SDM will be equal to the unconservative SDM minus the rod worth uncertainty and coolant void pcm.
Figures 14-17 showcase the worst stuck rod calculations performed prior to the SDM calculations. The calculation needed to be split into two cases due to exceeding the maximum line length in ANC caused it to crash. The worst stuck rod for both BOC and EOC was found to be the rod at position 3,5, with a reactivity worth of 1014.4 pcm at BOC and of 1596.1 at EOC. Figures 18 and 19 showcases the six eigenvalues used in the SDM calculations for BOC and EOC respectively. Table 3 showcases the attained SDMs for BOC and EOC compared to their limit of 1.600%Δρ. Equations 2, 3, and 4 contain sample calculations of the SDM for the most limiting case at EOC. The attained SDM were found to meet and exceed the safety limits, while the most limiting case, found at EOC, was confirmed in equation 4.

E-SRW STUCK ROD WORTH

STUCK ROD	EIGENVALUE	WORTH	FDH	FDH*U	LOCATION	FQ	LOCATION	BU-FQ	FXY	LOCATION
BASE CASE	0.93284									
(2, 8)	0.93592	328.9	7.494	8.094	(2, 8)	10.200	(2, 8,18)	217.	8.070	(2, 8, 2)
(3, 5)	0.94236	1014.4	15.290	16.514	(3, 5)	21.683	(3, 5,18)	239.	15.870	(3, 5, 9)
(3, 7)	0.93634	374.5	6.977	7.535	(3, 6)	9.782	(3, 6,19)	218.	7.680	(3, 6, 2)
(4, 4)	0.94070	838.9	12.887	13.917	(4, 4)	18.609	(4, 4,19)	222.	13.972	(4, 4,23)
(4, 6)	0.94082	850.9	10.162	10.975	(4, 5)	14.803	(4, 5,19)	18982.	10.560	(3, 6,23)
(4, 8)	0.93405	128.9	3.889	4.200	(4, 5)	5.666	(4, 5,19)	15752.	3.960	(4, 5,10)
(5, 3)	0.94223	1001.5	15.174	16.388	(5, 3)	21.623	(5, 3,18)	238.	15.710	(5, 3, 8)
(5, 5)	0.93295	11.1	2.974	3.212	(5, 4)	4.311	(5, 4,19)	15615.	3.030	(4, 5, 9)
(5, 7)	0.93727	473.7	6.332	6.838	(4, 5)	9.349	(4, 5,19)	15752.	6.447	(4, 5,14)
(6, 4)	0.94065	833.8	10.076	10.882	(5, 4)	14.839	(5, 4,19)	18830.	10.497	(6, 3,23)
(6, 6)	0.93755	502.8	6.899	7.450	(5, 4)	10.191	(5, 4,19)	15615.	7.023	(5, 4,15)
(6, 8)	0.93438	164.0	3.918	4.232	(4, 5)	5.709	(4, 5,19)	15752.	3.990	(4, 5,13)

HIGHEST WORTH STUCK ROD IS (3, 5), WITH WORTH OF 1014.4 PCM

IF MORE THAN TWO CONTROL RODS ARE DROPPED OR STUCK WITHIN A GIVEN CALCULATION, ADDITIONAL LOCATIONS DO NOT APPEAR IN THE ABOVE EDIT. THE USER SHOULD CONFIRM THIS VIA THE E-BNK EDIT.

CORE RELATIVE POWER IS 0.00

BORON CONCENTRATION IS 1089.5 PPM, 6.231 G/KG

Figure 14: Windsor Pond Unit 1 Worst Stuck Rod at BOC Part 1

E-SRW STUCK ROD WORTH

STUCK ROD	EIGENVALUE	WORTH	FDH	FDH*U	LOCATION	FQ	LOCATION	BU-FQ	FXY	LOCATION
BASE CASE	0.93284									
(7, 3)	0.93619	357.6	6.746	7.285	(6, 3)	9.540	(6, 3,19)	217.	7.498	(6, 3,23)
(7, 5)	0.93735	481.4	6.357	6.865	(5, 4)	9.413	(5, 4,19)	15615.	6.473	(5, 4,17)
(7, 7)	0.93446	172.8	4.177	4.511	(5, 4)	6.098	(5, 4,19)	15615.	4.253	(5, 4,17)
(8, 2)	0.93577	313.6	7.255	7.835	(8, 2)	9.932	(8, 2,18)	217.	7.780	(8, 2, 2)
(8, 4)	0.93405	129.0	3.887	4.198	(5, 4)	5.673	(5, 4,19)	15615.	3.956	(5, 4,18)
(8, 6)	0.93437	163.6	3.904	4.217	(5, 4)	5.695	(5, 4,19)	15615.	3.975	(5, 4,16)
(8, 8)	0.93344	63.5	2.944	3.179	(5, 4)	4.277	(5, 4,19)	15615.	3.000	(4, 5, 9)
(9, 1)	0.93288	4.2	2.751	2.971	(5, 4)	3.984	(5, 4,19)	15615.	2.802	(5, 4,11)
(9, 3)	0.93405	128.9	3.340	3.607	(13, 4)	4.839	(13, 4,19)	15752.	3.690	(9, 2, 2)
(9, 5)	0.93433	158.6	3.346	3.614	(13, 4)	4.868	(5, 4,19)	15615.	3.655	(9, 5,23)
(9, 7)	0.93347	66.6	2.901	3.134	(5, 4)	4.212	(5, 4,19)	15615.	2.960	(5, 4,10)
(9, 9)	0.93325	43.7	2.649	2.861	(5, 4)	3.843	(5, 4,19)	15615.	2.700	(4, 5, 8)

HIGHEST WORTH STUCK ROD IS (7, 5), WITH WORTH OF 481.4 PCM

IF MORE THAN TWO CONTROL RODS ARE DROPPED OR STUCK WITHIN A GIVEN CALCULATION, ADDITIONAL LOCATIONS DO NOT APPEAR IN THE ABOVE EDIT. THE USER SHOULD CONFIRM THIS VIA THE E-BNK EDIT.

CORE RELATIVE POWER IS 0.00

BORON CONCENTRATION IS 1089.5 PPM, 6.231 G/KG

Figure 15: Windsor Pond Unit 1 Worst Stuck Rod at BOC Part 2

```
E-SRW    STUCK ROD WORTH

         STUCK ROD   EIGENVALUE   WORTH    FDH   FDH*U   LOCATION     FQ     LOCATION    BU-FQ     FXY    LOCATION

         BASE CASE    0.92527
              ( 2, 8) 0.93788    1353.6   16.572  17.898   ( 2, 8)    38.052  ( 2, 8,21)  19439.   16.972  ( 2, 8,18)
              ( 3, 5) 0.94016    1596.1   18.580  20.066   ( 3, 5)    41.645  ( 3, 5,21)  18582.   18.972  ( 3, 5,14)
              ( 3, 7) 0.94015    1594.9   16.304  17.608   ( 3, 7)    37.389  ( 3, 7,21)  16907.   16.660  ( 3, 7,18)
              ( 4, 4) 0.93874    1444.9   17.061  18.425   ( 4, 4)    37.542  ( 4, 4,21)  17861.   17.620  ( 4, 4, 8)
              ( 4, 6) 0.93404     942.8   11.765  12.706   ( 3, 6)    27.271  ( 3, 6,21)  18646.   12.007  ( 3, 6,19)
              ( 4, 8) 0.92753     244.0    4.895   5.287   ( 3, 8)    11.387  ( 3, 8,21)  18958.    5.009  ( 3, 6,18)
              ( 5, 3) 0.94013    1593.3   18.585  20.072   ( 5, 3)    41.514  ( 5, 3,21)  18566.   19.010  ( 5, 3,11)
              ( 5, 5) 0.92563      38.6    3.016   3.257   ( 3, 6)     6.894  ( 3, 6,21)  18646.    3.082  ( 3, 6,17)
              ( 5, 7) 0.92817     312.4    5.323   5.749   ( 3, 6)    12.270  ( 3, 6,21)  18646.    5.439  ( 3, 6,18)
              ( 6, 4) 0.93399     937.6   11.712  12.649   ( 6, 3)    27.231  ( 6, 3,21)  18620.   11.954  ( 6, 3,19)
              ( 6, 6) 0.92787     279.8    4.696   5.072   ( 3, 6)    10.810  ( 3, 6,21)  18646.    4.892  ( 5, 4,23)
              ( 6, 8) 0.92703     189.4    3.699   3.995   ( 3, 6)     8.430  ( 3, 6,21)  18646.    3.784  ( 3, 6,17)

         HIGHEST WORTH STUCK ROD   IS         ( 3, 5), WITH WORTH OF    1596.1 PCM

         IF MORE THAN TWO CONTROL RODS ARE DROPPED OR STUCK WITHIN A GIVEN CALCULATION, ADDITIONAL
         LOCATIONS DO NOT APPEAR IN THE ABOVE EDIT. THE USER SHOULD CONFIRM THIS VIA THE E-BNK EDIT.

         CORE RELATIVE POWER IS  0.00

         BORON CONCENTRATION IS    0.0 PPM, 0.000 G/KG
```

Figure 16: Windsor Pond Unit 1 Worst Stuck Rod at EOC Part 1

```
E-SRW    STUCK ROD WORTH

         STUCK ROD   EIGENVALUE   WORTH    FDH   FDH*U   LOCATION     FQ     LOCATION    BU-FQ     FXY    LOCATION

         BASE CASE    0.92527
              ( 7, 3) 0.94006    1585.7   16.248  17.547   ( 7, 3)    37.195  ( 7, 3,21)  16866.   16.608  ( 7, 3,18)
              ( 7, 5) 0.92822     317.6    5.351   5.779   ( 6, 3)    12.330  ( 6, 3,21)  18620.    5.467  ( 6, 3,18)
              ( 7, 7) 0.92691     176.3    3.512   3.793   ( 3, 6)     8.024  ( 3, 6,21)  18646.    3.592  ( 3, 6,18)
              ( 8, 2) 0.93783    1348.5   16.557  17.881   ( 8, 2)    37.993  ( 8, 2,21)  19435.   16.962  ( 8, 2,18)
              ( 8, 4) 0.92755     245.6    4.914   5.307   ( 8, 3)    11.426  ( 8, 3,21)  18968.    5.023  ( 8, 3,21)
              ( 8, 6) 0.92703     189.3    3.690   3.985   ( 6, 3)     8.406  ( 6, 3,21)  18620.    3.776  ( 6, 3,17)
              ( 8, 8) 0.92568      43.9    2.566   2.771   ( 3, 6)     5.829  ( 3, 6,21)  18646.    2.625  ( 3, 6,17)
              ( 9, 1) 0.92545      19.7    2.662   2.875   (12, 3)     6.049  (12, 3,21)  16650.    2.724  (12, 3,17)
              ( 9, 3) 0.93041     553.6    8.429   9.103   ( 9, 2)    19.819  ( 9, 2,21)  18639.    8.679  ( 9, 2,20)
              ( 9, 5) 0.92770     261.6    4.253   4.593   ( 9, 5)     9.756  ( 9, 5,21)  19458.    4.323  ( 9, 5,22)
              ( 9, 7) 0.92606      85.0    2.717   2.935   (12, 3)     6.163  (12, 3,21)  18646.    2.779  (12, 3,17)
              ( 9, 9) 0.92556      30.8    2.380   2.571   (12, 3)     5.402  (12, 3,21)  18646.    2.435  (12, 3,17)

         HIGHEST WORTH STUCK ROD   IS         ( 7, 3), WITH WORTH OF    1585.7 PCM

         IF MORE THAN TWO CONTROL RODS ARE DROPPED OR STUCK WITHIN A GIVEN CALCULATION, ADDITIONAL
         LOCATIONS DO NOT APPEAR IN THE ABOVE EDIT. THE USER SHOULD CONFIRM THIS VIA THE E-BNK EDIT.

         CORE RELATIVE POWER IS  0.00

         BORON CONCENTRATION IS    0.0 PPM, 0.000 G/KG
```

Figure 17: Windsor Pond Unit 1 Worst Stuck Rod at EOC Part 2

```
E-SUM    SUMMARY OF   ANC   RUNS                                      END OF RUN

 NO   BU  POWER   EIGEN   BORON CON     TIN      XE SM   FQ    FDH    FZ    AO/ASI S 5    4    3    2    1     FILEID    TITLE
                          PPM  G/KG  DEG-F DEG-C                                *
  1   150 1.000 1.000007 1090  6.231 549.0 287.2 HD HD 1.928 1.635 1.142  0.55 0 Y 137 137 137 137 137              K1 - BOL BASE CASE
  2   150 1.000 0.998315 1090  6.231 549.0 287.2 HD HD 2.144 1.645 1.252-12.77 0 Y 103 137 137 137 137              K2   INSERT RODS T
  3   150 1.050 0.998064 1090  6.231 549.9 287.7 RC HD 2.157 1.640 1.299  8.35 0 Y 103 137 137 137 137              K3 - OVER-TEMP AT
  4   150 0.000 1.013429 1090  6.231 532.0 277.8 HD HD 2.923 1.737 1.662 39.94 0 Y 103 137 137 137 137              K4 - ZERO POWER, A
  5   150 0.000 0.935238 1090  6.231 532.0 277.8 HD HD 5.344 2.723 1.934 54.24 0 Y   0    0    0    0    0          K5 - ZERO POWER, A
  6   150 0.000 0.944687 1090  6.231 532.0 277.8 HD HD29.05415.220 1.904 53.13 0 Y   0    0    0    0    0          K6 - ZERO POWER, N
```

Figure 18: Windsor Pond Unit 1 BOC E-SUM Showcasing SDM Calculation Relevant Eigenvalues

```
E-SUM    SUMMARY OF  ANC  RUNS                                        END OF RUN

 NO   BU  POWER   EIGEN   BORON CON     TIN     XE SM   FQ   FDH   FZ    AO/ASI S 5   4   3   2   1     FILEID     TITLE
                          PPM  G/KG  DEG-F DEG-C                           *
  1 14660 1.000 1.000747    0  0.000 549.0 287.2 HD HD 1.756 1.563 1.103 -1.23 0 Y 137 137 137 137 137             K1 - BOL BASE CASE
  2 14660 1.000 0.997743    0  0.000 549.0 287.2 HD HD 2.209 1.565 1.390-21.39 0 Y 103 137 137 137 137             K2   INSERT RODS T
  3 14660 1.050 0.997851    0  0.000 549.9 287.7 RC HD 1.975 1.572 1.252  8.06 0 Y 103 137 137 137 137             K3 - OVER-TEMP AT
  4 14660 0.000 1.023816    0  0.000 532.0 277.8 HD HD 3.659 1.723 2.016 62.84 0 Y 103 137 137 137 137             K4 - ZERO POWER, A
  5 14660 0.000 0.929738    0  0.000 532.0 277.8 HD HD 6.502 2.433 2.656 78.42 0 Y   0   0   0   0   0             K5 - ZERO POWER, A
  6 14660 0.000 0.944724    0  0.000 532.0 277.8 HD HD49.41318.622 2.627 77.97 0 Y   0   0   0   0   0             K6 - ZERO POWER, N
```

Figure 19: Windsor Pond Unit 1 EOC E-SUM Showcasing SDM Calculation Relevant Eigenvalues

Table 3: Windsor Pond Unit 1 Cycle 13 Conservative and Unconservative SDMs, and Rod Uncertainties for BOC and EOC Compared to Safety Limits

Plant Configuration	SDM unconservative %Δρ	Rod Uncertainty %Δρ	SDM conservative %Δρ	Safety Limit %Δρ
BOC	5.4963	0.7024	4.74392	1.6
EOC	5.4711	0.804	4.6171	1.6

$$SDM_{unconservative} = \ln ln\left(\frac{0.997851}{.944724}\right) * 100 = 5.4711\%\Delta\rho \tag{2}$$

$$Rod\ Uncertainty = 0.1 * \ln ln\left(\frac{1.023816}{0.944724}\right) * 100 = 0.804\ \%\Delta\rho \tag{3}$$

$$SDM_{conservative} = 5.711 - 0.804 = 4.6171 \tag{4}$$

CHAPTER 3: SUMMARY AND FUTURE PLANS

As seen above all the safety requirements set by Westinghouse were met, except the rodded Fdh. The reason the Fdh was above the safety limits is described in the Fdh section.

The next step in the core design process to complete the operation data calculations for the Windsor Pond Unit 1.

CHAPTER 4: QUESTIONS

1. **What is the relationship between power distribution and rodworth?**

Rodworth is affected by the power distribution, as regions with higher power entail a higher neutron flux (and vice versa). This means that the rods will be more effective in high power regions as the reaction rate for neutron absorption will increase with the flux (R = Flux*Macroscopic Absorption Cross Section of boron, assuming a boron control rod).

2. What are RILs? Which calculations use RILs and why?

RIL stands for rod insertion limits and they are the maximum amount the rods can be inserted at any power level. Rodded Fdh and SDM use RILs. During rodded Fdh calculations, the rods are inserted at RILs to modify the neutron flux, and thus the power distribution. As discussed in section 2.1, this can lead to a suppression of the power distribution in one region while increasing it in another one. This phenomenon can lead to a higher Fdh than the un-rodded configuration. In the SDM calculations, the rods are inserted at the RILs to insert a negative reactivity into the system and diminish the SDM.

3. Describe the steps to perform a shutdown margin calculation. Describe each component of the calculation and whether it increases or decreases reactivity.

The shutdown margin calculation steps are described in detail in section 2.4. In short, there are six components. K1 is the ARO base case at BOC or EOC. K2 is when the rods are at insertion limits and reactivity decreases in this step. K3 is calculated so with a relative power of 105% and an axial power skew to the top of the core. Reactivity decreases in this step. At K4 the plant is set to HZP ARO and the reactivity rises sharply. The sharp rise in reactivity can be explained by the negative MTC. At K5 all the rods are in the core and the reactivity decreases significantly. In K6, we remove the worst stuck rod from the core which in turn slightly increases reactivity. The reason for removing the worst stuck rod is to satisfy requirements by the NRC. The difference in reactivity between K3 and K6 is the unconservative SDM. To attain a more conservative SDM, void effects and rod uncertainty (found by finding the change in reactivity between k4 and k5) are subtracted from the unconservative SDM value.E

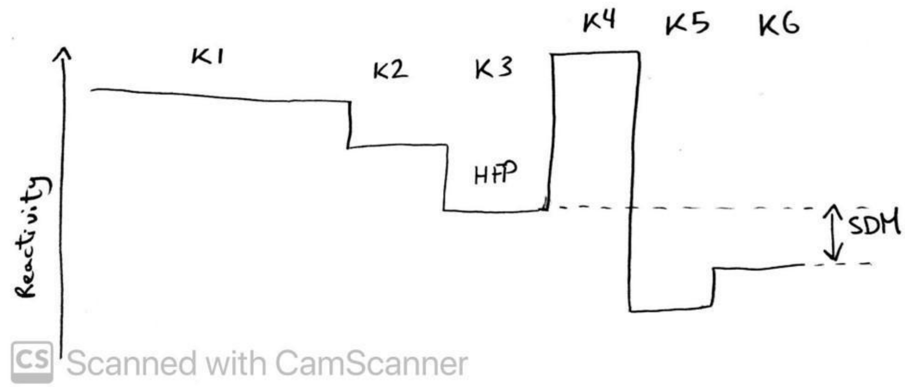

Figure 20: Representation of the Behavior of the Six Eigenvalues Calculated to Attain the SDM

4. Why do we reconstruct (i.e. skew) xenon in some calculations (in ANC, DEPLETE=RCXE)?

Xenon was skewed in the Rodded Fdh and the SDM calculations. We skew xenon to the bottom, in order to further emphasize the axial power skew. In the Rodded Fdh calculations, this leads to overemphasizing the control rod effects on the axial flux shape. In the SDM calculation this emphasizes the flux redistribution effect on the power defect. According to Westinghouse, flux redistribution refers to the reactivity due to flux axially peaking at the top of the core in HZP condition. During operation, the enthalpy rise in the core causes a modest flux tilt towards the bottom of the core. This means that the fuel at the top of the core is less depleted. When the reactor is at HZP conditions, the enthalpy rise disappears, and the neutron flux distribution is shifted to the top of the core which is more reactive. The reactivity change due to the axial burnup variation is accounted for by the redistribution factor.

5. Define power defect. Describe how it changes during the cycle and why.

Power defect is the positive reactivity insertion caused by a decrease in power, and the subsequent decrease in both fuel and moderator temperature. In the context of this safety analysis report, the power defect consists of the increase in reactivity from the reactor trip from HFP to HZP. There are four main contributing factors to the power defect: DTC, MTC, flux redistribution effect, and disappearance of coolant voids. The DTC and MTC cause a positive reactivity insertion when going from HFP to HZP due to decreases in fuel and moderator temperatures respectively. The trip also causes a change in the axial flux shape.

During steady operations, the flux peak is driven to the bottom of the core by the enthalpy rise in the subchannels (higher reactivity in colder bottom). At HZP, this enthalpy rise disappears and thus the flux peak moves to the top of the core as it is less depleted than the bottom. This change in flux shape, called the flux redistribution effect, also adds a positive reactivity insertion to the system. Finally, the disappearance of coolant voids at HZP, caused by bubbles in the boiling moderator, causes another positive reactivity insertion that contributes to the power defect. The power defect increases throughout the cycle, as the difference in depletion of the top and bottom of the assemblies further exacerbates the flux redistribution effect.

APPENDIX A: ROD INSERTION LIMIT

In Windsor Pond Unit 1, control rods are split into 5 control banks (1 through 5) and 2 banks dedicated solely to plant trips (A and B). The plant's control rod configuration is showcased in figure 21.

The RILs, calculated by the transient analyst and limited by rod ejection accidents, are calculated as a function of reactor fraction power. The RILs vs Fraction of Rated Thermal Power graph provided below (figure 22) allows one to determine the RILs at each power level. For the purpose of the safety calculations provided in this report, the RILs at HFP and HZP need to be determined.

For HFP (1.0 fraction of rated thermal power), the RILs consist of all control banks, except the lead one, completely withdrawn. The lead control bank, control bank 5, can be inserted for a maximum 25%, or 34 steps inserted (103 withdrawn for ANC inputs).

For HZP (0 fraction of rated thermal power), the RILs consist of control banks 5 and 4 being completely inserted, and control bank 3 inserted 60% into the core, or 83 steps inserted (54 steps withdrawn).

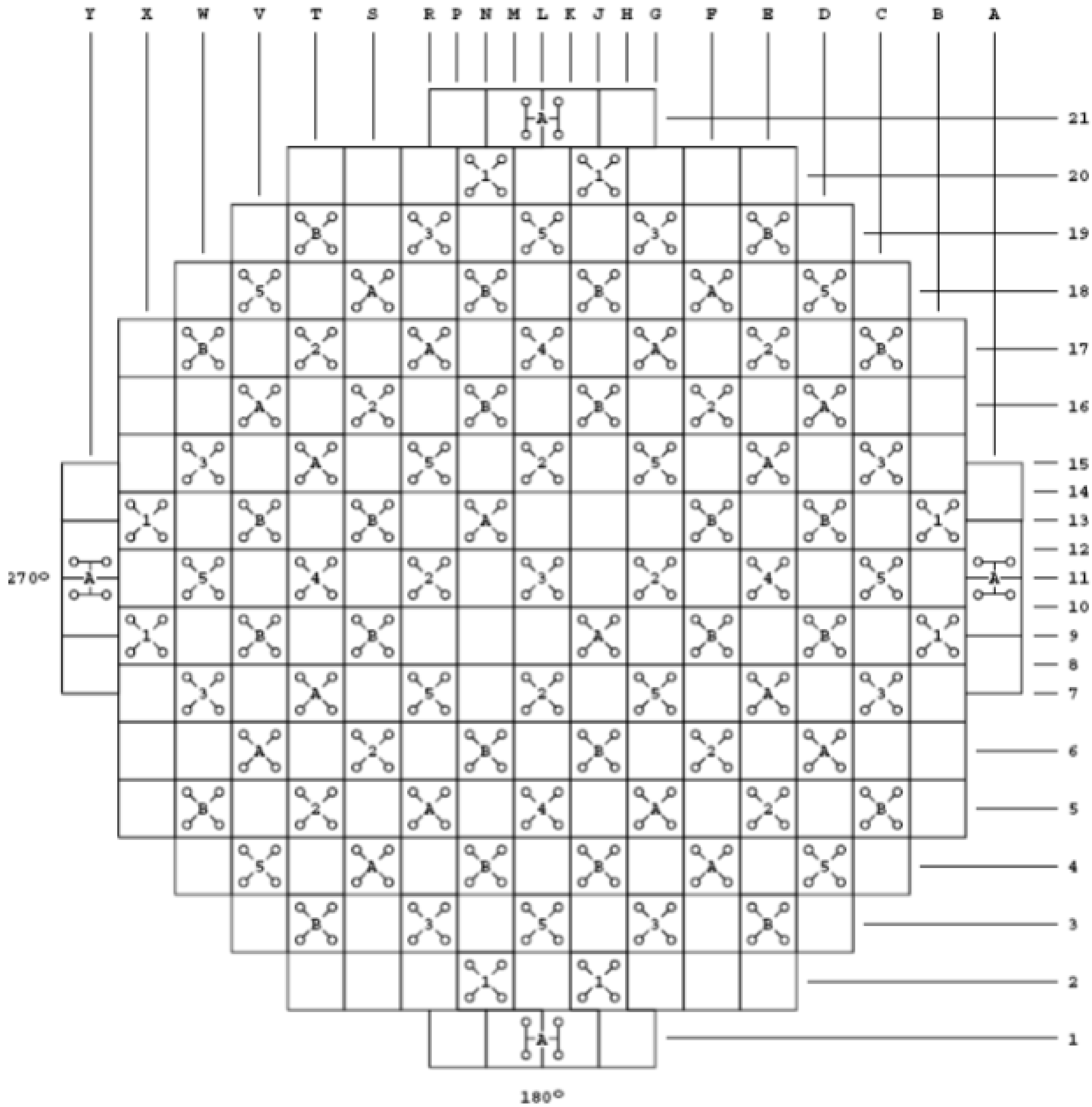

Figure 21: Windsor Pond Unit 1 Control Rod Configuration Courtesy of Westinghouse

APPENDIX B: ANC INPUTS FOR EACH CALCULATION

Appendix B.1: Rodded and Un-rodded Fdh calculations

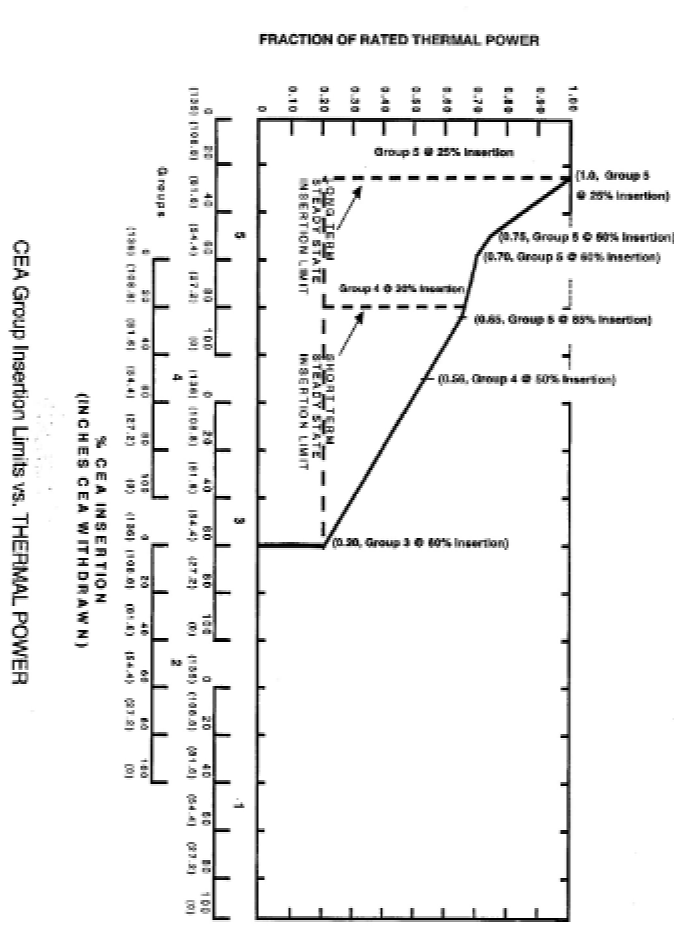

Figure 22: Windsor Pond Unit 1 Rod Insertion Limits as a Function of Fraction of Core Rated Thermal Power Courtesy of Westinghouse

```
TITLE =150 Burnup
/       DATABANK INFORMATION
/
RITEID      = SL213_BE02
RITEUNIT    =   1.00 /
BORONCON =  900.3046 /
DELTABU=150
TAPEDIT  =      0.00 /
```

Figure 23: Rodded and Un-rodded Fdh Calculation

Appendix B.2: Temperature Coefficient Calculations

```
TITLE= MTC CALCULATION
 READID= SL213_BE03
 READUNIT= 1.0
 DEPLETE=HDALL,NAXE
 DELTIME=0
 TMODCOEF=5
 RELPOW=0
 END
```

Figure 24: MTC Calculation

Appendix B.3: Rod Ejection Calculations

```
 TITLE       = HZP BOL ROD EJECTION
 READID      = SL213_BE01/ READ IN 0 MWD/MTU BURNUP STEP
 READUNIT    = 1.0/ READ IN DATABANK NUMBER
 DELTABU     = 0/ BURNUP DOES NOT CHANGE
 RELPOW      = 0/ SET POWER TO HZP
END
 TITLE       = UNFOLD TO FULL CORE RODS AT RIL
 RODSTEP     = 137,137, 54,0, 0/ SET RODS TO HZP RIL
 UNFOLD      = FULL/ UNFOLD TO FULL
END
 TITLE       = EJECT RODS IN FULL CORE
 STUCKROD    = 7/ NUMBER OF EJECTED RODS
 FEEDBACK    = 2/ FREEZE ALL (MOD. & DOP.) FEEDBACK
 KSURCH      = 0/ TURN OFF CRITICALITY SEARCH
 BANKSEQ     = 0307, 0404, 0703, 0707, 0903, 0905, 0909/
END
```

Figure 25: HZP Rod Ejection Calculation at 0 Burnup

```
TITLE       = HZP BOL ROD EJECTION
 READID      = SL213_BE15/ READ IN 14640 MWD/MTU BURNUP STEP
 READUNIT    = 1.0/ READ IN DATABANK NUMBER
 DELTABU     = 0/ BURNUP DOES NOT CHANGE
 RELPOW      = 0/ SET POWER TO HZP
 BORONCON    = 0.0 / SET BORON CONCENTRATION TO 0 AT EOC
END
 TITLE       = UNFOLD TO FULL CORE RODS AT RIL
 RODSTEP     = 137,137, 54,0, 0/ SET RODS TO HZP RIL
 UNFOLD      = FULL/ UNFOLD TO FULL
END
 TITLE       = EJECT RODS IN FULL CORE
 STUCKROD    = 7/ NUMBER OF EJECTED RODS
 FEEDBACK    = 2/ FREEZE ALL (MOD. & DOP.) FEEDBACK
 KSURCH      = 0/ TURN OFF CRITICALITY SEARCH
 BANKSEQ     = 0307, 0404, 0703, 0707, 0903, 0905, 0909/ DEF
```

Figure 26: HZP Rod Ejection Calculation at 14660 Burnup

```
 TITLE       = HFP BOL ROD EJECTION
 READID      = SL213_BE02/ READ IN 150 MWD/MTU BURNUP STEP
 READUNIT    = 1.0/ READ IN DATABANK NUMBER
 DELTABU     = 0/ BURNUP DOES NOT CHANGE
 DEPLETE     = EQXE/ HOLD ALL, EQUILIBRIUM XE
END
 TITLE       = UNFOLD TO FULL CORE RODS AT RIL
 RODSTEP     = 137,137,137,137,103/ SET RODS TO HFP RIL
 UNFOLD      = FULL/ UNFOLD TO FULL
END
 TITLE       = EJECT RODS IN FULL CORE
 STUCKROD    = 3/ NUMBER OF EJECTED RODS
 FEEDBACK    = 2/ FREEZE ALL (MOD. & DOP.) FEEDBACK
 KSURCH      = 0/ TURN OFF CRITICALITY SEARCH
 BANKSEQ     = 0404, 0707, 0903/ DEFINE YOUR EJECTED RODS
END
```

Figure 27: HFP Rod Ejection Calculation at 150 Burnup

```
 TITLE       = HFP BOL ROD EJECTION
 READID      = SL213_BE15/ READ IN 14640 MWD/MTU BURNUP STEP
 READUNIT    = 1.0/ READ IN DATABANK NUMBER
 DELTABU     = 0/ BURNUP DOES NOT CHANGE
 BORONCON    = 0.0 /
 DEPLETE     = EQXE/ HOLD ALL, EQUILIBRIUM XE
END
 TITLE       = UNFOLD TO FULL CORE RODS AT RIL
 RODSTEP     = 137,137,137,137,103/ SET RODS TO HFP RIL
 UNFOLD      = FULL/ UNFOLD TO FULL
END
 TITLE       = EJECT RODS IN FULL CORE
 STUCKROD    = 3/ NUMBER OF EJECTED RODS
 FEEDBACK    = 2/ FREEZE ALL (MOD. & DOP.) FEEDBACK
 KSURCH      = 0/ TURN OFF CRITICALITY SEARCH
 BANKSEQ     = 0404, 0707, 0903/ DEFINE YOUR EJECTED RODS AS
END
```

Figure 28: HFP Rod Ejection Calculation at 14660 Burnup

Appendix B.4: Shut Down Margin Calculations

```
 TITLE    = K1 - BOL Base Case at Power, ARO
 READID   = SL213_BE02/ READ IN 150 MWD/MTU BURNUP STEP
 READUNIT = 1.0/ READ IN DATABANK NUMBER
 DELTABU  = 0/ BURNUP DOES NOT CHANGE
 KSURCH   = 0/ TURN OFF CRITICALITY SEARCH

END
 TITLE    = K2 – Insert Rods to RIL
 RODSTEP  = 137,137,137,137,103/ SET RODS TO HFP RIL
END
 TITLE    = K3 - Over-Temp at Power, ARO, Xe Skewed
 RELPOW   = 1.05/ INCREASE POWER TO 105%
 DEPLETE  = RCXE/ RE-CONSTRUCT XENON
 DELXE    = -30/ INITIAL GUESS FOR XENON
 AOSURCH  = DELXE,8.05,0.05/ SEARCH ON DELXE, SET AO TO MAX POSITIVE, SET CONVERGENCE
END
 TITLE    = K4 - Zero Power, ARO, Xe Skewed
 RELPOW   = 0/ SET POWER TO HZP
 AOSURCH  = 0/ TURN OFF THE AO SEARCH
 DEPLETE  = HDALL/ HOLD ALL
END
 TITLE    = K5 - Zero Power, ARI, Full core, Xe Skewed
 UNFOLD   = FULL/ UNFOLD TO FULL
 RODSTEP  = 0,0,0,0,0,0,0/ FULLY INSERT ALL RODS
END
 TITLE    = K6 - Zero Power, N-1, Full core, Xe Skewed
 STUCKROD = 1/ SET EQUAL TO ONE
 BANKSEQ  = 0305/ DEFINE YOUR WSR AS XXYY
```

Figure 29: Shut Down Margin Calculation at BOC

```
 TITLE    = K1 - BOL Base Case at Power, ARO
 READID   = SL213_BE15/ READ IN 14660 MWD/MTU BURNUP STEP
 READUNIT = 1.0/ READ IN DATABANK NUMBER
 DELTABU  = 0/ BURNUP DOES NOT CHANGE
 BORONCON = 0/
 KSURCH   = 0/ TURN OFF CRITICALITY SEARCH

END
 TITLE    = K2 – Insert Rods to RIL
 RODSTEP  = 137,137,137,137,103/ SET RODS TO HFP RIL
END
 TITLE    = K3 - Over-Temp at Power, ARO, Xe Skewed
 RELPOW   = 1.05/ INCREASE POWER TO 105%
 DEPLETE  = RCXE/ RE-CONSTRUCT XENON
 DELXE    = -30/ INITIAL GUESS FOR XENON
 AOSURCH  = DELXE,8.05,0.05/ SEARCH ON DELXE, SET AO TO MAX POSITIVE, SET CONVERGENCE
END
 TITLE    = K4 - Zero Power, ARO, Xe Skewed
 RELPOW   = 0/ SET POWER TO HZP
 AOSURCH  = 0/ TURN OFF THE AO SEARCH
 DEPLETE  = HDALL/ HOLD ALL
END
 TITLE    = K5 - Zero Power, ARI, Full core, Xe Skewed
 UNFOLD   = FULL/ UNFOLD TO FULL
 RODSTEP  = 0,0,0,0,0,0,0/ FULLY INSERT ALL RODS
END
 TITLE    = K6 - Zero Power, N-1, Full core, Xe Skewed
 STUCKROD = 1/ SET EQUAL TO ONE
 BANKSEQ  = 0305/ DEFINE YOUR WSR AS XXYY
```

Figure 30: Shut Down Margin Calculation at EOC

```
 TITLE     = BOL BASE CASE
 READID    = SL213_BE02/ READ IN 150 MWD/MTU BURNUP STEP
 READUNIT  = 1.0/ READ IN DATABANK NUMBER
 DELTABU   = 0/ BURNUP DOES NOT CHANGE
 RELPOW    = 0/ SET POWER TO HZP
 KSURCH    = 0/ TURN OFF CRITICALITY SEARCH
END
 TITLE     = ARI UNFOLD
 UNFOLD    = FULL/ UNFOLD TO FULL
 RODSTEP   = 0,0,0,0,0,0,0/ FULLY INSERT ALL RODS
END
 TITLE     = BOL 3D WSR SEARCH
 STUCKROD  = 12/NUMBER OF WSRs
 BANKSEQ   = 0208,0305,0307,0404,0406,0408,0503,0505,0507,0604,0606,0608/

END
 TITLE     = BOL 3D WSR SEARCH
 STUCKROD  = 12/NUMBER OF WSRs
 BANKSEQ   =  0703,0705,0707,0802,0804,0806,0808,0901,0903,0905,0907,0909/
END
 TITLE     = BOL BASE CASE
 READID    = SL213_BE15/ READ IN 14660 MWD/MTU BURNUP STEP
 READUNIT  = 1.0/ READ IN DATABANK NUMBER
 DELTABU   = 0/ BURNUP DOES NOT CHANGE
 BORONCON  = 0/ Setting BORON CONCENTRATION TO 0 IN EOC
 RELPOW    = 0/ SET POWER TO HZP
 KSURCH    = 0/ TURN OFF CRITICALITY SEARCH
END
 TITLE     = ARI UNFOLD
 UNFOLD    = FULL/ UNFOLD TO FULL
 RODSTEP   = 0,0,0,0,0,0,0/ FULLY INSERT ALL RODS
END
 TITLE     = BOL 3D WSR SEARCH
 STUCKROD  = 12/NUMBER OF WSRs
 BANKSEQ   = 0208,0305,0307,0404,0406,0408,0503,0505,0507,0604,0606,0608/

END
 TITLE     = BOL 3D WSR SEARCH
 STUCKROD  = 12/NUMBER OF WSRs
 BANKSEQ   =  0703,0705,0707,0802,0804,0806,0808,0901,0903,0905,0907,0909/
```

Figure 31: Worst Stuck Rod Calculation

REFERENCES

- Andrew Shaffer, NUC E 431W Guest Lecture, 4-01-Overview_2020

- Group 6. (2020). ANC. Westinghouse

- NUC E 431W Lectures on Safety Calculations

- Penn State Core Design Project. Westinghouse. 2017

- Corey Prumo, NUC E 431W Guest Lecture, Westinghouse Lecture 4-1 Safety Calculations

- How to Fuel Manage Windsor Pond by Prumo, C. M. (2020, 02, 12). How to Fuel Manage Windsor Pond. Westinghouse.