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FLUX STABILITY AND POWER CONTROL
IN THE SOVIET RBMK-1000 REACTORS

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1.0 INTRODUCTION

As a result of the Chernobyl accident, the Soviets have studied and implemented various design changes to improve the safety of the RBMK reactors. The safety enhancements include modifications of the control rod configuration, fuel enrichment increase from 2.0 to 2.4 weight percent U-235, and installation of additional supplemental absorbers.¹

The control rod configuration was modified to eliminate the possibility of localized power increase during the initial seconds of control rod insertion. The pre-accident control rod design allowed the control rods to be completely withdrawn out of the reactor core leaving a water gap of 1.25 meters (4.1 feet) at the bottom of the core below the graphite rod follower (Figure 1.1a). Since water is a strong neutron absorber in an overmoderated RBMK core, the initial insertion of a fully withdrawn control rod causes a reduction in neutron absorption in the bottom of the core as the water is displaced by the graphite rod follower. This reduction in neutron absorption causes a local power increase. If a large number of control rods are fully withdrawn (as was the case just prior to the Chernobyl explosion), the local power increase can initiate extensive coolant boiling in the fuel channels. This boiling removes more water from the core, further increasing the power. Following the accident, the Soviets modified the control rod limit switch settings to fix the rods in the upper position at a depth of 1.2 meters (3.9 feet) into the core (Figure 1.1b). However, according to the Soviets, this configuration resulted in a distortion of the axial power distribution, and necessitated a power reduction of 10-15%.¹ Currently, the rod design has been modified by lengthening the connecting link between the control rod and the rod displacer (Figure 1.1c). The Soviets have reported that this design has reduced the distortion in the axial power distribution.

Another step taken by the Soviets to enhance the RBMK safety was to increase the fuel enrichment from 2.0 to 2.4 wt% U-235 to reduce the positive power feedback associated with loss of water from the core. The fuel enrichment

FIGURE 1.1. Control Rod Configurations

increase reduces the degree of over-moderation and, therefore, reduces the neutron absorption in water. Increasing the fuel enrichment results in a substantial increase in the overall core reactivity. To compensate for this reactivity increase, fuel was removed from 80 fuel channels and neutron absorbers put in their place. These 80 absorbers are to remain in place permanently. The Soviets have not reported any problems associated with the additional absorbers.

These safety improvements represent several significant changes in the operation of the RBMK reactor. In the past the Soviets have made changes much more slowly. They have already reported problems with the control rod configuration change. There may be other, unanticipated problems.

The purpose of this study is to investigate the effects of increased fuel enrichment, different control rod positions, and supplemental absorber loadings on reactivity control, power distribution within the large RBMK core, and relative stability against power oscillations.

2.0 SUMMARY

The safety modifications of the RBMK reactor implemented by the Soviets were investigated to determine their impacts on power distribution, control rod system worth, and xenon stability. Calculations were performed using a cell lattice code to generate cross section data and a three-dimensional diffusion theory code with xenon and temperature feedbacks to study the behavior of the reactor under various operating conditions with and without the proposed modifications.

It was determined that the coolant void reactivity feedback coefficient (a power feedback term associated with neutron absorption in water) is reduced by increasing the fuel enrichment from 2.0 to 2.4 weight percent U-235. The core-averaged void reactivity coefficients at an average fuel exposure of 10 GWD/MTU for the 2.0 and 2.4 percent fuel are 1.65% and 0.822% dK/K per unit void fraction, respectively. The reduction in the void reactivity coefficient helps to improve the stability of the reactor and reduces the rate of power increase associated with events resulting in removal of water from the core.

The fuel enrichment increase causes an overall reactivity increase of 53.7 mk. This reactivity increase is offset by the addition of the 80 supplemental absorbers and the insertion of an increased number of existing control rods during operation (about 30). The fuel enrichment increase also reduces the average worth of a control rod by 0.02 mk which has little impact on total reactivity control.

The 80 supplemental absorbers installed to reduce the reactivity margin were determined to have a worth of 41.2 mk. These supplemental absorbers have no effect on the control rod system worth.

Lengthening the connecting link between the control rod and the graphite follower eliminates the possibility of positive reactivity insertion during

the initial seconds of rod insertion. However, since the extra water region above the graphite follower acts as a poison in the control rod channel, axial power distortion still occurs at the top of the reactor. This may require operating constraints on the total reactor power.

The safety modifications implemented after the Chernobyl accident do improve the safety of the RBMK-1000 reactor. The new control rod design eliminates the possibility of positive reactivity insertion during reactor scram. Increased fuel enrichment effectively reduces the positive void reactivity coefficient. The additional reactivity caused by increasing the fuel enrichment is effectively compensated for by the additional supplemental absorbers and by operating with additional control rods in the reactor core. The control rod system worth is slightly reduced by the fuel enrichment increase, but is not affected by the additional supplemental absorbers.

This study was specifically performed to investigate the safety modifications for the RBMK-1000 reactors. Efforts to extrapolate the results for the RBMK-1500 reactors could not be performed due to a lack of information on the RBMK-1500 core configuration and reactor data. However, it is expected that the effects of higher fuel enrichment would be the same for the RBMK-1500 reactors. Since the thermal margin is less for the 1500-core than for the 1000-core, new control rod configurations in the 1500-core would probably reduce the maximum power level allowed during operation. The results related to xenon stability should not be extrapolated to the RBMK-1500 reactor.

3.0 REACTOR MODEL

3.1 Description

A three-dimensional two-group diffusion theory code, DELKOV, was used to model the Soviet RBMK-1000 reactor. DELKOV is a modified version of the DELPHI code⁹ which is used for modelling the Hanford N Reactor.

The two-group macroscopic cross sections were calculated using the WIMS² lattice cell code. The cell calculations employed 69 energy groups which were ultimately collapsed to the two-group set used in the reactor model. The macroscopic cross sections are dependent on fuel composition, fuel burnup, fuel temperature, and water density. Each node in the model can have different macroscopic cross section values depending on the nodal values of these variables.

The model can perform fuel depletion calculations. The core-averaged exposure is incremented in steps during which the operating parameters (control rod pattern, core power, etc.) experience only minor variations.

Fuel channel water density calculations include the effects of subcooled as well as saturated coolant boiling. Fuel temperatures are also calculated for each fuel node.

The model also contains xenon feedback and can perform xenon stability analysis using a quasi-static method. This method is based on the assumption that the fluxes remain constant over a specified time interval that is relatively short compared to the xenon oscillation time. The fluxes are recalculated at the end of each time step.

The model geometry consists of 56 x 56 x 32 nodes in the X, Y, and Z directions, respectively. The reactor coolant flow is along the Z-axis. Each node is a cube 25 cm on a side. The reactor model consists of 1884 core

channels and 604 reflector channels. The 2.0% fuel enrichment configuration contains 1661 fuel channels, while the 2.4% configuration contains 1581 fuel and 80 supplemental absorber channels. Both enrichment configurations contain 211 control rod and 12 vertical flux monitor channels. The 211 control rod channels are divided into 24 part-length rods (USP), 12 automatic rods (AR), 12 local automatic rods (LAR), and 163 regulating rods (RR).

Table 3.1 gives the reactor parameters used in the RBMK model.

TABLE 3.1. Reactor Core Data

Thermal Power, Mwt	3200
System Pressure, MPa (psia)	6.8 (988)
Core Coolant Inlet Temp, °C (°F)	270 (518)
Core Coolant Flow, Kg/sec (lbm/hr)	1.06×10^4 (84.3×10^6)
Graphite Temperature, °C (°F)	600 (1112)

3.2 Validation

The reactor code DELKOV and the model were validated by comparing the results with the Leningrad initial critical core data.³ The Leningrad critical data is reported for 1.8 weight percent enriched U-235 fuel and no water in the coolant channels. DELKOV results gave a k-effective of 1.01751. The small discrepancy (17.5 mk) for the dry core was expected. With no water in the core, neutrons freely escape from the core through the fuel channel voids in the axial direction. Since axial neutron streaming through these voids is not accounted for in the DELKOV calculations, the calculated neutron multiplication constant is higher than the measured value. The reactivity difference of 17.5 mk is reasonable for a dry core.

The model was also checked by comparing the DELKOV control rod system, xenon worths, and void reactivity coefficients with reported RBMK-1000 data for both fuel enrichments. The system worth was determined at hot zero power for the 2.0% fuel with the inlet water temperature of 270 °C (518 °F) and core

average exposure of about 10 GWD/MT. The rod system worth is 93.2 mk or 0.44 mk per control rod. The Soviets reported an average rod worth of 0.50 mk with about 30% uncertainty.⁴ Thus, the DELKOV system worth is on the low side but within the uncertainty range.

The xenon worth was determined by running cases at full power (equilibrium xenon) and at hot zero power (no xenon) for the 2.0% fuel with all control rods out. DELKOV gives a xenon worth of 29.0 mk. The Soviets reported a value of 29.8 mk.⁴ Thus, the values are in good agreement.

The void reactivity coefficients for an average fuel exposure of 10 GWD/MTU for the 2.0% and 2.4% fuels were calculated to be 1.65% and 0.822% dK/K per unit void fraction, respectively. The Soviets reported the reactivity coefficient values of about 1.5% and 0.8-1.1% dK/K per unit void fraction for the 2.0% and 2.4% fuel, respectively.^{1,4} The calculated and Soviet reported values are in good agreement.

4.0 STEADY STATE ANALYSES

4.1 Fuel Enrichment Effects

A series of calculations were performed to study the effects of different fuel enrichments on axial power peaking. Since axial power peaking is little affected by radial neutron leakage, a partial core model was used to simulate the full RBMK-1000 core. A 5 x 5 x 32 node model with reflecting boundary conditions in X and Y directions (that is, an infinite array of 5 X 5 lattice) was used for the calculations. The 5 X 5 model was arbitrarily chosen. Since core-averaged effects of different fuel enrichments are being determined, no control rods are used in the model. The presence of control rods in the model would be important if local effects were to be determined.

Each of the 25 fuel channels has an average channel power of 1.93 Mw. The inlet temperature and system pressure are 270 °C (518 °F) and 6.8 MPa (988 psia), respectively. The average fuel channel flow is 6.4 Kg/sec (5.08×10^4 lbm/hr).

Figures 4.1 and 4.2 show the results of using different fuel enrichments and fuel exposures. Due to positive reactivity feedback caused by boiling in the upper portion of the core, the power levels are higher in the upper portion of the reactor core. The void reactivity coefficient is a measure of the positive reactivity feedback associated with coolant loss due to boiling or other means. The DELKOV calculated core-averaged void reactivity coefficients for the 2.0% and 2.4% fuel at 10.2 GWD/MTU are 1.65% and 0.822% dK/K per unit void fraction, respectively. For the 2.4% fuel at a core average exposure of 12.2 GWD/MTU the value is 1.01% dK/K.

In Figure 4.1, the axial power profile with the 2.4% fuel enrichment has a slightly lower peaking than the power profile with the 2.0% fuel at a core average fuel exposure of zero (beginning-of-life core). Figure 4.2 shows a more pronounced difference between the two power curves at a higher core-

FIGURE 4.1. Impact of Initial Uranium Enrichment on Axial Power Profile, Exposure = 0.0 MWD/MT

FIGURE 4.2. Impact of Initial Uranium Enrichment on Axial Power Profile, Exposure = 10,200.0 MWD/MT

averaged fuel exposure. The difference is due to a higher void reactivity coefficient at the higher fuel exposure. As the fuel exposure increases, the reactor becomes more over-moderated due to burnup loss of fuel. Neutron absorption in water increases as over-moderation increases.

The axial power distribution with the 2.4% fuel has a lower peaking value shifted toward the center of the fuel channel than for the 2.0% fuel. The difference is due to the 2.4% fuel enrichment having a lower void reactivity coefficient. As the fuel enrichment increases, the reactor becomes less over-moderated. The worth of the water acting as a poison decreases, and thus, the void reactivity coefficient decreases.

With the higher fuel enrichment, the overall reactivity is increased by 53.7 mk. This reactivity increase must be compensated by additional use of existing control rods and by adding supplemental absorbers. The Soviets reported that an additional 23-28 operating control rods and about 80 supplemental absorbers are needed to offset the reactivity increase due to higher fuel enrichment.¹ The reactivity balance is shown in Table 4.1. The control rod worths in this table are the Soviet reported 0.5 mk per rod. It is seen that additional supplemental absorbers and operating control rods effectively compensate for the reactivity increase caused by increasing the fuel enrichment.

TABLE 4.1. Reactivity Balance

Fuel enrichment increase	53.7 mk
80 supplemental absorbers	-41.2 mk
23 to 28 control rods	<u>-11.5 to -14.0 mk</u>
Total	1.0 to -1.5 mk

4.2 Control Rod Configuration Effects

Calculations were performed to investigate the impacts of different control

rod configurations on power distributions within the core. Three rod configurations were considered:

1. Case 1 - rod configuration used before the Chernobyl accident (Figure 1.1a).
2. Case 2 - rod configuration with the upper limit set at a depth of 1.2 meters (3.94 feet) into the core (Figure 1.1b).
3. Case 3 - rod configuration with longer connecting link between the control rod and the graphite rod displacer (Figure 1.1c).

The results of the calculations are summarized in Figures 4.3 and 4.4. Both figures clearly show that axial power profiles are severely distorted at the top of the reactor using the deep rod configuration (case 2). The peaks for case 2 are higher and are shifted toward the center of the fuel channel due to the presence of the control rods at the reactor top. The current rod configuration (case 3) shows some improvements over the deep rod configuration, but not by much. Since water acts as a poison in the control rod channel, the added water region in the current rod configuration still causes some distortion in the power profile at the reactor top. This axial power distortion may impact the DNB (departure from nucleate boiling) ratio and reduce the maximum operating reactor power. Analyses of these thermal-hydraulic effects are beyond the scope of this study.

4.3 Supplemental Absorbers

The charging of the 2.4% enriched fuel in the reactor core requires 80 additional supplemental absorbers (DP rods) to help maintain the reactivity margin within an acceptable range. Since the exact pattern of the DP rods is not available, a series of calculations were performed to determine reasonable placements of the 80 DP rods in the reactor core. Figure 4.5 shows the best estimate assumed configuration of the DP rods in the core (the basis from Reference 5). Figure 4.6 shows average, normalized radial power

FIGURE 4.3. Impact of Operating Control Rod Position on Axial Power Profile,
Full Power = 2.0% Fuel, Exposure = 10,200.0 MWD/MT

FIGURE 4.4. Impact of Operating Control Rod Position on Axial Power Profile,
Full Power = 2.4% Fuel, Exposure = 10,200.0 MWD/MT

R - RR MANUAL REGULATING ROD
 D - DP SUPPLEMENTAL ROD
 U - USP PART LENGTH ROD
 L - LAR LOCAL AUTOMATIC REGULATING ROD
 A - AR AUTOMATIC REGULATING ROD
 V - VFM VERTICAL FLUX MONITOR

FIGURE 4.5. RBMK Core Map Post-Chernobyl Supplemental Absorbers Added

FIGURE 4.6. Impact of Post-Chernobyl Fixes on Radial Power Profiles, Full Power = 2.0% and 2.4% Fuel, Exposure = 10,200.0 MWD/MT

profiles across the core for 2.0% fuel without DP rods and 2.4% fuel with DP rods. Due to the presence of the 80 DP rods, the radial power profile for the 2.4% fueled core has several "peaks" and "valleys" across the reactor core. The DP rods are located in the "valleys" of the power profile. Additional calculations were performed to determine the total worth of the 80 DP rods. The results show that the total worth for the 80 DP rods is 41.2 mk or about 0.52 mk per DP rod.

4.4 Control Rod System Worth

A series of calculations were performed to determine the effects of higher fuel enrichment and the supplemental rods on the control rod system worth. The results as summarized in Table 4.2 show that the individual rod worths for the 2.0% and 2.4% fuel types are 0.44 and 0.41 mk, respectively. The rod worths are slightly lower (about 7%) for the 2.4% fuel due to a shift in the neutron spectrum toward a higher energy range (that is, a harder spectrum). The control rod absorber material, boron, has a lower efficiency for absorbing high energy neutrons than thermal neutrons. The table also shows that the presence of the supplemental absorbers has no effect on the rod worths (80 absorbers out of 1661 channels does not have a significant impact on the overall neutron energy spectrum).

TABLE 4.2. Control Rod System Worths

<u>Fuel Enrichment</u>	<u>Number of DP Rods</u>	<u>System Worth (mk)</u>	<u>Average Rod Worth (mk)</u>
2.0	0	93.2	0.44
2.4	0	87.0	0.41
2.4	80	87.3	0.41

The impact of this reduced rod system worth on reactor safety is expected to be minimal.

One operational aspect affected by this change in rod worth is the number of additional control rods required to compensate for the increased fuel enrichment. The reactivity balance shown in Table 4.1 is based on the Soviet reported rod worth of 0.5 mk per rod. Using this value, the reactivity balance shows approximately 25 additional controls rods are needed. Using the 0.41 mk per rod value calculated here, 30 rods are required for reactivity balance. In practice, differences in individual rod worths can be large enough such that proper selection of control rods can eliminate the need for 5 additional rods.

5.0 XENON TRANSIENT ANALYSES

Interaction between xenon fission product buildup and the changes in the neutron flux distribution that accompanies local reactivity changes can lead to spatial oscillations in the power distribution in a large thermal reactor core. Such power oscillations can cause severe distortions in the power distribution. Early RBMKs were known to exhibit xenon oscillation instabilities. As a result, the graphite moderator density was reduced and the fuel enrichment was increased in an effort to reduce the over-moderation. The xenon oscillations can be controlled by control rod motion, but such control rod adjustments could impact total reactor power and efficiency and reduce overall safety.

Xenon stability is usually not a problem for reactors with strong negative reactivity feedbacks. For large power reactors with positive reactivity feedbacks, such as Soviet RBMK and early Hanford graphite moderated reactors, xenon oscillations could present serious operating control problems. Some of the Hanford reactors encountered severe xenon stability problems such that the reactors had to be shutdown to eliminate the power fluctuations. The Soviets have published several articles⁶⁻⁸ on the effects of power distributions, reactivity coefficients, and other neutronic parameters on the stability of the RBMK reactors. A series of calculations were performed to investigate the impact of the modifications on power stability.

The xenon stability analysis was performed using the quasi-static method. This method is based on the assumption that the neutron fluxes remain constant over a specified time interval. The fluxes are recalculated at the end of each time step. A two-hour time interval was used based on past experience modelling Hanford graphite moderated reactors. The calculations were performed as follows:

1. Run a steady-state step at full power

2. Withdraw a group of control rods from the middle or side of the reactor core
3. Run many time steps with constant reactor power to allow xenon and iodine distributions to oscillate throughout the reactor core

Four cases were considered:

1. Case 1 - reactor core with 2.0% fuel with the middle group of four control rods withdrawn to initiate the xenon oscillation
2. Case 2 - reactor core with 2.4% fuel with the middle group of four control rods withdrawn (DP rods included)
3. Case 3 - reactor core with 2.0% fuel with the side group of three control rods withdrawn
4. Case 4 - reactor core with 2.4% fuel with the side group of three control rods withdrawn (DP rods included)

Figures 5.1 and 5.2 summarize the results of the calculations. The detailed radial power distributions for each time step are given in Appendices A and B. The power profiles in Figures 5.1 and 5.2 show the maximum radial peaking as a function of time. These peaking factors do not necessarily occur at the same fuel channel location. Both figures show that the power profiles level off faster for the 2.4% fueled core than the 2.0% fueled core. Both figures also show that the time dependent power profiles are flatter for the 2.4% case than for the 2.0% relative to the beginning-of-transient values of each. The improved damping effect and flatter time dependent peaking indicate that the 2.4% core with the DP rods is more stable than the 2.0% core.

The xenon transients were modeled over a period of time without reactor operator intervention. The initial transients during the first few hours after the rod pull exceed normal operating limits. It is likely that the operators would act before the power distortions exceed these limits.

FIGURE 5.1. Impact of Initial Uranium Enrichment on Xenon Stability, Center Rod Group Withdrawn

FIGURE 5.2. Impact of Initial Uranium Enrichment on Xenon Stability, Side Rod Group Withdrawn

6.0 CONCLUSIONS

In general, the modifications have improved the safety of the RBMK reactor. The positive void reactivity coefficient is reduced by increasing the fuel enrichment from 2.0 to 2.4 weight percent U-235, the control rod modification eliminates the positive power increase during initial rod insertion, and the core is more stable against xenon oscillations. The control rod system worth is slightly reduced with higher fuel enrichment, however, the change is small.

The 80 supplemental absorbers combined with increased use of existing operational control rods effectively maintains the overall core reactivity margin within acceptable limits. The extra supplemental absorbers have no effect on the control rod system worth.

Lengthening the connecting link between the control rod and the graphite follower eliminates the possibility of positive reactivity insertion during reactor scram. However, the added water region acts as a poison in the control rod channel and some degree of axial power distortion still occurs at the top of the reactor which may limit reactor power.

With respect to xenon transients, the 2.4% enriched core with 80 supplemental absorbers has improved power damping effects and a flatter time dependent power peaking than the 2.0% enriched core.

7.0 REFERENCES

1. Asmolov, V.G., et. al, "Chernobyl Nuclear Power Plant Accident: One Year Later", Paper presented at International Conference on Indices and Safety of Nuclear Power, Vienna IAEA, September 1987.
2. Askew, J.R., et al, "A General Description of the Lattice Code WIMS," JBNES, October 1966.
3. Emel'yanov, I. Ya, et al., "Physical Startup of the RBMK Reactor of Second Unit of the V.I. Lenin Nuclear Power Station, Leningrad," Atomnaya Energiya, Vol. 40, No. 2, pp. 127-132, February 1976.
4. Dollezhal', N.A. and Yemel'yanov, I. Ya, "Channel Nuclear Energy Reactor," Izdatel'stvo Atomizdat 1980.
5. Emel'yanov, I. Ya, et al., "Power Distribution Monitoring and Control for a RBMK Reactor," Atomnaya Energiya, Vol. 48, No. 6, pp. 360-365, June 1980.
6. Budnikov, V.I., et al., "Stability for the Radial and Azimuthal Energy Distribution in a Boiling Water Reactor," Atomnaya Energiya, Vol. 45, No. 5, pp. 331-335, November 1978.
7. Emel'yanov, I. Ya, et al., "Effects of Neutron Distribution Pattern on the Stability of a Power Reactor," Atomnaya Energiya, Vol. 48, No. 5, pp. 301-303, May 1980.
8. Emel'yanov, I. Ya, et al., "Effect of the Shape of the Height Distribution of Neutrons on the Stability of a Reactor to Xenon Oscillations," Atomnaya Energiya, Vol. 50, No. 6, pp. 385-387, June 1981.
9. Meriwether, G.H., Skeen, D.R., Erickson, D.G., "Development and Applications of Core Simulator for Hanford N Reactor," Trans. Am. Nucl. Soc., 53, 462 (1986).

APPENDIX A

XENON TRANSIENTS RADIAL POWER DISTRIBUTION FOR 2.0% AND
2.4% FUEL FOLLOWING WITHDRAWAL OF A CENTRAL ROD GROUP

APPENDIX A

XENON TRANSIENTS RADIAL POWER DISTRIBUTION FOR 2.0% AND 2.4% FUEL FOLLOWING WITHDRAWAL OF A CENTRAL ROD GROUP

LEGEND

0 = power peaking < 0.75
+ = 0.75 power peaking < 1.2
2 = 1.2 power peaking < 1.3
3 = 1.3 power peaking < 1.4
4 = 1.4 power peaking < 1.5
5 = 1.5 power peaking < 1.6
6 = 1.6 power peaking < 1.7
7 = 1.7 power peaking < 1.8
8 = 1.8 power peaking < 1.9
9 = 1.9 power peaking < 2.0
X = power peaking 2.0

2.0% ENRICHMENT

STEP - 1

TIME - 0.0 HRS

MAX RADIAL PEAKING - 1.28

2.4% ENRICHMENT

STEP - 1

TIME - 0.0 HRS

MAX RADIAL PEAKING - 1.38

2.4% ENRICHMENT

STEP - 2

TIME - 0.0 HRS

MAX RADIAL PEAKING - 1.80

2.0% ENRICHMENT

STEP - 2

TIME - 0.0 HRS

MAX RADIAL PEAKING - 1.89

2.4% ENRICHMENT

STEP - 4

TIME - 4.0 HRS

MAX RADIAL PEAKING - 1.81

2.0% ENRICHMENT

STEP - 4

TIME - 4.0 HRS

MAX RADIAL PEAKING - 2.03

2.4% ENRICHMENT

STEP - 5

TIME - 6.0 HRS

MAX RADIAL PEAKING - 1.80

2.0% ENRICHMENT

STEP - 5

TIME - 6.0 HRS

MAX RADIAL PEAKING - 1.99

2.4% ENRICHMENT
 STEP - 6
 TIME - 8.0 HRS
 MAX RADIAL PEAKING - 1.77

2.0% ENRICHMENT
 STEP - 6
 TIME - 8.0 HRS
 MAX RADIAL PEAKING - 1.93

2.4% ENRICHMENT
 STEP - 7
 TIME - 10.0 HRS
 MAX RADIAL PEAKING - 1.75

2.0% ENRICHMENT
 STEP - 7
 TIME - 10.0 HRS
 MAX RADIAL PEAKING - 1.85

2.4% ENRICHMENT
 STEP - 10
 TIME - 16.0 HRS
 MAX RADIAL PEAKING - 1.67

2.0% ENRICHMENT
 STEP - 10
 TIME - 16.0 HRS
 MAX RADIAL PEAKING - 1.63

2.4% ENRICHMENT
 STEP - 12
 TIME - 20.0 HRS
 MAX RADIAL PEAKING - 1.64

2.0% ENRICHMENT
 STEP - 12
 TIME - 20.0 HRS
 MAX RADIAL PEAKING - 1.53

2.4% ENRICHMENT
 STEP - 13
 TIME - 22.0 HRS
 MAX RADIAL PEAKING - 1.63

2.0% ENRICHMENT
 STEP - 13
 TIME - 22.0 HRS
 MAX RADIAL PEAKING - 1.49

2.4% ENRICHMENT
 STEP - 14
 TIME - 24.0 HRS
 MAX RADIAL PEAKING - 1.63

2.0% ENRICHMENT
 STEP - 14
 TIME - 24.0 HRS
 MAX RADIAL PEAKING - 1.47

2.4% ENRICHMENT
 STEP - 15
 TIME - 26.0 MRS
 MAX RADIAL PEAKING - 1.62

2.0% ENRICHMENT
 STEP - 15
 TIME - 26.0 MRS
 MAX RADIAL PEAKING - 1.45

2.4% ENRICHMENT
 STEP - 16
 TIME - 28.0 HRS
 MAX RADIAL PEAKING - 1.62

2.0% ENRICHMENT
 STEP - 16
 TIME - 28.0 HRS
 MAX RADIAL PEAKING - 1.44

2.4% DRIORIENT

STEP - 17

TIME - 30.0 HRS

MAX RADIAL PEAKING - 1.62

2.0% DRIORIENT

STEP - 17

TIME - 30.0 HRS

MAX RADIAL PEAKING - 1.44

2.4% ENRICHMENT
 STEP - 18
 TIME - 32.0 HRS
 MAX RADIAL PEAKING - 1.62

2.0% ENRICHMENT
 STEP - 18
 TIME - 32.0 HRS
 MAX RADIAL PEAKING - 1.44

APPENDIX B

**XENON TRANSIENTS RADIAL POWER DISTRIBUTION FOR 2.0% AND
2.4% FUEL FOLLOWING WITHDRAWAL OF A SIDE ROD GROUP**

APPENDIX B

XENON TRANSIENTS RADIAL POWER DISTRIBUTION FOR 2.0% AND 2.4% FUEL FOLLOWING WITHDRAWAL OF A SIDE ROD GROUP

LEGEND

0 = power peaking < 0.75
+ = 0.75 power peaking < 1.2
2 = 1.2 power peaking < 1.3
3 = 1.3 power peaking < 1.4
4 = 1.4 power peaking < 1.5
5 = 1.5 power peaking < 1.6
6 = 1.6 power peaking < 1.7
7 = 1.7 power peaking < 1.8
8 = 1.8 power peaking < 1.9
9 = 1.9 power peaking < 2.0
X = power peaking 2.0

2.0% ENRICHMENT

STEP - 1

TIME - 0.0 HRS

MAX RADIAL PEAKING - 1.27

2.4% ENRICHMENT

STEP - 1

TIME - 0.0 HRS

MAX RADIAL PEAKING - 1.37

2.0% ENRICHMENT

STEP - 2

TIME - 0.0 HRS

MAX RADIAL PEAKING - 1.33

2.4% ENRICHMENT

STEP - 2

TIME - 0.0 HRS

MAX RADIAL PEAKING - 1.63

2.4% ENRICHMENT

STEP - 3

TIME - 2.0 HRS

MAX RADIAL PEAKING - 1.72

2.0% ENRICHMENT

STEP - 3

TIME - 2.0 HRS

MAX RADIAL PEAKING - 1.44

2.4% ENRICHMENT

STEP - 4

TIME - 4.0 HRS

MAX RADIAL PEAKING - 1.73

2.0% ENRICHMENT

STEP - 4

TIME - 4.0 HRS

MAX RADIAL PEAKING - 1.47

2.0% ENRICHMENT

STEP - 5

TIME - 6.0 HRS

MAX RADIAL PEAKING - 1.49

2.4% ENRICHMENT

STEP - 5

TIME - 6.0 HRS

MAX RADIAL PEAKING - 1.73

2.0% ENRICHMENT

STEP - 6

TIME - 8.0 HRS

MAX RADIAL PEAKING - 1.51

2.4% ENRICHMENT

STEP - 6

TIME - 8.0 HRS

MAX RADIAL PEAKING - 1.71

2.4% ENRICHMENT
 STEP - 7
 TIME - 10.0 HRS
 MAX RADIAL PEAKING - 1.70

2.0% ENRICHMENT
 STEP - 7
 TIME - 10.0 HRS
 MAX RADIAL PEAKING - 1.52

2.4% ENRICHMENT

STEP - 8

TIME - 12.0 HRS

MAX RADIAL PEAKING - 1.67

2.0% ENRICHMENT

STEP - 8

TIME - 12.0 HRS

MAX RADIAL PEAKING - 1.52

2.4% ENRICHMENT
 STEP - 9
 TIME - 14.0 HRS
 MAX RADIAL PEAKING - 1.65

2.0% ENRICHMENT
 STEP - 9
 TIME - 14.0 HRS
 MAX RADIAL PEAKING - 1.52

2.4% ENRICHMENT

STEP - 10

TIME - 16.0 HRS

MAX RADIAL PEAKING - 1.62

2.0% ENRICHMENT

STEP - 10

TIME - 16.0 HRS

MAX RADIAL PEAKING - 1.51

2.4% ENRICHMENT

STEP - 11

TIME - 18.0 HRS

MAX RADIAL PEAKING - 1.59

2.0% ENRICHMENT

STEP - 11

TIME - 18.0 HRS

MAX RADIAL PEAKING - 1.51

2.4% ENRICHMENT
 STEP - 12
 TIME - 20.0 HRS
 MAX RADIAL PEAKING - 1.57

2.0% ENRICHMENT
 STEP - 12
 TIME - 20.0 HRS
 MAX RADIAL PEAKING - 1.50

2.4% ENRICHMENT
 STEP - 13
 TIME - 22.0 HRS
 MAX RADIAL PEAKING - 1.55

2.0% ENRICHMENT
 STEP - 13
 TIME - 22.0 HRS
 MAX RADIAL PEAKING - 1.48

2.4% ENRICHMENT
 STEP - 14
 TIME - 24.0 HRS
 MAX RADIAL PEAKING - 1.53

2.0% ENRICHMENT
 STEP - 14
 TIME - 24.0 HRS
 MAX RADIAL PEAKING - 1.47

2.4% ENRICHMENT
 STEP - 15
 TIME - 26.0 HRS
 MAX RADIAL PEAKING - 1.52

2.0% ENRICHMENT
 STEP - 15
 TIME - 26.0 HRS
 MAX RADIAL PEAKING - 1.46

2.0% ENRICHMENT

STEP - 16

TIME - 28.0 HRS

MAX RADIAL PEAKING - 1.44

2.4% ENRICHMENT

STEP - 16

TIME - 28.0 HRS

MAX RADIAL PEAKING - 1.50

2.0% ENRICHMENT

STEP - 18

TIME - 32.0 HRS

MAX RADIAL PEAKING - 1.41

2.4% ENRICHMENT

STEP - 18

TIME - 32.0 HRS

MAX RADIAL PEAKING - 1.49

2.4% ENRICHMENT
 STEP - 19
 TIME - 34.0 HRS
 MAX RADIAL PEAKING - 1.48

2.0% ENRICHMENT
 STEP - 19
 TIME - 34.0 HRS
 MAX RADIAL PEAKING - 1.39

2.0% ENRICHMENT

STEP - 21

TIME - 38.0 HRS

MAX RADIAL PEAKING - 1.35

2.4% ENRICHMENT

STEP - 21

TIME - 38.0 HRS

MAX RADIAL PEAKING - 1.48

2.0% ENRICHMENT

STEP - 23

TIME - 42.0 HRS

MAX RADIAL PEAKING - 1.31

2.4% ENRICHMENT

STEP - 23

TIME - 42.0 HRS

MAX RADIAL PEAKING - 1.48

2.0% ENRICHMENT

STEP - 24

TIME - 44.0 HRS

MAX RADIAL PEAKING - 1.30

2.4% ENRICHMENT

STEP - 24

TIME - 44.0 HRS

MAX RADIAL PEAKING - 1.48

2.0% ENRICHMENT

STEP - 25

TIME - 46.0 HRS

MAX RADIAL PEAKING - 1.29

2.4% ENRICHMENT

STEP - 25

TIME - 46.0 HRS

MAX RADIAL PEAKING - 1.48

2.4% ENRICHMENT
 STEP - 26
 TIME - 48.0 HRS
 MAX RADIAL PEAKING - 1.48

2.0% ENRICHMENT
 STEP - 26
 TIME - 48.0 HRS
 MAX RADIAL PEAKING - 1.29

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