MODIFICATIONS FOR BETTER CONTROL OF THE FIRST RADIAL MODE DURING LOAD-CYCLING OF THE ACR-1000

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Abstract

A load-cycling capability of the ACR-1000™[1] is an attractive feature of the new reactor. Changing the reactor power from 100% FP to a lower value and then returning back to full power is challenging, from a control point of view, because of the xenon transient induced and the flux perturbations that occur due to control rod movements.

New control logic in addition to the Reactor Regulation System algorithm was developed for the load-cycling transient. It is based on a newly introduced Radial Overpower Tilt Parameter (ROTP) as a measure of how much the first radial mode is excited due to transient reactivity disturbances in the core. The control algorithm is designed to reduce bundle and channel overpowers, (i.e., flattening the neutron flux) during load following operations by holding the ROTP close to unity as much as possible.

1. Introduction

The currently operating nuclear power plants were designed for base-load operation, due mainly to their high capital cost and relatively low fuel cost. However, for the ACR-1000, a load-cycling capability could prove to be an attractive additional feature. Changing the reactor power from 100% FP to lower value and then returning back to full power is challenging, from a control point of view, because of the xenon transient induced and the flux perturbations that occur due to control rod movements. The main features of the ACR-1000 are described in Reference 1.

To improve flux flattening at the center of the reactor core, the ACR-1000 design implements zone controllers that overlap in the center of the core. For better utilization of this increased flux flattening capability, a new control algorithm additional to Reactor Regulation System and based on control of a Radial Overpower Tilt Parameter (ROTP) was introduced. The ROTP is a measure of how much the first radial flux mode is excited due to transient reactivity disturbances in the core. For an unperturbed core its value should be 1.00 (see Section 2.2). The presented control algorithm is designed to reduce bundle and channel overpowers during load cycling operations by keeping the ROTP close to unity as much as possible.

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2. Methodology

The load transient analysed in this paper is Bruce Load Following (BLF), where the reactor power is steadily reduced from 100 %FP to 75 %FP in a 3 hour time interval; it stays at 75 %FP for 7 hours and then returns back to 100% FP in 3 hours. The zone controllers for the ACR-1000 are designed to move vertically from the top and the bottom of the reactor into or out of the centre of the core. This movement tends to excite the first radial flux mode. Therefore, in transients where the zone controllers' positions change significantly (i.e., in the BLF transients), larger overpowers result ("pinch" effect) if the radial flux tilt mode is not controlled, and xenon feedback excitation of the first radial mode is allowed to grow unchecked. To define the effect of device movement on the radial flux tilt mode better, a Radial Overpower Tilt Parameter (ROTP) was introduced.

The computer code RFSP, release REL_3-04HP [Reference 2], has been used to simulate the reactor power cycling. All simulations were performed with SIMULATE module including fuel temperature feedback. The flux tilt and bulk power control scheme currently implemented in RFSP for the ACR core was used throughout these simulations. No changes were made to this scheme, where the active set of zone controllers ("grey" rods) is used for flux tilt control and bulk reactivity control. The control of the ROTP parameter was introduced by manipulating the additional two sets of zone control rods not involved in active flux tilt and bulk power control (the "black" and "white" rods; "black" rods are nominally fully inserted, "white" rods are nominally out of core). The minimization of the ROTP parameter was implemented through logic external to the RFSP computer program while keeping the "grey" rods (nominally inserted by 50%) within an acceptable control range as determined by the RFSP control algorithm.

2.1 Assumptions

The following assumptions are made:

- The ACR-1000 reactor core was empirically divided in radial direction into inner and outer regions based on the radial overpower changes observed during BLF transient without ROTP control.
- The inner region has a simplified square shape.
- The BLF transient starts from a nominal time average reactor core.
- A 15-minute time step for simulating the BLF transient was chosen.
- If the "grey" control rods have average insertion between 25 % and 75 % , a constant insertion of the "white" and "black" zone controllers for ROTP control is assumed. The insertion is 1% for the black rods and 2% for the white rods over the 15-minute time step for the simulations. The different insertions reflect the different number of "black" and "white" rods.
- If the "grey" zone controllers have less then 25 % or more then 75 % average insertion, the "white" or "black" rods are moved in 10 % step increments over the 15 minutes in a direction to bring the "grey" rods back into their active control range.

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2.2 Radial Overpower Tilt Parameter – Definition

The Radial Overpower Tilt Parameter is defined as ratio of the average channel overpowers in the inner and outer regions of the core. The inner region is defined as all channels between (G, T) and (7, 19) (see Figure 1). Therefore ROTP is calculated as:

$$ROTP = \frac{\sum_{1}^{144} OCPi/144}{\sum_{1}^{376} OCPj/376}, \qquad (1)$$

where OCP_i is the overpower of the i_{th}-channel of the 144 inner zone channels, (i. e. $OCP_i = CP_{ti}/CP_{ri}$, where CP_{ti} is the transient channel power for channel i, and the CP_{ri} is the reference channel power for channel i, both normalized to the same reactor power). A value of 1.0 for ROTP means that there is no net excitation of the 1st radial neutron flux mode.

The reactor core was empirically divided in radial direction into these two regions based on the radial overpower changes observed during BLF transients without ROTP control. A "pulsing" overpower behaviour was observed between the peripheral and central parts of the core.

A small radial overpower tilt is defined as a flux tilt having values of ROTP $\in$ [0.995, 1.005] This interval defines a "dead band" where no control action is needed to minimize the radial overpower tilt. A big radial overpower tilt is tilt outside the "dead bend" and the control rods should be moved accordingly to reduce it.

It is proposed that the ROTP be calculated online by the RRS program using information of the channel power distribution from the on line flux map program for the ACR-1000 RRS.

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	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26
A											1.01	1.01	1.01	1.01	1.01	1.01										
B								1.01	1.01	1.01	1.01	1.01	1.01	1.01	1.01	1.01	1.01	1.01	1.01							
C							1.01	1.01	1.01	1.01	1.01	1.01	1.01	1.01	1.01	1.01	1.01	1.01	1.01	1.01						
D						1.01	1.01	1.01	1.01	1.01	1.01	1.01	1.01	1.01	1.01	1.01	1.01	1.01	1.01	1.01	1.01					
E				1.00	1.01	1.01	1.01	1.01	1.01	1.01	1.01	1.01	1.01	1.01	1.01	1.01	1.01	1.01	1.01	1.01	1.01	1.01	1.01			
F				1.00	1.00	1.01	1.01	1.01	1.01	1.01	1.01	1.01	1.01	1.01	1.01	1.01	1.01	1.01	1.01	1.01	1.01	1.01	1.01			
G			1.00	1.00	1.00	1.00	1.01	1.01	1.01	1.01	1.01	1.01	1.01	1.01	1.01	1.01	1.01	1.01	1.01	1.01	1.01	1.01	1.00	1.00		
H		1.00	1.00	1.00	1.00	1.00	1.00	1.01	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.01	1.00	1.01	1.00	1.00	1.00	1.00	
J		1.00	1.00	1.00	1.00	1.00	0.99	0.99	1.00	0.99	0.99	0.99	1.00	1.00	0.99	0.99	1.00	1.00	0.99	1.00	1.00	1.00	1.00	1.00	1.00	
K		1.00	1.00	1.00	1.00	0.99	0.99	0.99	0.99	0.99	0.99	0.99	0.99	0.99	0.99	0.99	0.99	0.99	0.99	0.99	1.00	1.00	1.00	1.00	1.00	
L	1.00	1.00	1.00	1.00	1.00	0.99	0.99	0.99	0.99	0.99	0.99	0.99	0.99	0.99	0.99	0.99	0.99	0.99	0.99	0.99	0.99	1.00	1.00	1.00	1.00	1.00
M	1.00	1.00	1.00	1.00	0.99	0.99	0.99	0.99	0.99	0.99	0.99	0.99	0.99	0.99	0.99	0.99	0.99	0.99	0.99	0.99	0.99	1.00	1.00	1.00	1.00	1.00
N	1.00	1.00	1.00	0.99	0.99	0.99	0.99	0.99	0.99	0.99	0.99	0.99	0.99	0.99	0.99	0.99	0.99	0.99	0.99	0.99	0.99	1.00	1.00	1.00	1.00	1.00
O	1.00	1.00	1.00	0.99	0.99	0.99	0.99	0.99	0.99	0.99	0.99	0.99	0.99	0.99	0.99	0.99	0.99	0.99	0.99	0.99	0.99	1.00	1.00	1.00	1.00	1.00
P	1.00	1.00	1.00	1.00	0.99	0.99	0.99	0.99	0.99	0.99	0.99	0.99	0.99	0.99	0.99	0.99	0.99	0.99	0.99	0.99	0.99	0.99	1.00	1.00	1.00	1.00
Q	1.00	1.00	1.00	0.99	0.99	0.99	0.99	0.99	0.99	0.99	0.99	0.99	0.99	0.99	0.99	0.99	0.99	0.99	0.99	0.99	0.99	1.00	1.00	1.00	1.00	1.00
R		1.00	1.00	1.00	0.99	0.99	0.98	0.99	0.99	0.99	0.98	0.99	0.99	0.99	0.99	0.99	0.99	0.99	0.99	0.99	1.00	1.00	1.00	1.00	1.00	
S		1.00	1.00	1.00	1.00	0.99	0.99	0.99	1.00	0.99	0.99	0.99	0.99	0.99	0.99	0.99	0.99	1.00	0.99	0.99	1.00	1.00	1.00	1.00	1.00	
T		1.00	1.00	1.00	1.00	1.00	1.00	1.01	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.01	1.00	1.00	1.00	1.00	1.00	1.00	
U			1.00	1.00	1.00	1.00	1.01	1.01	1.01	1.01	1.01	1.01	1.01	1.01	1.01	1.01	1.01	1.01	1.01	1.01	1.01	1.00	1.00	1.00		
V				1.00	1.00	1.01	1.00	1.01	1.01	1.01	1.01	1.01	1.01	1.01	1.01	1.01	1.01	1.01	1.01	1.01	1.01	1.00	1.00			
W				1.00	1.01	1.01	1.00	1.00	1.01	1.01	1.01	1.01	1.01	1.01	1.01	1.01	1.01	1.01	1.01	1.01	1.01	1.01	1.00			
X						1.01	1.00	1.01	1.01	1.01	1.01	1.01	1.01	1.01	1.01	1.01	1.01	1.01	1.01	1.00	1.01					
Y							1.00	1.00	1.01	1.01	1.01	1.01	1.01	1.01	1.01	1.01	1.01	1.01	1.01	1.01						
Z								1.01	1.01	1.01	1.01	1.01	1.01	1.01	1.01	1.01	1.01	1.01	1.01							
[											1.01	1.01	1.01	1.01	1.01	1.01										

Figure 1: Inner and outer regions used in the ROTP definition

2.3 Radial Tilt Control Algorithm

Spatial neutron flux tilt control is performed for the ACR-1000 by changing of the insertion of the individual grey zone controllers so the power in the individual zones matches the target power value. In addition bulk reactivity control is accomplished by changing all the grey zone controller level uniformly to keep reactor power constant at the required reactor power setpoint. During strong reactivity transients the requirement for maintaining bulk reactivity control could drive the grey rods out of their designed control range which has been set at between 25 % and 75 % average insertion. When this occurs additional negative or positive or bulk reactivity will be introduced by either moving the additional two sets of control rods (the “black” or the “white” rods) in or out of the core.

A study was performed to analyse the effect of the movements on the “black” and “white” rods on the channel overpower. Figures 2, 3 and 4 show the change of the reactor overpowers along the Y-axis with the variation of the insertion of the control rods (grey, white and black). The study is performed with spatial and bulk control “off” and only one set of rods is moved. The results were further processed to calculate the ROTP for each level of insertion and they are plotted on Figure 5. As it can be seen there is a level of insertion for each set of control rods where the overpower (i.e. “pinch” effect) is largest. It is around 50% insertion for the black and white rods and ~100% for the grey ones.

This dependence of the ROTP on the insertion of the black or white rods is the foundation of the decision logic applied when an insertion change has to be made.

The implementation logic for radial overpower tilt control is shown as a decision matrix in Table 1. In the case when the grey rod AZCL is ≤ 25% or grey rod AZCL ≥ 75%, the *Bulk Control* part of the logic is executed and the black and white rods are moved to compensate for the grey zones reaching the limits of their bulk control range (25, 75) % independently on the value of the ROTP.

In the case where the AZCL is between (25, 75)% and the value of ROTP is between (0.995, 1.005) (i.e., *Small Radial Tilt*) no action is required. If ROTP is outside (99.5, 100.5)% interval (i.e., *Big Radial Tilt*) the white and black rods are moved in a way to reduce the value of the ROTP.

Table 1, should be read in the following way: each cell in the last row of the table presents an action (movements of the black or white rods) that is a result of applying of all core conditions given in the column above this cell.

According to design requirements there is a priority in moving the "black" and the "white" sets of control rods. The" black" rods can move only when the "white" rods are outside the core (i.e. if the insertion if the "black" rods is $0\% \leq BR < 100\%$ then the "white" rods' insertion is $WR = 0\%$)

The "white" rods could be moved only when the black rods are 100% in the core (if the insertion of the "white rods" is $WR \geq 0\%$, the insertion of the "black" rods" is 100%.)

3. Results

Application of this control logic to the 13-hour Bruce Load Following transient shows a reduction of the maximum channel power at the end of the transient of ~5%, compared with simulations that are performed without the ROTP. The simulations started from a time-average core. A longer 3-day transient that mimics the load reduction to 75 %FP at the end of each day and the corresponding return to full power in the morning was simulated as well. The longer transient shows a clear periodic structure similar to the 13-hour transient.

4. Conclusion

The Bruce Load Following transient is a challenging cycle to control because of the steep power reduction/increase for relatively short time periods and the associated xenon excitations and rod movements. A controlled BLF cycle was achieved with an ACR-1000 reactor core with overlapping control rods and with a new radial overpower tilt parameter. The new control parameter reduces the maximum channel and bundle powers at the end of the BLF cycle and thus the transient can be executed.

The work done shows that the "pinch" effect of the insertion of the "white" and "black" control rods during BLF transient is directly related to the radial overpower tilt parameter. A strong correlation between radial overpower tilt parameter and the maximum channel power was found as well. Therefore, an optimized way of insertion of the "black" and "white" control rods that reduces the overpower tilt parameter leads to lower channel and bundle powers not only during the transient, but also after the transient because secondary spatial xenon transients in the first radial flux mode are suppressed. The rate and the distance the "white" and "black" zone control rods were moved during the BLF transient were selected in an empirical way and can be further optimized.

6. References

[1] A. Buijs, M. Bonechi, P.S.W. Chan and M. Ovanes, "Optimizing the ACR-1000 Core for Safety, Economics and Reliability", Proceedings of the European Nuclear Conference 2007, 16-20 September 2007, Brussels.

[2] B. Rouben, "RFSP-IST, The Industry Standard Tool Computer Program for CANDU Reactor Core Design and Analysis", in Proceedings of the 13th Pacific Basin Nuclear Conference, Shenzhen, China, 2002 October

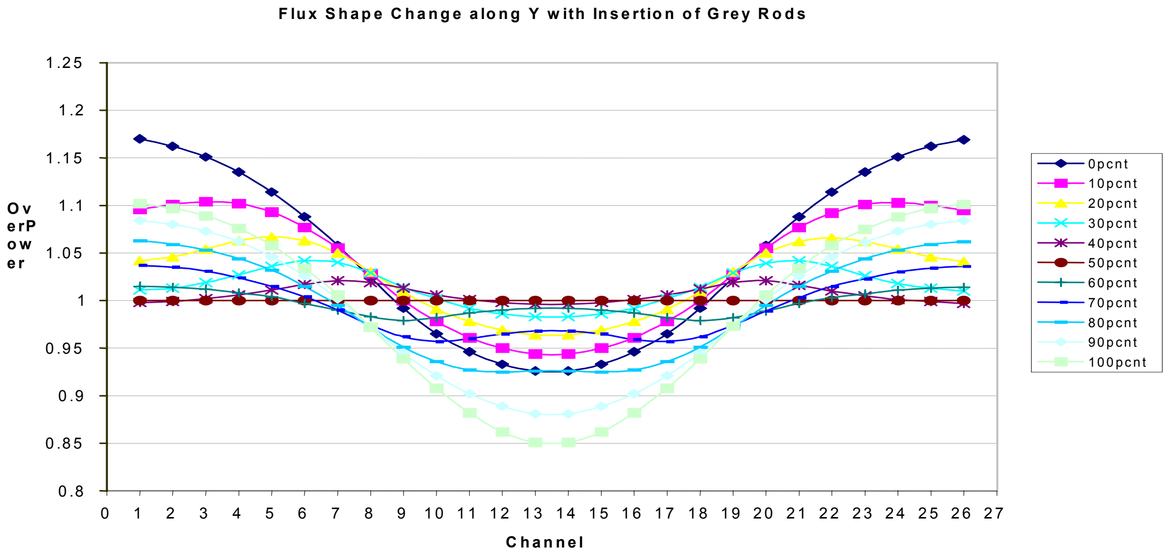

Figure 2: Flux Shape Along Y with Grey Rod Insertion

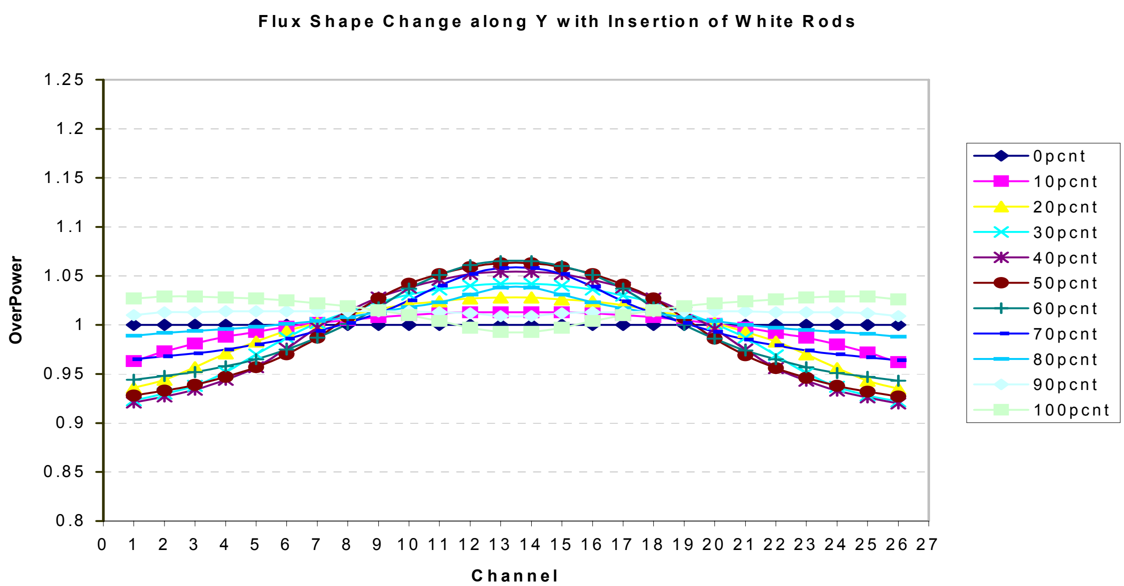

Figure 3: Flux Shape Along Y with White Rod Insertion

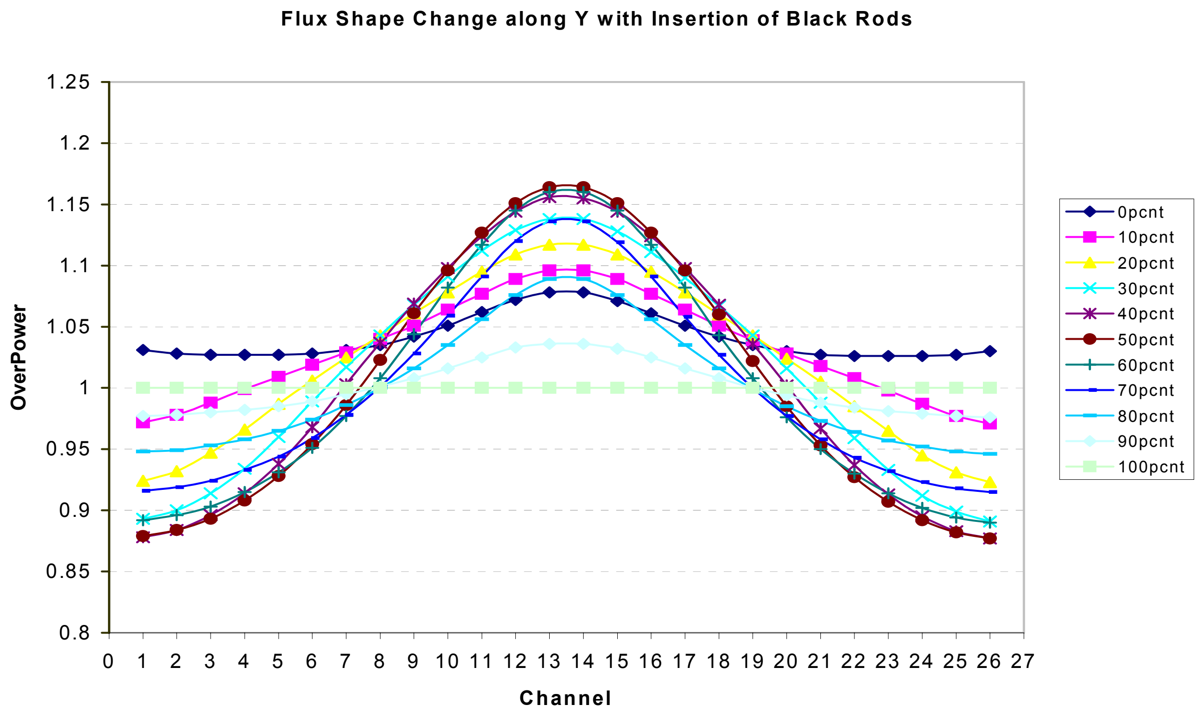

Figure 4: Flux Shape along Y with Black Rod Insertion

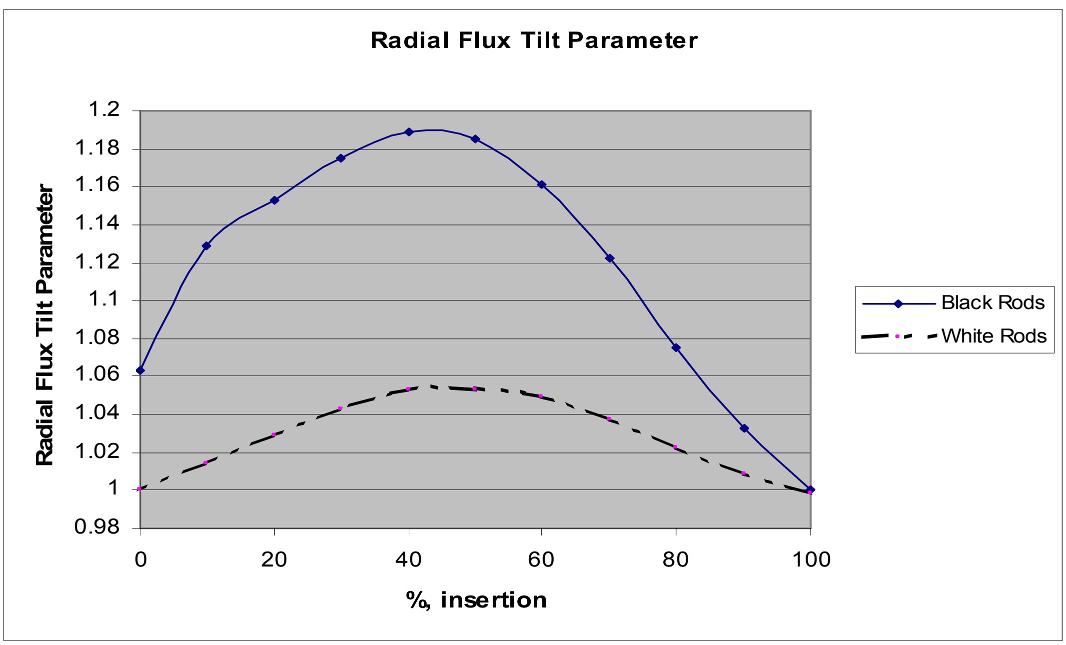

Figure 5: Radial Flux Tilt Parameter Change with Control Rods Insertion

<table>
<tr><td colspan="4">AZCL ≥ 25%</td><td colspan="4">AZCL ≥ 75%</td></tr>
<tr><td>WR ≥10%</td><td>0<WR< 10%</td><td colspan="2">WR = 0%</td><td>BR ≤ 90%</td><td>90% <BR < 100%</td><td colspan="2">BR = 100%</td></tr>
<tr><td></td><td></td><td>BR< 10%</td><td>BR≥10%</td><td></td><td></td><td>WR≤90%</td><td>WR>90%</td></tr>
<tr><td>WR=WR–10%
BR=NC</td><td>WR=0%
BR=NC</td><td>WR=NC
BR=0%</td><td>WR=NC
BR=BR– 10%</td><td>WR=NC
BR=BR+10%</td><td>WR=NC
BR=100%</td><td>WR=WR+10%
BR=NC</td><td>WR=
100%
BR=NC</td></tr>
</table>

<table>
<tr><td colspan="13">25% < AZCL < 75%</td></tr>
<tr><td>0.995 ≤ ROTP
≤ 1.005</td><td colspan="5">ROTP < 0.995</td><td colspan="7">ROTP > 1.005</td></tr>
<tr><td></td><td>0≤ BR<
50%</td><td>50%≤ BR<
100%</td><td colspan="3">BR = 100%</td><td>BR=
0%</td><td>0< BR<
50%</td><td>50%≤BR<100%</td><td colspan="4">BR = 100%</td></tr>
<tr><td></td><td></td><td></td><td>WR = 0%</td><td>0 < WR < 50%</td><td>50 ≤WR
≤100%</td><td></td><td></td><td></td><td>WR = 0</td><td>0< WR <
50%</td><td>50%< WR <
100%</td><td>WR=
100%</td></tr>
<tr><td>WR=NC
BR=NC</td><td>WR=NC
BR=BR
+1%</td><td>WR=NC
BR=BR –
1%</td><td>WR=NC
BR=BR –
1%</td><td>WR=WR+2%
BR=NC</td><td>WR=WR-2%
BR=NC</td><td>WR=NC
BR=NC*</td><td>WR=NC
BR=BR
-1%</td><td>WR=NC
BR=BR + 1%</td><td>WR=NC
BR=NC</td><td>WR=WR
-2%
BR = NC</td><td>WR=WR
+2%
BR = NC</td><td>WR=NC
BR=NC*</td></tr>
</table>

Table 1: Decision matrix for control rods movement based nn AZCL And ROTP

Note * in the Table means that there is not enough reactivity for controlling the transient
AZCL = Average Grey Rod Zone Control Level
WR ≡ White Rods Average Position
BR ≡ Black Rods Average Position **NC** ≡ No Change
ROTP ≡ Radial Flux Tilt Parameter
If the insertion if the "Black rods" is 0% ≤ BR < 100% then the "white" rods insertions are WR = 0%
If the insertion of the "White rods" is WR ≥ 0%, the insertion of the "Black" rods" is 100%.