Advances in the ACR-1000® Reactor Regulating System and Reactor Control

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Abstract

Advances in the control of the ACR-1000® reactor are presented. The ACR-1000 Reactor Regulating System's (RRS) capability to maintain reactor power at its set point, counteract zonal power deviations, initiate setback as required, and effectively control operational maneuvers including power load-cycling is demonstrated. Three fast core transients and a long Load Cycling transient are presented. For simulations of the fast transients a dynamic RRS Simulation Package (RRS_SP) was developed, where the core neutron kinetics calculations (*CERBERUS module of RFSP) were coupled to a thermal hydraulic code (CATHENA) at every time step. A quasi-static approach was used to demonstrate the RRS performance in the Load Cycling transient that covers five consecutive daily cycles followed by a 2-day weekend cycle.

1. Introduction

The new ACR-1000[1] design is a Generation III+ reactor design from AECL. It makes use of proven and successful features from the traditional CANDU[2] natural uranium reactor, such as at power refuelling, fuel bundles in pressure tubes, surrounded by a heavy water moderator tank. The ACR-1000 introduces evolutionary advances such as LEU fuel bundles with a centre poison pin, light water coolant, and solid reactor control rods. These advances are to improve safety, reliability and economic performance, particularly in the enhancement of fuel utilization.

The primary control devices for the ACR-1000 are solid control rods rather than the traditional CANDU light water filled control zones. The solid rod drive components and controllers are simpler and more reliable. However to accommodate the solid rods changes to the traditional CANDU control scheme, which was based on the liquid zone control compartments, are incorporated.

One of the fundamental design requirements and safety enhancements for the ACR-1000 is the incorporation of negative power reactivity feedback. Any increase in power from reactivity transients or control perturbations are opposed by the negative reactivity introduced from the increase in fuel temperature and consequent Doppler broadening of the neutron absorption peaks in the fuel. This makes the ACR-1000 more stable to asymmetric reactivity perturbations and control malfunctions.

One of the salient features of the enriched fuel used in the ACR is that for a given power level the thermal neutron flux is lower which results in a lower rate of xenon build-up

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[1] ACR-1000 (Advanced CANDU Reactor) is a registered trademark of Atomic Energy of Canada Limited (AECL)

[2] CANDU is a registered trademark of Atomic Energy of Canada Limited (AECL)

during power transients such as transients following start up after shut down and during power load cycling. Lower rate of xenon build-up results in enhanced manoeuvrability for load cycling and less poison out time during shutdown transients. For example after an unplanned shutdown transient the ACR reactor has up to 60 minutes before xenon poison-out occurs (typically 30 minutes for other CANDUs). In addition the total poison out time is 24 hours for the ACR as compared to about 48 hours for the CANDU natural uranium reactor. A week long load cycling transient and three fast core transients are presented in this paper.

2. ACR-1000 Reactor Regulating System

The ACR-1000 core design uses low enriched uranium fuel (LEU), light water (H_2O) coolant and heavy water (D_2O) as a moderator. The fuel channels are arranged in a square lattice array. Each channel has 12 fuel bundles. There are 43 pins in a fuel bundle. The 42 LEU fuel pins have an enrichment of 2.4 wt% U^{235} in total U. A small amount of gadolinium is mixed uniformly into the fuel elements to suppress the initial reactivity of the fresh bundles being inserted into the reactor and to limit the fuelling ripple. To reduce the coolant void reactivity the central pin of the fuel bundle does not contain fuel, but only burnable poison.

The ACR-1000 reactor regulating system includes a system of reactivity devices and power measurement modules, executed according to the RRS control logic.

The RRS control devices consist of eight pairs of “grey” rods (one pair per each reactor zone with both rods moving in synchrony), “black” rods (grouped in three banks, labelled as BB1 to BB3), “white” rods (grouped in 2 banks, labelled as WB1 and WB2), and control absorbers (grouped in two banks, labelled as CB1 and CB2). The rods in each bank are moving simultaneously. The “grey” rods are responsible for bulk and spatial power control during the normal operation of the reactor. The “black” rods are always in the core. They are used for flattening the flux at the center of the core and for providing additional positive reactivity when withdrawn from the core. The “white” rods and the control absorbers are normally outside the core and are used for providing additional negative reactivity during power manoeuvres or abnormal events. The RRS also withdraws the Shut-Off-Rods and Guaranteed Shutdown Rods from the core and adds poison to the moderator.

3. RRS Dynamic Model for Fast Transients

For very fast transient in the reactor core (of the order of seconds), the delayed neutrons lag behind the prompt neutrons. Therefore, an explicit treatment of these two neutron sources (prompt and delayed) has to be used for accurate flux calculations. Due to fast changes in the neutron flux/reactor power the core thermal-hydraulic properties are changing as well. Hence, time-dependent coupled neutronic and thermal-hydraulic simulations are performed for accurate analysis of the core condition.

For a more comprehensive assessment of the RRS functionalities and its dynamic response in fast transient scenarios, a RRS Simulation Package (RRS_SP) that models the

RRS actions in the time-domain has been developed. The RRS_SP is based on a Perl script, previously developed by I. Martchouk [2] with RRS functionality limited only to the “grey” rods. The extended RRS functionality includes the rest of the reactivity control devices: “black”, “white” rods and control absorbers grouped in corresponding banks. The RRS model is linked to the neutron kinetics calculations that provide data pertaining to the current core state i.e. what would be considered as “measurement data” for reactor power, zonal powers, in-core detector signals, rate of change of power, etc. The RRS model commands the device movements in response to the differences between the current and the desired core conditions, updates the device positions, and passes the new device configuration back to the neutronic calculation module. The RRS model also detects setback conditions in the core due to high flux tilt and acts accordingly to set up the power reduction rate and end-power to predefined values. The RRS also clears the setback when the setback condition does not exist any more. The currently modelled control logic cycle time is every 0.5 s.

The neutronic calculations are performed by the *CERBERUS module in RFSP [3], where the reactivity effects from changes in thermal hydraulic conditions and reactivity feedback from fuel temperature changes are taken into account through coupling to the thermal-hydraulic code CATHENA [4] at every time step. Xenon and other fission product evolutions arising from changing flux level and flux distribution are tracked. The updated flux/power distribution, power level and detector readings constitute the current “measured” core conditions, and they are monitored by the RRS as the basis for driving the control rods, or initiating power reduction as required. No delay in the detector response is modeled at this time, but will be included in the further revision of the RRS_SP.

3.1 Reactivity Device Movements

The ACR-1000 reactor core is divided into eight zones.

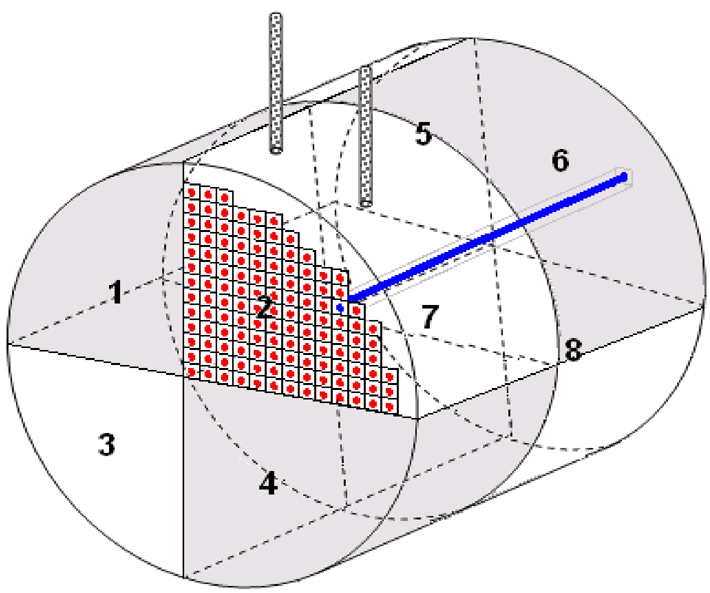


Figure 1: ACR-1000 Control Zone Arrangement

The movements (direction and speed) of the "grey" rods in $Zone_i$, $i= 1 \text{ to } 8$ is controlled by the bulk (E_B), spatial power errors (E_{SPi}) and the Average Zone Level (AZL).

The (bulk) power error is defined as:

$$E_B = k_B (P_M - P_D) + k_R (R_M - R_D) ,$$

where P_M is the measured power, P_D is the demand power, gain is k_B and R_M is the measured rate, and R_D is the demand rate. The second term, with gain factor k_R provides a measure of rate control.

Spatial power control is affected by further adjusting the drive speeds of the grey zone control rods individually in each control zone. The drive speed of the rods in zone *i* is proportional to the "spatial error", which is defined as:

$$E_{SPi} = k_T (P_i - P_{ave}) + k_L (L_i - L_{ave}),$$

where, k_T is the flux tilt gain factor, P_i is the normalized power in zone *i* , P_{ave} is the average of all 8 zone powers and k_L is the level tilt gain factor, L_i is the grey rod zone pair insertion level in zone *i* and L_{ave} is the average of all 8 zone pair insertion level.

The rules for movements of the "black" rods, "white rods and control absorber rods are governed primarily by the power error (E_B) and the Average Zone Level (AZL). The speed of movement is a function of E_B and it is common to these three rod types.

3.2 Application of RRS Dynamic Model to Fast Transients

A "Do-Nothing" dynamic transient was initially simulated to demonstrate that for a steady core state with flux/power in equilibrium with the xenon distribution, all the grey rods at 50% insertion level, measured bulk power matching the requested power and the zone powers matching those of the reference zonal powers, there will be no reactivity imbalance or any external perturbation that requires RRS actions. Furthermore, an all-quiet transient would demonstrate a steady core state with equilibrium xenon compatible with the flux/power levels, as well as numerical stability of the computational scheme. Tests with initial power at 100% FP, for a "do-nothing" duration of 1000s show that there are insignificant grey rod movements, and the AZL is maintained at 50% level; power error is essentially zero.

3.2.1 Setback Due to High Flux Tilt with Two SORs Half Inserted

This transient was selected to demonstrate RRS response to a local perturbation, and if setback would be initiated or cleared when the setback conditions are met. The local perturbation was artificially created by half-insertion of two SORs in one octant of the core.

At time 0s, the two SORs were inserted instantaneously, leading to an immediate power reduction to ~ 92 %FP, and a flux tilt (difference between maximum and minimum zone powers) greater than 0.2, hence a setback to 40 %FP at a rate of 0.1 %FP/s was initiated.

The demand power as calculated per setback rate from 100 %FP was initially higher than 92 %FP, and the AZL was lowered to raise the power. Thereafter, the AZL was raised to effect the power reduction, and the measured power closely followed the demand power. The pair of grey rods in the affected zone was withdrawing due to the presence of the two extra absorbers in the zone, thus reducing the magnitude of the tilt. The AZL steadily increased until the tilt was reduced to 0.15, and the setback was cleared. Upon clearance of the setback at ~215 s, the requested reactor power was set to the current power at ~77 %FP. The AZL was ~ 59% and remained there as a steady core state was reached. The pair of grey rods in zone 1 was fully withdrawn, and the tilt remained just below 15%. The transient is shown in Figure 2 and the corresponding control rod movements and zonal powers are shown in Figures 3 to 6.

The overall reactivity balance has components from the two half inserted SORs, the increase of the AZL from 50% to 59%, and the thermal-hydraulic reactivity feedback from the power reduction to 77 %FP. The RRS handled the local perturbation, initiated a power reduction to the required level, reduced the tilt to a safe level, and subsequently maintained a steady core condition. In these aspects, the RRS performance is adequate.

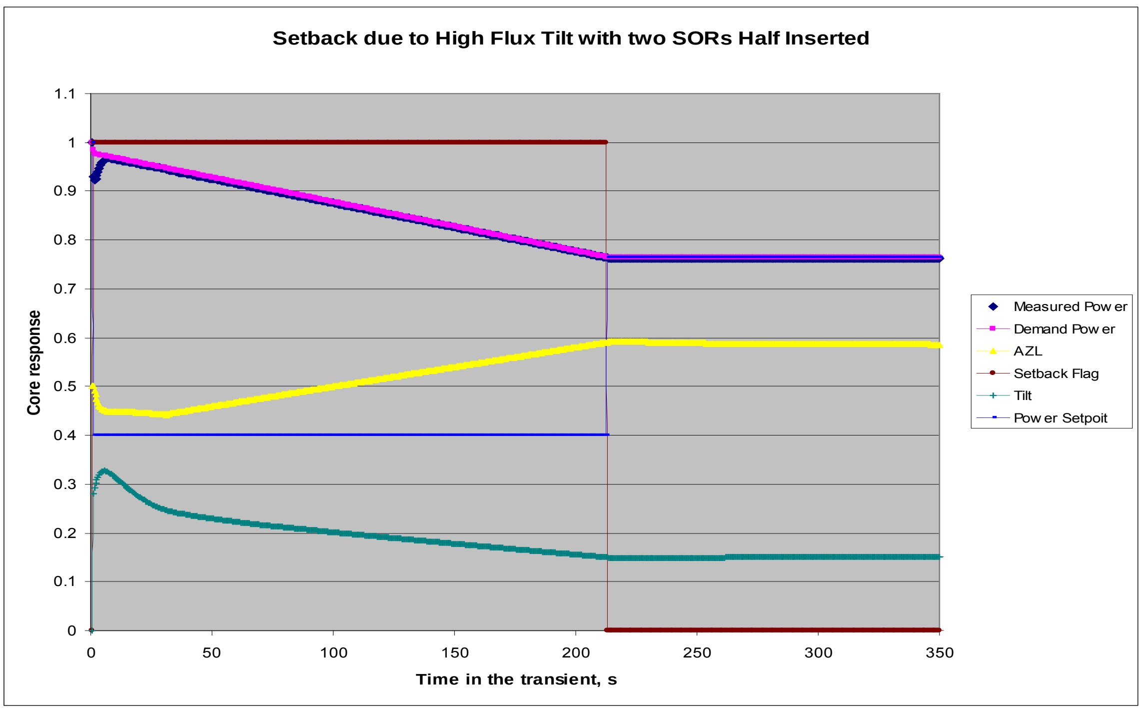
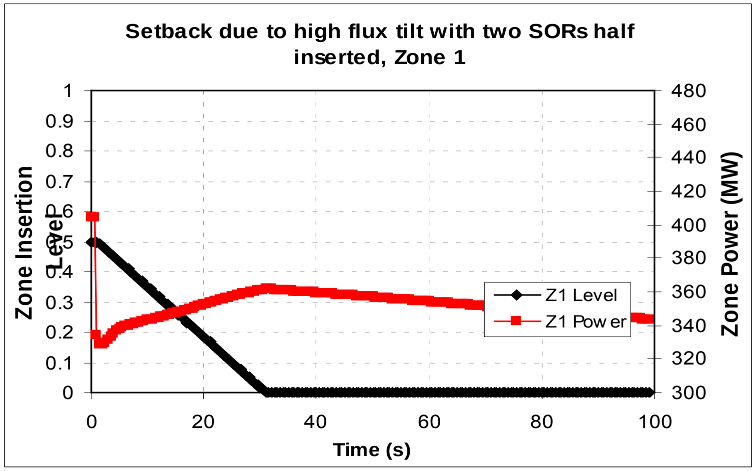


Figure 2: Setback due to high flux tilt with two SORs half inserted

3.3.2 One Grey Element Inadvertently Driven Out of Core

In this transient one grey element in Zone 3 was driven inadvertently out from 50% insertion at maximum speed. The requested power remained at 100% FP. The grey rod control system was impaired in this case with the other remaining rod in Zone 3 performing the function of 2 rods.

The overall results are shown in Figure 7. At the maximum speed of driving, the grey rod requires 30 s to drive from 50% insertion to fully out, as presented in Figure 8. The other grey rod in the pair started to drive in to compensate, and was able to maintain the bulk power at 100 %FP, and to limit the development of a flux tilt to any significant extent. The AZL remained at 50%. The channel and bundle powers in Zone 3 were somewhat different with one rod missing and one rod moving in compared to two rods at 50% insertion. The overpowers are small, less than 1.5% for channel power and 3% for bundle power. The other rod in the pair was inserted to 90% from 50%, zonal power shape was maintained, and reactivity perturbation was minimal. These conclusions are supported by independent static simulations using *SIMULATE module of RFSP, where the core response was followed for a longer time interval –up to 100 hours.



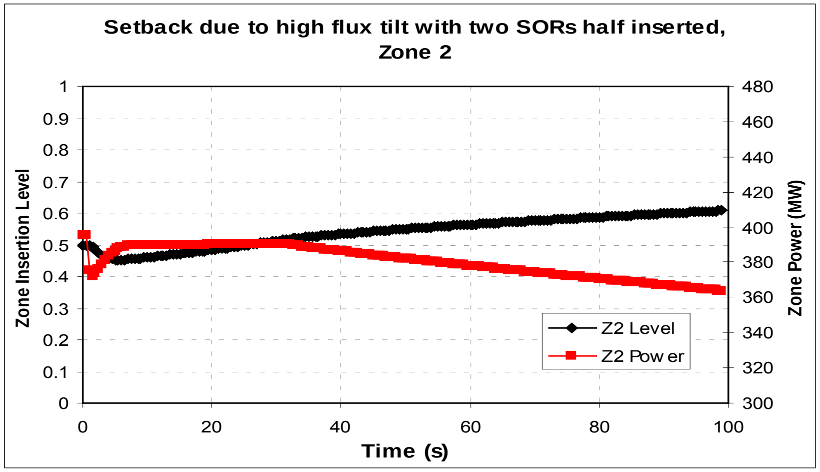
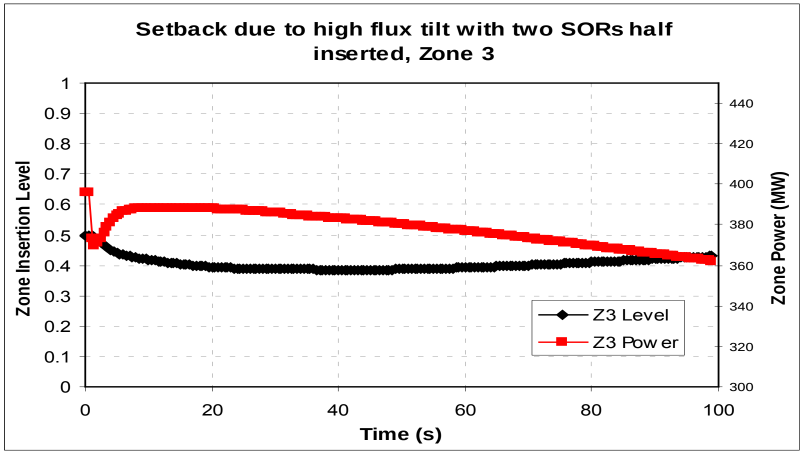


Figure 3: Setback due to high flux tilt with two SORs half inserted, Zone 1

Figure 4: Setback due to high flux tilt with two SORs half inserted, Zone 2



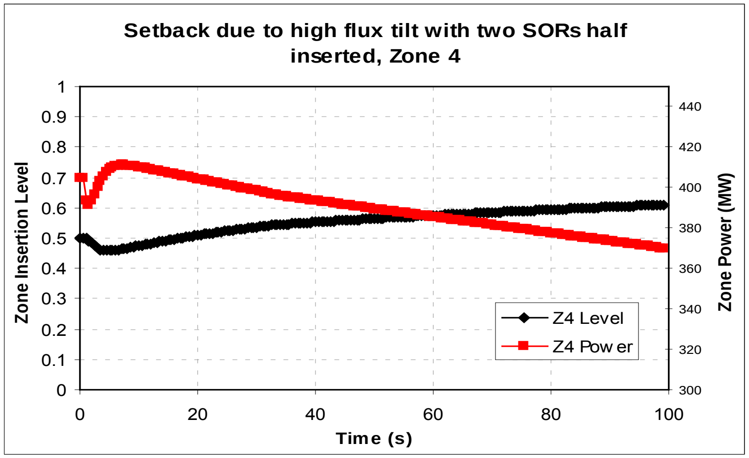


Figure 5: Setback due to high flux tilt with two SORs half inserted, Zone 3

Figure 6: Setback due to high flux tilt with two SORs half inserted, Zone 4

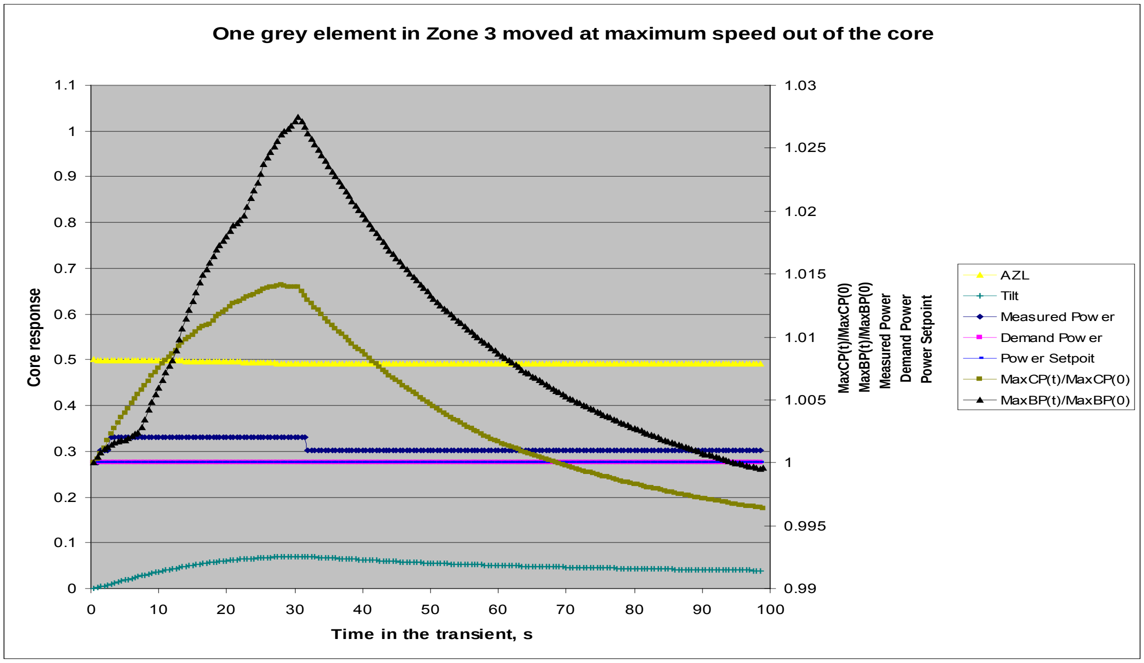


Figure 7: One lower grey element moved out of the core

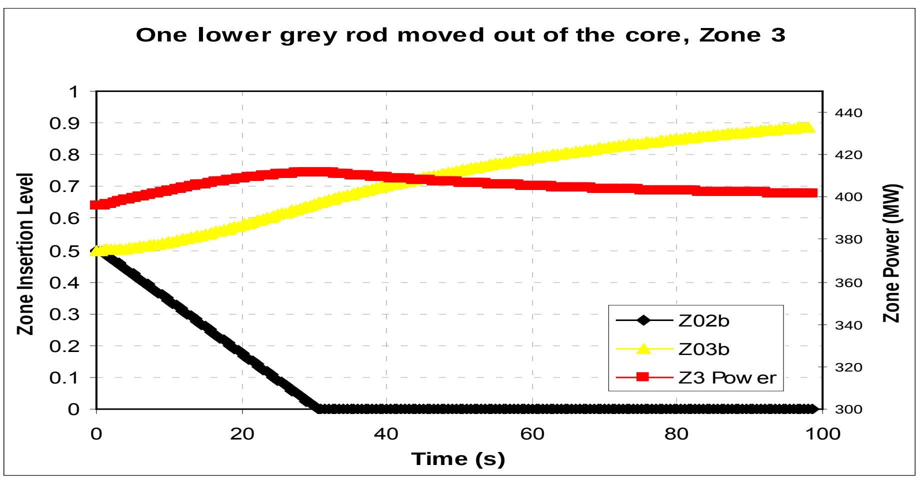


Figure 8: One grey rod out of the core, Zone 3

3.3.3 Activation of Setback on High Flux Tilt

This transient is designed to verify whether the tilt condition is correctly monitored, and the setback is initiated or cleared as required, and the input rate and end power are accepted and executed as requested.

From the initial steady core state with all grey rods at 50% insertion, it was specified that instantaneously the upper grey elements were positioned at 20% insertion, and all lower grey elements were positioned at 80% insertion. This condition created a top to bottom tilt, and since the difference in maximum and minimum zone power was greater than 20%, a setback was immediately initiated. (Note that in this transient a stepback might have been initiated on three or more zone powers being greater than 108 %FP. This stepback condition is not currently simulated in the RRS_SP).

The spatial control function would be expected to move the grey rods back to the original 50% insertion position, and the tilt would get smaller and eventually reach 15% when the setback condition would be cleared. The RRS rule is such that the requested power at the time of clearance of the setback would be set to the current power.

The results of this transient are shown in Figure 9. With the new configuration of the grey rod positions, there is a slight bulk reactivity imbalance at time 0 s, causing the reactor power to move up by a couple of percent. This condition was quickly controlled by an increase in AZL, and an initiation of a setback at 0.5 s. The movements of the grey rods in each of the eight reactor zones as a function of time are shown in Figures 10 to 14. The AZL continued to increase causing power reduction at the slow rate of 0.1% FP/s. As the rods moved toward the 50% position, the tilt was brought down to 15% and ~14 s from the beginning of the transient the setback condition was cleared. The power was reduced from the peak value of ~102 %FP to 98.7 %FP and, according to the RRS rules, the requested power was set at this level. The power setpoint switch from 40 %FP to 98.7 %FP is presented in Figure 9. The grey rods continued to move toward 50% insertion and the tilt was eventually eliminated after about 50 s.

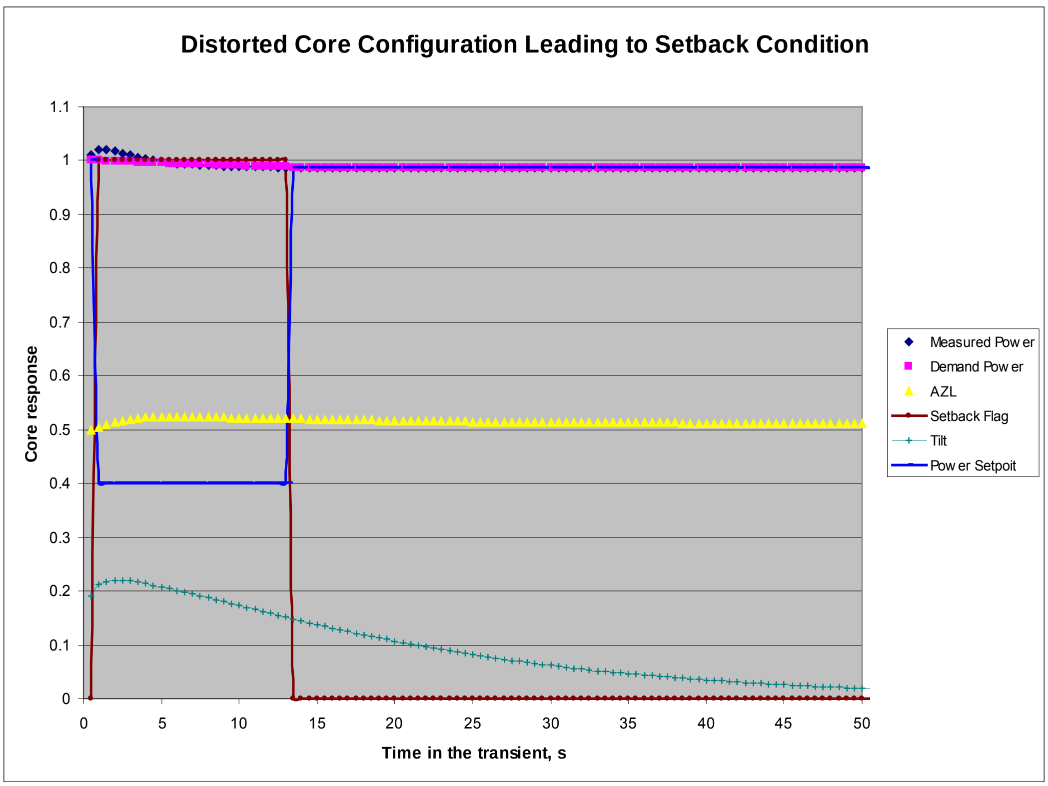
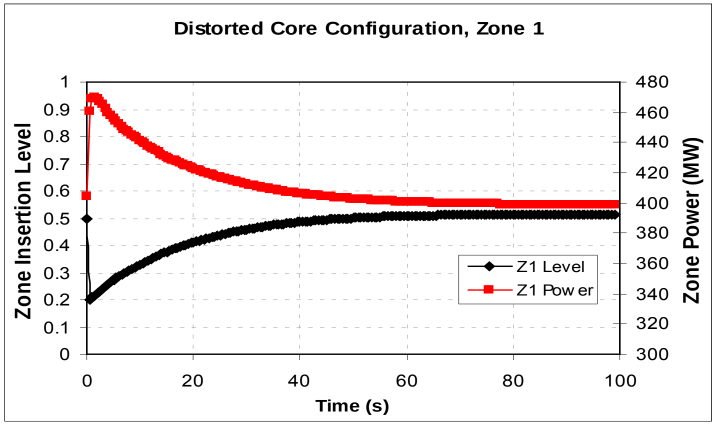


Figure 9: Distorted Core Configuration Leading to Setback Condition



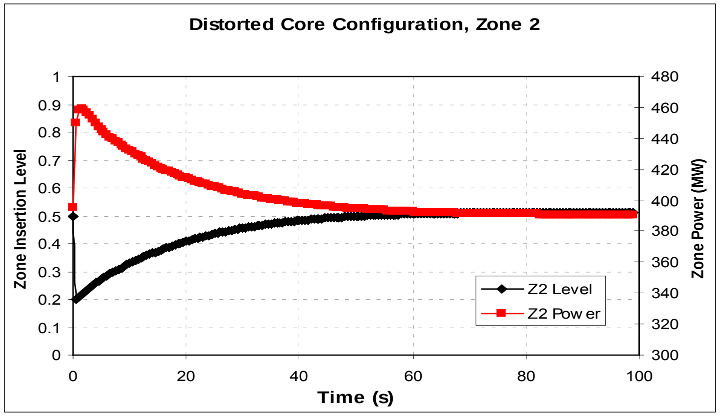
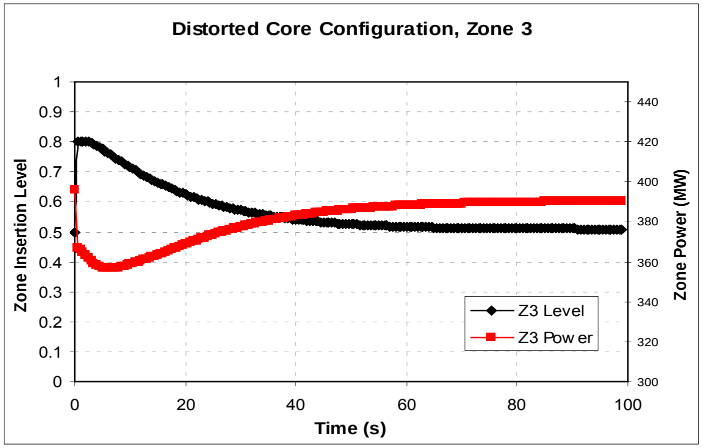


Figure 10: Distorted Core Configuration Zone 1
Figure 11: Distorted Core Configuration Zone 2



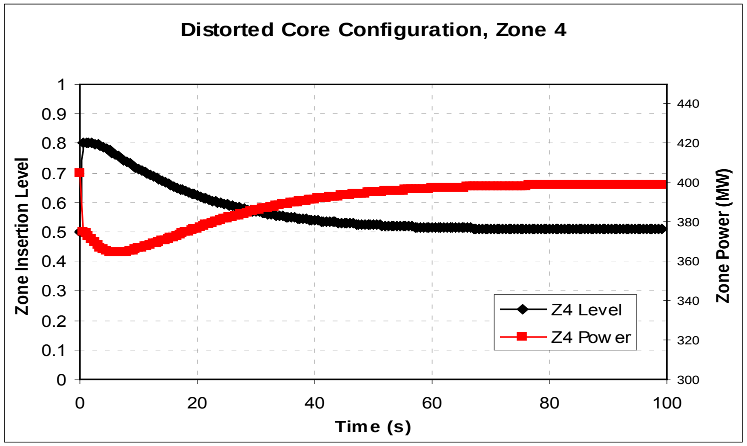


Figure 12: Distorted Core Configuration Zone 3
Figure 13: Distorted Core Configuration Zone 4

4. Quasi-Static RRS Modelling - Load Cycling

From physics considerations, for the study of maneuvers extending over a relatively long time frame such as load follow, shim mode operation etc., only quasi-static simulations need to be performed where the delayed neutrons are assumed to be in equilibrium with the prompt neutrons at each time step of the transient. A static simulation mode is available in *SIMULATE where the grey control rods are automatically moved to maintain reactivity balance and to match the nominal zone power distribution. The black/white control rods and the control absorber rods are moved in pre-defined steps by a script according to the overall RRS control logic when required. Xenon and fission product evolutions are properly tracked, as well as the power reactivity feedback. The simulation time steps are typically in the order of minutes.

Typical load cycles have been considered in this analysis. Other load cycle scenarios are possible and could be implemented by the owner/operator of the ACR-1000 power plant, but it is felt that the cycle considered here is representative of typical operations. A daily cycle is considered which consists of power reduction from 100 %FP to 75 %FP over a 3-hour time interval, steady power operation at 75 %FP for 7 hours and then a return to 100 %FP over a period of 3 hours. The whole duration of the power reduction and recovery is 13h. The reactor operates then at 100 %FP for 11 hours. This 24-hour cycle was simulated five times consecutively, and was immediately followed by a weekend cycle.

An ideal weekend power cycle is considered and consists of 4 hours power reduction from 100 %FP to 60 %FP, followed by 28 hours at 60 %FP and a power recovery to 100 %FP intended in 4 hours. The reactor then operates at 100 %FP for 12 hours.

Depending on the specific core conditions there could be deviations from the "ideal" daily/weekend scheme including holding on a slightly lower power for longer time periods on the way to restoring the full reactor power.

Five sequential daily cycles followed by a weekend cycle have been studied and the results are presented here. A combination of white bank insertion and moderator poison addition for reactivity balance was selected as an optimal approach for return to full power.

The simulation results for the 5 daily cycles are shown in Figure 15 and for the weekend cycle in Figure 16. Throughout the whole week, power level was maintained at the desired level, as indicated by reactivity balance centred around the target k-eff values. The first line of reactivity control is by the grey rods. They were supplemented by withdrawal of one black bank when power was reduced and xenon load was rising. BB1 was reinserted when power was raised and xenon started to burn out. Additional reactivity was required to supplement the grey rods. For optimal results this negative reactivity was provided by in-drive of a WB and Gd in the moderator.

Spatial power control is active throughout the simulation, and the peak Channel Power (CP) is indicated by the overpower ratio of maximum instantaneous CP to maximum time-average (at t = 0) – "(MaxCP(t)/MaxCP(0)". The peak transient overpower was around 103% for both the daily cycles and the weekend cycle. After the weekend cycle, the return to full power was delayed slightly by holding the power at 95 %FP for seven hours to avoid excessive channel overpower. The maximum channel and bundle powers through the whole transient are within the licence limits.

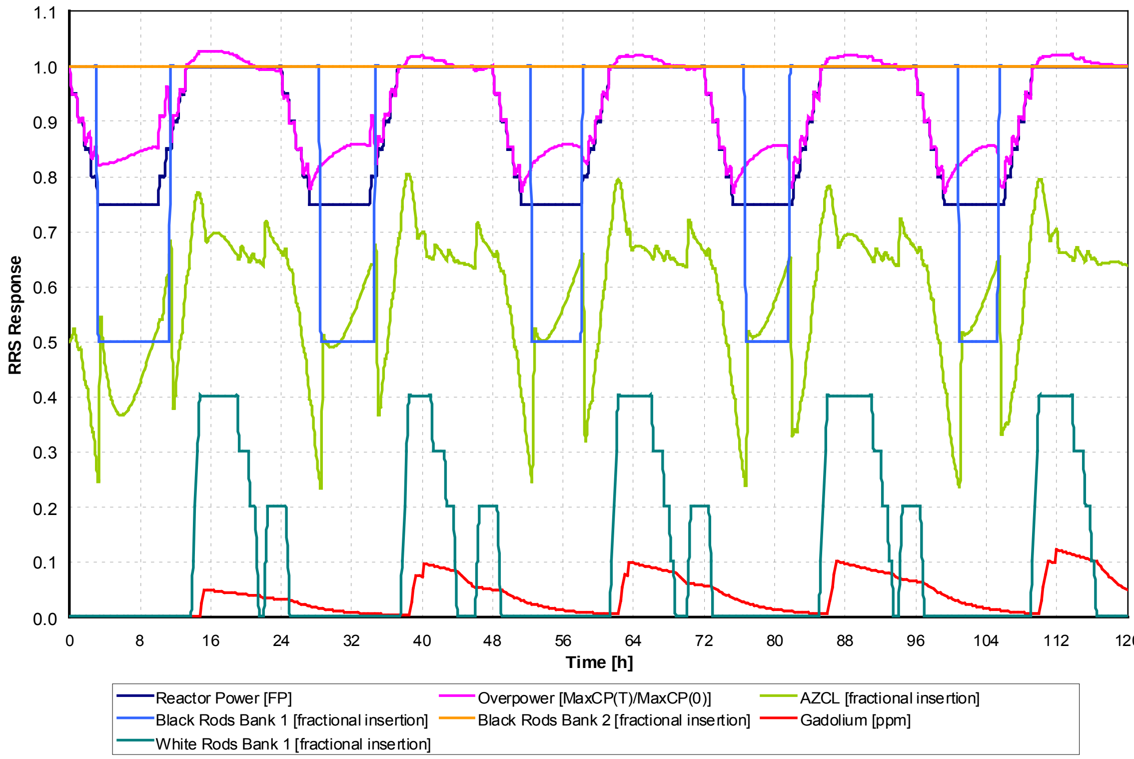


Figure 14: Weekdays Load Follow Cycling (100 %FP to 75 %FP)

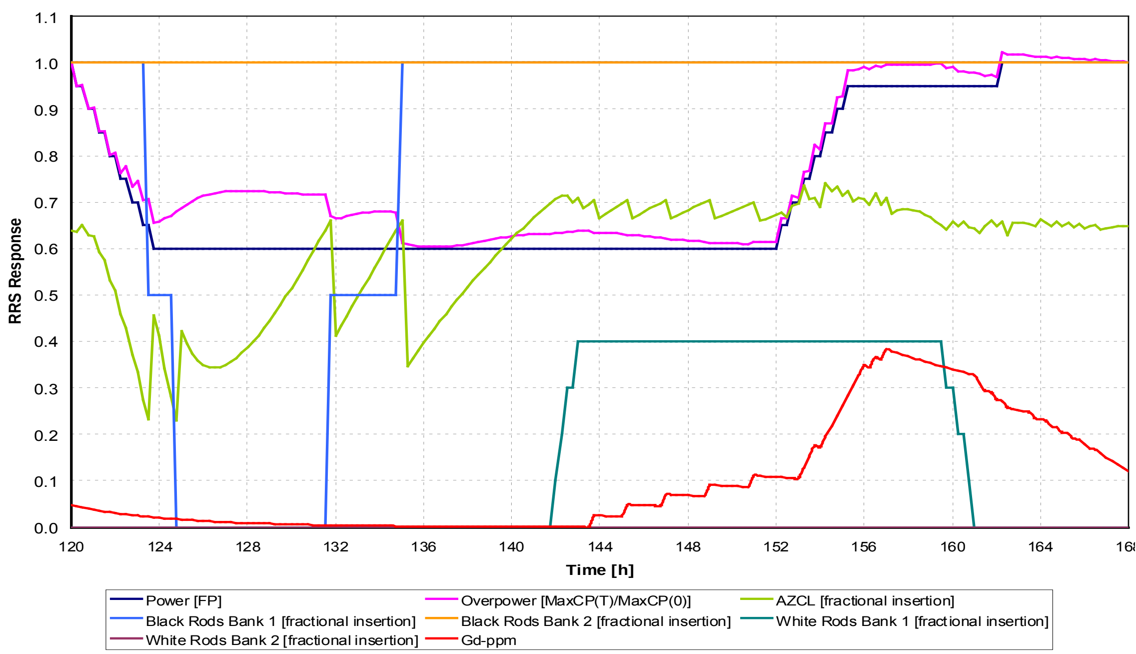


Figure 15: Weekend Load Cycling (100 %FP to 60 %FP)

5. Summary

The performance of the ACR-1000 RRS was demonstrated on three fast transients and on a week long load cycling. Solid control rods rather than the traditional CANDU light water filled control zones are used in the design of RRS. The solid rod drive components and controllers are simpler and more reliable. To accommodate the solid rods slight changes to the traditional CANDU control scheme are incorporated. The RRS design meets the performance requirements for normal control functions and operation maneuvers. In some cases, optimal core performance may be achieved by moderator poison addition as means of reactivity balance control.

6. References

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