Simulations of Power Transients in a Loss of the Liquid-Zone-Control-System Pumps in CANDU 6 Reactors

by

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Abstract

A loss of Class IV Power to the zone control system was one of the commissioning tests conducted at low power on Wolsong 2. It resulted in an increase in power of about 25%. The overpower was attributed to the relatively slow closing time of the valves in the discharge line. No trips or stepbacks occurred because of the low power at which the test was carried out. The occurrence of this transient led to the analysis of similar postulated events at higher power levels to gain an appreciation of the behaviour of the reactor regulating system under loss of the zone-control system conditions and of the sensitivity of the resulting transients to the closure time of the isolating valves in the discharge line. It is predicted that rapid valve closing (in less than one second) would result in a power increase of about 3-4%. The power is eventually limited by the Mechanical Control Absorbers driving in as a result of the power increase. A two second delay in the closing of the discharge valves would result in a ~125% overpower transient before the MCA, under drive control, are able to turn the power transient around. If the initial reactor power were at or close to full power, a stepback on high zone powers at 108% would arrest the power increase, causing the power to rapidly reduce to a low level. The analysis has concluded that a closing time of less than one second is desirable since it precludes relying on stepback to avoid a trip in the event of a loss of power to the light-water zone control water supply.

1. Introduction

In CANDU 6 reactors, fourteen light-water zone control units constitute the primary mechanism of short-term reactivity control. In each zone control compartment, the water level is adjusted by regulating the water in-flow. Helium cover gas above the water is maintained at a controlled pressure, thereby holding the water out-flow essentially at a constant rate. There are two isolation valves (PV#98/106) in parallel provided at the water discharge lines to minimize the reactivity disturbance that would result from a failure of the zone control system pumps. The configuration of the valves permits them to be individually tested during operation without excessively disturbing the process.

The signal to close the out-flow valves can be initiated either by the Reactor Regulating System (RRS) control software or by hardware design. When the in-flow water supply pressure falls from the normal 1075 kPa to 825 kPa, a "zone-control-system failure" setback signal is generated (with an end power set at 60% FP) together with a signal to close the valves. Closure of the valves is also initiated by hardware design when the pressure falls to 750 kPa.

When the power to the pump which maintains the in-flow water supply pressure is cut off, the in-flow rate slows down and the zone levels start to drop. As the pressure continues to drop, a signal to close isolation valves PV #98/106 is generated. When the valves are completely closed, the out-flow is stopped and the zone-level drop then comes to a halt. The time delay from loss of pump power to complete closing of the valves determines the zone level transient and hence the reactivity insertion, which in turn causes an overpower transient. With an impaired zone control system, the RRS responds to the reactivity perturbation and attempts to limit the overpower using primarily the Mechanical Control Absorbers (MCAs). Depending on the initial reactor power and the reactivity insertion rate, the protection system could also initiate a reactor shutdown. To reduce the magnitude of overpower and its associated risks, the closing time for valves PV # 98/106 had been considerably tightened at Gentilly-2 and other CANDU reactors from the original design.

In the Wolsong 2 commissioning test performed in 1997 March, test results showed some delay in closing of the out-flow isolation valves, which led to an observed overpower of about 125% from the initial power of 0.1% FP, i.e. to 0.125% FP. The station computer plots of the power error, the average zone level, the log power and the rate log power are shown in Figures 1-1a and 1-1b. The peak transient power was reached at about 10-12 s, measured from the time when the average zone level started to drop. Presumably the power excursion was turned over by the insertion of the MCAs even though the station computer record of the MCA positions was not available. The 125% overpower has caused some concern; and the isolation valve closure delay time was estimated to be about 2-4 s. The test results prompted an investigation into the valve performance and an analysis of similar postulated events at higher power levels to gain an appreciation of the behaviour of the RRS under loss of zone-control system-conditions, and the sensitivity of the overpower to the valve closure delay time.

With the impaired zone system, the MCAs would be the primary reactivity control mechanisms. For reference purposes, the rules governing the movement and speed of travel of the MCA banks in the CANDU 6 RRS design are shown in Figure 1-2.

2. Simulation Methods

Two sets of simulations have been performed, the first by HQ staff using the off-line FORTRAN EMULATOR [1] of the G2-SIMULATOR, and the second using the *CERBRRS [2] module of the RFSP computer code at AECL. With respect to neutronics modelling, the EMULATOR calculations are based on the fast-running modal synthesis method whereas the CERBRRS calculations use the more accurate finite-difference diffusion method as in the CERBERUS code [2]. Hence the neutronics modelling methods are quite diverse.

The RRS simulation routine packages in the EMULATOR and in CERBRRS originated from the same source - namely the SMOKIN-G2 code. However, the RRS routines in the EMULATOR represented a substantially modified and rewritten version of the SMOKIN control logic, for reasons of compatibility with the other EMULATOR/SIMULATOR modules. The RRS routines implemented in CERBRRS came directly from SMOKIN-G2. Verification of the implementation and integration with the neutronics calculation, and various functionality tests, have been documented in Reference 2. CERBRRS has not yet been validated against site measurement data, and this study is the first test application involving code-to-code comparisons.

The EMULATOR is an off-line replica of the SIMULATOR, and as such it has the capability to model the plant operation, including the process control of the zone-control system. Given the water in-flow supply pressure transient, and the valve closing stroke characteristic, the EMULATOR is capable of predicting the individual and average zone-level transients. On the other hand, CERBRRS models a fully functional zone control system. For the specific application in the current study, the code required some modification to allow user-specified zone level transient, and the by-passing of the normal zone calculation routines.

Two initial power levels were considered: 100% FP and 50% FP. Various delays in the isolation of the liquid zones were also assumed to check the magnitude of the overpower before the intervention of the MCAs, either by driving in because of power error or by stepback. Starting at 100% FP, it is expected that the "zone control failure" setback signal would be generated, and the requested power would then be set at the terminal power of 60% FP. A power stepback signal is also expected to be generated when the power excursion causes the stepback condition where "four or more zone powers exceed

108% of their nominal value". The overpower transient could be worse when the initial power is low, say at 50% FP, since in this case the power setback is not effective since the reactor power is below the setback end-power of 60% FP, and the stepback condition is not expected to occur.

In all simulated cases, reactor trip conditions were not monitored and reactor shutdown was not credited. Fuel-temperature reactivity feedback was accounted for via a reactivity coefficient, with the average temperature in each bundle calculated as a function of bundle power. Reactivity feedback due to other thermalhydraulic condition changes was ignored.

Three cases of pressure run-down and valve closure delay times were considered. In the simulations done with the EMULATOR, the pressure run down was assumed to be linear, from the operating pressure of 1078 kPa to the low-pressure setpoint of 750 kPa in 4 s and in 2 s for the first two cases as shown in Figures 2-1a and 2-1b. The pressure rundown for the third case is shown in Figure 2-1c, which was the actual measurement data from a test conducted at Gentilly-2 in 1996. The setpoint of 750 kPa was reached in about 0.7 s. The closing of the valve was modeled as instantaneous from fully open to fully closed at 4.3 s, 2.2 s and at 1 s respectively for the three cases. The EMULATOR would predict the individual and average zone fill transients, accounting for the loss of pressure and water in-flow rate reduction, cutting-off of the out-flow, as well as the re-distribution of water from the top zone to the bottom zones. The predicted average zone level (AVZL) transients are shown in Figures 2-2a, b and c respectively.

With CERBRRS which does not have the capability of modeling the process control and hence predicting the zone fill transient, it is necessary to by-pass the zone control routines and input the zone fill changes. For simplicity, an approximation was made that the average zone fill changes shown in Figure 2-2 were imposed on each of the 14 zone controllers.

3. Simulation Results

With two initial power levels at 100% FP and 50% FP, and three valve closure delay times, a total of 6 cases were simulated for each of the two calculation methods. However, results from selected cases only are presented below.

3.1 Initial Power at 100% FP, 4 s Delay

Figure 2-2a indicates that the average zone level dropped by 8.3% in 6 s. The steepest part of the curve has a slope of about 2%/s. The reactor power transient, in fraction of full power, predicted by the EMULATOR and by CERBRRS, is shown in Figures 3.1-1a and 3.1-1b respectively. The movements of MCA Bank 1 (Rods # 1 , 4) and Bank 2 (Rods # 2, 3), as predicted by the two codes, are compared respectively in Figures 3.1-2 and 3.1-3.

Shortly into the transient, at 1.2 s, the power error exceeded 1.5% and MCA Bank 1 started its in-drive, according to the rules in Figure 1-2. When the power error exceeded 3% at 2.5 s, both MCA Banks were driven in. The maximum speed of in-drive was such that full insertion would require about 150 s. The zone level drop and reactivity insertion could not be compensated by the initial insertion of the MCAs. The reactor power reached 108% FP at about 3.5 s when a stepback condition occurred. The MCAs were then released and dropped into the core, and the power was quickly turned over. There is good agreement between the two simulation methods up to this time. With a stepback, the end-power setpoint was at 0% FP. The RRS system continued to sample the core conditions every quarter of a second, and when it sensed that the stepback condition was cleared, the MCAs were arrested at mid-travel. At the time when the stepback condition cleared, the power setpoint would be set at the current measured power.

The detailed results from the two sets of simulations diverged somewhat once the stepback was initiated. In the context of the present study, the predicted core behaviour following stepback is somewhat irrelevant. Nonetheless, through the inter-code comparison, certain deficiencies in the CERBRRS stepback modeling were uncovered. The MCA dropping speed, as modeled in CERBRRS (0.6 of full travel per second) is about twice that in the EMULATOR. The latter is closer to the actual dropping speed. Also there is a delay of about 0.2 s from the time the stepback signal is generated to the time the rods start dropping, and that was not modelled with CERBRRS, which used a constant time step of 0.5 s. Thus with CERBRRS, the stepback condition was cleared in one time step of 0.5 s and the rods were arrested at mid-travel when about 30% inserted; the reactor power dropped from 108% FP to around 95% FP. The EMULATOR results, however, predicted that the stepback condition would clear after 1 s and the rods would be arrested in mid-travel at about 0.3 fraction insertion; the reactor power dropped from 108% FP to 79% FP in 1 s and then continued to drop at a slower rate.

Regardless of the differences in the predicted results after the stepback, the two simulation methods agree on the essential elements, namely that the reactor power increased to 108% FP in about 3.5 s, that a stepback occurred and that the power was turned over.

When the valve closure delay time was reduced from 4 s to 2 s, the AVZL dropped by 4.2% in about 4 s as shown in Figure 2-2b. The initial part of the reactivity perturbation was similar to the case with 4 s delay, and the power excursion was therefore similar, and a stepback was also predicted to occur at about 3.5 s by both the EMULATOR and CERBRRS. Details of the results are not included here.

3.2 Initial Power at 100% FP, 1 s Delay

As shown in Figure 2-2c, the AVZL dropped by 1.3% in 2.5 s, and then slowly rose again. This figure presents the average zone fill transient for the first 10 s only. Since this power transient was expected to be slow, it would be necessary to predict the long-term zone level transient behaviour. On loss of header pressure, the zone water out-flow was bottled up. The upper controllers would drain down to the lower zone, increasing the water levels in the lower controllers; and in the longer time frame of a few minutes, all controllers would start filling up due to water seeping in from the top biological shield and back-flow from the water return header. The long-term zone-fill dynamics behaviour for each of the fourteen control compartments was modeled using the EMULATOR. The predicted AVZL transient is shown in Figure 3.2-1, and the predicted power transient is shown in Figure 3.2-2. The initial reactivity increase due to the 1.3% drop in AVZL resulted in a peak overpower of ~103% around 15 to 20 seconds. The two MCA Banks started driving in due to large power error. The subsequent increase in zone water level drove the MCA banks back out and brought the reactor power down to a shutdown level.

The CERBRRS simulation of this case was done assuming the average zone fill shown in Figure 2-2c was applicable to all 14 control compartments, the subsequent refilling of all the zones was not modeled, and the AVZL was held constant after 10 s. Thus the modelling of the zone water transient was relatively crude and only the initial part of the predicted transient is meaningful. Nonetheless, the results did indicate a peak power of 104% at 23 s (Figure 3.2-3), which was turned over by MCA bank insertion (Figure 3.2-4). There is general agreement between the two sets of simulations that the overpower transient is controlled at 103-104% by the MCA bank in-drive. The EMULATOR further predicted a power drop to shutdown level due to zone water refilling.

3.3 Initial Power at 50% FP, 2 s Delay

The pressure rundown and isolation valves closing characteristics assumed for the 50% initial power cases were the same as those in the corresponding 100% initial power cases. The average zone level transient was also the same as the corresponding 100% initial power case. The simulation results for the 2 s delay case are presented below.

The EMULATOR was used to simulate the transient for the first ten seconds only. The reactor power reached 57% at 10 s and was still increasing when the simulation was terminated. The CERBRRS predicted power transient is shown in Figure 3.3-1. There is good agreement with the EMULATOR results for the first ten seconds. The CERBRRS simulation was then carried out to 200 s to investigate the overpower transient and the effectiveness of the MCA to turn over the power in the absence of a stepback. Details of the zone water level refilling transient were not available and it was conservatively assumed that the AVZL was held stable after 10 s. MCA Bank 1 and Bank 2 insertion is shown respectively in Figures 3.3-2a and 3.3-2b. The reactor power reached a peak of 62% FP at 29 s and turned over on in-drive of both MCA banks. The power was brought back and controlled near the 50% FP level. However, since the zone water refilling was ignored, the predicted long-term core behaviour, especially at times past the power peak and beyond, is not expected to match reality. It is, however, comforting to know that even without the zone filling up, the reactor power would still be controlled at around the

50% FP level. The peak overpower of 125% in this case is about the same as that observed in the Wolsong 2 commissioning test.

In the case of a 4 s delay in valve closing time, the general trend of the predicted power transient was similar to the 2 s delay case. The MCA in-drive still turned over the power. The peak overpower was, however, much higher at about160% (instead of 125%) of the initial power.

3.4 Initial Power at 50% FP, 1 s Delay

With a short valve closing delay time, the predicted overpower transient is not sensitive to the initial power level. The EMULATOR results showed very much the same trend for the power transient as in the 100% FP case, peaking at 51.5% (103% of the initial power which was 50%FP) and turned over by MCA Bank in-drive at about 15 s. Both MCA Bank 1 and Bank2 in-drive was also similar to the case with an initial power of 100% FP.

CERBRRS predicted a peak power of 52% and turn-over by MCA bank insertion at about 23 s.

4. Conclusion

The general conclusion from the simulations is as follows. When the initial power is high, the power increase will be mitigated by a stepback initiated at about 108% FP. However, if the out-flow control valves PV #98/106 act sufficiently fast as is currently implemented in G2, the peak power predicted is only around 103% FP and the in-drive of the MCAs control and turn around the power excursion. The subsequent refilling of the zone water would introduce further negative reactivity to reduce the reactor power to shutdown level. When the initial power is low, stepback conditions do not occur during the overpower transient. The power excursion is turned over by MCA in-drive. The peak power reached is a strong function of the delay time in the closure of the isolation valves.

The 125% overpower transient observed in the Wolsong 2 test is very similar to the results of the 2-s delay case presented above.

Setback conditions are monitored in the simulations but are irrelevant. Power setback on local high power and high flux tilt has a terminal power of 60% FP if the current power setpoint is higher than 60% FP. Since the zones are impaired and the MCA rods are already driving in at full speed, a power setback would not change the transient device movements in the cases studied above.

There is generally good agreement between the two simulation methods (G2 Desktop EMULATOR and CERBRRS) for the initial part of the transient, up to the occurrence of a stepback or to the power turn-over by MCA in-drive. Note, however, detailed quantitative validation of the CERBRRS code against site transient events has yet to be performed.

In view of the strong dependence of the magnitude of the overpower on the amount of zone level drop, which in turn depends on the delay time in closing of the control valves, it was recommended that the delay time in closing of the isolation valves PV #98/106 be reduced as implemented at G2. In Wolsong 3, sufficiently fast acting valves were installed for PV #98/106, and the same test was repeated in 1998 March. The data collected (sampled at 2-second interval) indicated there was only a small power increase which was estimated to be between 2-5% and lasted only a few seconds.

Acknowledgment

G. Pépin of Hydro Québec and V. Stobie of AECL provided measurement data from Wolsong 2 and 3 commissioning tests and made initial assessment. Their input is hereby acknowledged.

References

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2. H. Chow, M. Younis and D. Jenkins, "Capability to Model Reactor Regulating System in RFSP", Proceedings of the 16th Annual CNS Conference, Saskatoon, 1995 June 4-7.

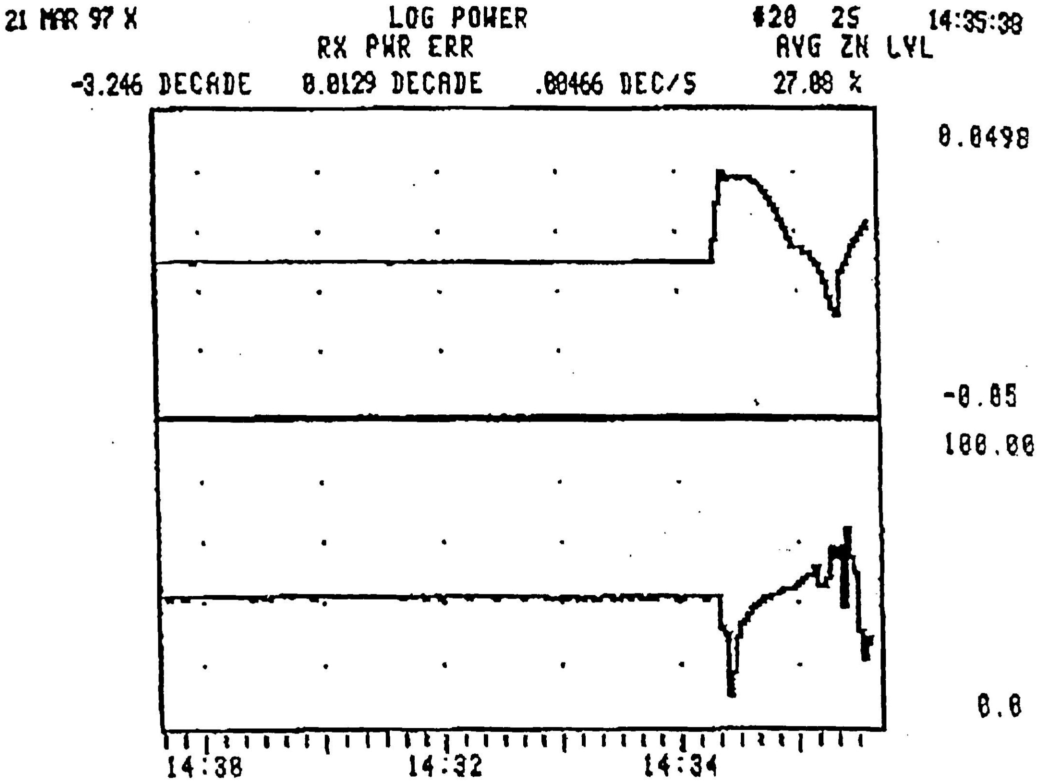

Figure 1–1a Station Data from Wolsong 2 Loss of Pump Test – Power Error and Average Zone Level

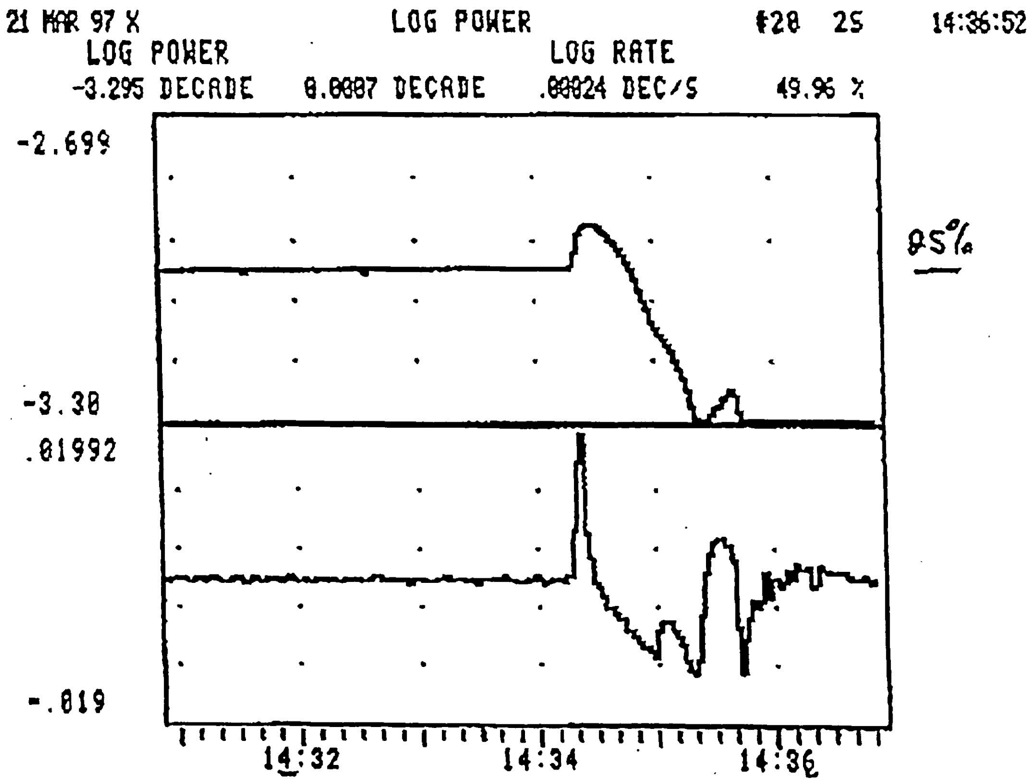

Figure 1–1b Station Data from Wolsong 2 Loss of Pump Test – Log Power and Rate Log Power

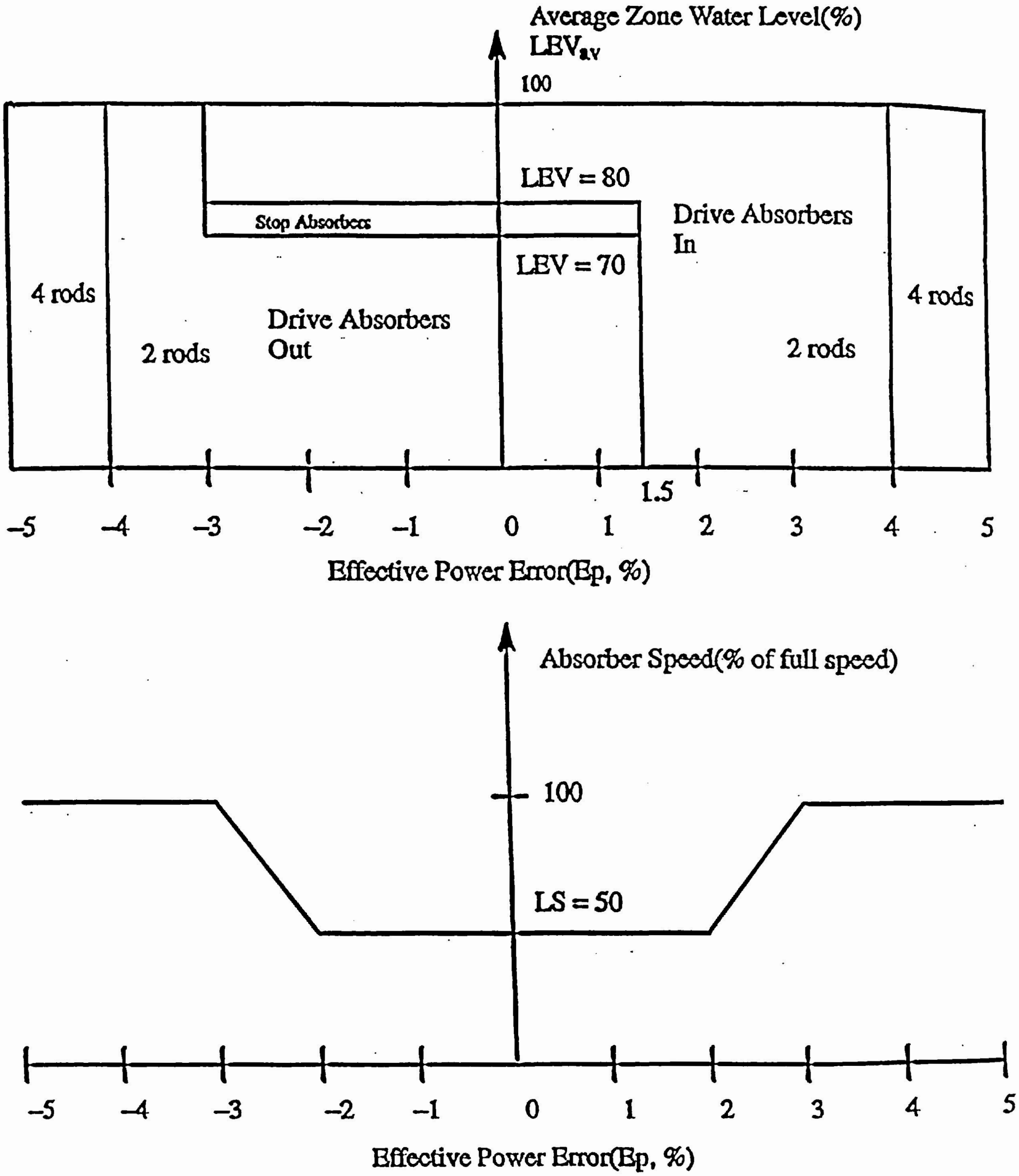

Figure 1–2 MCA Rod Drive and Speed Control

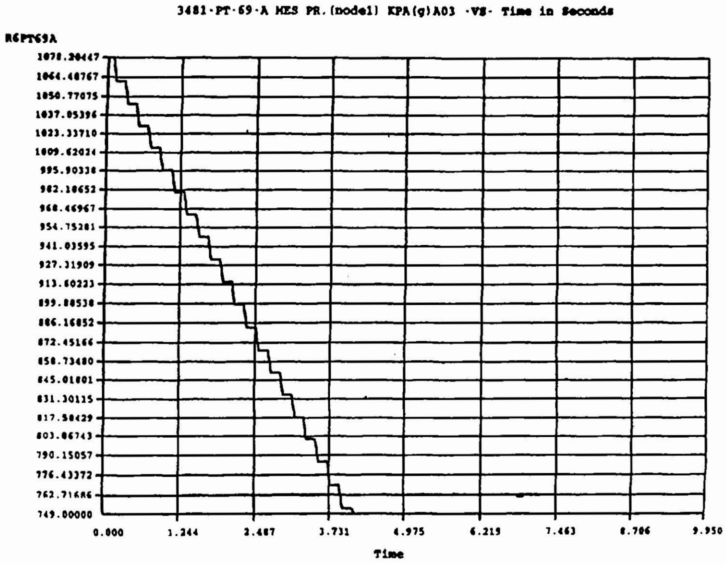

Figure 2–1a Pressure Run–Down in 4 s Delay Case

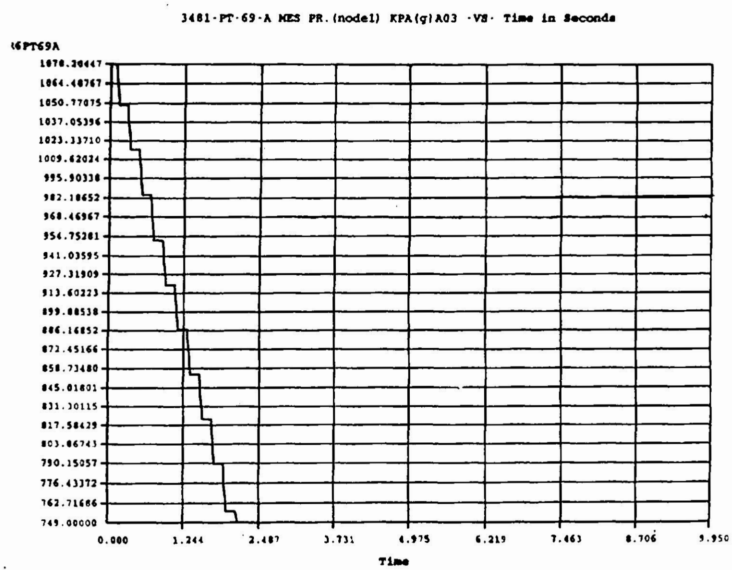

Figure 2–1b Pressure Run–Down in 2 s Delay Case

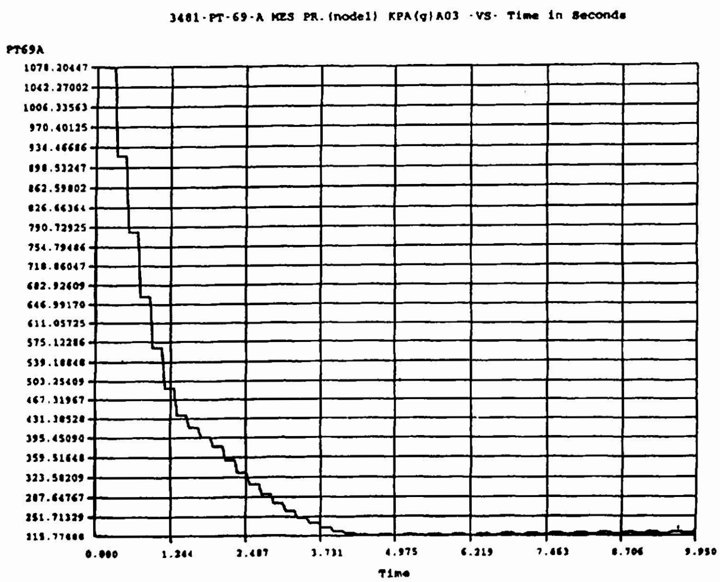

Figure 2–1c Pressure Run–Down as measured in reference 3

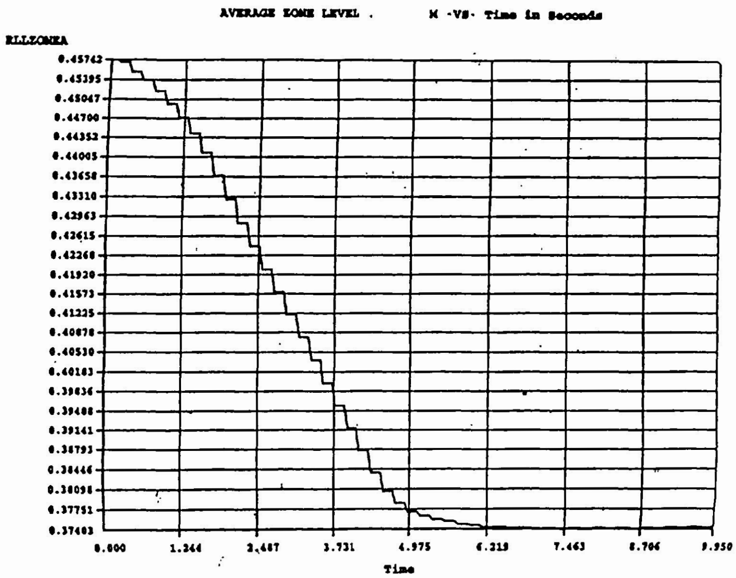

Figure 2–2a Average Zone Level Transient in 4 s Delay Case

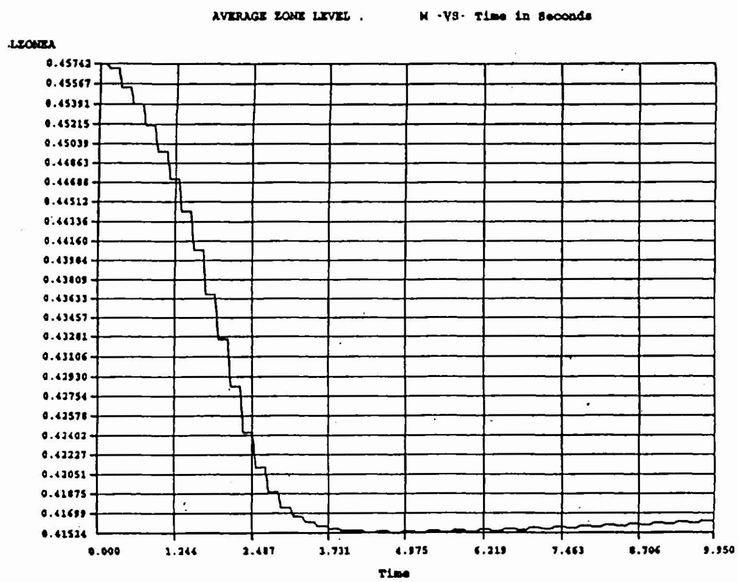

Figure 2–2b Average Zone Level Transient in 2 s Delay Case

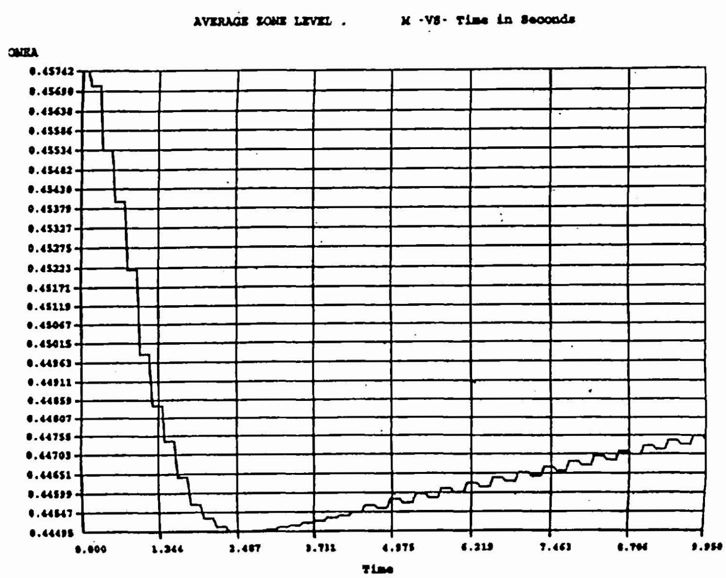

Figure 2–2c Average Zone level Transient with Measured Pressure Run–Down and Valve closing at 1 s

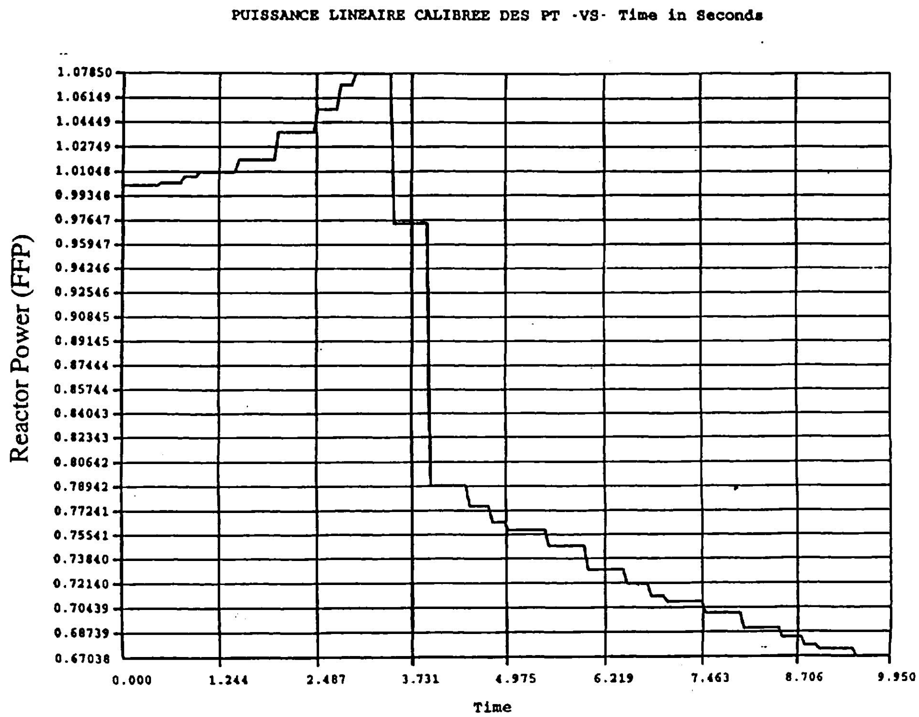

Figure 3.1–1a EMULATOR predicted Reactor power transient – 100% FP, 4 s Dealy Case

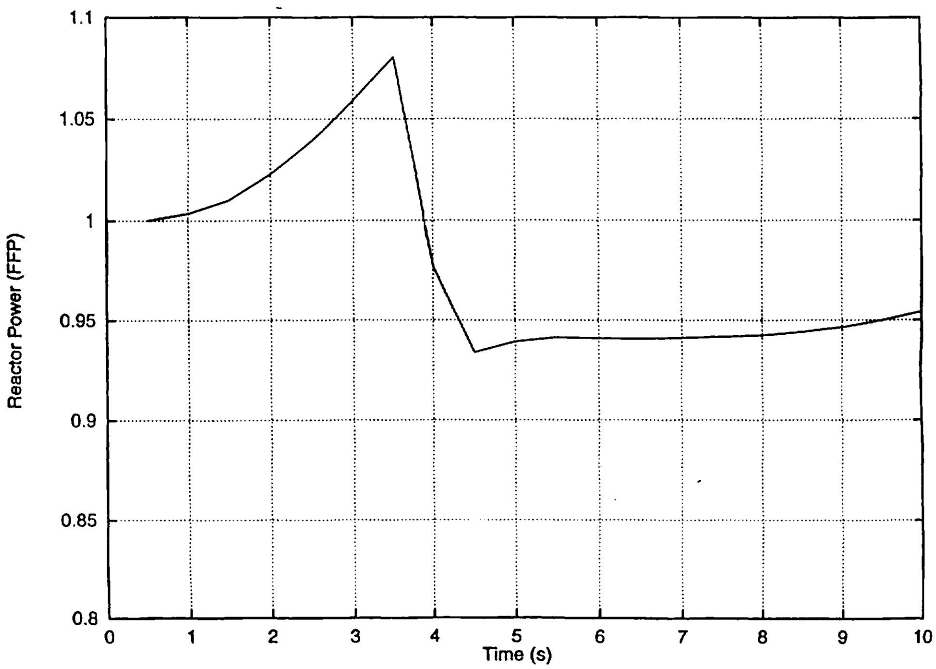

Figure 3.1–1b CERBRRS predicted Reactor power transient – 100% FP, 4 s Dealy Case

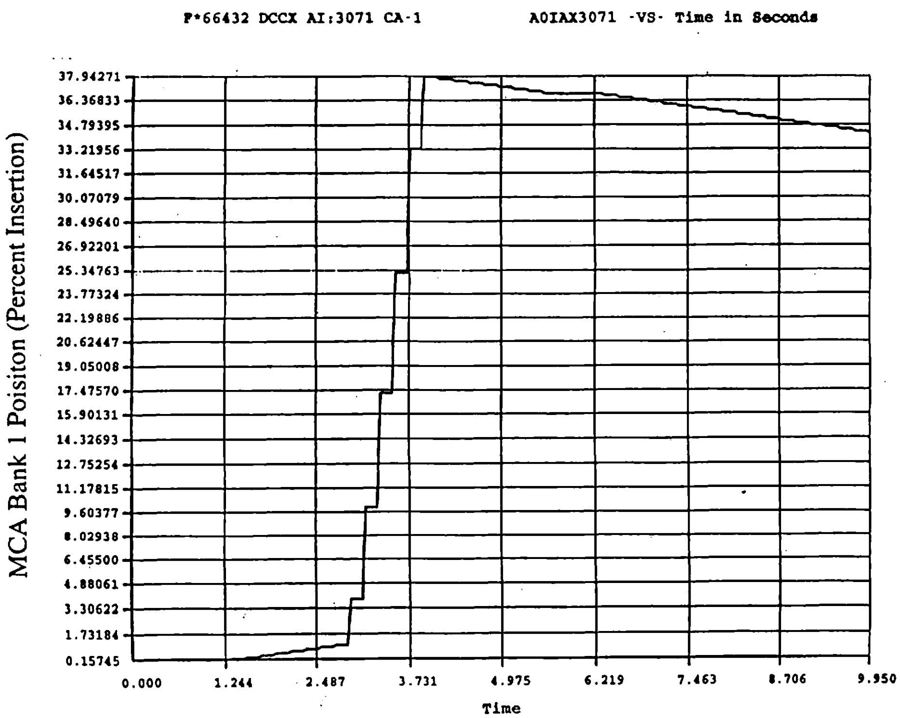

Figure 3.1–2a EMULATOR predicted MCA Bank 1 Movement – 100% FP, 4 s Dealy Case

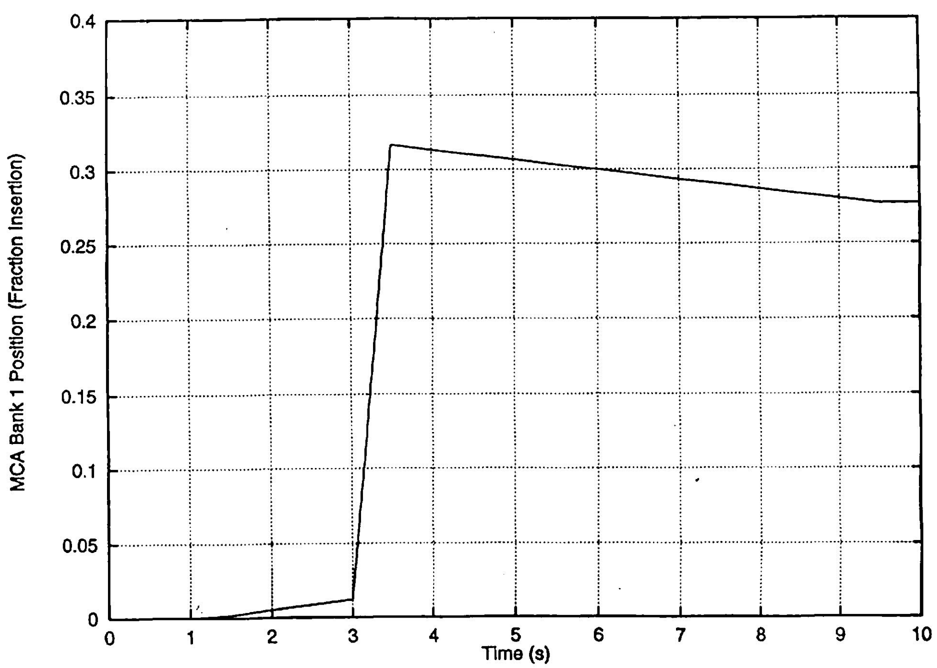

Figure 3.1–2b CERBRRS predicted MCA Bank 1 Movement – 100% FP, 4 s Dealy Case

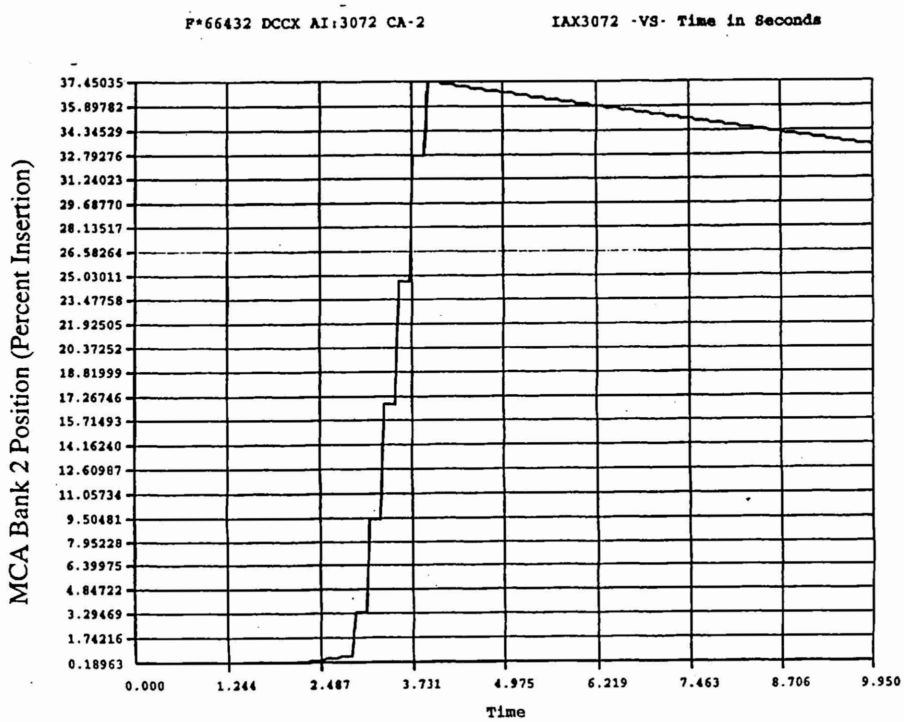

Figure 3.1–3a EMULATOR predicted MCA Bank 2 Movement – 100% FP, 4 s Dealy Case

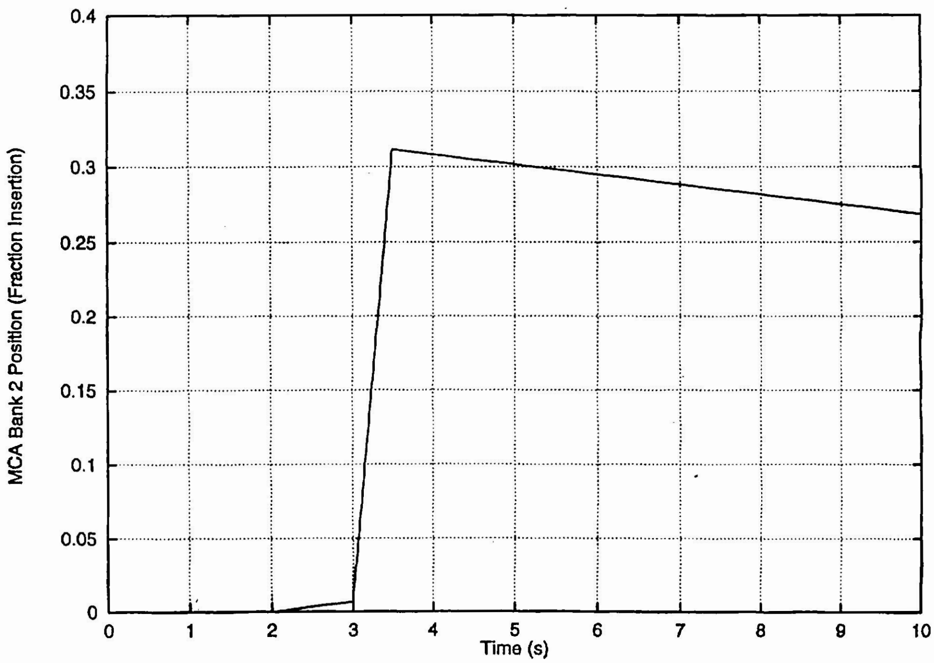

Figure 3.1–3b CERBRRS predicted MCA Bank 2 Movement – 100% FP, 4 s Dealy Case

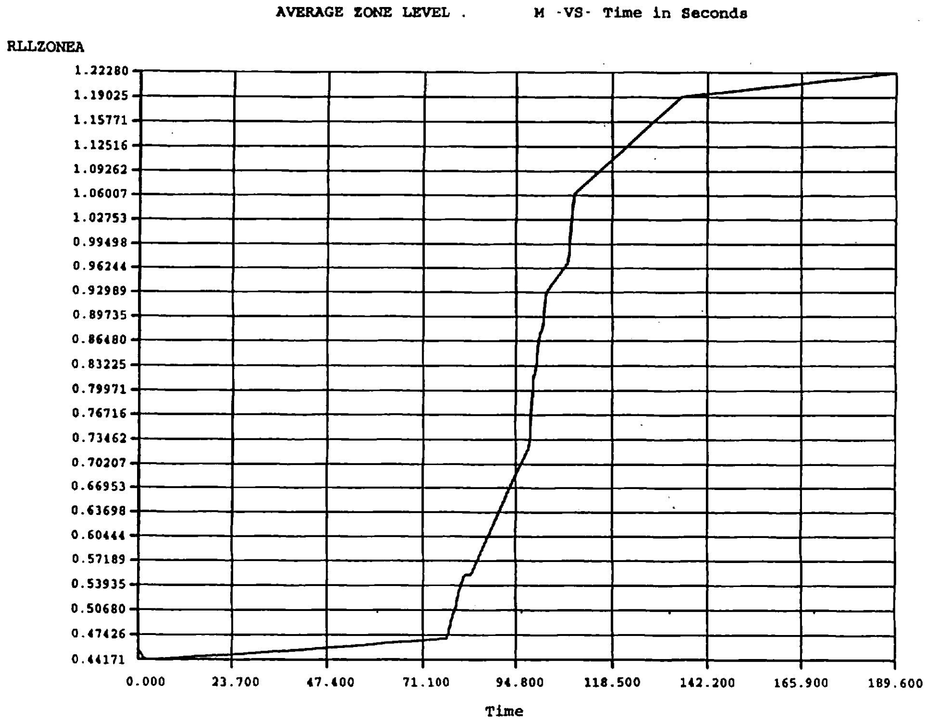

Figure 3.2–1 Long Term Average Zone level Transient with Measured Pressure Run–Down and Valve closing at 1 s

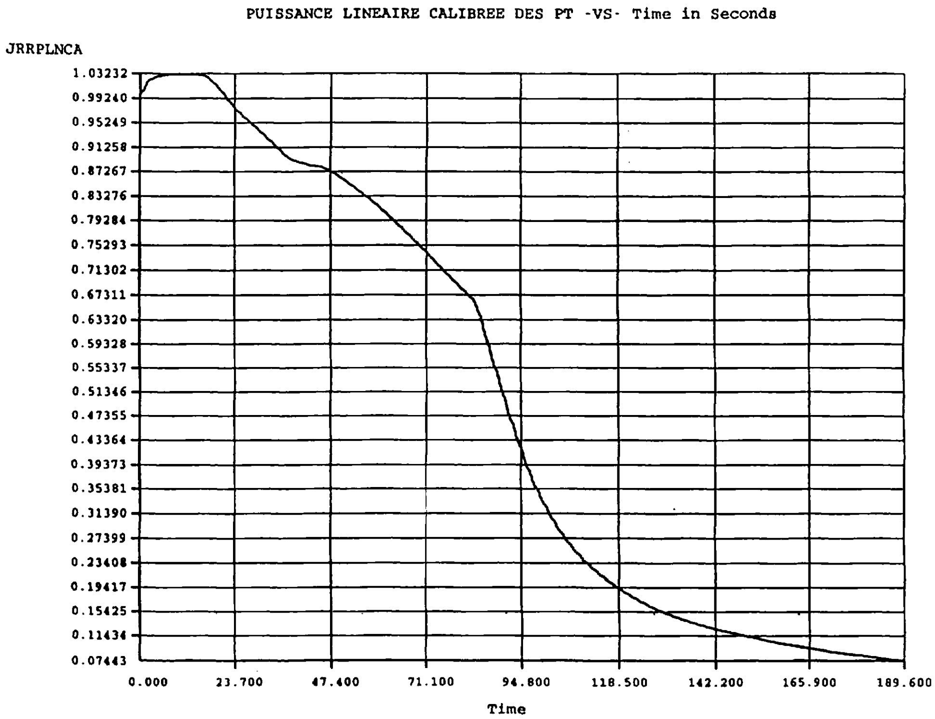

Figure 3.2–2 EMULATOR predicted Reactor power transient – 100% FP, 1 s Dealy Case

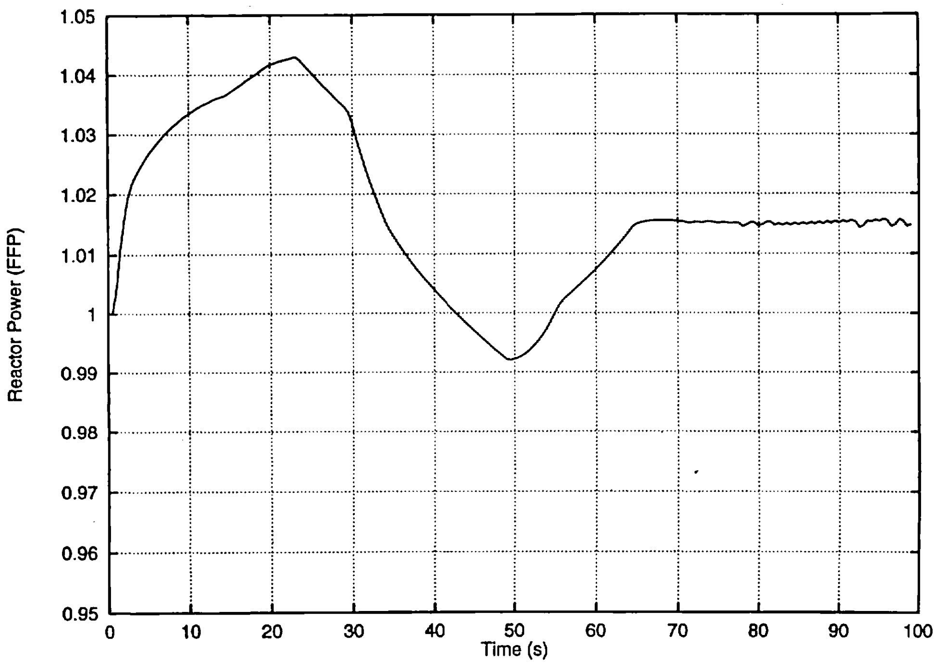

Figure 3.2–3 CERBRRS predicted Reactor power transient
– 100% FP, 1 s Dealy Case, Zone Refilling not modelled

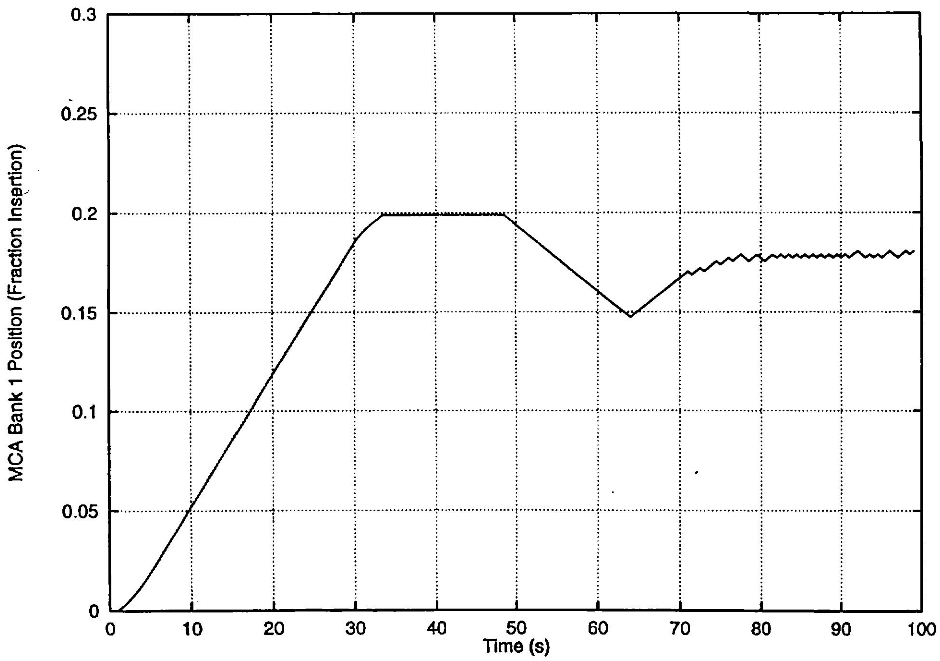

Figure 3.2–4 CERBRRS predicted MCA Bank 1 Movement
– 100% FP, 1 s Dealy Case, Zone Refilling not modelled

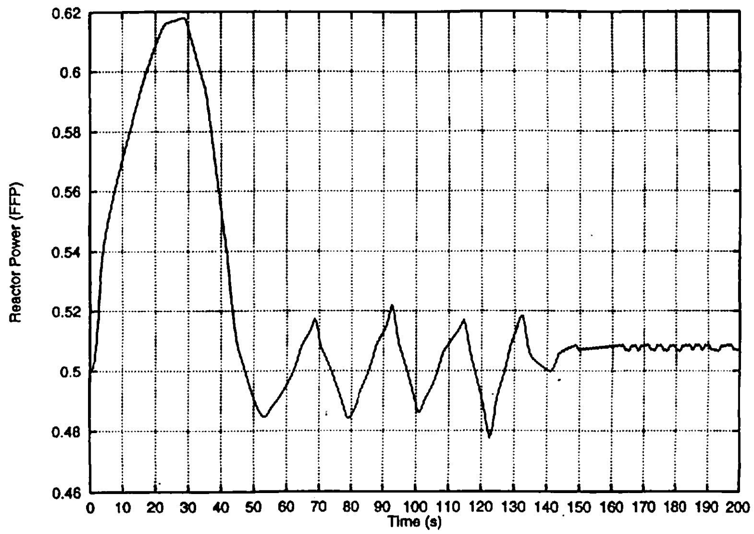

Figure 3.3–1 CERBRRS predicted Reactor power transient – 50% FP, 2 s Dealy Case

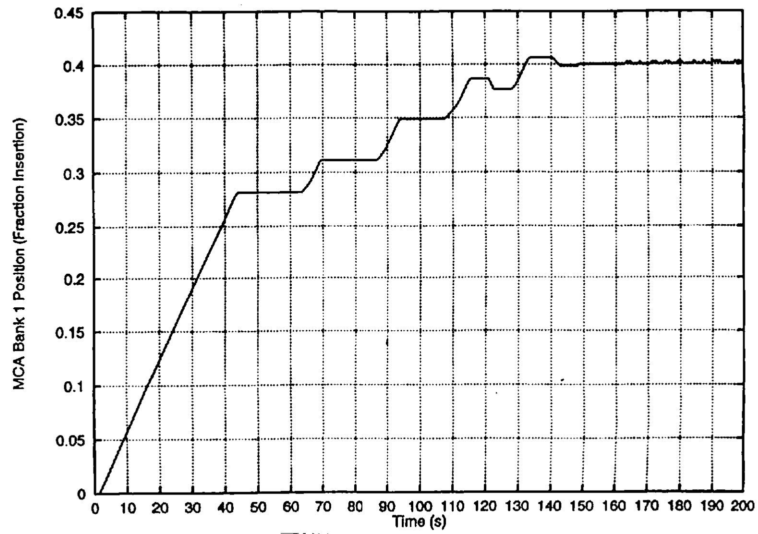

Figure 3.3–2a CERBRRS predicted MCA Bank 1 Movement – 50% FP, 2 s Dealy Case

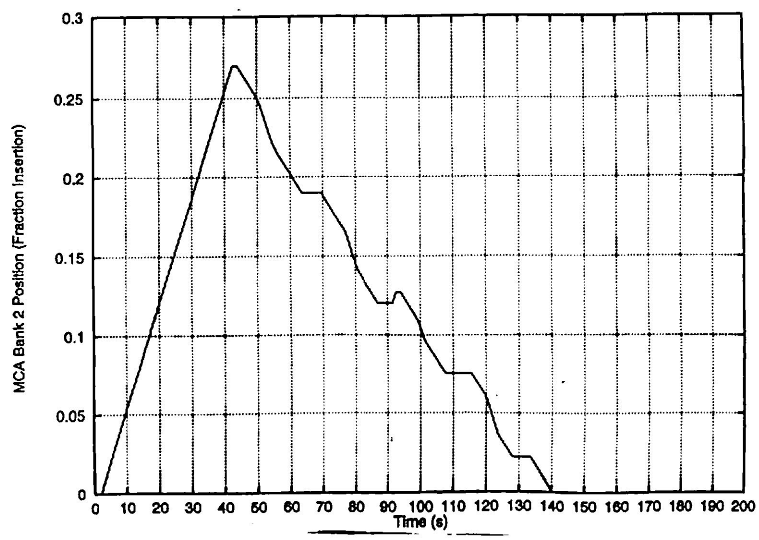

Figure 3.3–2b CERBRRS predicted MCA Bank 2 Movement – 50% FP, 2 s Dealy Case