Effectiveness of Setback in Liquid Zone Control Pump Failure[1]

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Abstract

A liquid zone control pump (LZC) system failure occurred at Cernavoda 1 on 2001 Jan. 05. In that event, Shutdown System 2 (SDS-2) tripped.

This paper presents an analysis of the event, to determine whether the SDS-2 trip was necessary to prevent fuel dryout, or whether the setback on low pressure in the water-supply header of the liquid zone controllers would have sufficed. In the incident the pumps were restarted within seconds, but in the simulation the pumps were purposely not restarted, in order to see whether the control-system response in the absence of the pump restart and the SDS-2 trip would have prevented dryout. The Reactor Regulating System (RRS) actions were modelled using the *CERBRRS module of RFSP-IST 3-00-05HP. In the analysis, modifications were made to *CERBRRS to disable the RRS control of the zone controllers while retaining the remaining functionality of the RRS. Cernavoda 1 Operations provided the critical channel power (CCP) map, which, together with the channel powers (CP) calculated by *CERBRRS, was used to determine the onset of dryout by means of the critical power ratio CPR = CCP/CP.

The results of the simulation show that the setback by itself provides adequate margin to dryout, and that a reactor trip is not needed to protect the fuel.

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1. Introduction

On January 5, 2001, at Cernavoda 1, Shutdown System 2 (SDS-2) tripped following a liquid zone control (LZC) pump failure. AECL was requested by Cernavoda 1 Operations to simulate the event to determine whether the reactor trip was necessary to prevent fuel dryout, or whether the setback, initiated on lower pressure of the zone control water supply, would have sufficed. [A setback is a controlled reduction of the reactor power setpoint at a pre-specified rate.]

2. Details of the Cernavoda 1 Shutdown

The following list of events, taken from the DCC X log of Cernavoda 1, chronicles the shutdown of the reactor.

<u>Time:</u>

13:07:43 - Computers detect a drop in pressure in the zone-control-system supply header.

13:07:45 - The isolating valves in the return header close and the control system initiates a setback [1] (controlled power reduction) to 60% full power (FP) at 0.1 %/s. The endpoint power of 60% FP is selected because the reactor is spatially stable at this power and tilts grow sufficiently slowly that the operator can take manual action if necessary. The closure of the isolating valves stops the out-flow of water from the zone compartments, thereby ensuring that the total amount of water left in the zones remains constant. This action minimizes the reactivity disturbance caused by the cumulative decrease in water levels due to the pump failure. Once the valves have closed, some redistribution of the liquid occurs from the upper compartments to the lower ones as fluid siphons through the drain lines.

13:07:47 - The reactor regulating system (RRS) closes the zone-controller inlet valves. Closing these valves prevents water from being pushed out the fill lines by the helium cover gas and thus prevents delaying the reintroduction of water into the zone compartments when the pumps restart.

13:07:52 - Logic channel H of SDS-2 trips on high power.

13:08:02 - At least one of the pumps restarts, as indicated by the increase in the supply header pressure.

13:08:05 - Logic channel J trips on high power. Since 2 of the 3 logic channels for SDS-2 have tripped, SDS-2 is actuated and shuts the reactor down.

13:08:06 - The first of the two isolating valves re-opens.

13:08:08 - The setback clears.

13:08:10 - The second isolating valve re-opens.

3. Modelling of the Cernavoda 1 Zone-Control-Pump Stoppage

In the incident, SDS-2 tripped even though one of the pumps had restarted. AECL was requested to simulate the zone-pump failure in the absence of both the SDS-2 trip and the restarting of the pump to determine if the control-system response would be sufficient to prevent fuel dryout.

The RRS actions were modelled using the *CERBRRS module of RFSP-IST, version 3-00-05HP. The *CERBRRS module solves the neutron-kinetics equation in two neutron-energy groups and three spatial dimensions. The module also simulates the action of the CANDU 6 RRS based on the rules of the Gentilly 2 RRS model. The spatial flux distribution is calculated at 0.5-s intervals, taking into account the action of the RRS. During each time step, the RRS calculation updates the information on power error, reactivity-device positions, and core configuration. This information is then passed to the neutronics calculation, which provides the updated neutron flux and power distribution required for the next RRS calculation. In this particular analysis, modifications were made to *CERBRRS to disable the RRS control of the liquid zone controllers (effectively removing the zone-control-pump action) while retaining the remaining functionality of the RRS. This allowed the zone fills to be input by the analyst at each time step during the transient to simulate the redistribution of the water between the zone compartments after the isolating valves have closed. However, the action of the RRS on the mechanical control absorbers (MCA) remained automatic.

Cernavoda 1 Operations provided an RFSP direct-access file corresponding to a reactor snapshot on the day of the pump failure, with lattice properties calculated using POWDERPUFS-V in the 1.5-group Westcott convention. The following specifications were also provided for purposes of simulating the event:

1. The simulation is to start with the reactor at 100% full power (FP) in steady state.

2. The effect of the zone-control pump stoppage is to be modelled by draining the zone controllers at a constant rate of 0.9%/s for 4 s starting at t = 0s.

3. The “zone-control-system failure” setback, resulting from the zone-control pump stoppage, is to be initiated at t = 2s.

4. The modelling of the redistribution of the water in the zone compartments is to commence at t = 4 s with zones 3 and 10 draining at 0.7%/s; zones 1, 6, 8, 13 draining at 0.3%/s; and zones 2, 7, 9, 14 filling at 0.7%/s. The redistribution is to continue until all zones are either completely drained or completely filled.

5. The simulation is to end when the reactor power reaches the setback endpoint power of 60% FP. The SDS-2 trip that occurred in reality is not to be modelled.

6. The margin to onset of fuel dryout is to be determined by comparing the channel-power (CP) map to the critical-channel-power (CCP) map provided by Cernavoda 1 Operations.

Issues to note:

1. The critical-channel-power map provided by Cernavoda 1 Operations was originally obtained from an assessment for Gentilly 2, conducted by AECL in 1982. The onset of dryout occurs in a channel when the critical power ratio CPR = CCP/CP is 1 or less for that channel. In other words, the critical channel power is the fuel-channel power at which fuel dryout is expected to occur [2].

2. In the actual simulation, zone 1 did not drain at 0.3%/s after 4 s, but continued to drain at 0.9%/s. This was an input error that was detected only after the completion of the simulation, but it does not affect the outcome because the scenario calculated is in fact even more severe than the postulated scenario.

3. Specification 4 above makes no mention of any changes to the drain/fill rates of zones 4, 5, 11, or 12. Thus, these zones were assumed to continue draining at 0.9%/s. This is conservative because these zones would fill rather than drain once the isolating valves have closed. Therefore, the scenario simulated is more severe than the postulated scenario.

Figure 1 shows the locations of the liquid-zone controllers in the core and Figure 2 shows the average zone fill (AVZL) versus time. From the zone fill/drain rates given above, zones 2, 7, 9, and 14 will have completely filled while all the remaining zones will have completely drained at a time of 153.5 s. Because the fill rates do not equal the drain rates, and because not all zones started at the same fill level, some of the zones will have completely drained before others have completely filled. As a result, Figure 2 shows an increase in the AVZL starting at 52.5 s. As zones 2, 7, 9, and 14 finish filling, the AVZL begins to drop again at 75.0 s and reaches a constant value of 28.57% fill after 153.5s.

4. Simulation Results

The simulation was performed for a total transient time of 59.5 s, at which point the reactor power had dropped to 73.5% FP. The simulation was ended at this point because the information gathered showed that the minimum CPR over all fuel channels was 1.22 (see Figure 3), having occurred when the reactor power peaked at 100.21% FP at a transient time of 17 s (see Figure 4). From that instant onward, the minimum CPR of all the channels steadily increased in response to the MCA action shown in Figure 4. It was therefore not necessary to follow the transient further. The setback is indeed sufficient to prevent fuel dryout following a LZC pump failure.

It should be noted that the CCP map used for Figure 3 is that of the Nominal Reactor Overpower Protection (ROP) Case resulting from the critical-channel-power assessment of Gentilly 2 and Pt. Lepreau conducted by AECL in 1991. ROP offers protection via SDS-1 and SDS-2 against overpowers high enough to cause fuel dryout [2]. The CCP map from the assessment done in 1991 was used instead of the CCP map from the assessment done in 1982 (see section 3) because the more recent map is based on bundle powers that are consistent with the detector data used in the most recent ROP analysis for Cernavoda 1. However, for completeness, the CCP map from 1982 was also used and provided an absolute minimum CPR of 1.23. This value is slightly higher than 1.22. Therefore, the absolute minimum CPR obtained from the CCP map of the 1991 assessment is the one that is quoted since it is a more conservative value.

Since the absolute minimum CPR occurred at transient time 17 s, a CPR map at that time is provided in Figure 5. At this time in the transient all the channels exhibit their lowest CPR value, with the absolute lowest value (i.e. 1.22) occurring at channel H-7. Beyond this time the margin to dryout increases for all channels. Again, this map was generated using the CCP map from the 1991 critical channel power assessment of Gentilly 2 and Pt. Lepreau.

For the particular setback on zone-controller failure, the controlled reduction of the reactor power setpoint is to an endpoint of 60% FP at 0.1%/s. As the setpoint reduction proceeds, the power error (the difference between the measured power and the setpoint, as displayed in Figure 4) builds up, demanding at first an increase in the zone-controller valve lift (which for this particular incident of pump stoppage is not permitted) followed by driving in of the mechanical control absorbers (MCA) and adjusters (if any are withdrawn). The absorbers are driven in two banks, the first bank at a power error of 1.5% and the second at a power error of 4%. Figure 6 shows the effective power error variable, PCPERR, calculated by *CERBRRS and the associated MCA movement during the transient. Figure 7 shows the rules governing travel of the MCAs. From Figure 6 the power begins decreasing as the MCAs start to enter the core at about 30 s into the transient. By the time the second bank has advanced 142.3 cm into the core the power error has dropped below 4% and the second bank comes to rest. The power error continues to fall below 1.5% as the first bank advances 172.0 cm into the core. At this point the first bank comes to rest while the second bank begins to retreat. This process of MCA insertion and removal in response to the power continues down to the setback endpoint power of 60% FP.

It should also be pointed out that during a setback induced by a LZC pump failure, the movement of water from the upper into the lower zone compartments helps to provide control for the lower half of the core while the MCAs drive in from the top. This feature was not completely accounted for in the simulation since it was assumed that zones 4, 5, 11, and 12 continued to drain until they were completely empty. Nevertheless, the onset of fuel dryout did not occur, which is demonstrated in Figure 3 by the fact that the CPR values of all the channels increased after the power peak at 17 s. Regarding the power peak, the margin between the onset of dryout (CPR = 1) and the 1.22 CPR value is slightly less than that between the onset of dryout and the minimum CPR that exists at t = 0. In other words, the minimum CPR at t = 0 is only slightly higher than 1.22, resulting in a difference between the two margins of only 0.13%. Because the CPR value at t = 0 can be interpreted as being typical for the reactor at 100% FP in steady state, the 1.22 CPR value that occurred during the power peak can be considered to provide almost the same amount of margin to dryout as exists under normal operating conditions.

4. Conclusion

The results of the simulation show that the setback by itself provides adequate margin to dryout, and that a reactor trip is not needed to protect the fuel. The minimum CPR of all fuel channels is 1.22 and occurs 17 s into the transient. After this time, MCA movement results in steadily increasing CPR values for all channels and effectively removes any possibility of fuel dryout.

7. References

[1] Chow, H.C., Delorme G., Baudouin, A., Stebbing J.D., "Simulations of Power Transients in a Loss of the Liquid-Control-system Pumps in CANDU 6 Reactors", Proceedings of the 19th Annual CNS Conference, Toronto, ON, 1998 Oct. 18-21.

[2] Pitre, J.S., "Regional Overpower Protection in CANDU Reactors", Journal of the Canadian Association of Physicists (Conference Issue), 1999 May/June.

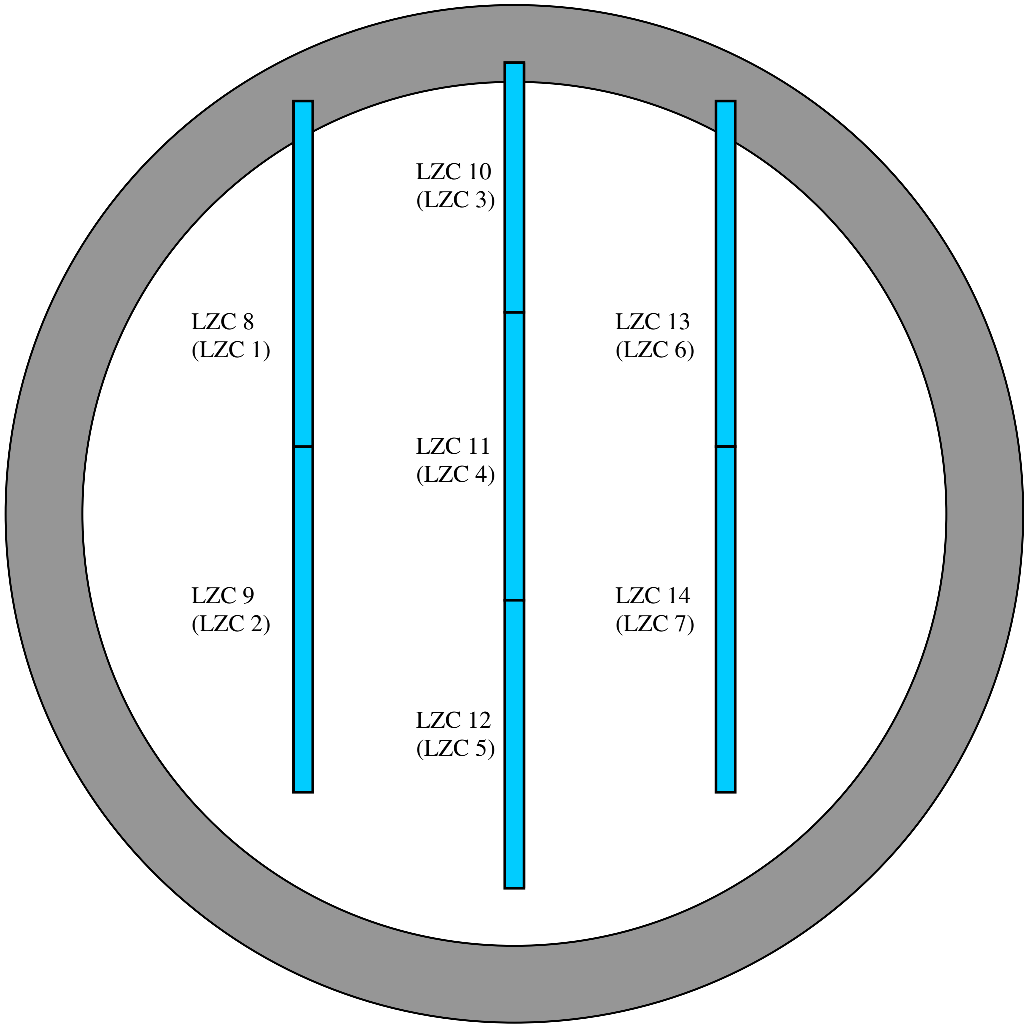

Figure 1. Liquid-zone controller (LZC) locations in the core as viewed from the pressurizer end. Zone controllers located at the other end (i.e. away from the pressurizer) are given in brackets.

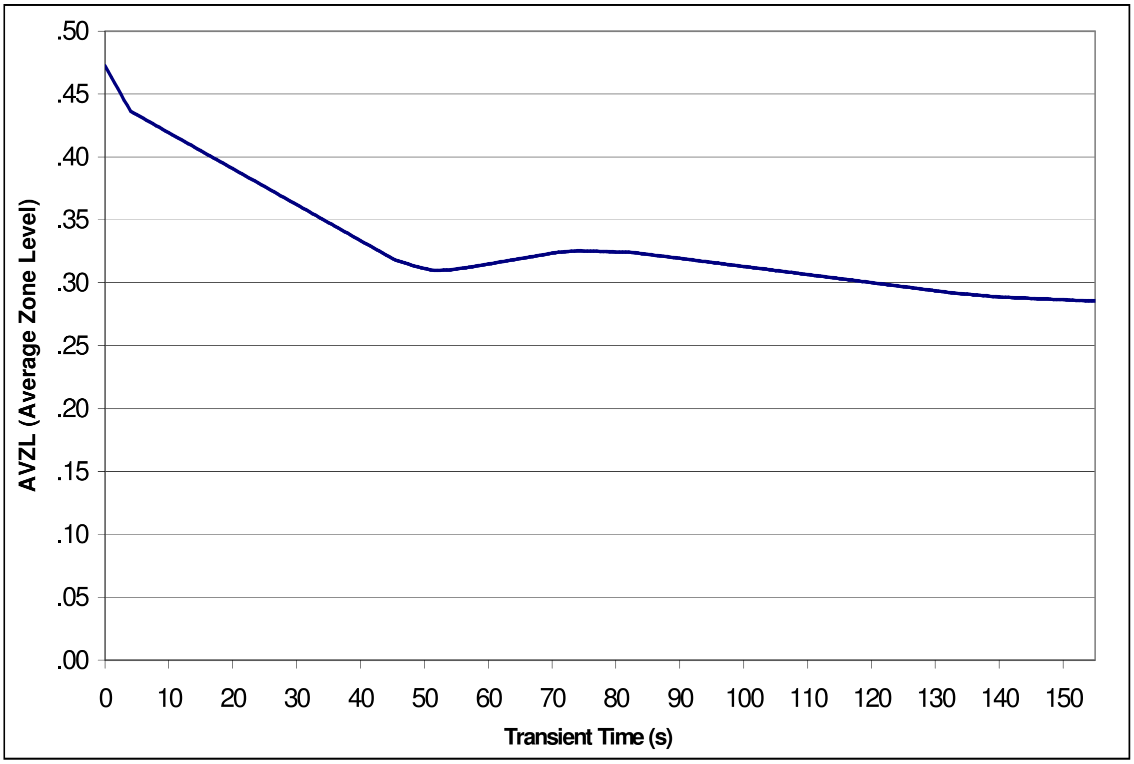

Figure 2. AVZL versus transient time. At 153.5 s, zones 2, 7, 9, and 14 have completely filled while all remaining zones have completely drained. Beyond 153.5 s, the AVZL remains constant at 0.2857. The rise in the AVZL at 60s occurs even though the pumps have stopped because water is leaking into some of the upper zone compartments from additional compartments located outside of the core above the bulkheads.

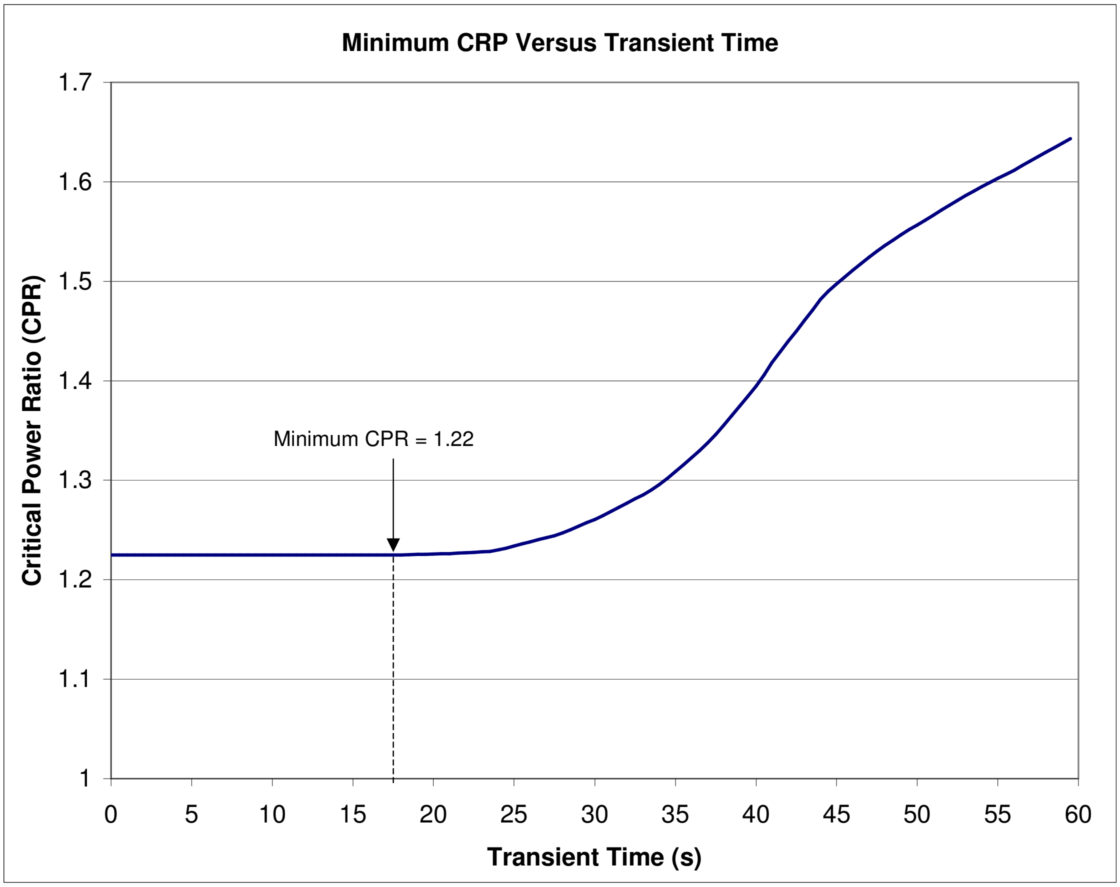

Figure 3. The minimum CPRs in the core over the course of the transient using the CCP map from the critical channel power assessment of Gentilly 2 and Pt. Lepreau conducted by AECL in 1991. The lowest, or absolute, minimum value is 1.22 and occurs at 17 s, when the reactor power is at its highest value.

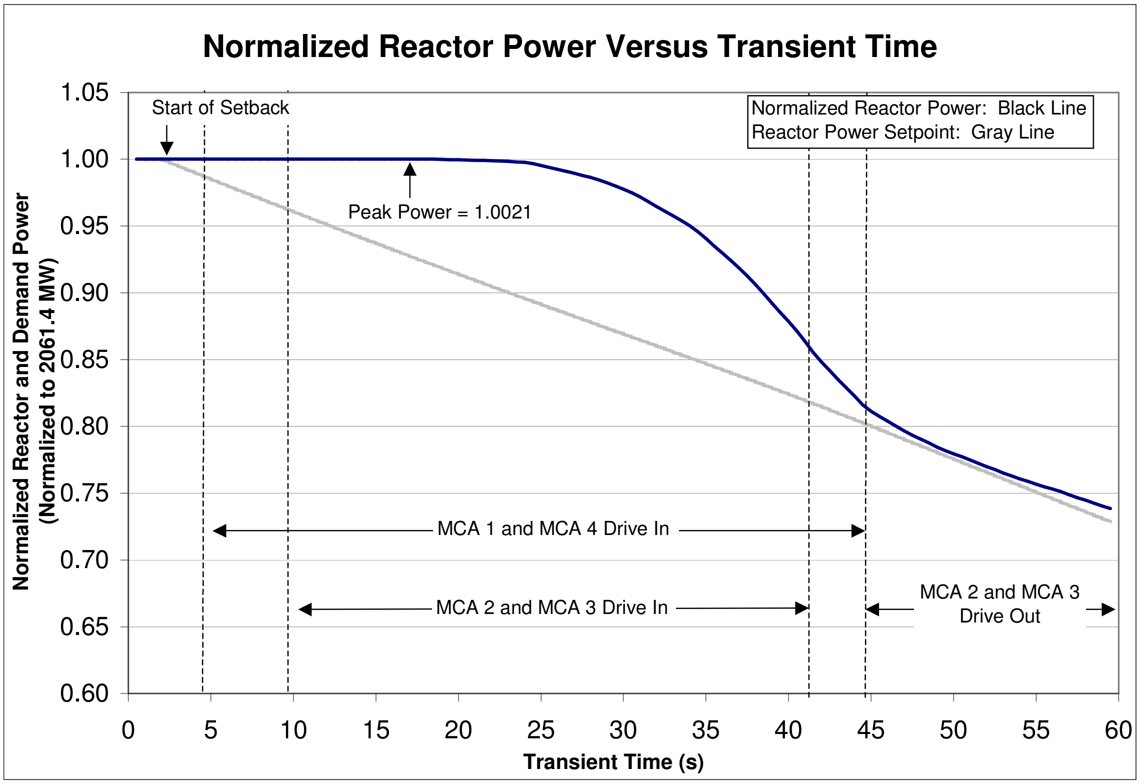

Figure 4. Shown are the normalized reactor power (or measured power) and the reactor power setpoint over the course of the liquid-zone-control pump failure simulation. The reactor power is normalized to the 100% FP value of 2061.4 MW at time 0. At time 17 s, the power peaks at 100.21% FP (2061.83 MW), resulting in an absolute minimum CPR value of 1.22, occurring in fuel channel H-7. The grey line represents the reduction, at a pre-specified rate, of the reactor power setpoint that occurs during the setback. The difference between the measured power and the power setpoint is termed the power error and determines the MCA action. Specifically, the first MCA bank (MCAs 1 and 4) drives into the core when the power error is 1.5%, followed by the second bank (MCAs 2 and 3) when the power error reaches 4%. As the MCAs drive in, the measured power decreases and follows the power setpoint down to the endpoint of 60% FP.

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22
A									1.71	1.67	1.82	1.69	1.87	1.76								
B						1.74	1.50	1.66	1.58	1.55	1.63	1.70	1.61	1.63	1.71	1.55	1.68					
C					1.58	1.59	1.49	1.45	1.41	1.39	1.56	1.44	1.43	1.41	1.51	1.50	1.51	1.50				
D				1.55	1.47	1.48	1.37	1.34	1.32	1.34	1.36	1.35	1.39	1.44	1.38	1.36	1.41	1.41	1.47			
E			1.68	1.43	1.50	1.39	1.33	1.28	1.26	1.35	1.43	1.33	1.27	1.33	1.38	1.43	1.35	1.42	1.37	1.59		
F			1.50	1.64	1.50	1.37	1.29	1.34	1.26	1.29	1.33	1.32	1.28	1.34	1.27	1.29	1.32	1.45	1.49	1.49		
G		1.58	1.55	1.41	1.41	1.32	1.24	1.34	1.28	1.33	1.31	1.36	1.27	1.31	1.24	1.23	1.34	1.41	1.39	1.59	1.58	
H		1.65	1.53	1.56	1.46	1.37	1.22	1.31	1.31	1.31	1.28	1.37	1.29	1.30	1.27	1.30	1.30	1.40	1.40	1.56	1.62	
J	1.77	1.59	1.48	1.40	1.37	1.32	1.34	1.27	1.30	1.30	1.39	1.33	1.45	1.36	1.30	1.28	1.30	1.31	1.34	1.55	1.59	1.52
K	1.54	1.61	1.40	1.32	1.41	1.34	1.25	1.29	1.40	1.34	1.30	1.36	1.50	1.33	1.40	1.34	1.36	1.32	1.28	1.41	1.47	1.50
L	1.61	1.51	1.48	1.37	1.34	1.32	1.27	1.35	1.40	1.30	1.33	1.38	1.35	1.43	1.37	1.33	1.30	1.43	1.35	1.40	1.52	1.60
M	1.59	1.59	1.37	1.29	1.32	1.27	1.24	1.33	1.40	1.34	1.32	1.44	1.38	1.37	1.47	1.37	1.35	1.29	1.28	1.43	1.47	1.64
N	1.70	1.53	1.46	1.31	1.31	1.23	1.27	1.28	1.35	1.38	1.30	1.31	1.41	1.34	1.37	1.38	1.28	1.31	1.28	1.39	1.50	1.82
O	1.90	1.61	1.43	1.36	1.30	1.33	1.35	1.28	1.28	1.30	1.35	1.27	1.36	1.37	1.30	1.26	1.25	1.27	1.27	1.44	1.59	1.73
P		1.89	1.74	1.44	1.38	1.27	1.26	1.28	1.30	1.33	1.28	1.29	1.35	1.34	1.31	1.29	1.30	1.40	1.42	1.62	1.65	
Q		1.78	1.73	1.59	1.42	1.34	1.25	1.29	1.38	1.37	1.40	1.33	1.45	1.33	1.32	1.37	1.40	1.52	1.54	1.69	1.69	
R			1.76	1.66	1.56	1.48	1.36	1.32	1.39	1.39	1.42	1.39	1.38	1.44	1.33	1.33	1.47	1.58	1.66	1.79		
S			1.92	1.81	1.64	1.53	1.45	1.36	1.35	1.44	1.37	1.41	1.49	1.38	1.37	1.48	1.53	1.79	2.01	1.98		
T				1.91	1.76	1.75	1.65	1.57	1.42	1.43	1.38	1.39	1.43	1.50	1.54	1.54	1.77	1.87	2.01			
U					1.98	1.76	1.85	1.86	1.70	1.57	1.49	1.52	1.53	1.60	1.70	1.76	1.77	2.09				
V						2.39	2.14	1.86	1.93	1.67	1.62	1.66	1.67	1.72	1.84	2.05	2.17					
W									2.10	1.95	1.88	1.94	1.90	2.10								

Figure 5. CPR map at transient time 17 s using the CCP map from the critical channel power assessment of Gentilly2 and Pt. Lepreau conducted by AECL in 1991. The lowest value is located in channel H-7.

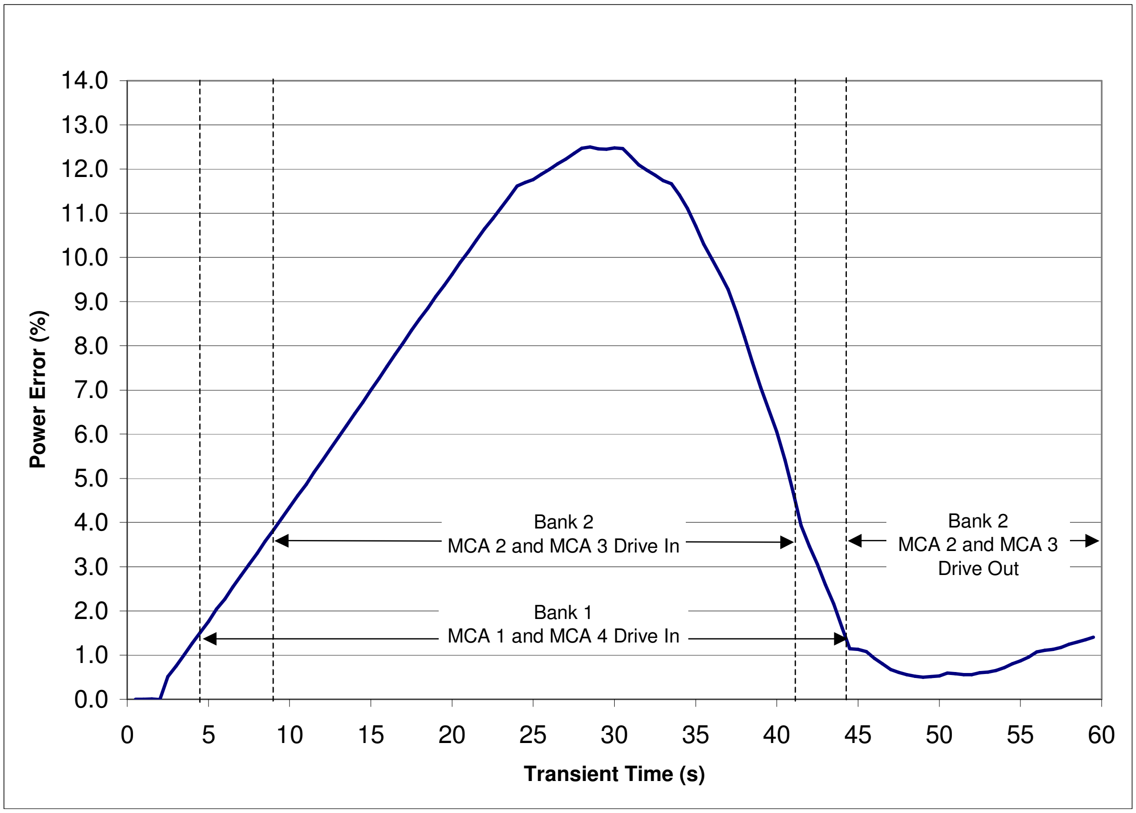

Figure 6. Effective Power Error over the course of the transient with corresponding MCA movement.

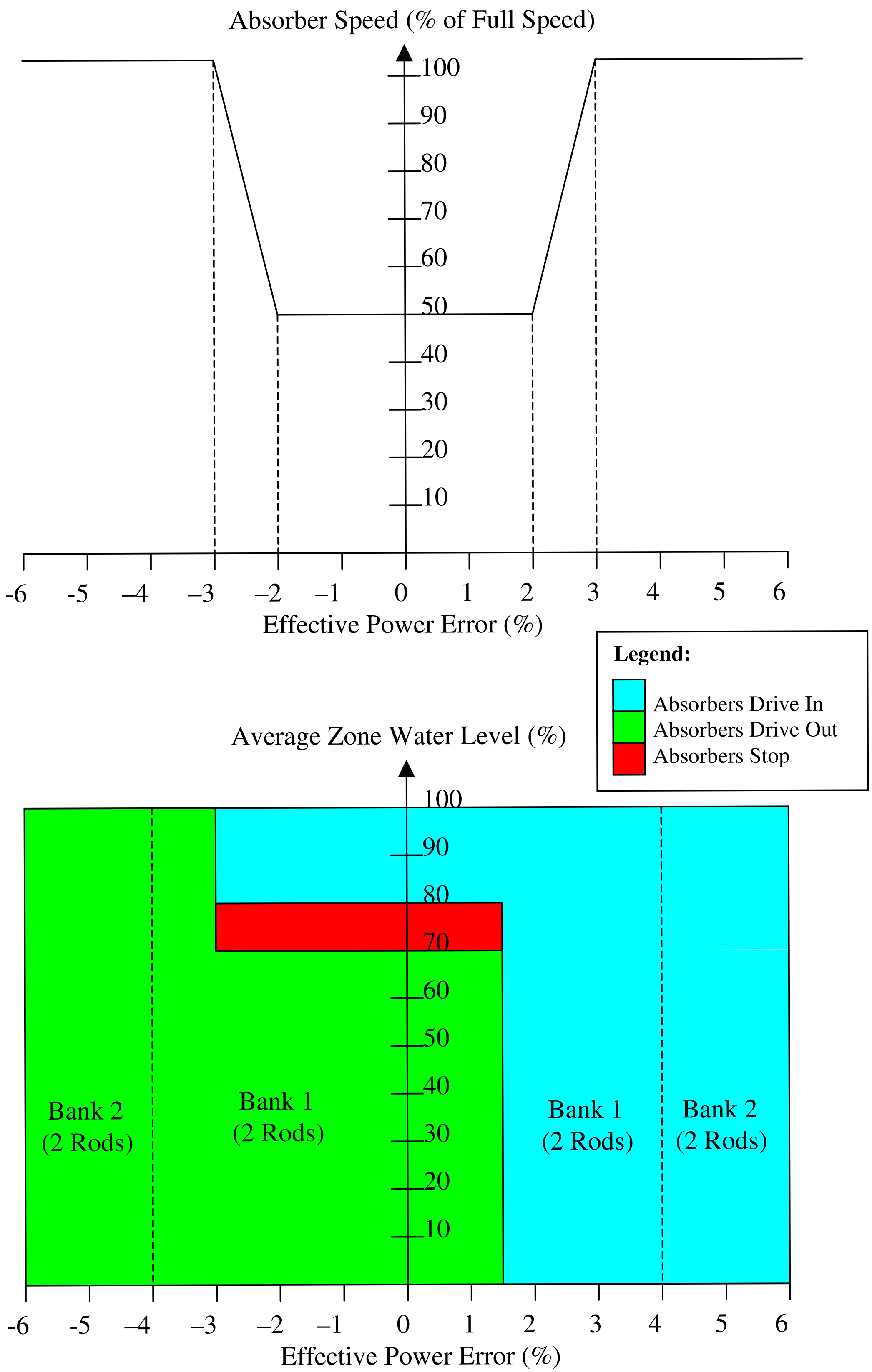

Figure 7. MCA Rod Drive and Speed Control [1]