Proceedings of the Korean Nuclear Society Spring Meeting
Cheju, Korea, May 1996

Modelling of CANDU NPP Reactor Regulating System using CATHENA

Cheon Hwey Cho, Hee Cheol Kim, Chul Jin Choi, Sang Yong Lee
Korea Atomic Energy Research Institute

A.C.D. Wright
Atomic Energy of Canada Limited

Abstract

A CATHENA model for the reactor regulating system is developed and tested independently. A CATHENA plant model is created by combining this model with the reference CATHENA model which has been developed to analyze a loss-of-coolant accident (LOCA) for the Wolsong 2 generating station. This model is intended to provide a trip coverage analysis capability. The CATHENA reactor regulating system model includes the demand power routine, the light water zone control absorbers, mechanical control absorbers and adjusters. The CATHENA model is tested for steady state at 103% full power. A postulated accident transient (small LOCA) was also tested. The results show that the control routines in CATHENA were set up properly.

1. Introduction

CATHENA is a one-dimensional, two-fluid thermalhydraulic computer code. The CATHENA code(1 to 3) has been developed over a number of years by Atomic Energy of Canada Limited (AECL) for analysis of postulated reactor upset conditions in CANDU reactors. This code has mainly been used for analysis of loss of coolant accidents.

A CATHENA model is developed for the reactor regulating system (RRS) and tested independently. The heat transport (HT) pressure and inventory system was previously modelled in CATHENA for the purpose of the trip coverage analysis(4). A CATHENA plant model is created by combining this model with the reference CATHENA model which has been developed to analyze loss-of-coolant accidents (LOCA) for the Wolsong 2 generating station. This model is intended to provide a trip coverage analysis capability. The functional requirement of the CATHENA RRS model is to reproduce the logic described in the program specifications of the corresponding control computer programs.

2. Reactor Regulating System Model

The CATHENA RRS model includes the demand power routine and the reactivity mechanism control routines which include the light water zone control absorbers, mechanical control absorbers and adjusters. The reactor regulating system program specifications(5 to 9) are used to develop the CATHENA models of the control programs.

2.1 Light Water Zone Control Absorbers

The main method for controlling reactor power is adjustment of average water level in the zone controllers. In a CANDU reactor there are fourteen independently controllable compartments to control reactor power. The zone water level and hence reactivity is adjusted via a flow control valve which regulates water inflow over the range 0 – 0.9 l/s. In the actual reactor, flux tilts are possible resulting in some variation in the water levels of the individual zones. In the CATHENA zone control model, there is no spatial representation because all zones are modelled as one zone. The total reactivity worth of all zone controllers used in the CATHENA model is 7.106 mk.

The liquid zone control valve position in the CATHENA RRS model is calculated from the demand valve lift by numerically integrating the following equation.

$$\frac{d^2P}{dt^2} + 2\alpha\omega \frac{dP}{dt} + \omega^2 P = \omega^2 LIF$$

where P = valve position
t = time (seconds)
α = valve damping coefficient
ω = valve natual frequency
LIF = valve lift

The new valve position, which is calculated for each internal time step, is used to determine the flow into the zones through the use of a table of flow versus valve opening. The new flow is used to determine the change in zone level using:

$$LZCLEV^n = LZCLEV^{n-1} + (FLOW - FLOW_{drn}) \times \Delta t$$

where $LZCLEV$ = normalized zone level which is limited between 0 and 1
$FLOW$ = normalized flow into the zones
$FLOW_{drn}$ = normalized drain flow from the zones
Δt = internal time step

The zone reactivity worth (LZCREA) is determined using a table of zone level versus reactivity worth.

2.2 Mechanical Control Absorbers

Two banks (four solid control absorbers) with a total reactivity worth of 9.0 mk (in equilibrium fuel) are used in CATHENA RRS model. The absorbers drive logic is governed by the switching lines in Figure 1. As seen in Figure 1, the number of banks in motion is a function of both the effective power error and the average light water zone level. The normalized speed at which the banks are moved is a function of the effective power error. The order in which the banks are moved is determined by whether they are being inserted or withdrawn. During insertion, bank 1 is inserted first, followed by bank 2. When withdrawing the banks, bank 2 is withdrawn before bank 1.

The position of the absorbers after the current time step is computed in the RRS model. The velocities and drive flags from the control algorithm are used to determine the new position. At maximum speed, absorber drive time for travel between the mechanical fully in and fully out end stops is approximately 150 seconds. In the case where the reactor trip is in progress, the absorber rods are dropped (drive in). If the new position of absorber is calculated(8), then the MCA reactivity worth (MCAREA) is determined using a table of normalized insertion versus reactivity worth.

2.3 Adjusters

Twenty one adjuster rods are provided for flux shaping, positive reactivity shim, and xenon override purposes. Normally fully inserted in the core for flux shaping, they are withdrawn when the average water level in the zones indicates a shortage of positive reactivity. The withdrawal of all 21 adjusters provides approximately 15 mk of reactivity, and makes it possible to start up the reactor up to 30 minutes after shutdown from full power. However, adjuster rods in CATHENA RRS for conservatism of trip coverage assessment are modelled as being divided into two banks (bank 1 and bank 2) with a total reactivity worth of 3.7 mk (in equilibrium fuel). The adjuster drive logic is governed by the switching lines in Figure 2. Adjusters drive is very similar to that of the mechanical control absorbers. As seen in Figure 2, the number of banks in motion is a function of both the effective power error and the average light water zone level. The normalized speed at which the banks are moved is a function of the effective power error. The order in which the banks are moved is determined by whether they are being inserted or withdrawn. During withdrawing the banks, bank 1 is withdrawn first, followed by bank 2. When inserting the banks, bank 2 is inserted before bank 1.

The position of the adjusters after the current time step is computed in RRS model. The velocities and drive flags from the control algorithm are used to determine the new position. At maximum speed, adjuster drive time for travel between the mechanical fully in and fully out end stops is approximately 60 seconds. If the new position of adjuster rod is calculated(9), then the adjusters reactivity worth (ADJREA) is determined using a table of normalized insertion versus reactivity worth.

3. Results and Discussion

The present CATHENA RRS model was tested for the two cases; steady–state and a small LOCA. The normal mode of operation was simulated in the two cases. Power rundown and runup transients are simulated to test the transient between of the model. However, the results of power rundown and runup transients are not included in this paper.

Figures 3 to 5 give the power, header pressure, pressurizer level and reactivity transients for 5000 seconds at 103% full power. It can be seen that all transients are very steady at 103% full power. The predicted steady state parameters are very close to the desired values.

A postulated accident transient (0.5% reactor inlet header, RIH, break) is simulated to ensure that the CATHENA RRS is modelled properly according to the steam generator pressure control program. Small LOCA is chosen because of its slow transient behaviour. For the fast transient, the operation of the reactor regulating system usually has very little effect on the results. To examine the effectiveness of the reactor regulating system, two cases (RRS operating vs. RRS frozen) are considered (Table 1).

3.1 Results for Reactor Regulating System Operating

A small LOCA simulation for a 0.5% RIH break at 103% full power was performed using CATHENA code. The normal operating conditions for the reactor regulating system and pressurizer heaters were assumed. Other assumptions such as the feed and bleed modelling and reactor outlet header (ROH) quality are given in Table 1.

The effective power error and the zone controller transients are shown in Figures 6 and 7, respectively. The effective power error was used in the reactivity mechanism routines for control purposes. The zone level was increased by adjusting the lift of the inflow valve proportional to the effective power error. Figure 8 shows that at the initiation of the small break, the reactivity coefficient due to fuel temperature change was negative, while the reactivity coefficient due to coolant density (void) change was positive. However, the overall reactivity worth begins to increase, due to voiding in the core from the beginning of transients. To compensate for this positive reactivity worth, the reactor regulating systems begin to adjust reactor power as can be seen in Figures 7 and 8.

The movement of the mechanical control absorbers and the adjusters were not significant during the transients, since the zone controllers had enough negative reactivity worth to maintain constant reactor power (see Figure 9). It can be seen from this analysis that the zone controller is the dominant method of controlling the reactor power until the reactor trips.

Table 1 also gives the initial conditions and results for 0.5% RIH small LOCA from 103% full power and fouled steam generator with equilibrium fuel. SDS1 low HT pressure trip was credited. The transient results for CATHENA are shown in Figure 9. For 0.5% RIH break size, the reactor was tripped at about 435 seconds. The maximum fuel centreline temperature and sheath temperature are predicted to be about 1400 °C and about 350 °C, respectively.

3.2 Results for Reactor Regulating System Frozen

For a simulation of a small LOCA where the RRS is assumed to be frozen, allowing power to increase, the behaviour is somewhat different. Table 1 gives the initial conditions and results of the analysis for the case of RRS frozen. The results were also compared with those for RRS operating case.

The normalized power and the header pressure transients are shown in Figure 10. As seen in Figure 10, the power begins to increase slowly, reaching trip setpoint at about 70 seconds. The reactor was tripped on high power (trip setpoint of 115% full power). The pressure also increases slowly as the power increase, due to voiding in the core.

4. Conclusion

CATHENA models have been prepared for the reactor regulating system. The models have been combined with the reference CATHENA model which has been developed to analyze a loss-of-coolant accident (LOCA) for the Wolsong 2 generating station. The resulting CATHENA plant model was tested for steady state at 103% full power. A postulated accident transient (small LOCA) was also tested. The results show that the control routines in CATHENA are set up properly

5. References

1. D.J. Richards, "CATHENA MOD 3.2n THEORETICAL MANUAL AND INPUT REFERENCE", THD-CD-012, May 1990.
2. B.N. Hanna, Editor, "CATHENA Input Reference", AECL–WL Report: RC–982–4/ COG–93–140, Rev. 1, May 1993.
3. J.P. Mallory, Editor, "CATHENA GENHTP Input Reference", AECL–WL Report: RC–982–5/ COG–93–140, Rev. 1, May 1993.
4. H.S. Lim, C.H. Cho, J.H. Choi, and S.Y. Lee, "CANDU–6 Pressure and Inventory Control System Modelling using CATHENA", KAERI/TR–563/95, November 1995.
5. M. Jankovic, "Program Specification – Steam Generator Pressure Control", Ps-79-200, Rev. 0, December 1987.
6. A. Keates, "Program Specification – Demand Power Routine", Ps-86-102, Rev. 0, May 1992.
7. A. Keates, "Program Specification – Light Water Zone Control Absorbers", Ps-86-103, Rev. 0, May 1992.
8. A. Keates, "Program Specification – Mechanical Control Absorbers", Ps-86-106, Rev. 0, May 1992.
9. A. Keates, "Program Specification – Adjusters", Ps-86-105, Rev. 0, May 1992.

Table 1 CATHENA results of 0.5% RIH break at 103% FP

Parameters	CATHENA	CATHENA
Initial Reactor Power	103% FP	103% FP
Reactor Regulating System	operating	frozen
Pressurizer Heaters	operating	operating
Feed and Bleed	not credited	not credited
Initial ROH Quality	4.5 %	4.5 %
Initial Break Discharge (kg/s)	90.8 kg/s	90.8 kg/s
Initial Fuel to Coolant Power	2111 MW	2111 MW
SDS1 Low HT System Pressure Trip Time	about 435 s	–
SDS1 High Power Trip Time	–	about 70 s

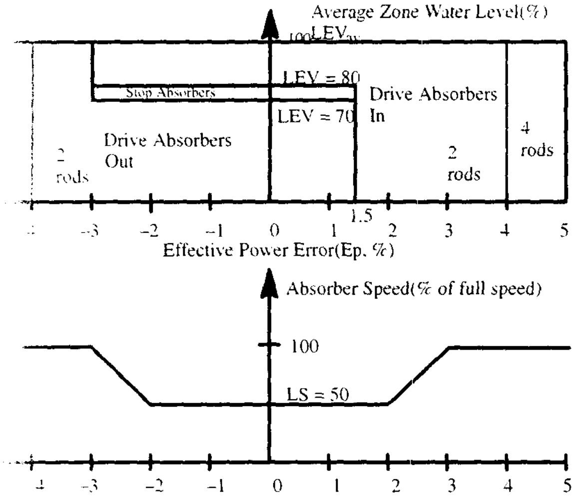

Fig. 1 Absorber Drive and Speed Control

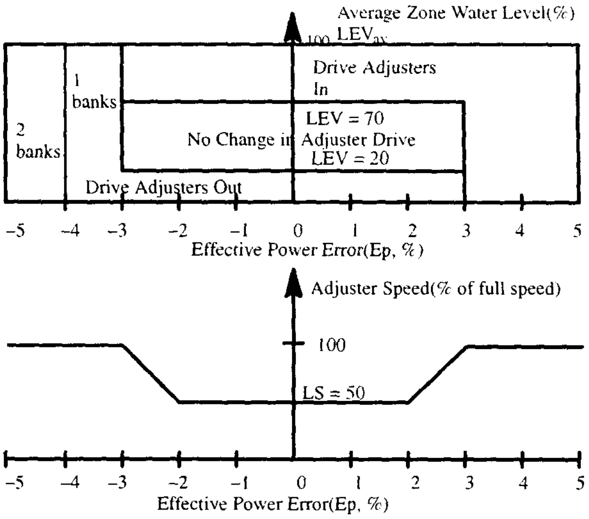

Fig. 2 Adjuster Drive and Speed Control

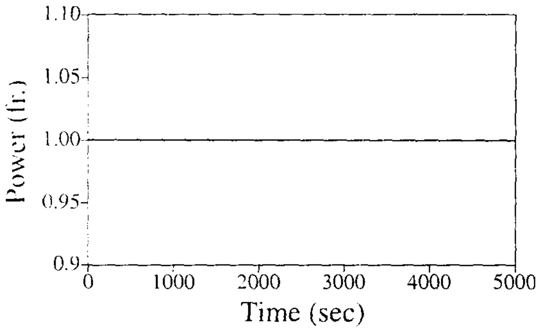

Fig. 3 Power Transients in Steady State

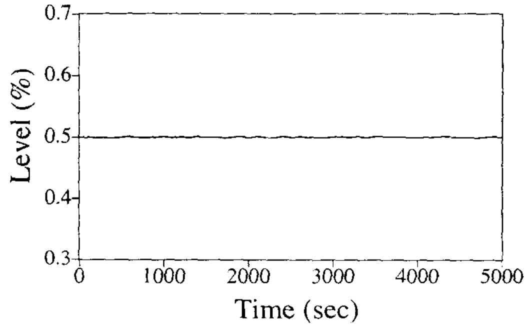

Fig. 4 Zone Controller Level in Steady State

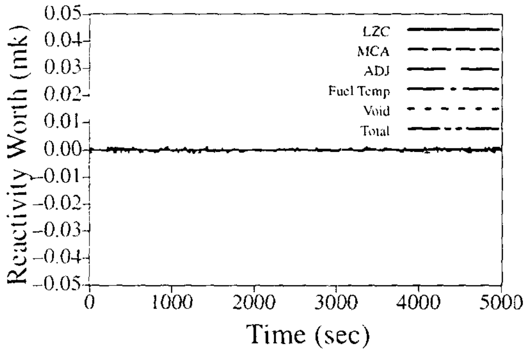

Fig. 5 Control System, Coolant Temperature and Void Reactivity Worths in Steady State

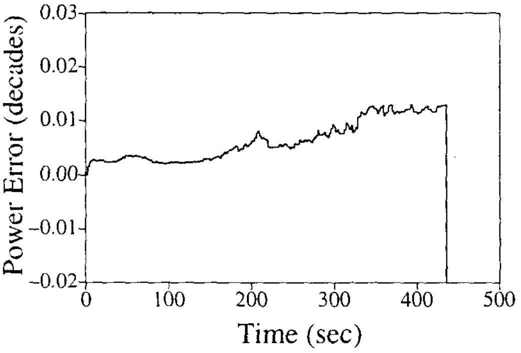

Fig. 6 Power Error Transients – 0.5% RIH Break,103%FP, RRS Operating Low Pressure Trip

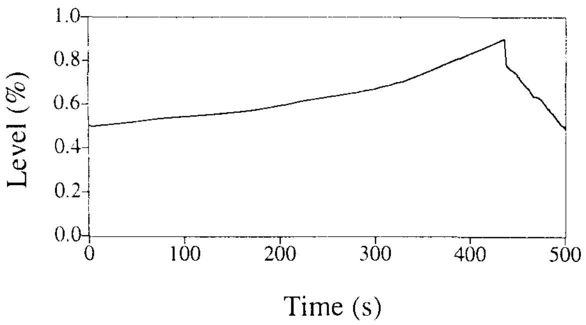

Fig. 7 Zone Controller Level – 0.5% RIH Break, 103%FP, RRS Operating, Low Pressure Trip

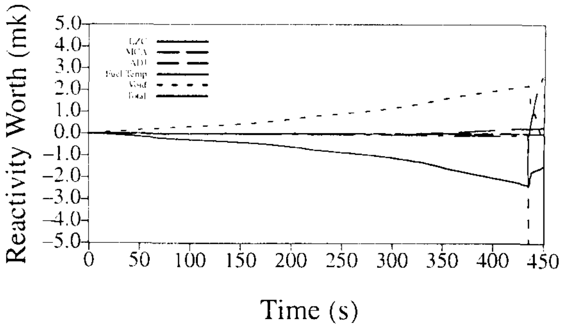

Fig. 8 Reactivity Change Transients – 0.5% RIH Break,103%FP, RRS Operating, Low Pressure Trip

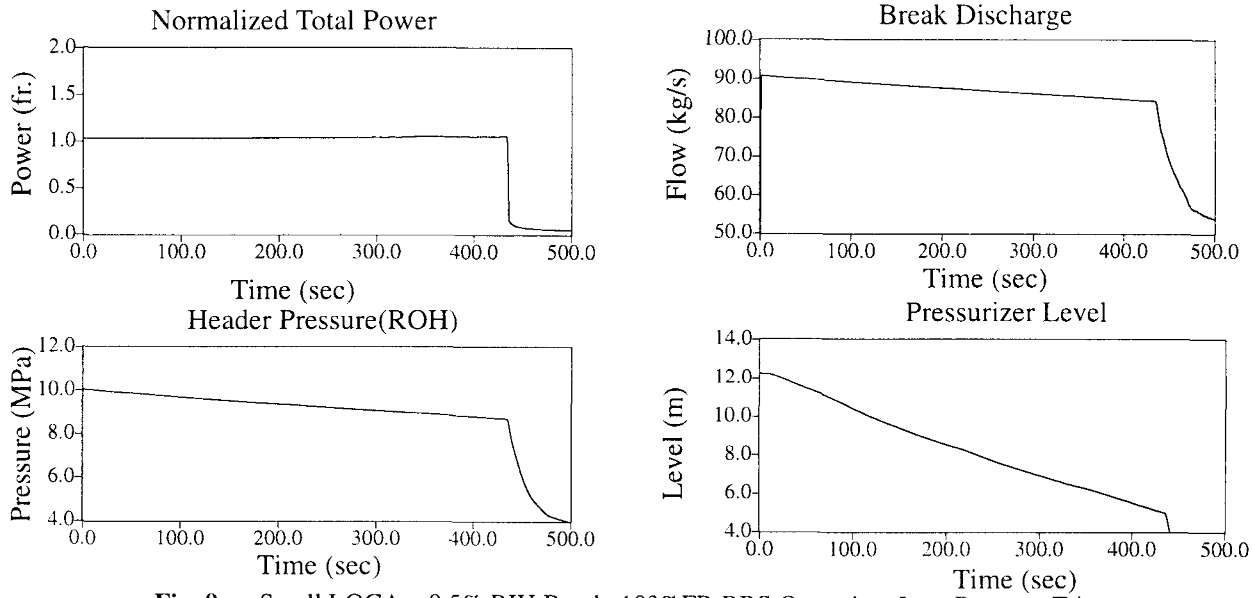

Fig. 9 Small LOCA – 0.5% RIH Break, 103%FP, RRS Operating, Low Pressure Trip

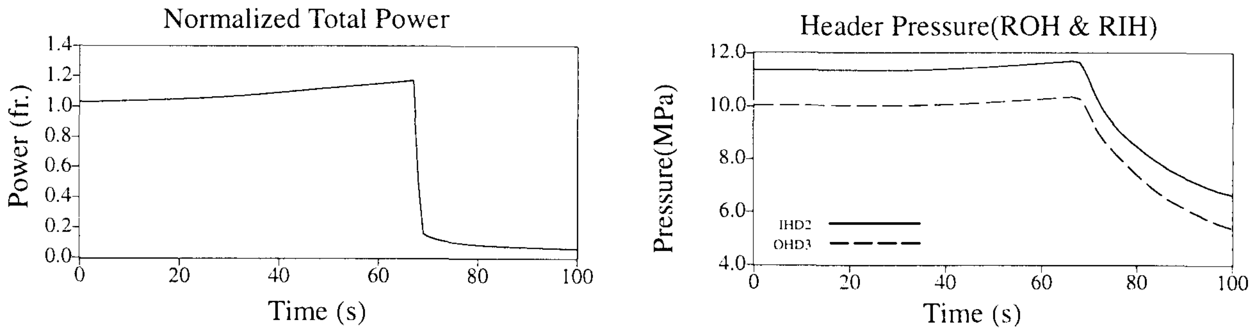

Fig. 10 Small LOCA – 0.5% RIH Break, 103%FP, RRS Frozen, high neutron power Trip