Proceedings of the Korean Nuclear Society Autumn Meeting
Seoul, Korea, October 2001

CATHENA Code Validation with Wolsong 4 Plant Commissioning Test Data

Jong Ho Choi, Hae Ryong Hwang, and Jong Tae Seo

Korea Power Engineering Company, Inc.
150 Duckjin-Dong, Yusong-Gu, Daejeon, Korea, 305-353

Byung Joo Min

Korea Atomic Energy Research Institute
150 Duckjin-Dong, Yusong-Gu, Daejeon, Korea, 305-353

Abstract

The turbine trip test at 100 % full power performed during Wolsong 4 commissioning test period is simulated with CATHENA code to validate its application for plant transient analysis. The purpose of the turbine trip test is to check the correct actuation of condenser steam discharge valves and atmospheric steam discharge valves without opening the main steam safety valve and to show the plant can be maintained in the poison prevent mode. The turbine trip test at 100 % full power shows that the capacity of steam discharge valves is enough to prevent the MSSV opening while maintaining the plant in the poison prevent mode. The CATHENA simulation results show very good agreement with plant test data. Therefore, it is concluded that the CATHENA modeling for various plant systems including control programs are correct and the CATHENA code is appropriate to simulate CANDU plant transients.

1. Introduction

The CATHENA[1] is an one-dimensional, two fluid thermalhydraulic computer code developed for safety analysis of CANDU reactors. The CATHENA model includes major systems and components necessary for transient analysis including the primary heat transport system, the secondary heat transport system, the pressure and inventory control system, the emergency core cooling system, the shutdown systems No.1 and No.2, and the related plant control programs. Although the current CATHENA model includes major systems and components necessary for safety analysis, additional models are required in order to simulate the real plant behavior[2]. Therefore, the plant control systems as shown in Figure 1 are newly modeled including the heat transport pressure and inventory control system, the steam generator level and pressure control system, and the reactor regulating system. The turbine trip test at 100 % full power (FP) performed during Wolsong 4 commissioning test period is simulated with CATHENA code. The purpose of this test is to check the correct actuation of condenser steam discharge valves (CSDVs) and atmospheric steam discharge valves (ASDVs) without opening the main steam safety valve (MSSV). Another purpose is to show the plant can be maintained in the poison prevent mode even after the turbine trip[3]. This test is the best one to validate the CATHENA code since it involves relatively strong thermalhydraulic transient including the various actions from the plant control program.

2. Overall Plant Control Scheme

Figure 1 shows the overall plant control scheme for Wolsong nuclear power plant unit 4. The major control program includes the reactor regulating system (RRS), the heat transport system pressure and inventory control (HTS P&IC) program, the steam generator pressure control (SGPC) program and the steam generator level control (SGLC) program.

2.1 Reactor Control

Reactor power is controlled to a given setpoint by means of the reactivity control devices, which include the liquid zone controllers, the adjusters and the mechanical control absorbers. The liquid zone controllers are the primary control devices, and perform flux tilt control as well as reactor bulk power control. The adjusters are normally fully inserted in the core and are withdrawn for positive reactivity shim purposes when the reactivity demand exceeds the capabilities of the liquid zone controllers. Similarly, the mechanical control absorbers are negative reactivity shim, normally withdrawn from the core. The adjusters are generally required during startup and after power reductions to overcome the buildup of xenon poison. The mechanical control absorbers are required for controlled power reductions to help overcome the negative power coefficient of reactivity during long setbacks with fresh fuel, and for quick reductions of power under normal conditions.

2.2 HTS Pressure and Inventory Control

The pressure in reactor outlet header (ROH) is maintained at the desired value by controlling the pressure of the pressurizer steam space using the electric heaters and the pressurizer steam bleed valves. The HTS inventory control includes the calculation of pressurizer level setpoint and the feed/bleed flow.

2.3 Plant Loads Control

The steam flow to turbine, and therefore turbine power, is controlled by the Mark-V controller acting on the governor valves (also called control valves). The Mark-V is a computerized triplicated controller, in which electrical signals of turbine speed, load reference positions, load limiting and turbine unloading are combined to give a governor valve position demand.

The condenser steam discharge valves are controlled by steam generator pressure control program. The capacity of total 12 CSDVs is 100% steam flow at normal operation pressure. These valves are always on steam generator pressure control duty, with an opening based on a feedforward term proportional to the mismatch between reactor power and generator load, and a feedback term proportional to steam generator pressure error. Normally, a pressure offset term is included to bias the valves closed, but this term is removed during upset conditions when CSDVs operation is intended.

The atmospheric steam discharge valves are under the control of steam generator pressure control program and are always on pressure control duty, with an opening proportional to a feedforward term, steam generator pressure error, normally with an offset in the pressure setpoint. The capacity of total 4 ASDVs is 10% steam flow at normal operation pressure.

2.4 Steam Generator Pressure Control

The steam generator pressure control (SGPC) program has two main functions:

a. To control the warmup or cooldown of the heat transport system at a specified, constant temperature rate by changing the steam generator pressure setpoint at the appropriate rate.
b. Once warmup is complete, to control the steam drum pressure to a fixed setpoint of 4593 kPa(g) under all circumstances.

During normal at-power operation or in a special automatic warmup mode, SGPC adjusts the reactor power setpoint to control the steam generator pressure to its setpoint. If the steam generator pressure error for any reason exceeds a defined offset, the steam discharge valves (SDVs) relieve the excess steam.

During low power operation or unusual conditions at high power, the flux power setpoint is controlled by the operator or by automatic derating condition, and steam generator pressure is controlled by adjusting the turbine load reference setpoint and the SDVs opening (alternate mode or setback).

2.5 Steam Generator Level Control

The steam generator water level is controlled by the feedwater flow. The demand lift of feedwater control valve is the sum of bias and swell term, level error term and mass balance term. The steam generator level setpoint is a function of steam generator power.

2.6 Reactor Regulating System

The reactor regulating system (RRS) is a collection of subprograms that controls the reactor flux power to its setpoint. RRS interacts with SGPC through one of its subprograms, demand power routine (DPR). Other programs that have some relevance to the overall plant control scheme are the setback and stepback routines. The main input for RRS program is power demands from either SGPC or the keyboard (for manual reactor power setpoint commands).

The DPR serves three functions:

a. it determines the plant operating mode
b. it calculates the reactor flux power setpoint
c. it calculates an effective power error as the weighted sum of the difference between measured neutron flux and its setpoint and the rate of change of this difference. This effective power error signal is used by other programs within RRS to drive the reactivity control devices.

The reactor setback is a gradual power reduction, initiated on conditions that could lead to damage of equipment or to a reactor trip. The setback routine monitors a number of plant variables to see whether the requirement for a reactor setback exists.

The reactor stepback is a sudden reduction in reactor power caused by dropping the mechanical control absorbers into the reactor core. The function of the stepback is either to protect against equipment damage or to allow operation at a reduced power when the alternative may be a reactor trip.

3. CATHENA Modeling

3.1 Plant System Modeling

The CATHENA model for Wolsong 4 is shown in Figure 2. This model includes the primary heat transport system, the secondary heat transport system, a part of pressure and inventory control system, shutdown system No.1 and No.2, and related control programs. The primary side model uses two loop representation and the secondary side model covers from the deaerator storage tank to the high pressure turbine.

3.2 Steady State Simulation

Before the start of transient simulation, the real plant operating condition for 100 %FP is simulated. Table 1 summarizes the result from the CATHENA steady state simulation. The point neutronics data, the fuel temperature and the coolant density reactivity data for fresh fuel are used to represent the beginning of life (BOL) plant condition. The heat transfer coefficient in steam generator is increased to match the coolant temperature at reactor inlet header (RIH). The rated head and flow of heat transport pump are increased to raise the primary loop flow so the coolant become single phase liquid at reactor outlet header.

4. Simulation Results and Discussion

4.1 Turbine Trip Test

The turbine trip test at 100%FP was performed on June 7, 1999 during Wolsong 4 phase C commissioning test period. The purpose of this test is to verify:

a. the relief valves, both primary and secondary, do not lift
b. the plant can be maintained in poison prevent mode
c. to show that CSDVs and ASDVs operate properly

The test starts by trip turbine manually. The turbine trip generates the reactor power setback signal. The end point and the rate of the reactor power setback are 60 %FP and 1 %FP/s respectively. The test result showed that:

a. the capacity of steam discharge valves is enough to prevent the MSSV opening while maintaining the plant in the poison prevent mode
b. CSDVs and ASDVs operate as per design

4.2 Secondary System Behavior

Figure 3 compares the CATHENA predictions with the test data for the ASDVs and CSDVs behavior. The calculation of SDVs lift is performed in the steam generator pressure control program. In order to ensure that the second set of SDVs starts to open immediately after the first set has opened fully, the two sets of valves (ASDVs and CSDVs) are treated together as a composite valve. The signal is composed of the feed forward signal for power term (difference between reactor and turbine powers) and the feedback signal for pressure term (difference between steam generator pressure setpoint and measured pressure). In the poison prevent mode, CSDVs open first and the pressure offset for the feedback signal is zero. As shown in Figure 3, ASDVs are closed at about 60 seconds and CSDVs are remained at partially open state since the power term does not change. The calculated opening fraction of CSDVs is slightly higher than that for the test data since the calculated reactor power after arriving at the end point of setback remains higher than the plant data.

As shown in Figure 4, the steam flow from steam generator decreases suddenly by turbine trip, and then recovers by SDVs opening. Finally, the steam flow approaches to the value corresponding to reactor power level. Figure 5 shows the steam generator pressure transient. The pressure buildup caused by the turbine trip is limited by opening the steam discharge valves. The CATHENA simulation results match with the plant data very well up to about 60 seconds considering the fact that CATHENA does not take into account the response time for pressure measurement. The peak steam generator pressure is predicted to be 4.86 MPa(g) which is well below the lowest MSSV setpoint of 5.01 MPa(g).

Figure 6 shows the steam generator level setpoint and level transient. The level setpoint decreases continuously up to the end of reactor setback since it is a linear function of steam generator power. The CATHENA simulation shows the level maintained at higher than setpoint during the setback period.

4.3 Primary System Behavior

The turbine trip generates the reactor power setback signal. The end point and the rate of the reactor power setback are 60 %FP and 1 %FP/s respectively. As shown in Figure 7, the reactor power is gradually reduced to 60 %FP by reactor setback routine.

Figure 8 shows the pressure transient at reactor outlet header. The coolant pressure of the primary side increases initially since the heat transfer through the steam generator decreases by the increase of secondary pressure and temperature. And then, the primary pressure decreases continuously during the reactor setback period since the heat removal through steam generator is larger than the heat generation at core. The electrical heaters in the pressurizer are actuated to recover the coolant pressure to setpoint. The primary pressure starts to increase after the end of reactor setback.

The coolant temperature transient at reactor inlet header (Figure 9) is directly related to the heat transfer through steam generator. The primary temperature follows the secondary temperature transient with delay time. The CATHENA simulation shows earlier response compared to test data since CATHENA does not account the delay time for measurement.

Figure 10 shows the level transient in the pressurizer. The pressurizer level setpoint is determined by the required pressurizer mass. The coolant mass in primary circuit increases during the reactor setback period since the coolant density increases by the decrease of average coolant temperature. Therefore, the pressurizer level setpoint must be decreased. The HTS pressure and inventory control program keep the maximum bleed flow and minimum feed flow since the pressurizer level remains at higher than setpoint.

Figure 11 shows the light water level in the liquid zone controllers. The water level remains at 0.5 during the normal operation. The level increases to give negative reactivity required by reactor setback. As shown in Figure 12, the mechanical control absorbers start to move at 10 seconds since the effective power error exceeds 3%. The adjuster rods remain at fully inserted state.

5. Conclusions

The turbine trip test at 100 %FP shows that the capacity of steam discharge valves is enough to prevent the MSSV opening while maintaining the plant in the poison prevent mode. The CATHENA simulation results show very good agreement with plant test data. Therefore, it is concluded that the CATHENA modeling for various plant systems including control programs are correct and the

CATHENA code is appropriate to simulate CANDU plant transients.

6. References

1) B.N. Hanna et al., "CATHENA Theoretical Manual and Input Reference," AECL, 1995 October.
2) J.H. Choi et al., "Development of Trip Coverage Analysis Methodology," KAERI/CM-465/2000, 2001 May.
3) "Wolsong 2,3,4 Final Safety Analysis Report," KEPCO, 1995 May.

Table 1 Steady State Results for 100 %FP

Parameters	Desired Value	Pass 1	Pass 2	Pass 3	Pass 4
RIH Pressure (MPa(a))	11.35	11.55	11.55	11.55	11.55
RIH Temperature (°C)	262.5	262.8	262.9	262.8	262.9
ROH Pressure (MPa(a))	9.99	10.03	10.03	10.03	10.03
ROH Temperature (°C)	310	310.4	310.5	310.4	310.5
ROH Flow Quality (%)		0.	0.	0.	0.
Core Flow (kg/s)		2092.7	2092.5	2092.7	2092.6
Fuel Power per Pass (MW)	511.75	512.5	512.5	512.5	512.5
Pumping Power (MW)	17	17.7			
Heat to 2nd Side per SG (MW)	516	517.2	516.2	517.9	516.4
Pressurizer Level (m)	8.7	8.8			
Pressurizer Pressure (MPa(a))	9.87	9.98			
Pressurizer Temperature (°C)	309	309.7			
SG Level (m)	2.50	2.56	2.57	2.56	2.56
Steam Drum Pressure (MPa(a))	4.69	4.70	4.70	4.70	4.70
Steam Drum Temperature (°C)	260	260	260	260	260
SG Recirculation Ratio	5	5.3	5.3	5.2	5.3
Steam Flow (kg/s)	258.3	257.8	259.1	259.1	258.1
Feedwater Flow (kg/s)	258.5	258.4	257.3	260.1	257.7
Total Steam Flow (kg/s)	1033	1034.1			
Total Feedwater Flow (kg/s)	1034	1033.5			
Feedwater Temperature (°C)	187	186.9	186.9	186.9	186.9

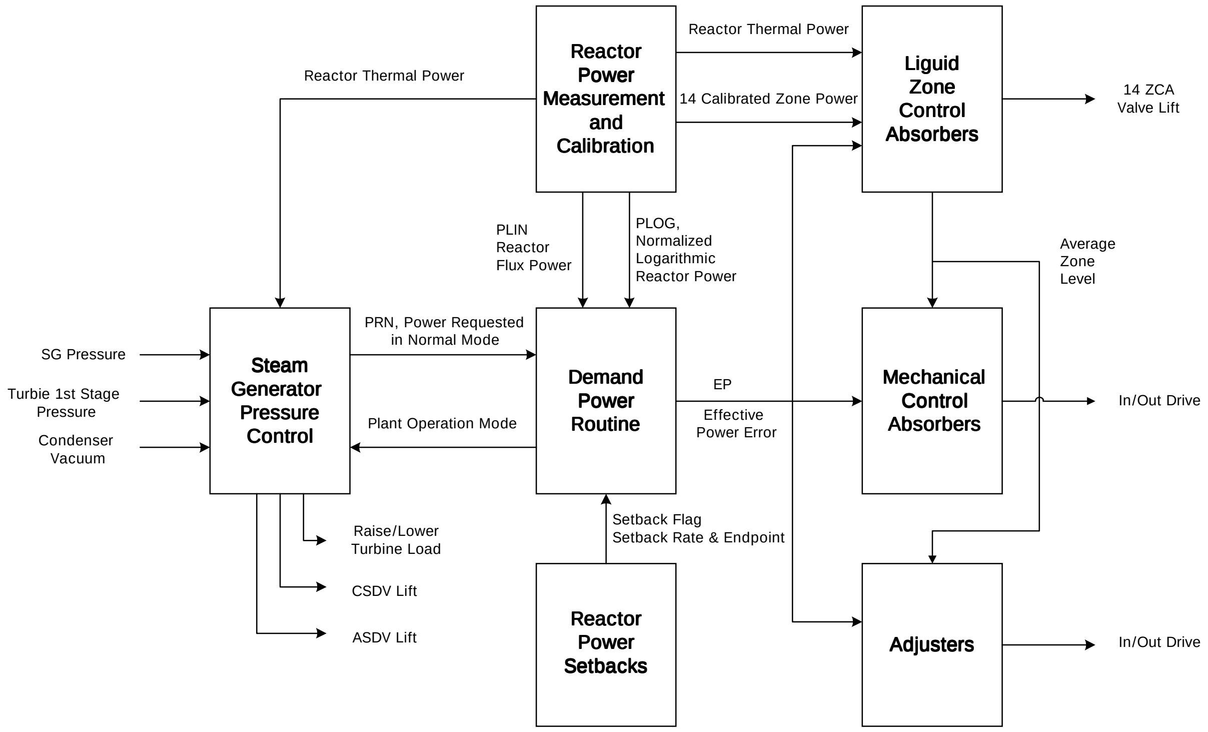

Figure 1 Overall Plant Control Scheme for Wolsong Nuclear Power Plant Unit 4

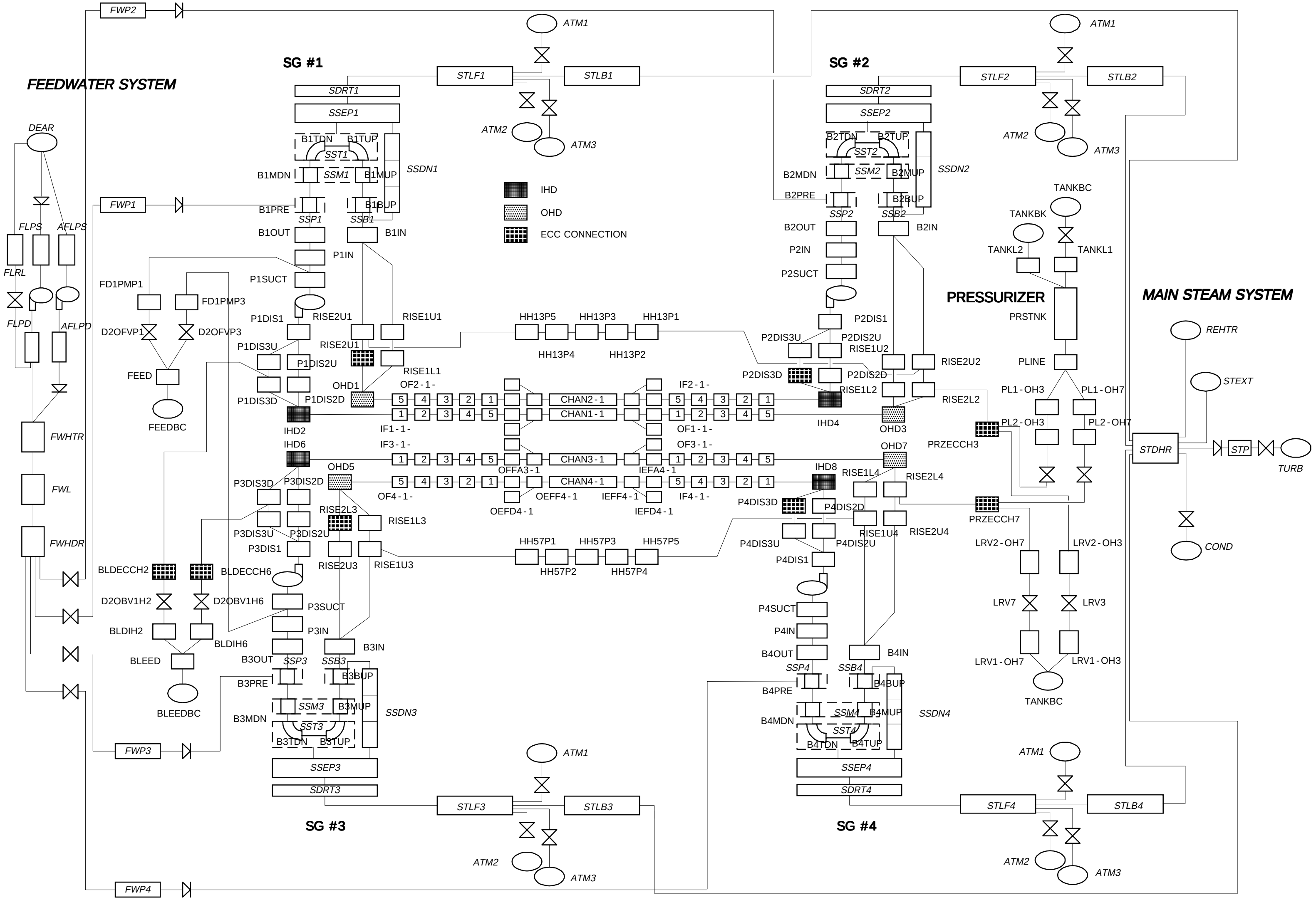

Figure 2 CATHENA Model for Wolsong 4 NPP

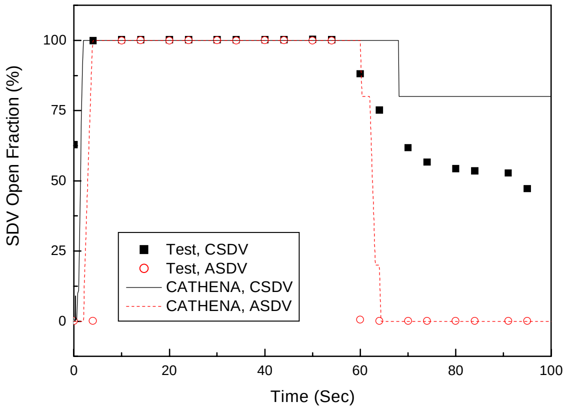

Figure 3   ASDV and CSDV Behavior

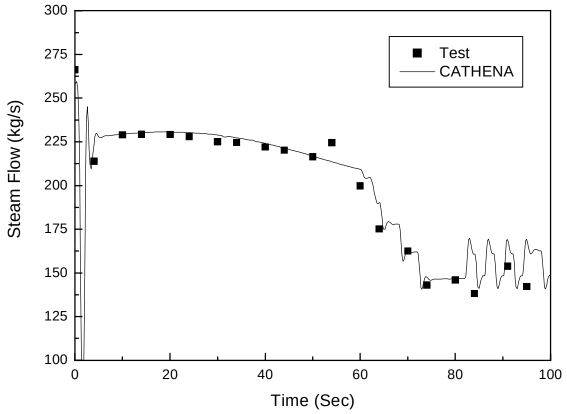

Figure 4   SG Steam Flow Transient

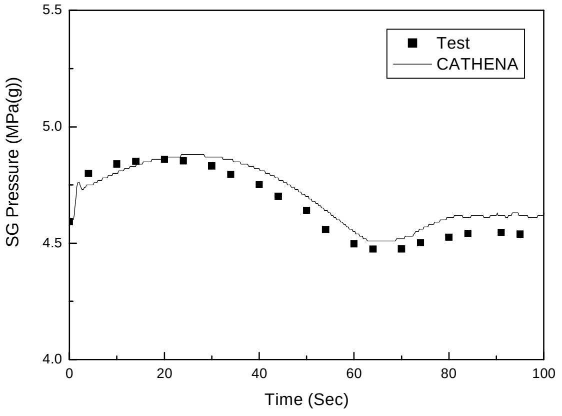

Figure 5   Steam Generator Pressure

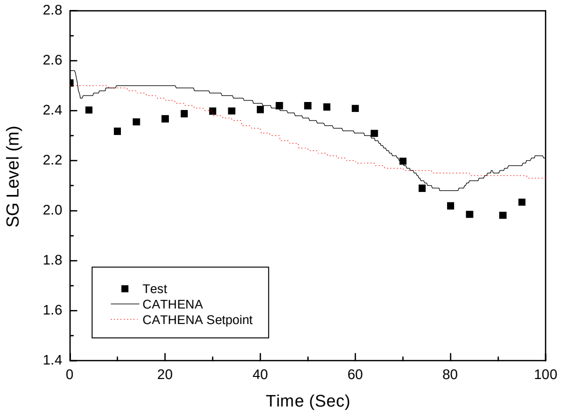

Figure 6   SG Level Transient

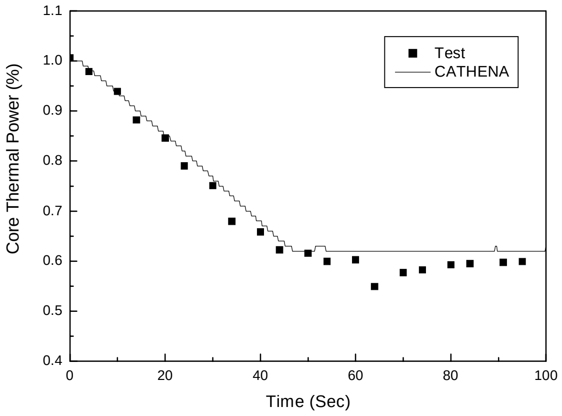

Figure 7   Reactor Power Transient

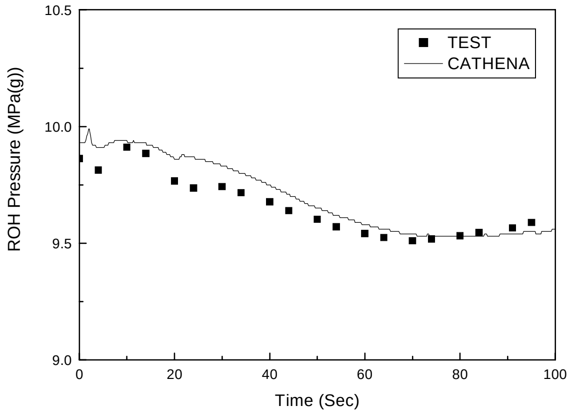

Figure 8   ROH Pressure Transient

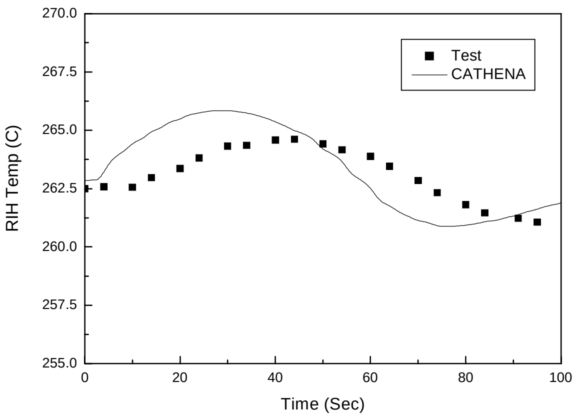

Figure 9 RIH Temperature Transient

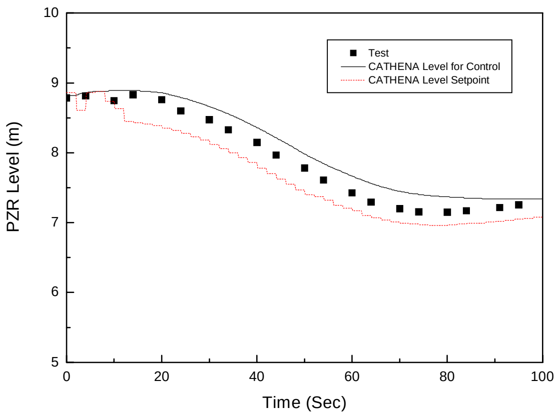

Figure 10 Pressurizer Level Transient

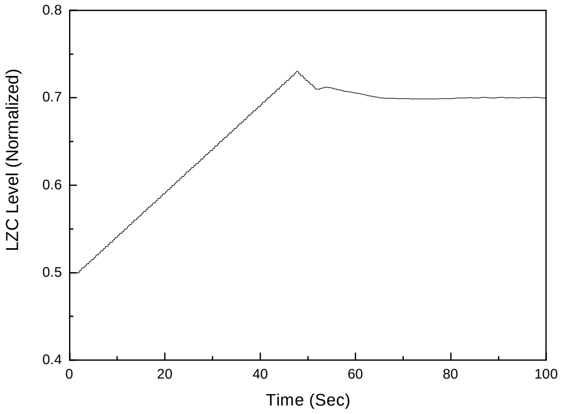

Figure 11 LZC Level Transient

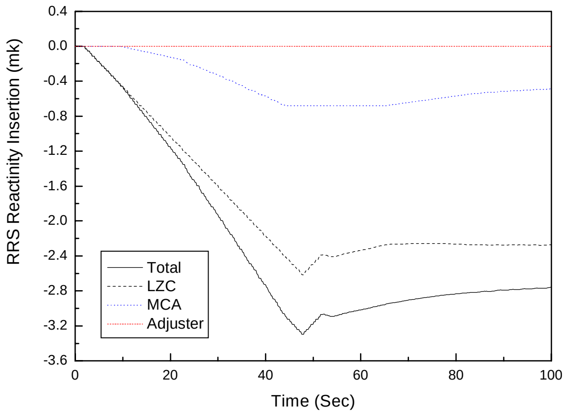

Figure 12 RRS Reactivity Insertion