RELAP5 Simulation of the Small Inlet Header Break Test B8604 Conducted in the RD-14 Test Facility

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Abstract

The RELAP5 code has been developed for best-estimate simulation of transients and accidents for pressurized water reactors and their associated systems, but it has not been fully assessed for those of CANDU reactors. However, a previous study suggested that the RELAP5 code could be applicable to simulate the transients and accidents for CANDU reactors. Nevertheless, it is indicated that there are some works to be resolved, such as modeling of headers and multi-channel simulation for the reactor core, etc. Therefore, this study has been initiated with an aim to identify the code applicability for all the postulated transients and accidents in CANDU reactors. In the present study, the small inlet header break experiment (B8604) in the RD-14 test facility was simulated with RELAP5/MOD3.2 code. The RELAP5 results were also compared with both experimental data and those of CATHENA analyses performed by AECL and the analyses demonstrated the code's capability to predict major phenomena occurring in the transient with sufficient accuracy for both qualitative and quantitative viewpoint. However, some discrepancies in the depressurization of the primary heat transport system after the break and the consequent time delay of the major phenomena were also observed.

Key Words : RELAP5, RD-14 Test, CANDU reactor, simulation, B-8604

1. Introduction

Failure of heat transport piping is one of accidents postulated in assessing performance of reactor safety system. An accident analysis assumes instantaneous failure of a pipe in a primary circuit, with a break size and location as parameters. The break size is considered in Loss-Of-Coolant Accidents (LOCA), which is categorized with a range from small sizes to large ones. As for the large break, there are a lot of critical breaks which are identified by a prolonged period of flow stagnation in one or more of heated channels.

To examine the behavior of a figure-of-eight heat transport loop subjected to LOCA

Table 1. Comparison of Characteristics of RD-14 and CANDU Reactor

Parameters	RD-14	Typical Reactor
Operating Pressure (MPa)	10	10
Loop Volume (L)	951.4	57,000
Loop Piping I.D. (m)	0.074	Varies
Heated Sections:	37-rod bundles	37-element bundle
Length (m)	6	12 x 0.5
Rod diameter (m)	0.0131	0.0131
Flow tube diameter (m)	0.1034	0.1034
Power (kw/channel)	5,500.	5,410
Pumps:	single stage	same as RD-14
Impeller diameter (m)	0.381	0.813
Rated flow (kg/s)	24	24(max/channel)
Rated head (m)	224	215
Specific speed	565	2,000
Steam Generators:	recirculating U-tube	recirculating U-tube
Number of tubes	44	37/channel
Tube diameter I.D. (m)	0.01363	0.01475
Secondary heat transfer area (m^2)	41	32.9/channel
Heated Section-to-Boiler Top Elevation Difference (m)	21.9	21.9

conditions, a series of experiments were conducted in the RD-14 thermal-hydraulic test facility at the Whiteshell Nuclear Research Establishment (WNRE) [1,2].

In this study, the small inlet header break test (B8604) [3] conducted in the RD-14 test facility was simulated with RELAP5/MOD3.2 code [4]. The RELAP5 code has been developed for best-estimate transient simulation of pressurized water reactors (PWRs) and their associated systems. The inside fluid flow model of RELAP5 code is based on a non-homogeneous and non-equilibrium model for one-dimensional, two-phase system and the code enables to solve partially implicit numerical scheme fast. The RELAP5 code has been used worldwide for thermal-hydraulic simulation for PWRs nowadays and has been being continuously improved for years. Recently, there has been an effort to apply the code for CANDU reactors, which has

different structures with inside fluid flow models of the RELAP5 code. A previous analytical study performed by S. Lee et. al. [5] suggested that the RELAP5 could be applicable to assess the simulation of transients and accidents for CANDU reactors. However, there are some more further studies be resolved, likely, modeling of headers, multi channel simulation for the reactor core, etc.

The results of RELAP5 simulation were compared with both the experimental data and those of CATHENA simulation conducted by Atomic Energy of Canada Limited (AECL). The CATHENA code [6] was developed by AECL primarily for analysis of postulated LOCA events for CANDU Reactors

2. RD-14 Experimental Facility

The RD-14 test facility is a full-scale

pressurized-water loop, but it is not a "scale" model of any particular CANDU reactors. However, the test facility itself possesses not only many geometric features of heat transport system in the CANDU reactor, but is also capable of operating at similar conditions in a reactor under normal operation and some postulated accident conditions either. Moreover, the facility was designed to produce the same fluid mass flux, transit time, pressure, and enthalpy distributions in the primary system as those in a CANDU reactor under forced circulation conditions [1, 2]. The main design parameters of RD-14 test facility are compared with those of a typical CANDU reactor in Table 1.

The heat generation system in RD-14 facility consists of two full-scale (6 m long), full-power horizontal channels (maximum of 5.5 MW) for representing reactor fuel channels. Each channel contains 37 electrically heated fuel element simulators, which have uniform heat flux distribution and almost the same heat capacity as a reactor fuel. End-fitting simulators are also provided to connect each channel with the rest of the primary system.

3. Test Procedure and CATHENA Results

3.1. Test Procedures

The test B8604 [3] was a small inlet header break test conducted with emergency coolant injection (ECI) system under the conditions of primary pump rundown and surge tank isolation. The Primary pump storage was simultaneously initiated as the power was tripped and thereafter ECI flow to headers 3 and 4 was initiated. Although some heater temperatures were recorded near by 400 °C between 150 and 200 sec, heaters were quickly quenched so as to maintain adequate cooling temperature for the remainder of the injection period.

After initiation of the break at 10 sec, the pressure in the primary circuit dropped rapidly up to about 8.9 MPa at the outlet headers by 30 sec and both the heated section power and pump speed reduction ramps started thereafter. At 50 sec the primary pressure reached at 5.5 MPa and high pressure ECI initiated to flow into headers 1 and 3. At the outlet of heated sections, void instantaneously formed due to falling pressure, but it collapsed again later when the power was reduced and ECI began. By 80 sec all ECI fluid flow was directed to header 3, while the ECI flow into header 1 was stopped. At 140 sec the primary pumps were stopped and the heated sections raised the primary pressure temporarily in accordance with stopping the ECI fluid flow due to reduction of primary fluid flow. During this period, the upper fuel element simulators (FESs) elements in both heated sections became uncovered (stratified flow in channel) and began to heat-up. Therefore, void (vapor) generated in channels moved to outlet feeders eventually and small positive thermosiphoning flow was established thereafter due to density difference. As void was pushed out from heated sections (quenching hot upper FES elements) and was condensed in steam generators, the primary pressure fell down so as to allow resumption of ECI fluid flow into headers 3 and 4. A period of stable thermosiphoning persisted up to about 880 sec until ECI flow stopped due to depletion of water in a high-pressure tank. Shortly after stopping thermosiphoning, the heated section upper FES became uncovered and began to heat-up thereafter. The experiment was finally terminated at about 1,160 sec by a high temperature trip (sheath temperature above 600°C) in heated section 2.

3.2. Test Condition
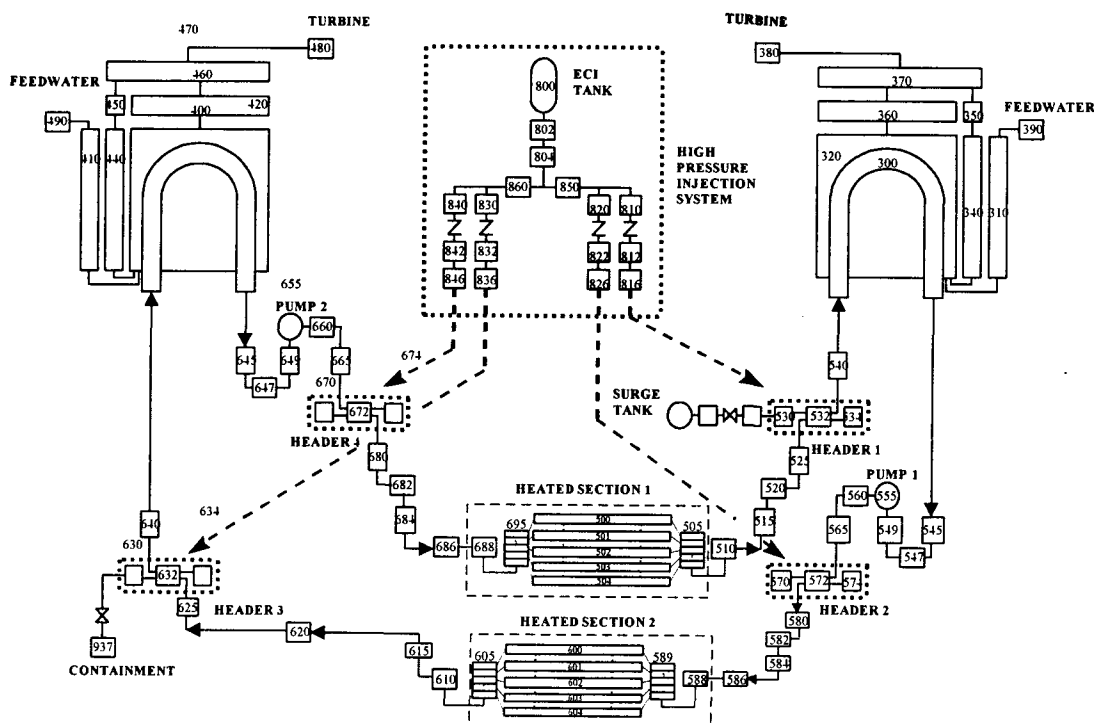
Primary System : Outlet Header Pressure-10 MPa

Fig. 1. Nodalization of RD-14 for RELAP 5 Analysis

Input Power - 5.0 MW per heated section
Flowrate - 27 L/s
Secondary System : Steam Drum Pressure-4.5 MPa
Feedwater Temperature - 187 °C
ECI : Accumulator Tank Pressure at 5.5 MPa
Break : 7.0 mm diameter, located at Inlet Header 4

3.3. CATHENA Analysis Results

CATHENA simulation [3] showed, in general, good agreement with the experimental observations after primary pump rundown until the primary flows stopped at about 140 sec. In this primary pressure, the onset of ECI was accurately estimated and ECI flow was correctly directed to headers 1 and 3, while some limited flow was incorrectly predicted at headers 2 and 4

for brief periods of time. After 140 sec CATHENA simulation predicted that a thermosiphoning flow established in the negative direction, not the positive direction, as observed in the experiment. Therefore, there are some significant differences in the plotted parameters due to the error of flow direction. Besides, ECI flow distribution after the primary pumps stopping was also not well predicted while the primary pressure was correctly estimated until depletion of ECI tank. It seemed that nitrogen gas in ECI tank was injected into the primary loop since ECI system was not isolated from the primary loop after drainage of ECI fluid flow from tank. In this reason, there were significantly differences between predicted and experimental pressures, but this event was not considered in the simulation

4. RELAP5/MOD3 Simulation

4.1. Nodalization

Nodalization of system model for RELAP5 calculation is shown in Fig. 1, which is basically similar to that of CATHENA model [1,2] in order to reduce the effect of nodalization. The system model composes of primary heat transport system including heaters, pumps, secondary system, ECI system, accumulator, break model, etc.

At the time test B8604 was conducted, the spiral-arm separators had not been installed in the steam generators. Instead of recirculating via the external downcomer, the secondary side operated in a "kettle-like" fashion. While experiments conducted before and after installation of the spiral-arm separators showed little effect on the test results, the operation of the secondary side after installation of the spiral-arm separators is more influenced.

In the RELAP5 calculation, the horizontal pipes (heated sections) were divided into 5 channels with the same flow areas and hydraulic elevations, so as to simulate the phenomena of stratified fluid flow in the horizontal pipes. Also, the channels were linked each other through cross flow junctions in order to calculate the heat and mass transfer due to the convection. A previous study performed by S. Lee et. al. [7] suggested that this nodalization scheme could be improved to assess the simulation of transients and accidents for CANDU reactors.

Besides, the steam separator model was also considered. The upstream regions of secondary side circuit in the steam generators and the secondary side control system were not modeled as idealized in CATHENA simulation. In the meanwhile, the steam separators were modeled to represent recirculating flow in the steam generators.

4.2. RELAP5 Base Calculation

The RELAP5 analysis results showed that the primary circuit pressure dropped rapidly after initiation of the break, reaching to 8.9 MPa at the outlet headers by 60 sec (30 sec in the test) and starting both the heated section power and pump speed reduction ramps. By 100 sec the primary pressure reached to 5.5 MPa initiating high pressure ECI to headers 1 and 3. By 170 sec, ECI flow to header 1 stopped and all ECI flow was directed to header 3. At 140 sec the primary pumps stopped and the sections
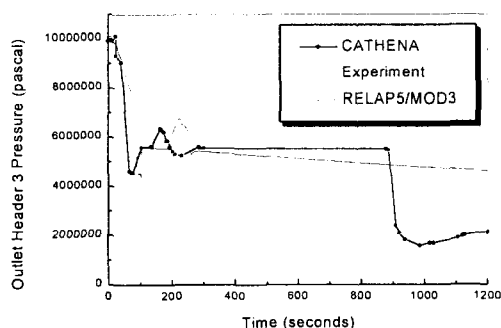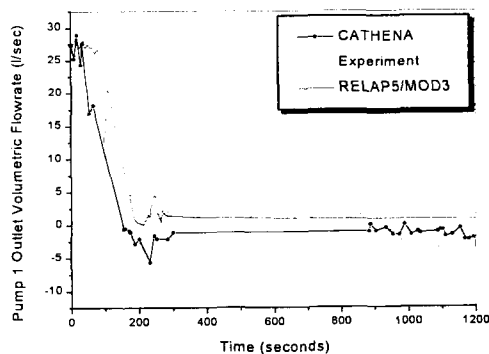

Fig. 2. Pressure Profile at Outlet Header 3

Fig. 3. Volumetric Flowrate at Outlet of Test Section

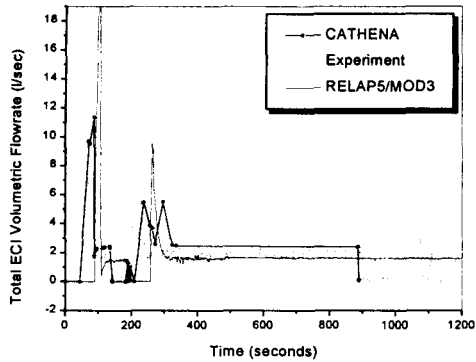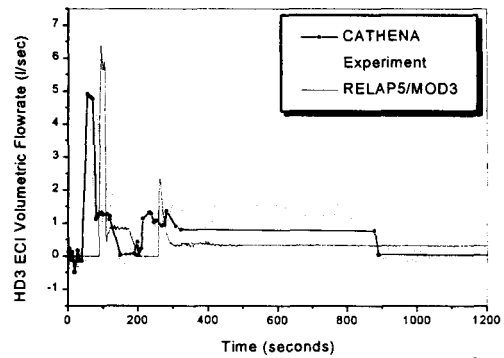Fig. 4. Total ECI Volumetric Flowrate

Fig. 7. ECI Flowrate into Header 3

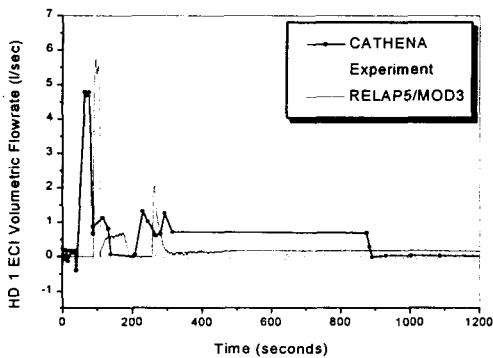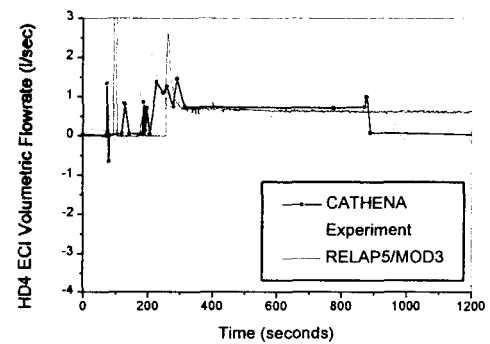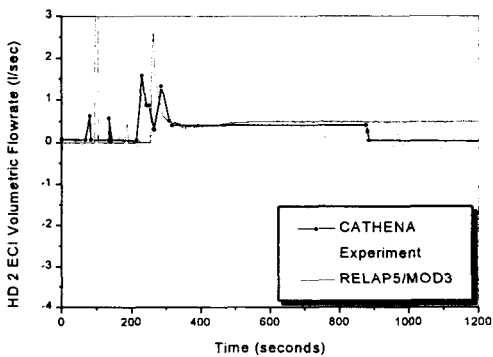Fig. 5. ECI Flowrate into Header 1

Fig. 8. ECI Flowrate into Header 4

Fig. 6. ECI Flowrate into Header 2

flow. During this time, upper FESs elements in both heated sections became uncovered and began to heat-up. Void generated in the channels eventually reached the outlet feeders and a small positive thermosiphoning flow was established as observed in the test. The calculation was finally terminated at 1,200 sec the same as in the test.

The results of each major parameter are summarized as follows:

4.2.1. Pressures

temporarily raised the primary pressure to stop the flow of ECI as a result of the reduced primary

Fig. 2 shows pressure profiles at the header 3.

As the break was opened, the pressure was sharply declined until the void generated at the outlet of both heated sections. Pressure decreased more slowly because of void generation in the piping between the heated section outlets and steam generator inlets. The heated section power ramp and the primary pump speed ramp reduced void generation and caused the primary pressure to decline again. RELAP5 predicted a lower rate of pressure decrease than that in the experiment between 30 and 100 sec. This seems that the lower depressurization rate is caused by an underestimate of the boiler heat transfer coefficient and lower break flowrate. The decrease of pressures in the headers resulted in the delay of ECI flow to the system. However, the overall transient behavior was, in general, recorded in RELAP5 simulation except the time delay of the sequence in the events.

A sharp rise in pressure occurred at the primary loop since liquid filled (void collapsed) and primary pressure rose to match pressure in the ECI tank at 100 sec (80 sec in the test). The loop was pressurized due to the generation of void in the heated sections because the time of pressure rise occurred in coincidence with zero primary flow and the formation of void at the heated section outlets at 170 sec (130 sec in the test). As the primary pump stopped, the thermosiphoning flow was established due to the pressure drop and ECI flow to the primary loop. A period of stable pressure remained to the end of the transient.

4.2.2. Fluid Flow

The loop volumetric flow at the outlet of test section is shown in the Fig. 3. The agreement is generally good except delay of sequences due to lower decrease of pressure aforementioned. The figure shows that high volumetric flow was

temporarily occurred at outlet of test section 1 at about 140 sec, which is coincident with the formation of a steam bubble at the same location. REALP5 predicted this behavior at 220 sec.

Figures 4 to 8 show the ECI flow into the four headers. The initial surge of the fluid flow between 50 and 100 sec was injected into headers 1 and 3 only, since the continuing operation of the pumps maintained pressure above the ECI system pressure in the other two headers, 2 and 4, during this period. RELAP5 could well simulate this flow regime by reproducing the time and overall magnitude of fluid flow in this time-span.

Following this period, i.e. all ECI flows were stopped, injection was recommenced to headers 1, 3, and 4 for the range from 160 sec (at header 3) to 200 sec (at header 1). The resumption of fluid flow at these three headers was counterfeited by RELAP5 simulation. Besides, the simulation also predicted the phenomena of the fluid flow into header 2 after 250 sec, but it did not occur in the experiment.

4.2.3. Void Fractions

The present of void was indicated at the heated section outlet before initiation of the break in the experiment and it seemed to be generated in the channels as a subcooled vapor phase. In the analysis, a small amount of subcooled vapor was also shown at the heated section outlets and it was condensed later. However, there was not any void was predicted at the steam generator inlets like as observed in the test.

The void fraction at the outlets of the test sections was predicted well. However, that at the inlets of the heated sections was not shown a large amount of void after 1,000 sec like as observed in the test.
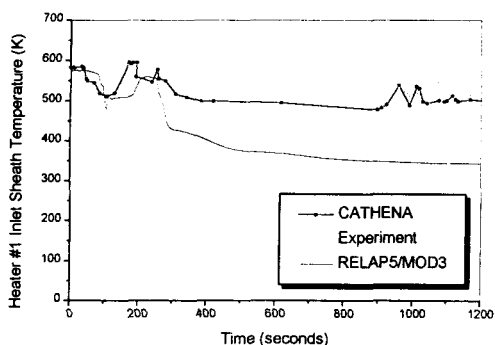
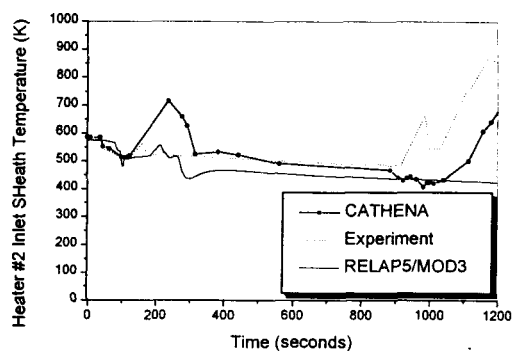**Fig. 9. Temperature Profiles at Inlet Sheath of Header 1**

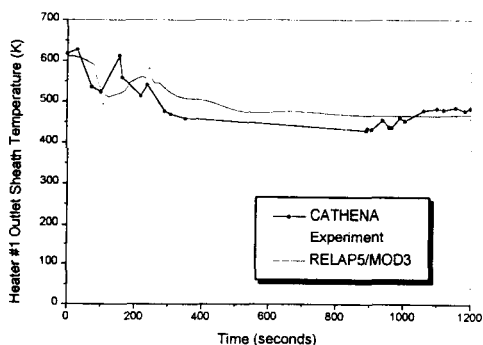**Fig. 11. Temperature Profiles at Inlet Sheath of Header 2**

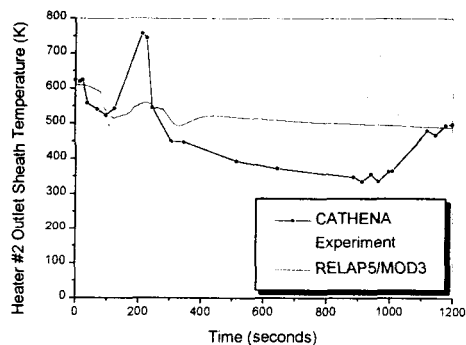**Fig. 10. Temperature Profiles at Outlet Sheath of Header 1**

Fig. 12. Temperature Profiles at Outlet Sheath of Header 2

4.2.4. Sheath Temperatures

The fluid temperatures at the inlet and outlet were well predicted throughout the transient period. After depletion of the ECI (about 900 sec), an increase of inlet temperatures at both heaters were, however, not predicted since the ECI was not used up during this time-span in the analysis.

Most sheath temperatures in both heated sections showed that dryout occurred on and off during the period between 100 and 300 sec.

Comparisons between RELAP5 and experiment are shown in Figures 9 to 12, which illustrated sheath temperatures at the inlet and outlet ends of the heated sections. In figures, there seemed that the occurrence of dryout and temperature excursion in the sheath was predicted. After 300 s, the RELAP5 simulation predicted that all sheath temperatures maintained close to the coolant temperature. Since RELAP5 code enables to calculate only one-dimensional temperature gradient, the code can not predict a peripheral temperature distribution resulted from the flow stratification in the FES with the current fluid flow

model inside RELAP5 as referred in the previous study [4]. In this regard, temperature calculated by the present RELAP5 code should be considered as an averaged one. This is one of limitation of the RELAP5 code to apply the simulation of CANDU reactors. In spite of this limitation, an agreement between the RELAP5 simulation and experiment is reasonably good.

4.3. Sensitivity Studies

4.3.1. Break Flow Discharge Coefficients

Although discharge coefficients for single phase, two-phase and mixture fluids were varied for the range from 1.0 to 1.5 in the analysis, there was not any effect on the pressure change in the headers. It is seemed that the lower depressurization rate after the break opening resulted mainly from underestimation of boiler heat transfer coefficients.

4.3.2. Break Modeling

As for modeling the break valve, a single volume upstream and environment condition were modeled and considered in the analysis. Therefore, the predicted results were better on the depressurization rate in the headers. However, too much cooling in the primary loop was observed and the overall results were not better than those of the base calculation in general.

5. Conclusions

RELAP5/MOD3 simulation of the small inlet header break in the RD-14 facility has been performed, with an aim to identify the RELAP5 applicability in a CANDU system, in comparison with the experimental results and the CATHENA

simulation. The general conclusions from the present study are as follows:

1. The RELAP5/MOD3 predicted reasonably well for thermal-hydraulic behaviors in the small inlet header break tests. However, some discrepancies were observed in the depressurization after the break and consequent time delay of the major phenomena. It may be considered due to an underestimate of the boiler heat transfer coefficient or lower break flowrate either.

2. As the RELAP5 calculates one-dimensional temperature gradient, the code, therefore, can not predict the peripheral temperature distribution, resulted from the flow stratification of FES with the current RELAP5 model. Temperatures calculated by the present RELAP5 analysis should be considered as an averaged one. Regardless of this limitation, an agreement between the RELAP5 analysis and experiment is reasonably good.

3. Issues identified from the present study will be examined through further sensitivity study and in particular the model development of the multi-channel analysis will be also necessary. in the near future.

References

1. P. Malloy, "CATHENA idealization- Documen-tation of the RD-14 Test facility", RC-54-1, AECL, (1988).

2. B.N. Hanna and T.E. MacDonald, "CATHENA Idealization Documentation of the RD-14 Test Facility, Secondary Side Charcterization Tests", RC-54-2, AECL, (1988).

3. J.P. Malloy and G. Sabourin, "CATHENA MOD-3.3g Simulation of RD-14 Experiment B8604," THB-CD-021, AECL, Sept. (1990).

4. S. Lee, et.al., "RELAP5 Code Assessment in a

CANDU Reactor," NURETH-8, Kyoto, Japan, October (1997).

5. V.H. Ransom, et. al., "RELAP5/MOD3 Code Manuals, Vil. I-V", EG&G Idaho, June (1988).

6. N.N. Hanna, " CATHENA MOD-3.2n, Theoretical Manual", THB-CD-002, AECL-WL, (1989).

7. S.H. Lee et. al, "Assessment of CANDU Thermal-hydraulic Safety Analysis Code System", MOST, KINS/GR-111, 252-260, (1996).