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A Comparative Assessment Result of B9401 Multi-channel RIH Break Experiment with Canadian Test Facility RD-14M using RELAP5/MOD3 and RELAP5/CANDU+

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ABSTRACT

The experiment, B9401, performed in RD-14M multi-channel experimental facility, was preliminarily analyzed using RELAP5/MOD3 and RELAP5/CANDU+ and compared with experimental results. The RELAP5 code has been developed for best-estimate transient simulation of pressurized water reactors and associated systems, but the RELAP5/CANDU+ code has been developed since 1998 inorder to have auditing tool of CANDU NPP. The RELAP5/CANDU+ code is under developing and they have not been assessed much for a CANDU reactor. Therefore, this study has been initiated with an aim to identify the code applicability in a CANDU reactor by simulating some of the tests performed in the RD-14M facility and to get the assessment results for RELAP5/CANDU+ code. The RD-14M test facility at Whiteshell Nuclear Research Establishment is a full-scale multi-channel pressurized-water loop. The RD-14M is not a "scale" model of any particular CANDU reactor. It possesses many geometric features of a CANDU reactor heat transport system, and is capable of operating at conditions similar to those expected to occur in a reactor under normal operation and some postulated accident conditions. As preliminary results, the RELAP5/MOD3 and RELAP5/CANDU+ analyses demonstrate the code's capability to predict reasonably the main phenomena occurring in the transient, in qualitative view. In quantitative view, the RELAP5/CANDU+ predicted better than that of RELAP5. However, some discrepancies after emergency coolant injection, the behaviors of the ECI mass flow rate and the sheath temperatures were observed commonly.

I. INTRODUCTION

In Korea, four, Canadian nuclear power plant, CANDU have been operated in Wolsong site, named Wolsong unit 1,2,3 and 4. Wolsong unit 1 had been operated since 1983 and others since 1997, 1998, 1999 respectively. In Canada, the effectiveness of emergency core cooling system (ECCS) have been considered as "generic safety issues" identified by the Canadian regulatory body, AECB, as being applicable to all or most of the CANDU nuclear power plants in Canada. To provide information on the effectiveness of ECCS in a CANDU reactor, various series of experiments has been carried out in the RD-14 pressurized water loop at the Whiteshell Nuclear Research Establishment from 1984 to 1987. As a proceeding experimental facility, the RD-14M had been constructed and operated since 1988.

In early 1997, IAEA (International Atomic Energy Agency) Coordinated Research Program was proposed on “The Intercomparison and Validation of Computer Codes for Thermal-hydraulics Safety Analysis” under the auspices of CANDU Owner’s Group (COG). In summer 1999, it was decided that this project should proceed sponsored by AECL. This study is also included in the project.

In this study, the multi channel experiment B9401 was analyzed preliminarily using RELAP5/MOD3.2 [5] and RELAP5/CANDU+ and compared to experiment results. The RELAP5 code has been developed for best-estimate transient simulation of pressurized water reactors (PWRs) and associated systems. The model is based on a non-homogeneous and non-equilibrium model for one-dimensional, two-phase system is solved by a fast, partially implicit numerical scheme to permit economical evaluation of system transients. Without any relation of the above project, the RELAP5/CANDU+ code has been developed since 1998 in order to have independent audit tool and now still under development. This code has been modified in the area of CANDU specific phenomena based on RELAP5/MOD3.2 gamma version. The important model were selected among the modified or new model using engineering judgement and applied to this study. However, it has not been extensively assessed for the CANDU reactor. Therefore, the present study aims to identify the feasible areas of analysis with the RELAP5/MOD3.2 in a CANDU system and assess the developing code, RELAP5/CANDU+ by simulating B9401 tests performed in the RD-14M facility.

II. Background

A. RD-14M Facility Description [1]

RD-14 was designed and constructed starting 1981. Due to funding limitation, the RD-14 reference design chosen was two, 5.5 MW, 37-element channels, (i.e., one channel per pass), with 1:1 scaling of vertical distances throughout the loop. This determined the sizing of piping and various components (e.g., steam generators, pumps, headers). The values for various loop parameters dictated by the choice of reference design were 5.5 MW maximum thermal power per pass, 590 kW/m maximum surface heat flux per pass and 24 kg/sec rated flow rate (one 37-element channel).

The modification of RD-14 to RD-14M provides for the study of the interaction of multiple heated channels in parallel in a full height loop. As multiple channel, five 7-element heated sections per pass were chosen to replace the single, 37-element channel. The cross sectional area of the associated below header pipe-work was scaled at 7:37 to preserve heat and mass fluxes in the multi-channel facility.

As noted in references [1,2,3], the large number of non-dimensional groups to be considered precludes the scaling of two-phase flow dynamics with complete similarity. However, if the model is made of a similar solid material and has a similar fluid under the same system pressures as the prototype, scaling is simplified. References [1,3] present an appropriate set of similarity criteria to be used under such conditions. Using 1:1 scaling of vertical elevations and axial lengths simplifies the scaling of the facility. It is appropriate to choose the piping diameters such that the flow velocities will be scaled 1:1. This ensures that the characteristic transit times will be approximately equal in both the facility and the reactor.

In RD-14M, consideration was given to the several experimental program in the design of the loop, the loop peripherals and the loop instrumentation. The experimental programs were categorized into three groups, safety-type transients, process dynamics and control-type transients, and component-type transients.

B. B9401 Experimental Procedure[1]

A series of experiments to investigate the thermal-hydraulic consequences of critical break with emergency coolant injection is in progress in the RD-14M test facility. The experiment used in this study is B9401 experiment – 30 mm inlet header break experiment with high pressure pumped emergency coolant injection.

The nominal initial conditions for the first experiment in this series, B9401, were 10.0MPa(g) outlet header pressure, 4.0MW per pass nominal input power, 4.4 MPa(g) steam pressure, and 186^{o}C feed water temperature.

Before the experiment, the loop was evacuated, filled and degassed, all instrument lineswere vented, and instrument readings were checked and adjusted. The loop was warmed using low power and reduced pump speed. Input power and pump speed were then increased to bring the loop to the desired steady-state single phase starting conditions. The output from all instruments was then scanned and printed as a final check. Then data gathering started. The detailed sequence of events during the experiment was described in Table II.

A programmable pump-speed controller was used in some experiments to simulate pump rundown following a loss of class-IV power. The pump began ramping down at 12s. Cold water was injected into the loop when the primary pressure fell to or below the emergency coolant injection (ECI) pressure. The isolation valves at the ECI pipes to all four headers were opened as soon as the pressure in header 7 fell below 5.5 MPa. As long as the pressure in any header was above 5.5 MPa (pressure in the ECI tank), no ECI water entered that header. When the pressure in any header was below 5.5 MPa, ECI water entered the header at a rate determined by the pressure difference between the ECI tank and the header.

The actual flow rate of ECI is determined by the size and location of the break. Orifices in the injection lines provide scaled simulation of reactor injection flow rate. The high-pressure injection may be from the ECI tank at high pressure, or from the ECI tank at low pressure via corresponding pumps. In either case, the high-pressure ECI water is delivered to the ECI system at approximately constant pressure during the transient. However, as the pressure in any header varies, so does the ECI flow rate into a particular header.

The heated sections are protected from overheating by high-temperature interlocks. if the heater sheath temperature exceeds the set point selected by the loop operator, the heated section power supplies are shut down.

Table I Comparison of Characteristics of RD-14 and CANDU reactor

Parameters	**RD-14**	**RD-14M**	**Typical Reactor**
Operating Pressure (MPa)	10	10	10
Loop Volume (m^3)	0.95	1.01	60.
Heated Sections:	37-rod bundles	7-rod bundles	37-element bundle
Number per pass	1	5	95
Length (m)	6	6	12 x 0.5
Rod diameter (mm)	13.1	13.1	13.1
Flow tube Dia. (mm)	103.4	44.8	103.4
Power (kW/channel)	5500.	3x750, 2x950 per pass	5410.
Pumps:	single stage	single stage	same as RD-14
Impeller diameter(mm)	381	381	813
Rated flow (kg/s)	24.	24.	24. (max/channel)
Rated head (m)	224.	224.	215.
Specific speed	565.	565.	2000
Steam Generators:	recirculating U-tube	recirculating U-tube	recirculating U-tube
Number of tubes	44	44	37/channel
Tube diameter I.D.(mm)	13.6	13.6	14.8
Secondary heat-transfer area (m^2)	41	41	32.9/channel
Secondary Volume (m^3)	0.9	0.9	0.13
Heated Section-to-Boiler Top Elev. Difference (m)	21.9	21.9	21.9

C. RELAP5/CANDU+ Code Description [9]

As described in the above, the safety of CANDU plant have been focused due to increasing the number of CANDU plants. Until now, Korea had no independent audit calculation tool because CANDU plant has its own special design such as horizontal core, channel type core, header design, etc. Therefore the development of RELAP5/CANDU+ code has been initiated by KINS cooperated with KAERI. The modifications were performed as following procedure;

1) RELAP5/MOD3.2 gamma version was selected as base code.
2) Identify important process and phenomena in CANDU
3) Prioritization of the selected process and phenomena using engineering judgment
4) The selected and prioritized items were divided into two group, called LOCA and non-LOCA and perform the modification.

Until now, the modified and added models for RELAP5/CANDU+ as follows;

1) Critical Flow Model
2) Nuclear Kinetics Model
3) Critical Heat Flux Model
4) Reactor Core Control Model
5) Valve and Spray Model
6) Improvement of Horizontal Flow Regime Map
7) Heat Transfer Model in Horizontal Channel

Details are described in reference [9].

Table II. B9401 test (30mm inlet header break) procedure

Experiment Time	Event Description
0	start data gathering
10	open break valve, p14 start
12	step input power to decay level & RCP ramped down
20.6	ECI isolation valve open
22.8	pressurizer tank (surge tank) isolated
116.2	HP ECI terminated, LP ECI start
213.2	primary pumps off
229.2	scan stopped
231	scan start
350.7	LP ECI terminated
460	scan stopped
463	scan start
692	scan stopped
695	scan start
924	scan stopped

III. RELAP5 SYSTEM MODEL

System model for RELAP5 calculation is shown in Figures 1 and 2, which is basically similar ones found in CATHENA model [6-8] and therefore may help reduce the effect of nodalization. The system model composes of primary heat transport system including heaters and pumps, secondary system, ECI system, accumulator, and break model. The same nodalization was used to RELAP5/CANDU+ analysis.

IV. ANALYSIS RESULTS AND COMPARISONS

A. RELAP5 Results

This base case means that almost all of options uses standard or recommended in RELAP5 manual and standard CATHENA nodalization was used without any modifications. in figures, the (a) is RELAP5 calculation

Header Pressures

Experiment started at 10 seconds as the p14 valve opened and RCP (Reactor Coolant Pump) and reactor trip occurred at 12 seconds. The break location was located in inlet header 8. After the break initiated at that time, the primary system pressure rapidly decreased as the inventory lost. Due to void generation, the slope of the depressurization rate decreased and few seconds later depressurization rate recovered as the ECI injection delivered into the HTS.

In view of break flow, B9401 experiment did not measure the break flow, and the pressure behavior was only clue to judge whether the break flow was correctly calculated or not. Generally, break flow quality could vary according to the upstream conditions and depressurization characteristic through the break piping. Initially, the break flow was liquid single phase and the inventory loss was larger than other phase. As primary heat transport system pressure reduced and the vaporization was occurred, the break flow had vapor. As the void fraction of break flow increases, the break mass flowrate decreases due to decreasing mass flux.

In the case of RELAP5, figure 3 shows the header pressures, and RELAP5 predicted header pressure slightly higher than the experiment during the period after depressurization. Before the emergency coolant injection (ECI), the pressure transient was correctly predicted during short period, but after the initiation of ECI, the pressure decrease rate was reduced. After that, the calculated was slightly higher than the experiment, as shown in figure 3. One of these differences might be the smaller break flow after the initial rapid depressurization. The sensitivity study of break modeling had been studied including the modeling of downstream of the break and break junction options. But there were no differences among the sensitivity cases.

Emergency Coolant Injection

In RD-14M and CANDU NPP, the ECI coolant delivered into each headers and the coolant could cool the heater section. ECI injection in RD-14M was actuated when header 7 pressure decrease below 5.5 Mpa. After initiation of break at header 8, the header 7 pressure continuously decreased under 5.5Mpa at 26 seconds. The calculated ECI Flow well predicted, but the difference was shown during the initial high-pressure emergency injection period (~116 seconds). After the injection was finished, the calculated ECI flowrate had big differences. But this kind of behavior resulted from the piping of ECI system. After the end of ECI injection, the residual coolant in ECI piping showed the oscillatory behavior. Because the ECI valves in each header connection piping were closed at 350 seconds, the behavior could not be shown in results.

Related to the heat transport system (HTS) pressure behavior, the depressurization rate recovered after the initiation of the ECI (at 26 seconds), which collapses the generated void. The RELAP5 predicts broken header pressures well during blowdown period, while it over predicts them during ECI period. These discrepancies might be arisen from the complicated effects, such as header model itself, amount of ECI flowrate and the predictability of steam condensation, etc.

FES (Fuel-Element-Simulator) Sheath Temperatures of Heated Section

In experiment, the stratification in header did not occur, and the comparison among channels might be meaningless. The results showed the differences only depend upon the channel power. Figures 5, 6, 7 show the fuel element sheath temperatures in each channel. It is shown in figures of channels 8 and 13, which is the most highest power channel. In these figures, the experimental data were divided into three groups, top, middle, and bottom.

In channel 8, upstream of the break, the calculated results show several differences. RELAP5 underestimated peak of sheath temperature near 200 seconds, but in other periods, RELAP5 can predict well. In the case of channel 13, downstream of the break, different phenomena were occurred. In experiment, two peaks were shown in figure xx, such as initial peak, and later peaks. RELAP5 extremely underestimated the initial peak. The later peak can be seen in the top sets of experimental data but there were no later peaks in the other experimental data set. These sheath temperature behaviors are resulted from the characteristics of horizontal channel. Fuel rod located in the top uncovered in early phase and the uncovered duration also relatively longer than that in the middle and bottom.

Eventually, this kind of deficiencies resulted from the lack of CANDU specific model, such as horizontal channel model, header model, etc.

B. RELAP5/CANDU+ Results

This base case means that almost all of options uses standard or recommended in RELAP5 manual and standard CATHENA nodalization was used without any modifications.

Moody Critical Flow Case

In the above RELAP5 calculation results, header pressure over predicted the experimental results and this means that the calculated break flow was smaller than that of experiment. Originally, RELAP5 has mechanistic critical flow model and Henry Fauske model, and in this RELAP5/MOD3 gamma version, default model was Henry Fauske model. In B9401 case, that model under-predicted the critical flow through break as shown in the above results. In the previous study[ ], the RELAP5 critical flow model under low pressure (2 bar) and low void fraction (0.01~0.2) calculated 40~50% underestimated results. Therefore, the Moody Critical Flow model added to RELAP5/CANDU+ was used to this calculation.

Results show that the break flowrate was slightly increased and the header pressure gave more reasonable behavior. Relatively higher break flow made system pressure decrease during low-pressure periods. These results were consistent with the previous study. But the critical flow model did not affect on other behavior, such as FES sheath temperature, ECI coolant injection flowrate, etc.

<u>CANDU Channel Model</u>

CANDU channel model was developed from the idea of a kind of characteristic length, such as distance from the center of channel to the specific fuel rod. If the water level touches the specific fuel rod, the fuel rod regards as wet rod and the rod is cooled by water. But if not, the fuel rod regards as dry rod and the rod is cooled by steam or air (or non-condensable gas). This model is activated when the horizontal stratification occurs and CANDU specific criteria for the stratification were modeled in CANCHAN component. Details of the models and interrelationship among models were described in reference [9].

To utilize the CANDU channel model, the heat structures that simulate heater rods should be modified according to their elevation. In this analysis, the 7 heater rods in one channel were classified into three group, top, middle and bottom and in this study 20 heat structure was added because each 10 channel had had 1 heat structure. Currently, serveral calculations have been stopped due to numerical errors. These error will be solved in near future.

V. CONCLUSIONS

RELAP5/MOD3 and RELAP5/CANDU+ simulations of the 30mm inlet header break test in the RD-14M multichannel facility have been performed, preliminarily with an aim to identify the RELAP5 applicability in a CANDU multi-channel system in comparison with the experimental results. The RELAP5/MOD3 predicted reasonably the main phenomena occurring in the transient. The general conclusions from the present work are summarized as follows:

1) The RELAP5/MOD3 predicted reasonably thermal-hydraulic behaviors in the inlet header break tests, particularly multi-channel. In case of RELAP5/CANDU+ analysis.
2) In case of RELAP5/CANDU+, Moody critical flow model predicted more precisely the header pressure. However, some discrepancies were observed after the ECI in both cases. Pressure transient in the broken header was over-predicted after the ECI. This might be arisen from the complicated effects, such as header model itself, amount of ECI flowrate and the predictability of steam condensation.
3) Pressure differences between headers govern the flow characteristics through the heated sections, particularly after the ECI. In determining header pressure, there are many uncertainties arisen from the complicated effects as mentioned above. Therefore, it would be concluded that further works are required to reduce these uncertainties, and consequently predict appropriately thermal-hydraulic behaviors in the reactor coolant system during LOCA analyses.
4) RELAP5/MOD3 and RELAP5/CANDU+ did not predict well the heater sheath temperature. In the case of RELAP5/CANDU+, it is expected that the predictability will be improved if the channel model were worked.
5) The channel model in RELAP5/CANDU+ did not calculate successfully due to numerical error. This error will be corrected in near future.

Besides the above assessments, the RELAP5 sensitivity study of B9401 experiment, re-analysis using RELAP5-CANDU version etc. is undergoing. Issues identified from the present analysis will be examined and the developments of RELAP5/CANDU+ including the correction of the channel model are in progress.

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RD-14M Experimental Facility Nodalization for RELAP5/MOD3

(Heat Structure 는 표시안함.)

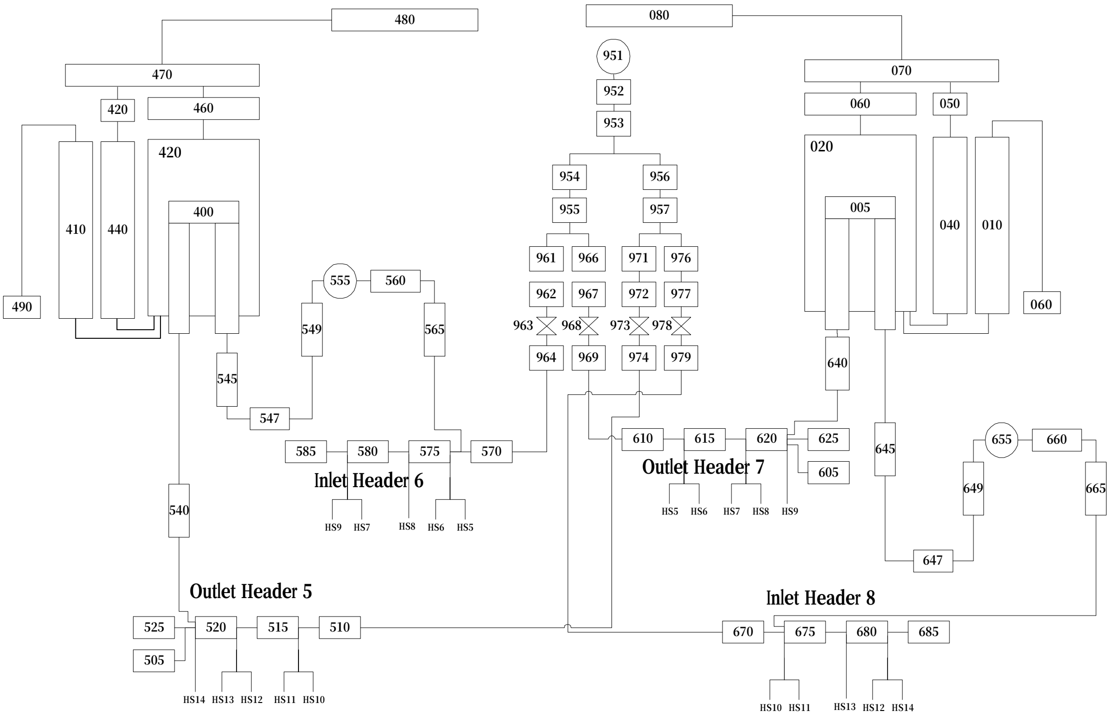


Figure 1. RD-14M Nodalization using RELAP5

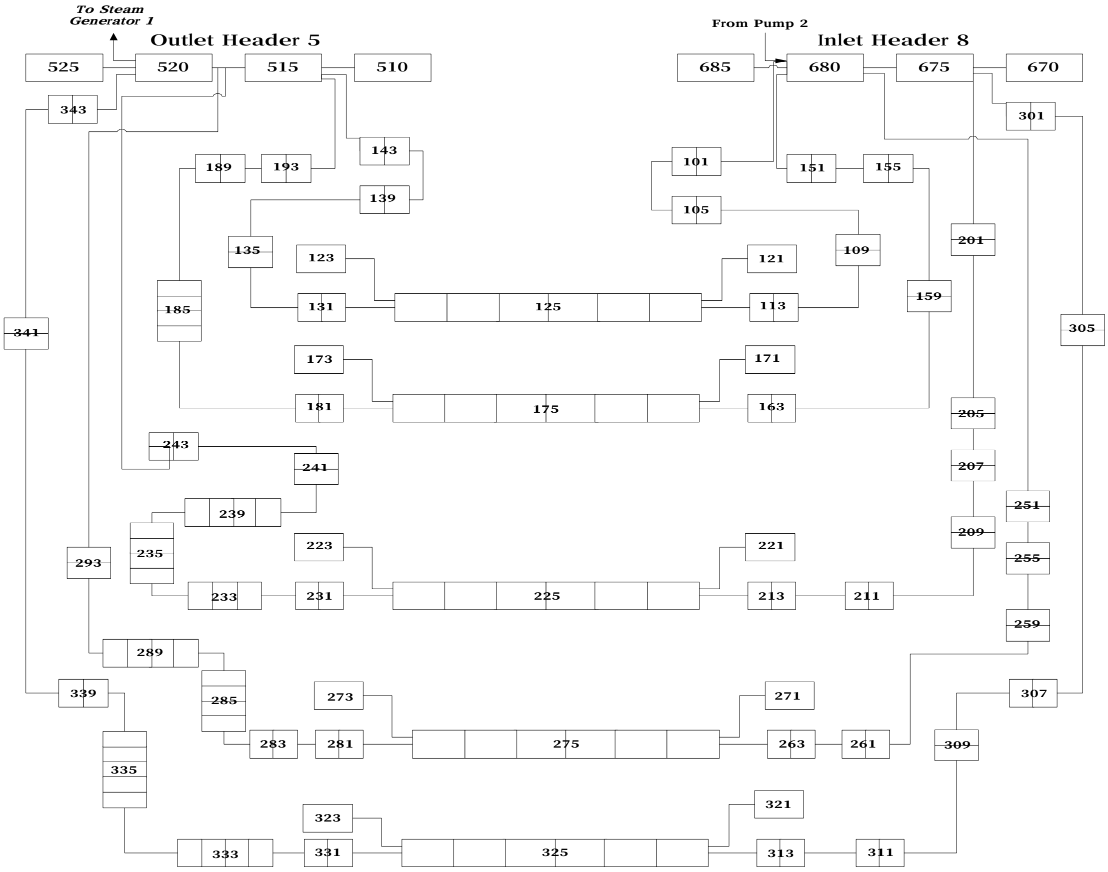


Figure 2. RD-14M Nodalization below Headers using RELAP5

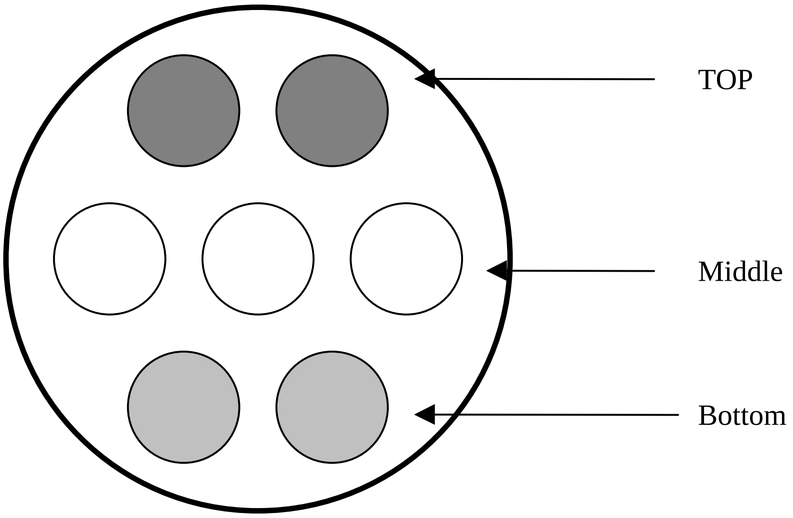
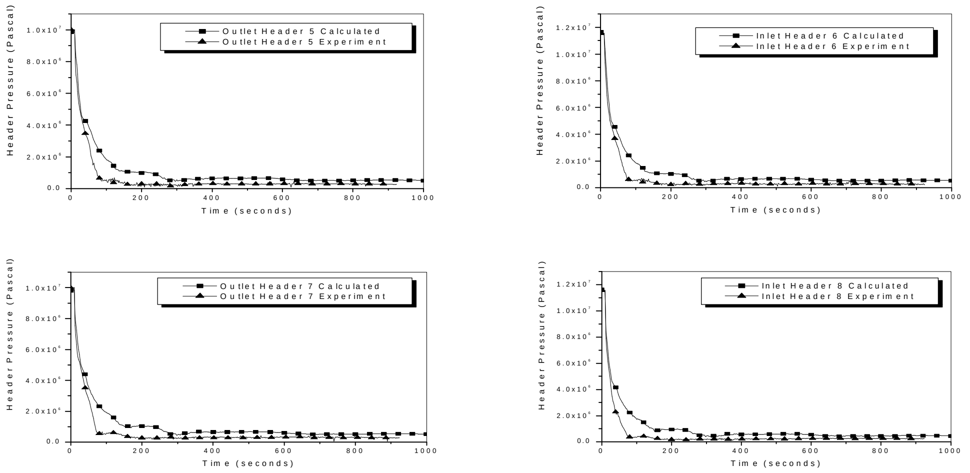
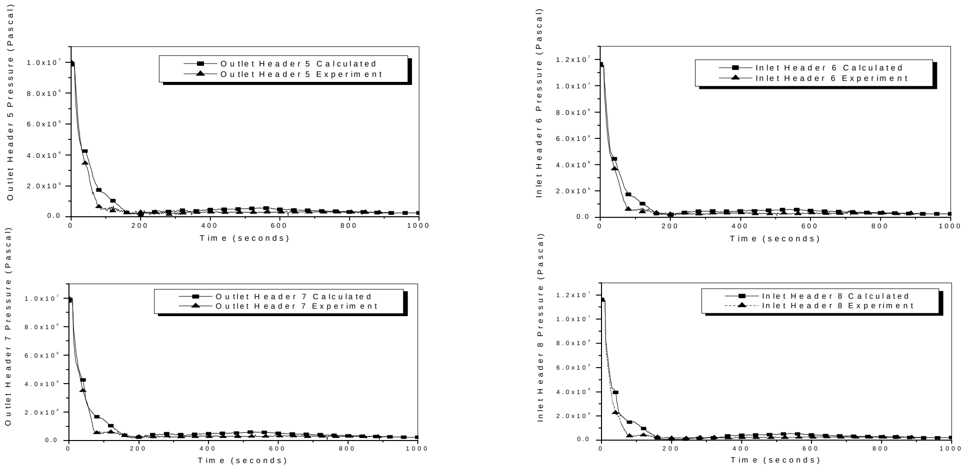


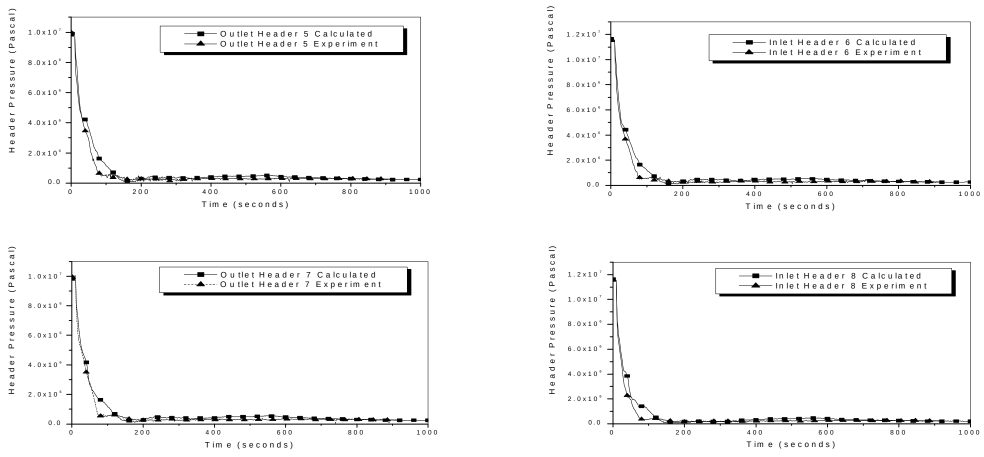
Figure 3 Shape of Fuel Channel Geometry



(a) RELAP5/MOD3 Calculation

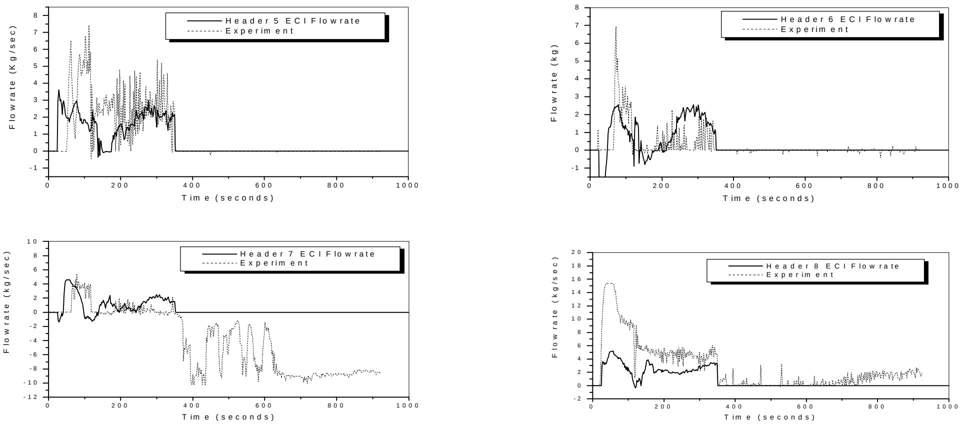


(b) RELAP5/CANDU+ without abrupt area change option

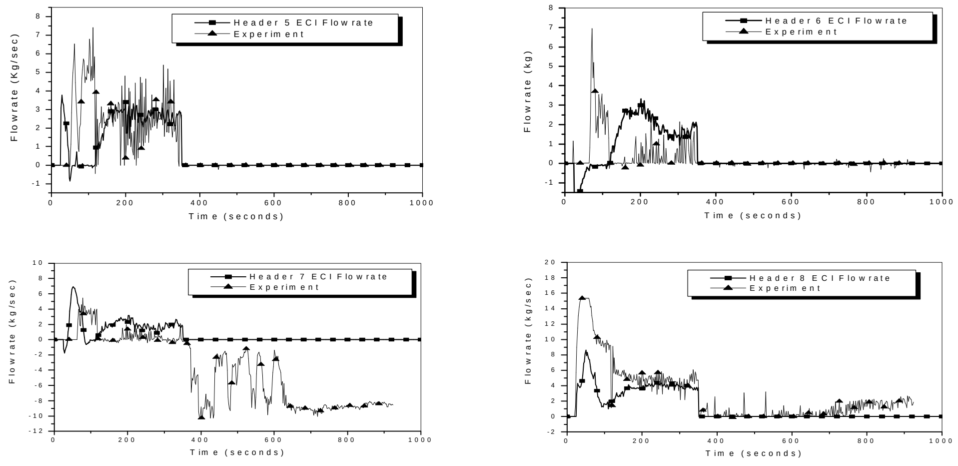


(c) RELAP5/CANDU+ with Moody Critical Flow Model

Figure 4. Header Pressures



(a) RELAP5/MOD3 Calculation



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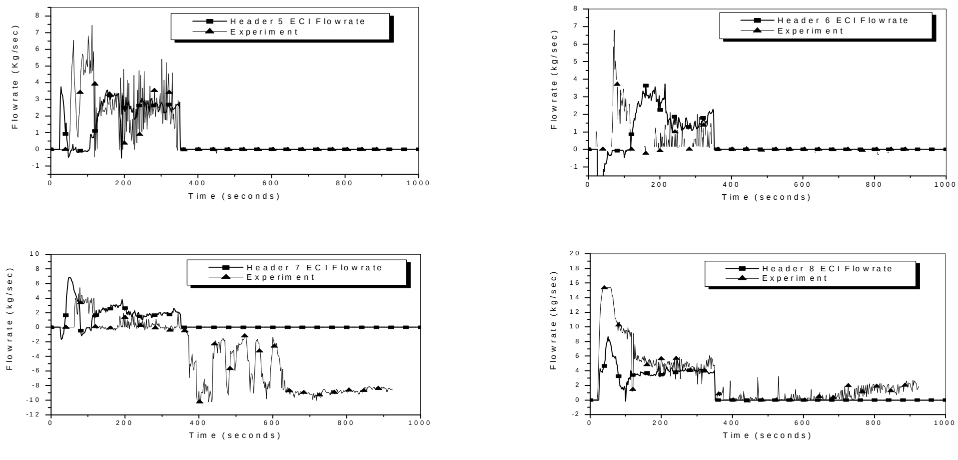
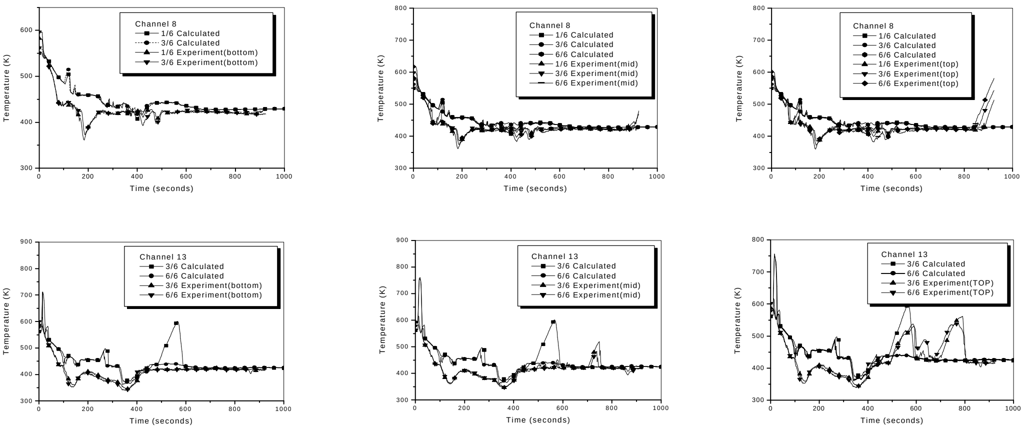
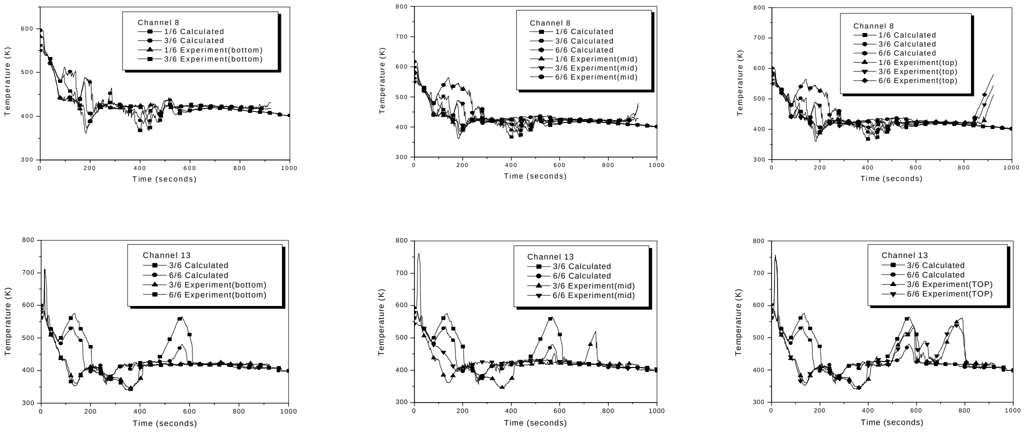


(c) RELAP5/CANDU+ with Moody Critical Flow Model

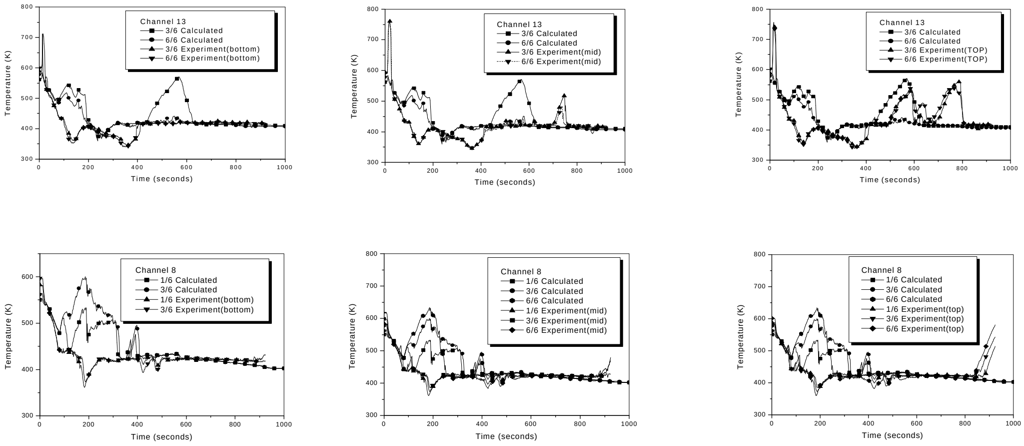
Figure 5. ECI Header Mass Flowrates



(a) RELAP5/MOD3 Calculation



(b) RELAP5/CANDU+ without abrupt area change option



(c) RELAP5/CANDU+ with Moody Critical Flow Model

Figure 6. Test Section Fuel Element Simulator Sheath Temperatures