IAEA ICSP on Evaluation of System Codes for HWR SBLOCA

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Abstract

Activities within the frame of the IAEA's Technical Working Group on Advanced Technologies for HWRs (TWG-HWR) are conducted in a project within the IAEA's sub-program on nuclear power reactor technology development. One of the activities recommended by the TWG-HWR was an international collaborative standard problem (ICSP) entitled "Comparison of HWR thermal-hydraulic code predictions with SBLOCA experimental data". Its main objective is to enhance the confidence in the predictions made by computer codes used in different countries for thermal-hydraulics safety analyses through their inter-comparison and validation. Two RD-14M Small Break Loss Of Coolant Accident (SBLOCA) tests, simulating HWR LOCA behavior, that were conducted by Atomic Energy of Canada Ltd (AECL) were selected for this ICSP project. This paper provides some results and lessons learned from the ICSP.

1. Introduction

Inter-comparison and validation of computer codes for thermal-hydraulic safety analyses of HWRs is an International Atomic Energy Agency (IAEA) activity designed to facilitate international co-operative research and promote information exchange on computer codes for thermal-hydraulic safety analyses. The objective is to enhance the safety analysis capabilities of the participants and the effective use of their resources through this international co-operation.

In 1999 the first IAEA ICSP was started on "Inter-comparison and Validation of Computer Codes for Thermal-hydraulic Safety Analysis of Heavy Water Reactors." This ICSP was completed in 2003 using data from AECL's RD-14M Large Break Loss-of-Coolant-Accident (LBLOCA) experiment B9401. The comparison of results obtained from six participating countries, using four different computer codes, was documented in IAEA TECDOC-1395 [1].

A second ICSP was discussed and endorsed in 2005 December by the TWG-HWR to conduct a code comparison using a SBLOCA experiment from the RD-14M facility. Specific SBLOCA relevant tests were presented to the TWG-HWR in 2007 June and two tests, B9006 and B9802, were recommended by the group.

The specific objectives of this ICSP are for the participants to:

- Improve understanding of important phenomena expected to occur in SBLOCA transients,

- Evaluate code capabilities to predict these important phenomena, their practicality and efficiency, by simulating integrated experiments, and
- Suggest necessary code improvements or new experiments to reduce uncertainties.

The ICSP, "Comparison of HWR Code Predictions with SBLOCA Experimental Data," started with the first meeting of the participants in Vienna in 2007 November. During this meeting the lesson learned from the previous IAEA ICSP on LBLOCA prediction for RD-14M test were discussed and several SBLOCA tests and important phenomenology during a SBLOCA in a CANDU plant was presented. Two tests were selected for this activity, test B9006, a 7-mm inlet header break experiment with pressurized accumulator emergency coolant injection, performed in 1990, and test B9802, a 3-mm inlet header break experiment, performed in 1998, to provide data on the influence of condensation rates in the steam generators on primary loop response under conditions where such a sensitivity is expected. The participants agreed on a subset of 52 measurements (plus several additional code-to-code comparison variables), out of the available experimental data of almost 600 measurements, as a basis for the code comparison, and that both blind and open calculations would be performed. The facility description [2], test summary [3] and electronic boundary and initial conditions were distributed to participants in early 2008.

The second meeting was held in Winnipeg, Canada, in 2008 August and included a visit to the RD-14M facility, located in AECL's Whiteshell Laboratories. The meeting objectives were to discuss results of steady state calculations for initial conditions of RD-14M Tests B9006 and B9802 and to develop ground rules and common assumptions for blind transient calculations. The facility visit and discussion with operations staff proved very useful for the participants in resolving questions related to the facility configuration, operations, and code input models and nodalization.

All participating institutes provided the results of blind transient simulation for RD-14M tests B9006 and B9802, which were discussed at the third meeting in Vienna in 2009 August. Individual participants presented their model assumptions, nodalizations and sensitivities, and AECL presented the transient measurements. Several significant discrepancies between code predictions of the test behaviour and test observations were noted, and attributed to input errors, or incorrect assumptions, in particular related to the ECI system. Therefore, a second round of blind calculations was started (the test data was not distributed yet) to allow correction of obvious errors. This second round was completed in late 2009 and all transient test data was subsequently made available for the open calculations.

The fourth and final meeting was held in Daejeon, Republic of Korea, in 2010 November. The purpose of the meeting was to discuss all calculation results, formulate conclusions and recommendations, and review and finalize the draft report.

2. Description of RD-14M experiments

The RD-14M facility layout, shown in Figure 1, is a pressurised-water loop with essential features similar to the primary heat transport loop of a typical CANDU reactor. The facility is designed so that reactor typical conditions, such as fluid mass flux, transit time, pressure and enthalpy can be achieved in the primary-side for both forced and natural circulation. The design incorporates the basic "figure-of-eight" geometry of a CANDU reactor, with five horizontal channels per pass and a 1:1 scaling of the vertical elevations throughout the loop. Each six-meter-long channel, or heated section (HS) contains 7 electrically heated Fuel Element Simulators (FES) and is connected to end-fitting simulators. The feeder volumes, areas, and metal masses are appropriately scaled to the channels. The thermal characteristics of the FES are similar to real plant in terms of power density, heat flux and heat capacity.

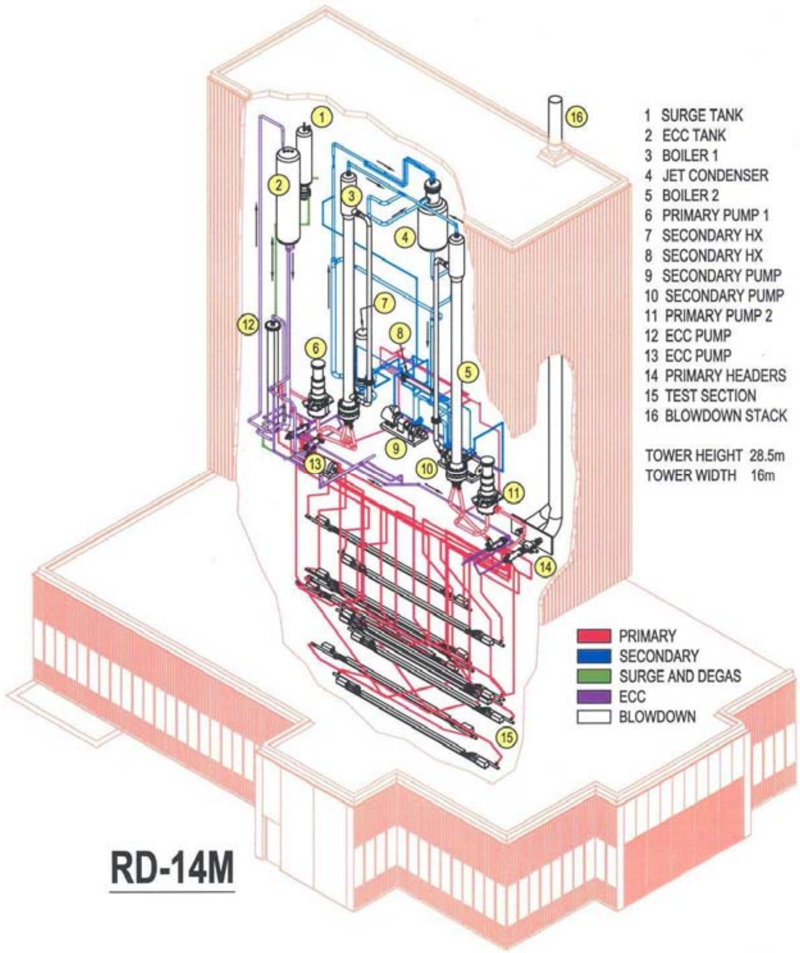

Figure 1 RD-14M loop layout

The RD-14M loop is extensively instrumented. Approximately 600 instruments are used to scan and record various thermal-hydraulic parameters. In addition to above-header pressures, temperatures, volumetric flows, and void fraction measurements, the test sections are extensively instrumented. Inlet and outlet temperature, pressure, volumetric flow and void fraction are measured for each test section. Fuel element sheath temperatures are measured at various locations on the test bundle and along the length of the test section.

3. ICSP participants and codes

A list of participants, along with the computer code and version used, is provided in the following Table 1. Eight organizations from six countries participated in this ICSP with four different system thermal-hydraulic computer codes. CATHENA code was used at five organizations, with three different versions.

Table 1 Participants organization, country and code

Participant Organization	Country	Code and Version
AECL, Atomic Energy of Canada Ltd.	Canada	CATHENA MOD-3.5d/Rev 2
AERB, Atomic Energy Regulatory Board	India	RELAP5/MOD3.2
CNE, Centrala Nucleara Electrica (Cernavoda)	Romania	CATHENA MOD-3.5d/Rev 1
CNEA, Comisión Nacional de Energía Atómica	Argentina	CATHENA MOD-3.5c/Rev 0
KAERI, Korea Atomic Energy Research Institute	Republic of Korea	CATHENA MOD-3.5d/Rev 2
KINS, Korea Institute of Nuclear Safety	Republic of Korea	MARS-KS
NPCIL, Nuclear Power Corporation of India Ltd.	India	ATMIKA
THU, TsingHua University	China	CATHENA MOD-3.5d/Rev 2

NPCIL participated with the system thermal hydraulic/neutronic computer code ATMIKA developed in NPCIL for the analysis of LOCA scenarios in Indian pressurized heavy water reactors. ATMIKA is based on Unequal Velocity Equal Temperature (UVET) model using three conservation equations with a drift flux model. A staggered mesh arrangement is adopted where pressure, density and enthalpy are defined at a node, and flow is defined along a flow path at the junction of two control volumes. Mass and energy conservation equations are applied on lumped control volumes and the momentum equation is applied on flow paths. A semi-implicit scheme has been adopted for solving the set of differential equations.

Five participants used the CATHENA code [4]. It was developed primarily for the analysis of postulated upset conditions in CANDU reactors; but is also used to model research reactors and thermal-hydraulic test facilities. CATHENA uses a transient, one-dimensional, two-fluid representation of two-phase flow in piping networks. In the thermal-hydraulic model, the liquid and vapour phases may have different pressures, velocities, and temperatures. The thermal-hydraulic model consists of solving six partial differential equations for the conservation of mass, momentum and energy for each phase. Interface mass, energy and momentum transfer between the liquid and vapour phases are specified using constitutive relations.

KINS used MARS-KS, a multi-dimensional thermal-hydraulic system code developed for analysis of thermal-hydraulics transients in pressurized water reactors, by consolidating and restructuring the RELAP5/MOD3.2 and COBRA-TF codes. The two codes were adopted to take advantage of the very general, versatile features of RELAP5 and the realistic three-dimensional hydrodynamic module of COBRA-TF.

RELAP5 was used by AERB. The RELAP5 code has been developed for best-estimate transient simulation of light water reactor coolant systems during postulated accidents. The RELAP5 hydrodynamic model is a one-dimensional, transient, two-fluid model for flow of a two-phase steam-water mixture that can contain non-condensable components in the steam phase and/or a soluble component in the water phase. The numerical solution scheme used results in a system representation using control volumes connected by junctions.

4. Comparison of code predictions with experiment

4.1 Blind and open simulation for test B9006

Test B9006 was a 7-mm inlet header break experiment with pressurized accumulator emergency coolant injection, performed in 1990 May. The break was represented by a fast-opening valve connected to an inlet header (HD8), and an orifice plate, scaled by the ratio of break area to loop volume to represent a CANDU feeder-sized break. Once the break valve was opened, single-phase liquid was discharged through the orifice, changing to two-phase flow when the inlet header pressure reached saturation. The break discharge flow was not measured directly. This is the most complete SBLOCA test conducted in RD-14M in terms of including all the phases of the transient (blowdown with power ramped down to decay power, exponential pump ramp, secondary pressure ramp (crash cool), high-pressure ECC, low pressure ECC, and natural circulation).

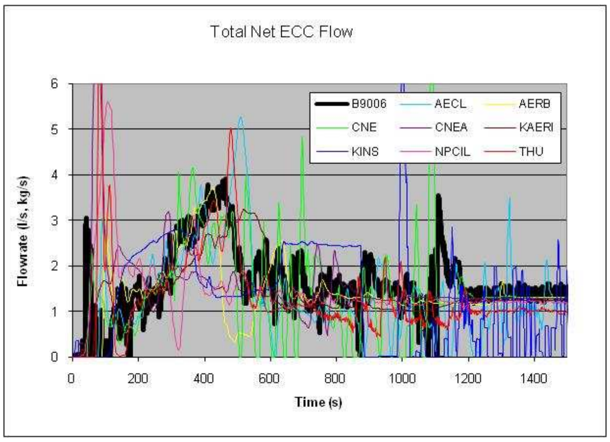

Figure 2 Total net ECI flow into loop (blind)

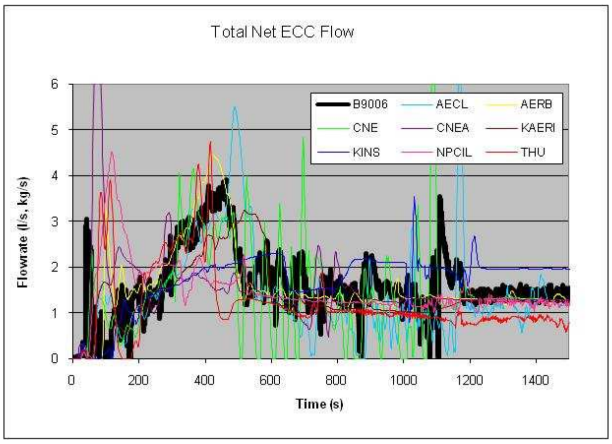

Figure 3 Total net ECI flow into loop (open)

In this test the modelling of the ECC system was the determining factor in calculating the correct loop temperatures and refill behaviour (From the experimental measurements it is inferred that the loop initially refills around 400-500s). Over-prediction in ECC flowrates caused faster depressurization and early refill times. The experiment clearly showed ECC flowrates which slowly increased throughout the HPECC injection phase, while some calculations showed the opposite trend, namely an initially high injection rate, which slowly decreases with time (Figures 2 and 3). Different modelling strategies were evident in applying the boundary conditions to simulate the ECC system. Prediction of parameters in the loop could be improved by imposing the ECC flowrates as boundary conditions; however, this was not done because modelling of the ECC system was part of the scope of this exercise. The need for accurate boundary and initial conditions became clear in the analysis of this experiment. An accurate representation of the ECI systems is necessary to correctly predict the flow split among the various headers and consequently the void distribution in the system and subsequent establishment of bidirectional flow in the parallel channel geometry.

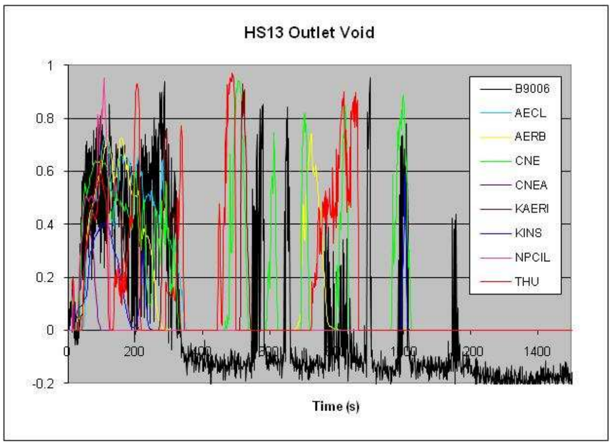

Figure 4 Heated section HS13 outlet void

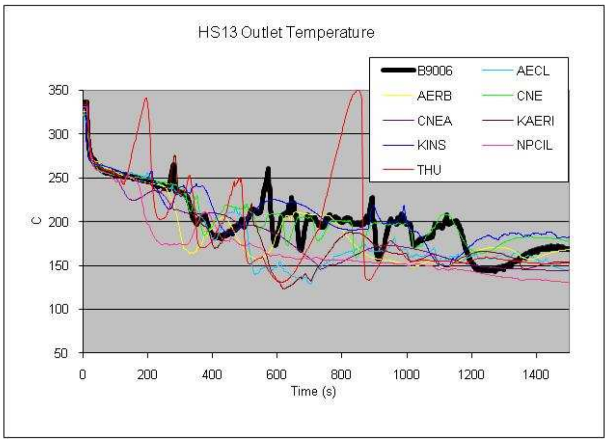

Figure 5 Heated section HS13 outlet FES temperature

Correct void predictions throughout the loop were initially believed to be critical in predicting other safety or trip related parameters, such as header pressure and FES temperatures. However, this exercise showed that, while there was a very large scatter in the timing of voiding and refill in various loop locations (namely the heated sections (Figure 4) and also boiler plenums and pumps), as well as in the levels of void calculated at various phases of the transient, the overall pressure and temperature response was calculated quite accurately, with very few exceptions. Since there were no significant FES temperature excursions (Figure 5) observed or calculated (due to the relatively low heater powers), even differences in the prediction of flow direction in the channels (including flow stagnation and reversal) did not generate large differences in overall loop behaviour. Short periods of mild temperature stratification within a channel (in the order of 10 s duration and 20-30ºC magnitude) were observed and predicted (at different times and with different, usually higher, magnitude) by CATHENA simulations that allowed flow stratification and had different FES groups (upper, middle and bottom). Prediction of flow stratification is dependent on code capability, user options and nodalisation. Again, the void predictions at the channel ends showed a much higher scatter and deviation from measurements (Figure 4) than the FES temperatures.

Flow reversal of significant flow rate and duration was observed predominantly in the high-elevation, low-powered channels in both passes (HS5/10, Figure 6), and also in one of the mid-elevation channels (HS12) of the broken pass. Several participants also predicted significant and sustained flow reversal in HS13, another mid-elevation broken-pass channel (Figure 7). During significant reverse flow, heat removal is effective, but inlet header temperatures stabilize at a higher value, therefore, increasing inlet temperature of forward-flowing channels. This phenomenon accounted for some of the differences in FES temperature predictions. The significant differences in transient flowrates through the heated sections are noteworthy. It was evident in the code comparison that those participants, who tuned the feeder hydraulic resistances to match the steady-state experimental flowrate distribution among channels, were better able to reproduce the observed flow reversal behaviour during the transient. Also, small changes in feeder resistance could result in different channels experiencing flow reversal. As compared to a LBLOCA simulation, however, FES temperatures are less sensitive to variations in the feeder loss coefficients.

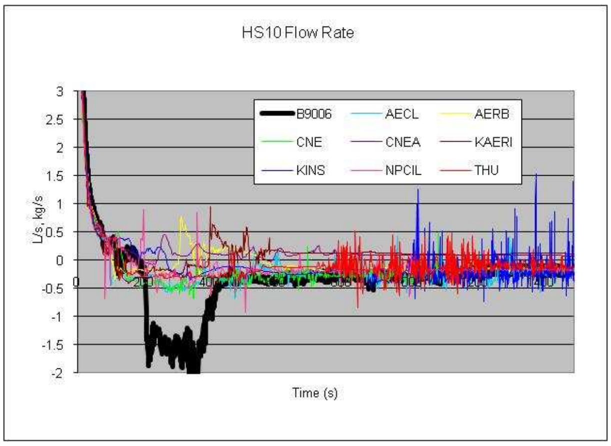

Figure 6 Flow through heated section HS10

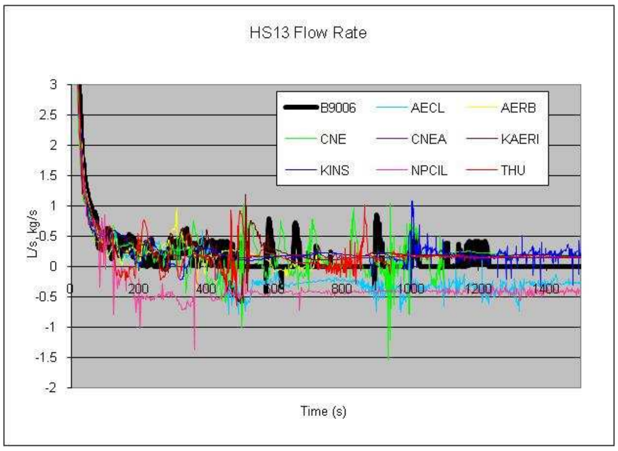

Figure 7 Flow through heated section HS13

4.2 Blind and open simulation for test B9802

Test B9802 was a 3-mm inlet header break experiment, performed in 1998 January, to provide data on the influence of condensation rates in the steam generators on primary loop response under conditions where such sensitivity is expected. The break was represented by a 3-mm orifice installed in the drain line from header HD8 to an inventory tank. The break discharge flow was condensed and measured. Test B9802 had a smaller break than B9006, continuous high-power to the heaters, no ECC injection, no pump ramp, and no secondary pressure ramp. Channel power remained at full power during most of the transient, and pump speed was slightly reduced from nominal in order to achieve higher initial enthalpy in the channels and thus more boiling. This test was intended to study boiling in channels and condensation in steam generators in a slowly depressurizing loop rather than a blowdown. An important feature of this test was the direct measurement of the break flow rate.

In this test the prediction of the break flow rate (Figure 8) was the determining factor in calculating the correct loop behaviour, in particular the timing of flow oscillations and temperature excursions. All codes predicted overall loop pressure and flow oscillations to various degrees, resulting from boiling in the channels and condensation in the boiler tubes, and the resultant void generation/collapse cycles, but at different times and with slightly different amplitudes and frequencies (Figure 9). Prediction of the pump head under degraded conditions, which influences coolant flow and subsequent FES heat up upon the loss of forced circulation, is influenced by the PHTS pump characteristics under two phase flow.

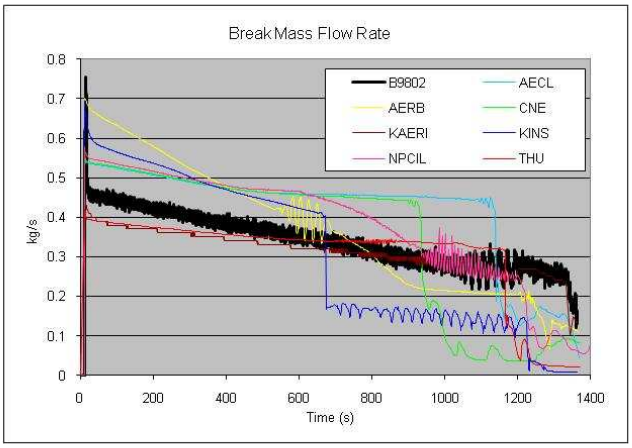

Figure 8 Break flow

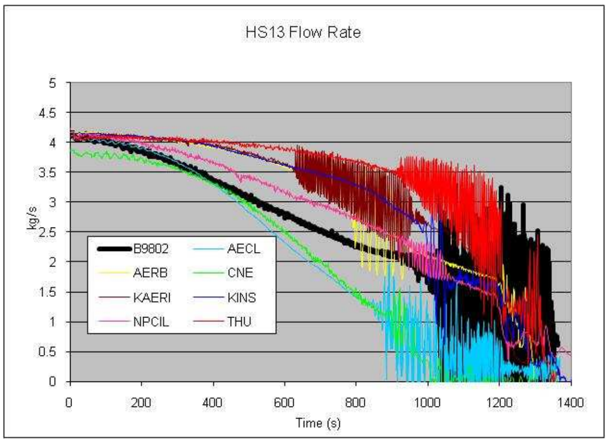

Figure 9 Flow through heated section HS13

None of the codes predicted the FES temperature oscillations that occurred at channel voids above ~ 80% correctly or the relatively slow increase in temperature during the post-dryout (PDO) heat transfer phase thereafter. All codes calculated a faster temperature increase without the initial dryout/rewet oscillations, leading to generally early power trip times, due to the codes' inability to correctly model the PDO heat transfer and rewet behaviour observed in the test, both in their blind and open calculations (Figure 11 shows the "open" results). One simulation was able to predict the relatively slow heatup once in dryout, by using a "developing PDO correlation with modified coefficients" (tuned correlation).

Axial temperature gradients in the channels were positive (increasing temperature in the flow direction) during the initial phase of the voiding transient (up to about 70% outlet void), while the FES's were covered by the liquid phase. In the later phase of nucleate boiling, the temperature gradient reversed, in particular for the top FES's, due to the decrease in saturation pressure and temperature of the coolant along the flow direction. This lower fluid temperature, combined with increased vapour velocity resulting from the rapidly increasing void, improved FES cooling towards the channel outlet. Whether this phenomenon was captured in the calculations depended on the PDO model, FES grouping, and whether stratification was allowed by the code. It also affected whether subsequent FES temperature excursions into the PDO regime were predicted to be larger/earlier near the channel inlet or outlet.

The calculated break flow rates varied significantly among participants, primarily due to different critical flow models and coefficients used. Since there was no ECC injection, the break flow resulted in the slow but steady depletion of loop inventory, and different break flow rates caused different overall loop void generation rates and thus different times for FES dryout and heatup. Since the flow remained forced throughout the transient, the flow directions in the heated sections were fixed, and with a relatively high heating rate, the outlet void development was predicted with acceptable accuracy by all codes (Figure 10).

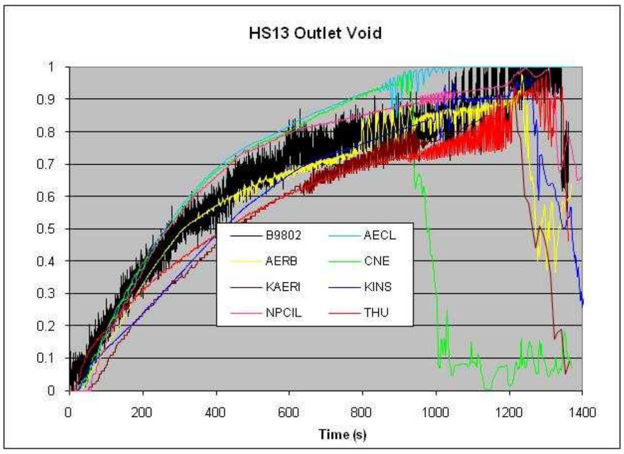

Figure 10 Heated section HS13 outlet void

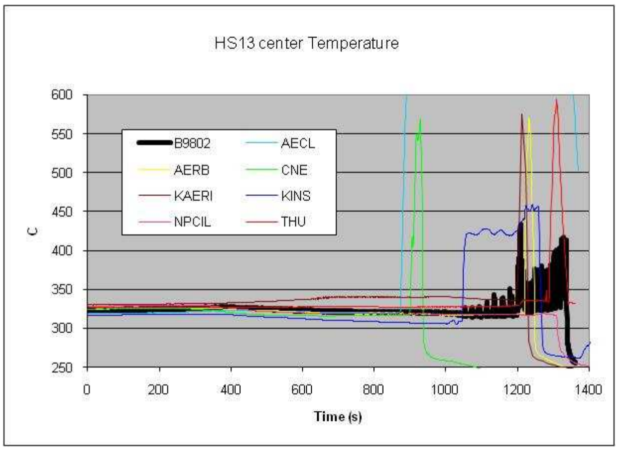

Figure 11 Heated section HS13 center FES temperature

5. Lessons learned from ICSP

The ICSP on code comparison for HWR offered a constructive platform giving a unique opportunity to code developers/experts, users and experimentalists to jointly verify and validate their thermal-hydraulic codes. The direct technical interaction among experts was helpful to improve/enhance understanding of important thermal hydraulic phenomena observed in a parallel channel facility under Small Break LOCA transients. The experience gained during participation has been fruitful in identifying code strength and areas requiring improvement. The lessons learned from participation in the IAEA-ICSP blind as well as open calculation in various important areas that are generic in nature, such as user effects, code deficiencies and need for capability improvement, experimental considerations and ICSP specification, are highlighted below.

5.1 User effects

User effects were evident in a few isolated instances and explained some of the difference in the results obtained with the various codes. User qualification is necessary in the areas of modeling of experimental facilities and representation and interpretation of experimental data, which greatly influence the selection of a modeling scheme and subsequent simulation of the transient. There were no fundamental differences in the adopted nodalization schemes, except that some users employed relatively coarse nodalizations. It is noted that the comparison between code results and test data is simplified and improved if instrument location is given due consideration in the nodalization of the entire facility. The following user options resulted in noticeable differences in predicted behaviour:

- Significant differences in ECC system modelling (valve logic, flow resistances, ECC tank model and/or pressure boundary condition), especially during the blind calculations, were responsible for significant differences in the code predictions of loop pressure and refill behaviour. An accurate representation of the ECI systems is necessary to correctly predict the coolant distribution among the various headers and subsequently the coolant distribution into the channels.

- PHTS pump characteristics play an important role and influence the prediction of pump head under degraded conditions, affecting coolant flow and subsequent FES heat up.
- Significant differences in break discharge modelling were responsible for significant differences in the code predictions of loop pressure and refill behaviour.
- Grouping of FES within channels, to allow temperature stratification, resulted in some participants replicating short periods of temperature stratification, although they were over-predicted. In fact, those that did not allow stratification (e.g. by lumping all heated FES into one group) predicted maximum FES temperatures closer to those measured, because any stratification periods in the experiments were small and of short duration.

The following general areas were also deemed important in obtaining acceptable results:

- Experience in the application of the code to test facilities: All codes have numerous user-selectable options and the quality of the results strongly depends on the choice of the appropriate models and model parameters. Available documentation and guidelines for specific options should be followed.
- Familiarity with the facility: This was mostly helped by the facility visit during the second meeting, and the interaction with facility operations staff.
- Availability of a reference input file increased confidence that the nodalization was adequate (only CATHENA reference files were available to, and used by AECL and KAERI). However, the use of a reference file discouraged fine-tuning of the feeder flow resistances and resulted in generally poorer agreement of the flow split among channels of the same pass during steady-state and transients.

5.2 Code deficiencies and need for capability improvement

All codes were able to replicate important phenomena, which are generally considered challenging during simulation of SBLOCA scenarios, namely:

- Two-phase pressure drop, provided the pump degradation is well captured
- Low flows and flow reversal in parallel channels, however, the quality of agreement is strongly dependent on matching steady-state flow distribution
- Loop refill as a result of ECC injection (at varying times)
- Timing of LPECC start
- Channel voiding
- Condensation in boilers (steam generators), although using the appropriate condensation model is important

- FES dryout

All codes experienced difficulties in the following areas (B9802):

- Precise matching of break discharge flow rate, even with tuning of discharge models
- Dryout/rewet cycles, prior to PDO heat transfer, in the channels
- Slow heat-up in PDO regime (only achieved by tuning the developing PDO model in one case)
- FES temperatures in PDO operation were generally overpredicted

Table 2 Summary on code deficiencies and capabilities

Phenomena	Experiments		System Codes			
	B9006	B9802	CATHENA	RELAP5	MARS	ATMIKA
Break discharge characteristics and critical flow	o	+	+	+	+	+
Coolant voiding	+	+	o	o	+	o
Phase separation	o	o	+	o	+	o
Single phase pressure drop	+	+	+	+	+	+
Two phase pressure drop	+	+	+	+	o	+
PHT Pump characteristics	o	o	+	+	+	+
Convective heat transfer	o	o	o	o	+	+
Nucleate boiling	o	o	+	o	+	+
Dryout behaviour	o	+	o	+	o	+
Condensation heat transfer	o	+	+	+	+	+
Core flow distribution	+	+	o	+	o	+
Natural circulation	+	-	+	+	+	+

Experiments:
+ well defined
o occurring but not well characterized
- not occurring or not measured

System codes:
+ predicted with accuracy
o qualitatively predicted
- not predicted

Sensitivity cases for the blind calculation phase were well chosen for the two tests and generally showed expected trends and no surprises or very large changes in important code results. Some participants performed additional sensitivity cases on code models (e.g liquid discharge coefficient) and test parameters (e.g. heater power, pump speed) as part of the open calculation phase and while results could be improved slightly, a perfect match to all measured parameters could not be obtained. This indicates that (1) the codes are robust and the "best-estimate" assumptions give acceptable results which can only be slightly improved by further tuning, however, also (2) that there still remain some code deficiencies. A qualitative comparison of all codes against the SBLOCA phenomena is presented in Table 2.

5.3 Experimental considerations and ICSP specification

During the initial phase of this ICSP some facility parameters, test boundary conditions, and measurement techniques were unclear. Through discussion and code "experimentation" it became clear that the following are very important considerations when specifying such a SBLOCA comparison exercise:

- Exact physical description and operation of ECC system and secondary side
- PHTS pump characteristics
- Factors affecting differential pressure measurements, in particular those spanning a significant elevation difference
- Unambiguous units for pressure measurements (MPa(a) or MPa(g)) and pressure-related trip set-points and logic
- Calibration, accuracy limits, and uncertainty of void meters and flow meters
- Timing (including instrument delays) of power and pump rundowns and other trips, such as valve open and close times

Sensitivity studies indicate that a significantly lower liquid discharge coefficient (compared to the default in all codes) is appropriate for this break geometry used in RD-14M SBLOCA tests. Critical flow model selection as well as two-phase or gas discharge coefficients had small effects.

6. Conclusions and recommendations

This is the second international code to experiment comparison exercise of this type in an HWR system and was made possible, within the framework of an IAEA project, by the availability of experimental data from AECL. Different insight into SBLOCA behaviour and code capabilities were gained from each of the two tests of this ICSP. All calculations were capable of achieving steady state conditions consistent with the experimental data apart from deviations in flow distribution among the individual parallel channels in each pass where no effort was made to tune the feeder hydraulic resistances. The transient pressure, temperature and void development in both tests were strongly influenced by the transient loop inventory.

For SBLOCA, channel voiding is not a concern as much as for LBLOCA and code accuracy for void prediction is not essential. However, maximum FES temperatures are important, and therefore, improvements in PDO models and in the critical break discharge models are required. Also, ECC effectiveness for channel refilling and SG effectiveness for condensation are important phenomena that affect FES heatup. While in B9006 (ECC active) some FES temperature stratification was observed during low flow periods; they were of very short duration and low magnitude, and occurred near the time when maximum loop void of about 35% was predicted. It can be concluded that up to that level of void in the loop, no significant stratification and sheath heatup periods (dryout) should be expected.

All main phenomena (e.g. break discharge, coolant voiding, pressure drop, boiling and condensation heat transfer, and temperature excursion in the heated sections) are qualitatively captured by the participants. Discrepancies in quantitative terms, in particular in void predictions, are observable and explainable but these do not significantly affect the prediction of the overall system performance or of those parameters that are critical in defining safety margins.

The application of codes developed outside the HWR technology did not show any special deficiency in the comparison with the present experimental database. Therefore, it can be concluded that HWR systems do not need special tools for the analysis of benchmark experiments of this type. However, the existence of parallel channels, and the potential of flow reversal in some of them, is untypical in other PWR reactor systems and requires special attention in the modeling. One dimensional thermal-hydraulic codes combined with an appropriate nodalization, accurate hydraulic resistances, and consistent set of assumptions are able to grossly predict the parallel channel effects as experienced during the simulation of current ICSP exercise.

The performed activity is relevant in assessing the capabilities of codes and permitted the quantification of the amount of discrepancy between measured and calculated values, however, it has not been immune from code user effect. The participants received great benefit from the analysis of this experiment having had the opportunity of direct contacts with developers of HWR technology and the transfer of information that is not available in open literature. Moreover, they increased the confidence in the prediction capabilities of system codes and achieved a better understanding of physical phenomena related to HWR SBLOCA transient scenarios.

The exercise confirmed the importance of having built and operated complex facilities like RD-14M and showed, within an international context, the quality level achieved by some computational tools developed within the HWR technology. It is recommended to further extend the use of RD-14M or other large-scale data for the benefit of the scientific and engineering community engaged in carrying out safety analysis of HWRs. One area of interest is the prediction of multi-channel loop behavior under natural circulation (thermo-syphoning) conditions.

7. References

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