Modelling a RD-14M LOCA Experiment with the TRACE Thermal-Hydraulics Code

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Abstract

RD-14M Test B9401, simulating a critical break loss-of-coolant accident in a CANDU primary heat transport system, is of note for serving as benchmark data for an IAEA code validation exercise. It has thus been modeled with the TRACE code to study the code's applicability towards modeling CANDU. TRACE reproduces the transient with fidelity comparable to other codes in the IAEA exercise, however predicts some phenomena with less accuracy than codes developed specifically for modeling CANDU-typical thermal-hydraulics. This was found to be due to limitations in TRACE's ability to account for some horizontal stratification effects common in CANDU accident analysis.

1. Introduction

The core issue of nuclear thermal-hydraulics safety analysis and research has been performance of the plant during transient conditions. Experiments carried out at test facilities intended to recreate plant behaviour in a small-scale manner have been one of the primary methods of gaining insight into the complex phenomena that occur during system transients [1]. For this purpose the RD-14M thermal-hydraulics test facility was constructed at AECL's Whiteshell Laboratories, with funding for construction and operation provided by the CANDU Owners Group (COG) [2]. Data collected at the facility is used to improve the understanding of the thermal-hydraulic behaviour of the CANDU reactor, as well as form a database for verifying and validating computer code models used to predict CANDU behaviour.

The TRAC/RELAP Advanced Computational Engine (TRACE) is a new thermal-hydraulic system code developed by the U.S. Nuclear Regulatory Commission (U.S.NRC) that combines the capabilities of its active and legacy system codes (RELAP5, TRAC-B and TRAC-P) into a single modernized computational tool. It has been designed to perform best-estimate analyses of loss-of-coolant accidents (LOCAs), operational transients and other accident scenarios in both Pressurized light-Water Reactors (PWRs) and Boiling light-Water Reactors (BWRs) [3]. Through participation in the international Code Applications and Maintenance Program (CAMP), the U.S.NRC also encourages international assessment of TRACE for the purposes of code verification and validation [4].

Computer codes that are part of CAMP (including TRACE) provide many benefits over exclusively domestic codes, including access to a wider range of code support, user groups, international expertise and breadth of validation activities. However, it is first necessary to demonstrate the applicability of the code in modeling CANDU-like behaviour before it can be considered in CANDU safety analysis. A TRACE model of the RD-14M facility has thus been created to demonstrate the applicability of the TRACE code towards modeling CANDU thermal-hydraulics.

RD-14M Test B9401 was chosen for simulation in TRACE because its status as benchmark data for an International Atomic Energy Agency (IAEA) code intercomparison and validation exercise provides a wealth of information regarding the behaviour of other established codes in modeling RD-14M. Test B9401 modeled a specific type of Loss of Coolant Accident (LOCA) called a critical break, wherein a flow stagnation through the broken core pass results in the rapid heatup of the fuel element simulators. The participants in this exercise (and the codes used) included Argentina (FIREBIRD-III), Canada (CATHENA), India (RELAP5), Italy (RELAP5), the Republic of Korea (RELAP5/CANDU) and Romania (FIREBIRD-III). Notably, these include codes that share a similar development history as TRACE (e.g. RELAP5) and codes developed independently (e.g. CATHENA) [5]. The objective of this work is to provide comparison between TRACE predictions and measured, expounding on significant deviations and ultimately proposing methods to account for, or correct, these behaviours in order to further improve the applicability of the TRACE code to CANDU safety analysis.

2. Methodology

2.1 RD-14M Facility Description

The RD-14M experimental facility is a full-elevation-scaled thermal-hydraulic test facility intended to represent the key components of a CANDU Primary Heat Transport System (PHTS). Experiments are conducted using RD-14M to foster an understanding of the thermal-hydraulic behaviour of a CANDU reactor during loss-of-coolant accidents, natural circulation conditions and reactor shutdown. The data collected from these experiments are used to identify and examine thermal-hydraulic phenomena as well as provide a database for validating computer models used for predicting CANDU reactor behaviour.

The facility (Figure 1) is arranged in a CANDU two-pass, figure-of-eight configuration, with the reactor core simulated by ten horizontal channels 6 m in length, each of which contains seven electrical heaters functioning as fuel element simulators (FES) [5]. Each test section is connected to full-length feeders via end-fitting simulators. The feeders lead to headers which are in turn connected to two full-height U-tube steam generators and two bottom-suction centrifugal primary heat transport pumps. The steam generated in the shell side of the steam generators is condensed in a jet condenser and then returned to the boilers via feedwater pumps. Primary-side pressure is controlled by a pressurizer utilizing an electric heater. The facility also includes an emergency coolant injection (ECI) system, capable of delivering both accumulator driven or high and low pressure pumped coolant injection into the primary circuit. There is extensive instrumentation, with approximately 600 instruments recording various thermal-hydraulic parameters during tests [5].

In order to accurately represent the CANDU PHTS, the RD-14M facility operates at typical CANDU primary system pressures and temperatures and was designed to produce similar fluid mass flux, transit time, pressures and enthalpy distributions [5].

2.2 RD-14M Test B9401

RD-14M Test B9401 simulated a 30 mm diameter inlet-header break with high-pressure pumped ECI available. This break size was specified through the installation of a 30 mm orifice in the flow path between the broken header and the break valve.

Approximately two seconds after the break valve was opened the power to the test sections was decreased to decay levels and the primary system pump speeds were exponentially decreased to represent the rundown resulting from loss of AC power. The ECI isolation valves opened and the pressurizer was isolated after the primary system pressure fell below 5.5 MPa (g). The outlet header pressure at the beginning of the test was approximately 10.0 MPa (g) with a nominal power of 4.0 MW per pass. The steam drum pressure was approximately 4.4 MPa (g) with the feedwater entering the steam generators at 186 °C [5].

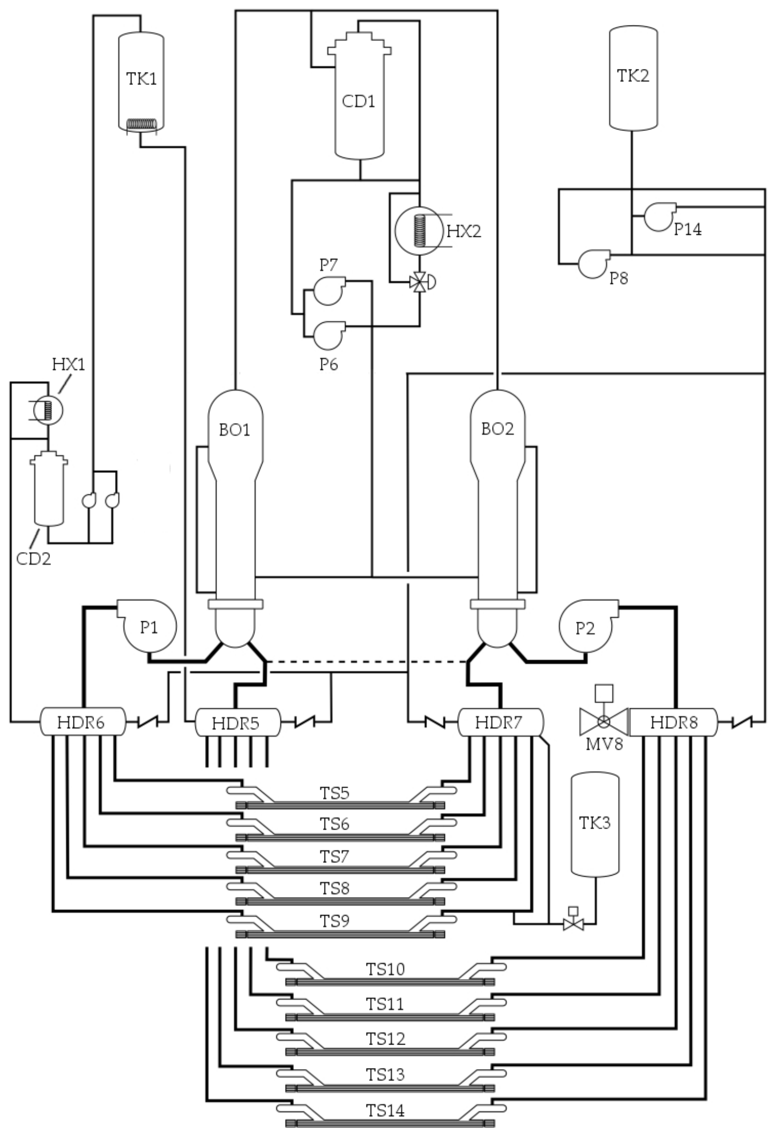

Figure 1 Drawing of the RD-14M experimental facility

2.3 TRACE Model Description

The RD-14M experimental facility was modeled with TRACE V5.0 using the Symbolic Nuclear Analysis Package (SNAP) graphical user interface for creation of the TRACE input file. The model includes the primary heat transport system, a simplified secondary heat transport systems and the high-pressure pumped ECI system (Figure 2). Since only the influence of the secondary side on the PHTS was judged to be of interest, the jet condenser and feedwater pumps were modeled as boundary conditions as functions of time for simplicity.

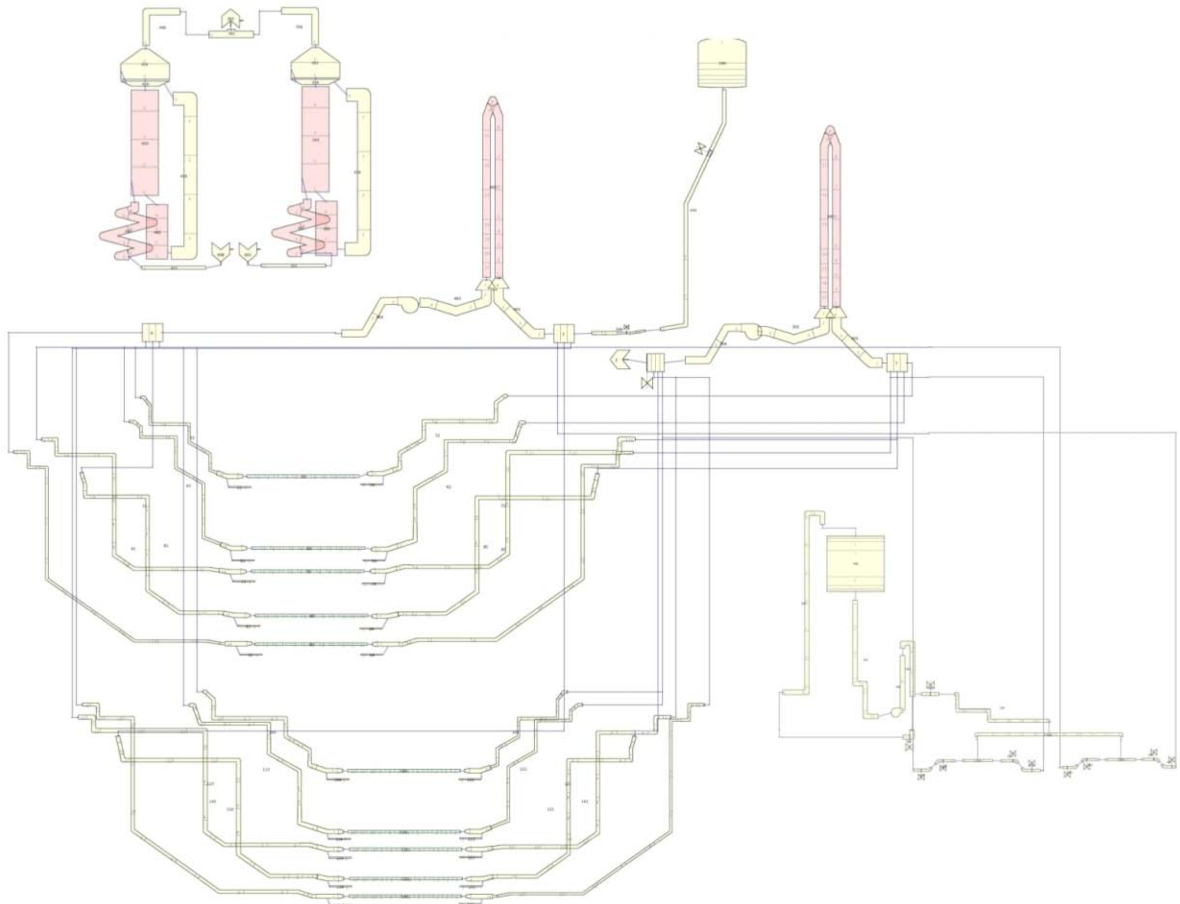

Figure 2 TRACE idealization of the RD-14M facility

All the primary, secondary and ECI system piping and valves were modeled with PIPE and VALVE components, nodalized such that the lengths, flow areas and elevation changes from the facility description were represented as well as the position of every piping elbow, orifice, or reducer/expander. K-factors were input to represent the irreversible pressure losses associated with the flow direction changes, area changes and various obstructions [6].

Each heated section was modeled with a single PIPE component, split into 12 equally sized control volumes 0.495 m in length (identical to the discretiziation of each FES, intended to be representative of 12 CANDU style fuel bundles) [5]. K-factors were input based on measured values for the entire test sections, including both the heated sections and the end fittings. All seven FES in each channel were modeled as a single heat structure of equivalent mass and heat transfer area with the outer radial surface coupled to the hydraulic PIPE component. A unique POWER component for each heated section was coupled to the radial node corresponding to the Inconel heater in each FES heat structure.

There is an inherent averaging effect in representing each test section as a one-dimensional hydraulic component in that there is no discrimination between the seven FES (they can only be represented as a single coupled heat structure). This poses an issue when modeling LOCAs in CANDU geometries, where horizontal flow stratification effects may produce higher temperatures in the top FES relative to those on the bottom. TRACE has no models to represent the temperature effects of flow stratification in horizontal fuel channels, and so in order to examine these effects a second nodalization of TS13 was made where the heated section was represented by two parallel PIPE components (Figure 3). This new hydraulic nodalization allowed for the top two FES to be modeled as a separate heat structure independent of the remaining five, with both still coupled to the same POWER. Results produced by this "stratified" model of TS13 are presented separately from the base model.

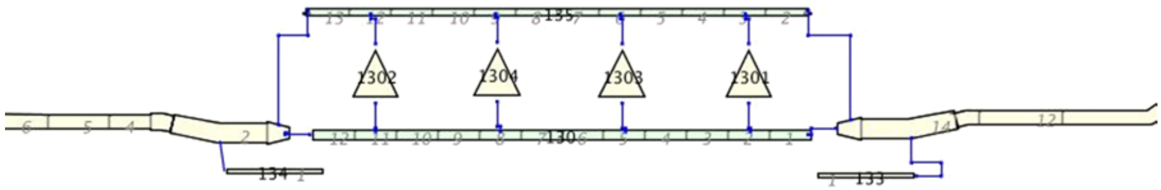

Figure 3 Pseudo two-dimensional nodalization of TS13

Header 8, the location of the break in RD-14M Test B9401, was modeled as a VALVE component consisting of four hydraulic cells and a valve interface flow area of 7.7×10^{-4} m^2, (equivalent to the 30 mm break orifice). In transient calculations the VALVE opened directly to a BREAK boundary condition set to atmospheric pressure and temperature, omitting the discharge pipe and blowdown stack present in the physical RD-14M facility. Standard practice (as shown in the IAEA benchmark study) has been to omit the discharge pipe, and so it has not been included in the TRACE model [5].

The explicit fluid choking calculation at the break was disabled after it was found to be in error, substantially under-predicting break discharge flow. The fluid conditions in the broken header during the test satisfy TRACE's horizontal stratification criteria, and the explicit choked flow model in TRACE V5.0 makes no allowances for stratification effects. Instead, the Semi-Explicit Two Step (SETS) numerical solver implemented in TRACE was used to perform a "natural" choking calculation (i.e. strictly through solution of the field equations with no special models). This was possible because the SETS solver has no Courant limitation, although it is warned that the natural choking calculation may suffer from reduced accuracy and computational efficiency [7]. Nevertheless, TRACE's prediction with the explicit choking model disabled was comparable to that of other codes, and so disabling the choking model was deemed necessary to accurately simulate the conditions of the test.

The conditions for Test B9401 were input into the TRACE model by setting the initial values of all the secondary side FILL and BREAK component boundary conditions, primary system pump rotational speeds, test section powers and the pressurizer pressure to match the corresponding steady-state experimental data. The primary system pump rundowns and power rampdowns were taken directly from the experimental data and input as tabular functions of time for the transient calculation.

A Generalized Steady-State (GSS) calculation with the TRACE RD-14M model was first performed, generating a restart file that contained the initial conditions for the transient calculation. Time 0 for the transient calculation was the time of break opening with calculation continuing for 90 seconds (approaching the termination time of high pressure pumped ECI), corresponding to the interval of 10 s to 100 s in the experiment.

3. Results

There were 558 instrumentation channels active during RD-14M Test B9401, rendering comparison between each measurement and the corresponding TRACE prediction impractical. A subset of the measured parameters is needed that gives meaningful details about the relevant thermal-hydraulic behaviours while providing insight into the quality of the code predictions. Some of the variables used for comparison of code predictions with experiment in the IAEA study on test B9401 have thus been selected for comparison with the TRACE model results as well [5]. To help elucidate the behaviour of TRACE, the code results provided by Canada (CATHENA), Italy (RELAP5) and Korea (RELAP5/CANDU) for the benchmark study are included on the plots of the transient variables. These provide context against which the relative quality of the TRACE predictions can be evaluated.

The turbine flow meters in the PHTS were only designed and calibrated for single-phase flow [5]. In two-phase flow conditions the turbine flow meters are commonly over-ranged, and since fluid void is encountered very early in blowdown transients (like Test B9401) the flow measurements have been considered invalid for the purposes of code comparison [5]. The differential pressure across the broken pass nonetheless gives a qualitative indication of the flow at a given time.

The differential pressure between Headers 8 and 5 is shown in Figure 4. The flow stagnation occurs within the first 10 seconds, after which the measured differential pressure is much more negative than the TRACE prediction, indicating less reverse flow through the test sections. The transient flow was found to be largely driven by the break discharge, and other code predictions for this differential pressure correlate well with their respective break flow predictions (Figure 5). It is noteworthy that the code prediction most similar to TRACE (i.e. that does not show the more negative differential pressure in Figure 4) was made with RELAP5, one of the progenitors of the TRACE code, whereas the other code predictions were made with CATHENA and RELAP5/CANDU (codes specifically designed for or with special considerations for modeling CANDU behaviour).

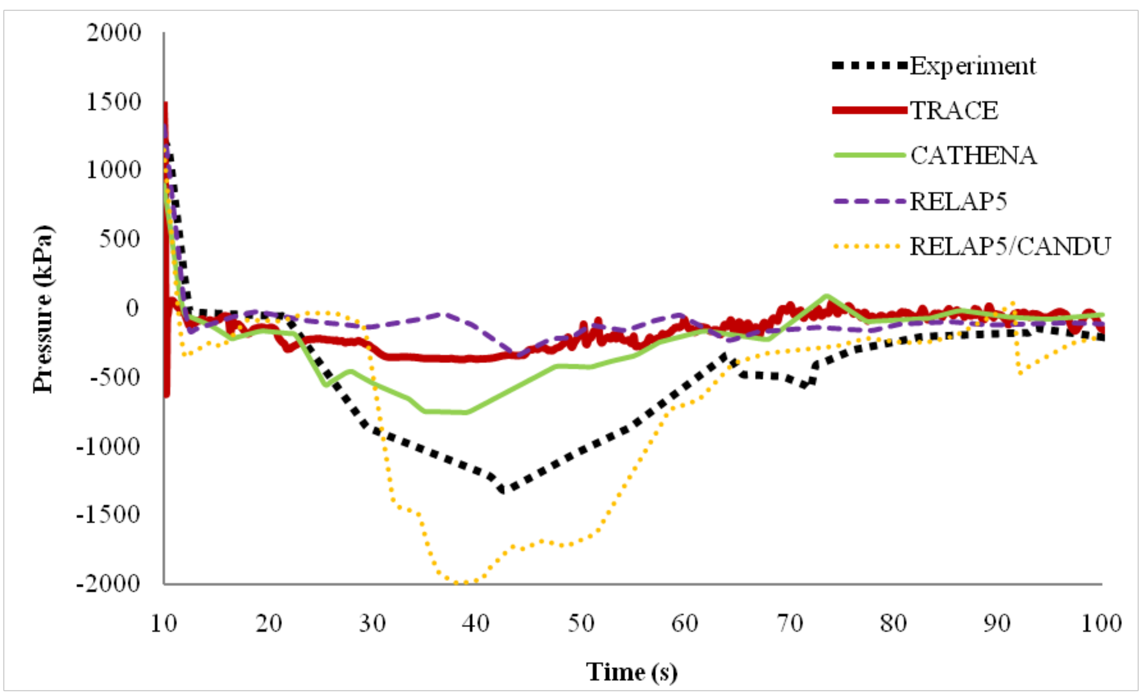

Figure 4 Differential pressure from Header 8 to Header 5

The break discharge flow has one of the largest governing influences on the behaviour of the transient. Although there was no measurement of break flow in RD-14M Test B9401, a code to code discharge comparison is shown in Figure 5. All codes are in reasonable agreement until approximately 20 seconds in the transient, where the onset of significant void in the broken header results in the choking of the break flow. The code predictions diverge at this point. The codes that show the larger increase in break flow after the inception of two-phase fluid choking seem to be closer to the experiment as indicated through the differential pressure measurement on the broken pass.

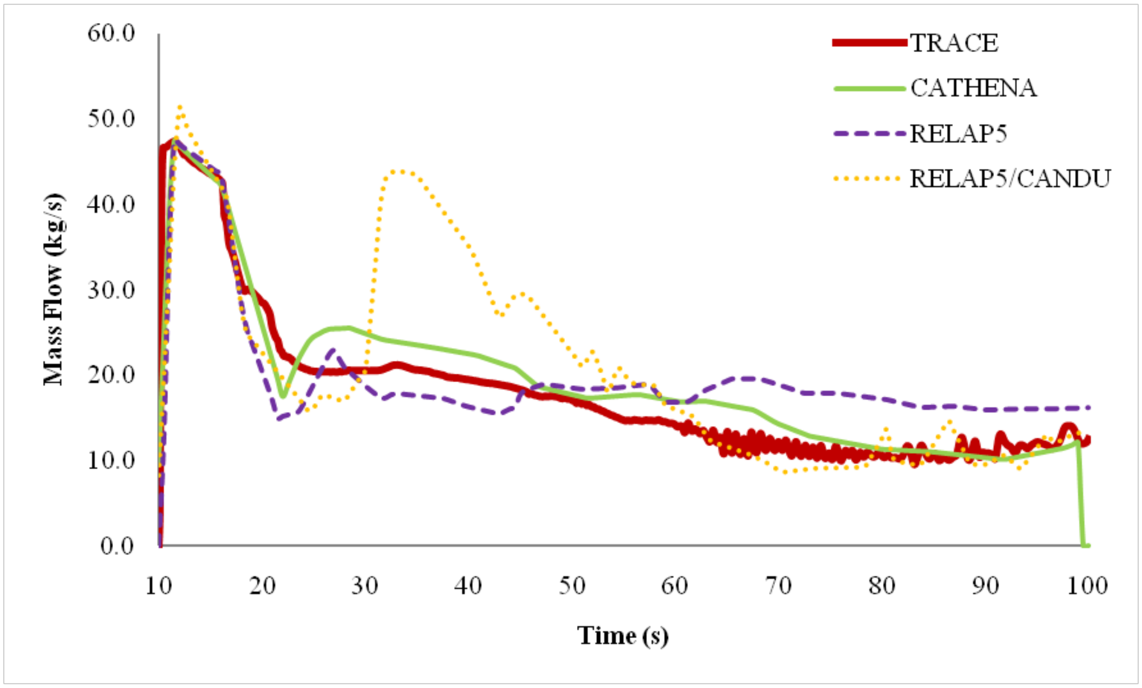

Figure 5 Break discharge flow

The flow of emergency core coolant into the PHTS is largely determined by the pressures in the headers. The signal to open the ECI system isolation valves is sent after the pressure in Header 7 falls below 5.5 MPa. In the experiment this occurred at 20.7 seconds and in the TRACE simulation at 20.5 seconds. Figure 6 and Figure 7 show the volumetric ECI flows into Header 5 and Header 8 on the broken pass. TRACE shows substantial ECI flow into Header 5 considerably earlier than measured (whereas the initiation of ECI flow into Header 8, the broken header, is well predicted). Predictions of ECI flow distribution vary considerably from code to code, with none corresponding especially well to the experiment. Generally, the TRACE prediction is shown to fall within the extremes predicted by the participants in the IAEA study, and all codes predict earlier significant ECI flow into the unbroken headers than measured.

Errors in the ECI flow predictions likely arise from the idealization of the ECI system used for the TRACE model. Components in the RD-14M high pressure ECI system were not characterized as thoroughly as in the PHTS, especially with regards to hydraulic losses of valves. The assumptions that the valves were identical and performed identically are likely erroneous, however there is insufficient data to justify changes to the model outside of tuning the component characteristics to explicitly give better transient results.

The ECI flow to Header 8 is very closely correlated to the break discharge flow. Codes that predict greater break flows correspondingly predict greater ECI flow, and so codes that predict similar break flows as TRACE (i.e. RELAP5) also show a similar ECI flow transient into the broken header.

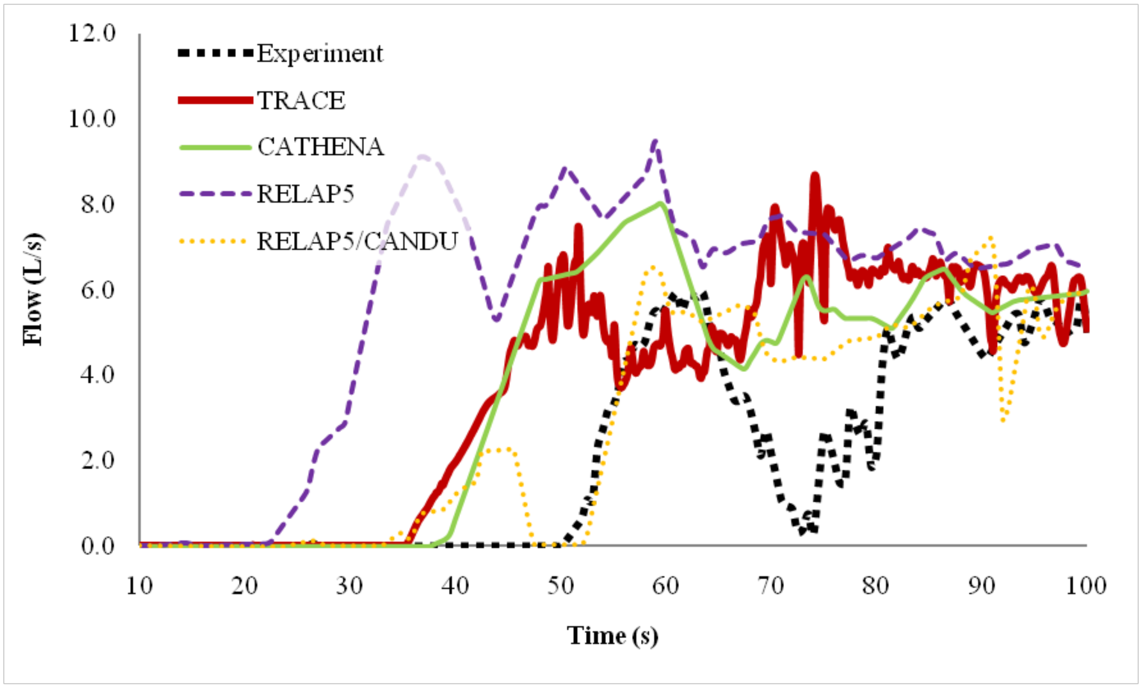

Figure 6 ECI flow to Header 5

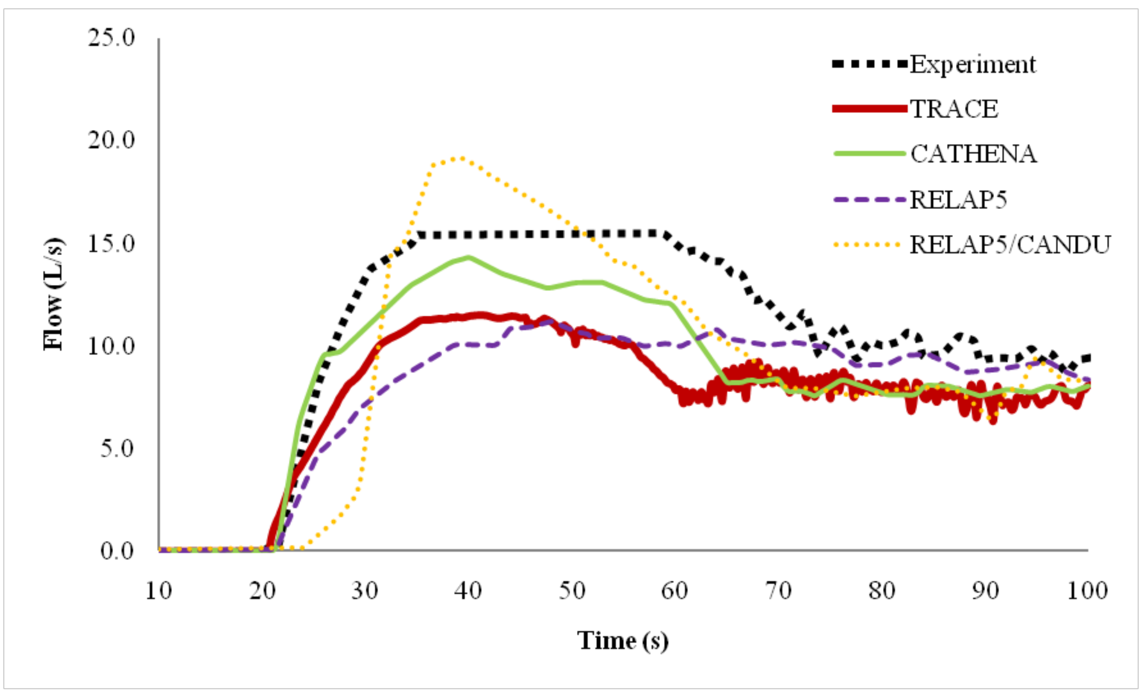

Figure 7 ECI flow to Header 8

The maximum sheath temperature is one of the most important parameters in safety analysis [5]. In RD-14M Test B9401, the maximum FES temperature occurs in the high power channel on the broken pass that experiences the flow stagnation (TS13). As described earlier, two separate TRACE nodalizations of HS13 were constructed, a purely one-dimensional representation identical to the other heated sections, and another with two parallel PIPE components at different elevations to explicitly model the effects of flow stratification. The results of both are plotted presented for comparison.

Figure 8 shows the sheath temperature of the top FES in the middle of HS13. The temperature peak resulting from the flow stagnation and subsequent power reduction is evident between 10 and 30 seconds. Given that the predicted flow through the test section is much lower than measured intuitively TRACE would predict a higher FES temperature as well. However, this is not the case as TRACE lacks specific models for wall-liquid heat transfer in stratified flow conditions. The predicted peak temperature in the top FES is resultantly lower in the one-dimensional model. The quasi-two-dimensional or 'stratified' model partially corrects for this, showing a much higher peak temperature for the top FES. After 50 seconds the flow is no longer stratified as cooler fluid from the ECI systems enters the heated section (earlier than predicted), and both model results converge together.

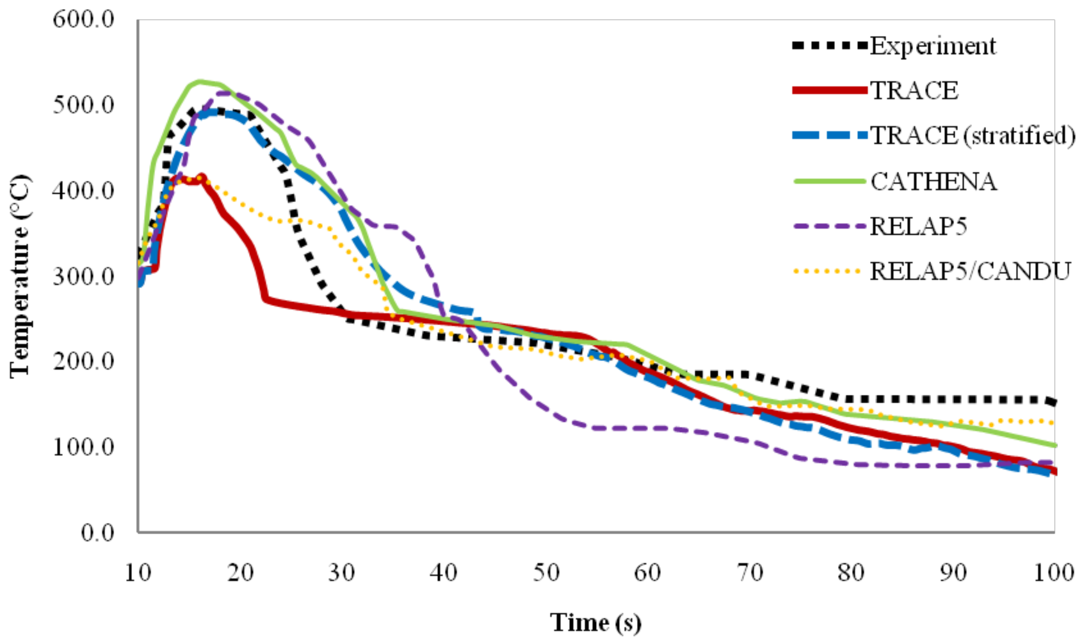

Figure 8 Top FES sheath temperature at middle of TS13

The void measurements at the test section inlets and outlets give insight into the FES temperature behaviour as well as the arrival time of ECI into the heated sections [5]. The outlet void fraction of TS13 is shown to be representative of the void transients on the broken pass (the void at the test section outlet is presented first because the flow is reversed through most of the transient). The void fraction measurement should only be considered accurate to within ± 0.05 void given the uncertainty in calibrating the measurement devices.

Figure 9 and Figure 10 show the near complete voiding of TS13 almost immediately in the transient. With the high enthalpy fluid reversing and going back through the test section, significant voiding occurs immediately and the fluid stratification effects have severe impacts on the FES temperatures. The earlier ECI flow into Header 5 in this case results in the earlier decrease of void at the outlet of TS13, followed by the inlet.

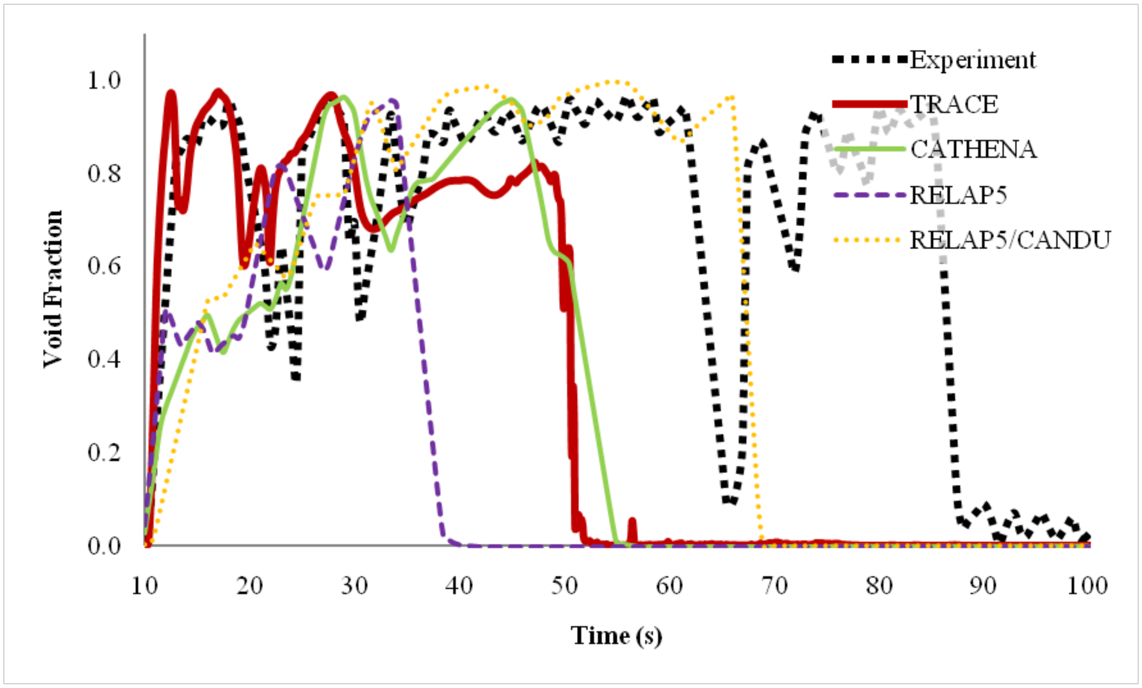

Figure 9 Void fraction at outlet of TS13

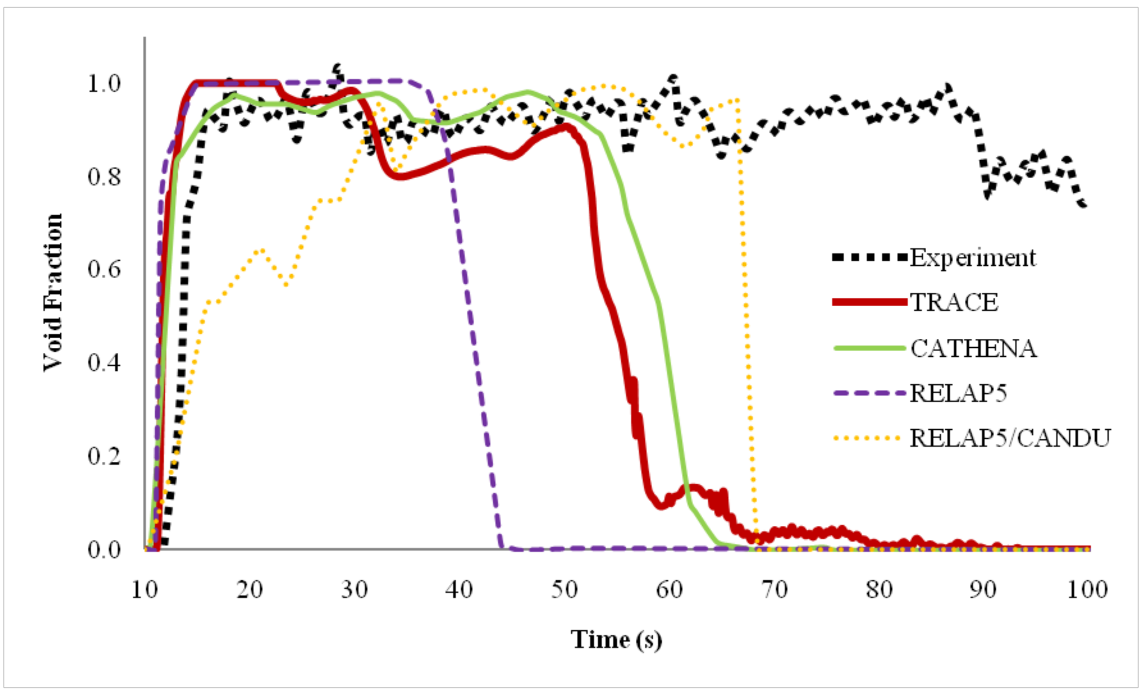

Figure 10 Void fraction at inlet of TS13

4. Conclusions

A TRACE model of the RD-14M integral effect test facility was developed to demonstrate the capability of the TRACE code to model CANDU PHTS behaviour. The TRACE calculation correctly predicted the general trends during the transient (a critical break LOCA) with fidelity comparable to that of the other codes that modeled RD-14M Test B9401 in the IAEA code intercomparison and validation exercise. In this respect, TRACE behaves most similar to RELAP5, which is unsurprising given the TRACE code's ancestry in other U.S.NRC codes (RELAP5, TRAC-B and TRAC-P). The ability of a newly developed code such as TRACE V5.0 to produce comparable results to established codes such as RELAP5 speaks towards its maturity as an analysis tool. However, the TRACE code predictions generally do not follow experiment as closely as codes designed exclusively for CANDU safety analysis (e.g. CATHENA) due mainly to a lack of horizontal fuel modeling and complete stratification models.

In modeling a critical-break such as RD-14M Test B9401, one of the most important variables is the peak FES sheath temperature. In addition to the test section modeling methodology, the temperature behaviour of the FES has been shown to be largely governed by the break discharge and depressurization in the early transient, and later on by the arrival ECI fluid in the test sections. The TRACE code contains no explicit models to capture the effect of horizontal flow stratification on wall-fluid heat transfer in one-dimensional hydraulic components. This has been shown to result in under-prediction of the peak FES temperatures during the transients, although it has been demonstrated that this effect can be lessened through a multi-dimensional nodalization of the heated sections.

The rate of break discharge effects the flow stagnation and subsequent reverse flow through the test sections in the early transient. It was found that TRACE's choked flow model is not suitable for modeling breaks sized and located like in RD-14M Test B9401 because it does not take into account the effects of horizontal stratification in the broken header. Disabling the explicit choked-flow model resulted in break discharge predictions more in line with the experiment; however, neither method captured the surge of flow after the initial onset of two-phase fluid choking. This is in line with RELAP5, which also does not predict the surge in break flow. The late flow surge was, however, captured to some extent in the other CANDU specific codes used in the IAEA benchmark study.

The flow of ECI fluid into the loop cools the FES during the later transient, and is necessarily a function of the header depressurization as well as the hydraulic characterization of the system. Large deviations between the different code predictions for ECI flow into each header suggest uncertainty in the ECI system characterization. The TRACE model generally predicts earlier ECI flow into the headers furthest from the break, although this should be regarded as a modeling uncertainty rather than an affect of the code.

5. Acknowledgements

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