NUREG/IA-0446

International Agreement Report

Assessment of Channel Coolant Voiding in RD-14M Test Facility using TRACE

Prepared by:
Andrew Oussoren
Aleksandar Delja

Canadian Nuclear Safety Commission
280 Slater Street
P.O. Box 1046 Station B
Ottawa, Ontario, Canada
K1P 5S9

K. Tien, NRC Project Manager

Division of Systems Analysis
Office of Nuclear Regulatory Research
U.S. Nuclear Regulatory Commission
Washington, DC 20555-0001

Manuscript Completed: December 2013
Date Published: August 2014

Prepared as part of
The Agreement on Research Participation and Technical Exchange
Under the Thermal-Hydraulic Code Applications and Maintenance Program (CAMP)

Published by
U.S. Nuclear Regulatory Commission

AVAILABILITY OF REFERENCE MATERIALS IN NRC PUBLICATIONS

NRC Reference Material

As of November 1999, you may electronically access NUREG-series publications and other NRC records at NRC's Public Electronic Reading Room at http://www.nrc.gov/reading-rm.html. Publicly released records include, to name a few, NUREG-series publications; *Federal Register* notices; applicant, licensee, and vendor documents and correspondence; NRC correspondence and internal memoranda; bulletins and information notices; inspection and investigative reports; licensee event reports; and Commission papers and their attachments.

NRC publications in the NUREG series, NRC regulations, and Title 10, "Energy," in the *Code of Federal Regulations* may also be purchased from one of these two sources.

1. The Superintendent of Documents
   U.S. Government Printing Office
   Mail Stop SSOP
   Washington, DC 20402–0001
   Internet: bookstore.gpo.gov
   Telephone: 202-512-1800
   Fax: 202-512-2250
2. The National Technical Information Service
   Springfield, VA 22161–0002
   www.ntis.gov
   1–800–553–6847 or, locally, 703–605–6000

A single copy of each NRC draft report for comment is available free, to the extent of supply, upon written request as follows:

Address: U.S. Nuclear Regulatory Commission
Office of Administration
Publications Branch
Washington, DC 20555-0001
E-mail: DISTRIBUTION.RESOURCE@NRC.GOV
Facsimile: 301–415–2289

Some publications in the NUREG series that are posted at NRC's Web site address http://www.nrc.gov/reading-rm/doc-collections/nuregs are updated periodically and may differ from the last printed version. Although references to material found on a Web site bear the date the material was accessed, the material available on the date cited may subsequently be removed from the site.

Non-NRC Reference Material

Documents available from public and special technical libraries include all open literature items, such as books, journal articles, transactions, *Federal Register* notices, Federal and State legislation, and congressional reports. Such documents as theses, dissertations, foreign reports and translations, and non-NRC conference proceedings may be purchased from their sponsoring organization.

Copies of industry codes and standards used in a substantive manner in the NRC regulatory process are maintained at—

The NRC Technical Library
Two White Flint North
11545 Rockville Pike
Rockville, MD 20852–2738

These standards are available in the library for reference use by the public. Codes and standards are usually copyrighted and may be purchased from the originating organization or, if they are American National Standards, from—

American National Standards Institute
11 West 42nd Street
New York, NY 10036–8002
www.ansi.org
212–642–4900

Legally binding regulatory requirements are stated only in laws; NRC regulations; licenses, including technical specifications; or orders, not in NUREG-series publications. The views expressed in contractor-prepared publications in this series are not necessarily those of the NRC.

The NUREG series comprises (1) technical and administrative reports and books prepared by the staff (NUREG-XXXX) or agency contractors (NUREG/CR-XXXX), (2) proceedings of conferences (NUREG/CP-XXXX), (3) reports resulting from international agreements (NUREG/IA-XXXX), (4) brochures (NUREG/BR-XXXX), and (5) compilations of legal decisions and orders of the Commission and Atomic and Safety Licensing Boards and of Directors' decisions under Section 2.206 of NRC's regulations (NUREG-0750).

DISCLAIMER: This report was prepared under an international cooperative agreement for the exchange of technical information. Neither the U.S. Government nor any agency thereof, nor any employee, makes any warranty, expressed or implied, or assumes any legal liability or responsibility for any third party's use, or the results of such use, of any information, apparatus, product or process disclosed in this publication, or represents that its use by such third party would not infringe privately owned rights.

NUREG/IA-0446

International Agreement Report

Assessment of Channel Coolant Voiding in RD-14M Test Facility using TRACE

Prepared by:
Andrew Oussoren
Aleksandar Delja

Canadian Nuclear Safety Commission
280 Slater Street
P.O. Box 1046 Station B
Ottawa, Ontario, Canada
K1P 5S9

K. Tien, NRC Project Manager

Division of Systems Analysis
Office of Nuclear Regulatory Research
U.S. Nuclear Regulatory Commission
Washington, DC 20555-0001

Manuscript Completed: December 2013
Date Published: August 2014

Prepared as part of
The Agreement on Research Participation and Technical Exchange
Under the Thermal-Hydraulic Code Applications and Maintenance Program (CAMP)

Published by
U.S. Nuclear Regulatory Commission

ABSTRACT

Coolant voiding in fuel channels of CANDU reactors during a Loss of Coolant Accident (LOCA) is important to reactor behaviour due to the power pulse arising from positive void reactivity. The prediction of voiding in fuel channels is therefore of fundamental importance to LOCA safety analysis. The CNSC is evaluating the applicability of the TRACE thermal hydraulics code to CANDU reactor simulation.

In this study, inlet header LOCA test B0106 from AECL's RD-14M thermal hydraulic test facility was modeled using TRACE. RD-14M is a scaled CANDU heat transport system containing 10 electrically heated fuel channels and full elevation feeders and boilers. In this test, a break in an inlet header is simulated using a fast opening valve. The size of the break is such that it creates near stagnation flow in the affected loop. A neutron scatterometer installed on one of the test channels measures void fraction in the channel during the transient.

The TRACE code was capable of predicting channel voiding trends with good accuracy, while the extent of voiding was generally over predicted. System pressure is predicted very well over the first several seconds of the transient; however pressure is under-predicted later in the transient. This under-prediction can be corrected through modifying the multiplying coefficients in the TRACE critical flow model. Fuel sheath temperature was under predicted for most of the test; this is due to limitations in the ability to represent a horizontal fuel channel in TRACE.

CONTENTS

Page

FIGURES

Page

TABLES

Page

ACKNOWLEDGMENTS

The authors would like to acknowledge the Canadian Nuclear Safety Commission for supporting involvement in the Code Applications and Maintenance Program (CAMP), Atomic Energy of Canada Limited for providing the experimental data necessary to perform this analysis, and the US NRC for making the TRACE code available to the international community.

ABBREVIATIONS

AECL	Atomic Energy of Canada Limited
BWR	Boiling Water Reactor
CANDU	Canadian Deuterium Uranium reactor
CNSC	Canadian Nuclear Safety Commission
ECC	Emergency Core Cooling
FES	Fuel Element Simulator
LOCA	Loss Of Coolant Accident
PHTS	Primary Heat Transport System
PHWR	Pressurized Heavy Water Reactor
PWR	Pressurized Water Reactor
TRACE	TRAC/RELAP Advanced Computational Engine
US NRC	United States Nuclear Regulatory Commission

1. INTRODUCTION

The Canadian nuclear power industry is based on CANDU technology. CANDU is a Pressurized Heavy Water Reactors (PHWR) design, using heavy water to moderate and cool natural uranium fuel. In 2013 there were 31 CANDU reactors operating in 7 countries around the world [1].

One of the design basis events for CANDU safety analysis is a postulated Loss of Coolant Accident (LOCA). The use of a heavy water moderator and natural uranium fuel results in a positive void reactivity coefficient. Coolant voiding in the fuel channels during a LOCA will result in an increase in reactor power prior to initiation of shutdown systems. For this reason prediction of channel voiding during LOCA is a critical parameter in CANDU safety analysis.

RD-14M is a thermal hydraulic test facility operated by Atomic Energy of Canada Ltd. (AECL) which reproduces most of the key components of a CANDU Primary Heat Transport System (PHTS). RD-14M is used to investigate PHTS behavior under different postulated operating and accident scenarios. Experiment B0106 was conducted at RD-14M in 2001 as part of a series of experiments investigating channel coolant voiding rates during a simulated LOCA. These tests were performed in partial fulfillment of the requirements of CNSC Generic Action Item 00G01: “Channel Coolant Voiding During LOCA”, [2]. Experiment B0106 simulates an inlet header break which creates near-stagnation conditions in the fuel channels downstream of the break.

TRACE is a thermal hydraulics system code which has been developed by the US NRC to provide best estimate analysis of thermal hydraulic transients in Pressurized Light Water Reactors (PWR) and Boiling Water Reactors (BWR). The CNSC is evaluating the applicability of TRACE to model transient behavior in CANDU reactors. To date there is limited validation of TRACE for CANDU-type geometries.

In this study, RD-14M test B0106 is modeled using TRACE V5.0 Patch 3. Modeling results are compared to experimental measurements to assess the suitability of TRACE to model CANDU-typical LOCA phenomena.

2. MODELING CANDU WITH TRACE

The TRACE thermal hydraulics code was developed for analysis of PWR and BWR behavior. There are some features which are unique to CANDU reactor design which are not easily reproducible in a TRACE nodalization. These limitations are outlined in this section.

2.1 Unique CANDU Geometries

Two CANDU-specific components which are of particular importance for thermal hydraulics modeling are the horizontal fuel channels and the headers.

2.1.1 Horizontal Fuel Channels

The fuel channels in a CANDU reactor are horizontal pipes called pressure tubes which contain twelve or thirteen fuel bundles, each comprised of 28 or 37 individual fuel elements. Under LOCA conditions flow through the fuel channels can become stratified; this has important implications for heat transfer, as lower fuel elements which are surrounded by liquid will transfer much more heat to the coolant than upper elements which are surrounded by vapour. Consequently, fuel sheath temperatures in upper elements will be greater than in the lower elements.

TRACE predicts flow in horizontal pipes to be stratified if the relative velocity (gas velocity minus liquid velocity) is below a critical velocity defined by the Taitel-Dukler criterion. This criterion was developed for flow through unobstructed, circular pipes [3, p154], and is therefore not directly applicable to flow through a CANDU fuel channel. The obstruction of the fuel bundles would allow stratification to occur at higher relative velocities than in an open pipe [4], therefore TRACE would be expected to under predict the length of time during which stratified flow conditions exists in a fuel channel.

The TRACE stratified flow model includes a stratified wall drag correlation, however there is no special heat transfer model for the stratified flow regime; instead TRACE uses the average fluid properties across each cell. Therefore the differential heat transfer between upper and lower elements cannot be captured in a TRACE model.

For modeling fuel assemblies in PWR and BWR, TRACE provides a VESSEL component which is capable of 3-D modeling of the core. However the VESSEL component is restricted to a vertical orientation, thus it cannot be used to model CANDU fuel channels.

2.1.2 Headers

The headers in a CANDU reactor are large horizontal pipes: coolant from the main heat transport pumps enters the top of an inlet header and divides into many different feeder outlets, which deliver flow to the fuel channels through feeder pipes. The feeder outlets are arranged in rows along the bottom half of a header and enter at various angles. The process is reversed in the outlet header, with hot coolant entering from the feeders and exiting the top of the header to the steam generators. Headers represent complex flow geometries for modeling.

The feeder connections to the headers are best modeled in TRACE using side junctions; however the TRACE Theory Manual notes that: “A rigorous formulation for momentum transfer terms has not been developed for the case where flow is out through the side [junctions]”, [3, p20]. The modeling of an inlet header may therefore present some difficulties in correctly predicting momentum transfer. In this study the model had to be calibrated to achieve accurate flow division between the channels, described in Section 4.3.

In stratified flow conditions the void fraction of flow through a side junction will depend on the connection location relative to the water level in the pipe. TRACE accounts for the void fraction in side junction outflow, including liquid entrainment and vapour pull-through, using an off-take model. The off-take model requires side junctions to be at 90 degrees to the main flow path of a pipe and be oriented vertically up, vertically down or horizontal (see **Figure 1**). CANDU headers contain feeder connections at a variety of angles in between horizontal and vertically down; these connection angles cannot be accounted for with the TRACE off-take model. The connection to the break valve is horizontally oriented but is in line with the main flow path of the header pipe, and therefore the off-take model is not applicable.

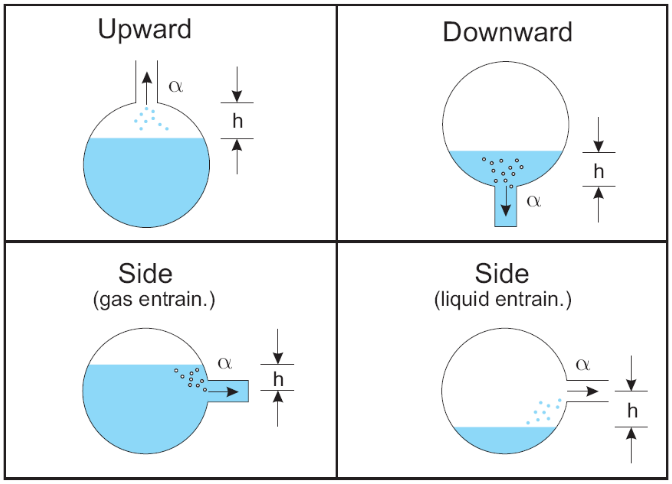


Figure 1: Allowable side junction angles for TRACE off-take model, pipe cross-section

2.2 TRACE Modeling of CANDU To Date

There is limited validation of TRACE for CANDU-type geometries; there are 3 notable reports on TRACE modeling in the CANDU community which are summarized briefly below.

A. Mysen (2008) modeled the RD-14M facility test B0104, a LOCA simulation with measured channel voiding (part of the same test series as the test described in this report). Mysen found the TRACE predicted the general trends of the experiment well, noting that both header pressure and fuel clad temperature were under predicted [5].

A master's thesis by D. Hummel (2010) modeled RD-14M test B9401, a LOCA simulation with ECC. This test was notable for being used for an IAEA benchmark study on code inter-comparison and validation. Hummel found that TRACE "predicted the important test parameters as well as or better than some of the established codes used in the IAEA exercise" [9]. It is notable that Hummel found the best results were obtained with the TRACE critical flow model disabled, a finding not shared by this study.

A. Delja (2011) modeled RD-14M test B0113, a LOCA experiment with a simulated power pulse. Delja found that the general trends of the experiment were reproduced well compared to the CANDU-specific thermal hydraulics codes CATHENA and TUF, [6].

3. EXPERIMENT DESCRIPTION

This section describes the RD-14M test facility and the details of experiment B0106.

3.1 RD-14M Facility

RD-14M is a thermal hydraulic test loop at AECL's Whiteshell Laboratories. The facility contains scaled representations of most of the key components of a CANDU reactor. **Figure 2** shows a simplified schematic of the facility. The heat transport system is scaled to produce CANDU-typical conditions including pressure, mass flux, temperatures and transit times under forced and natural circulation.

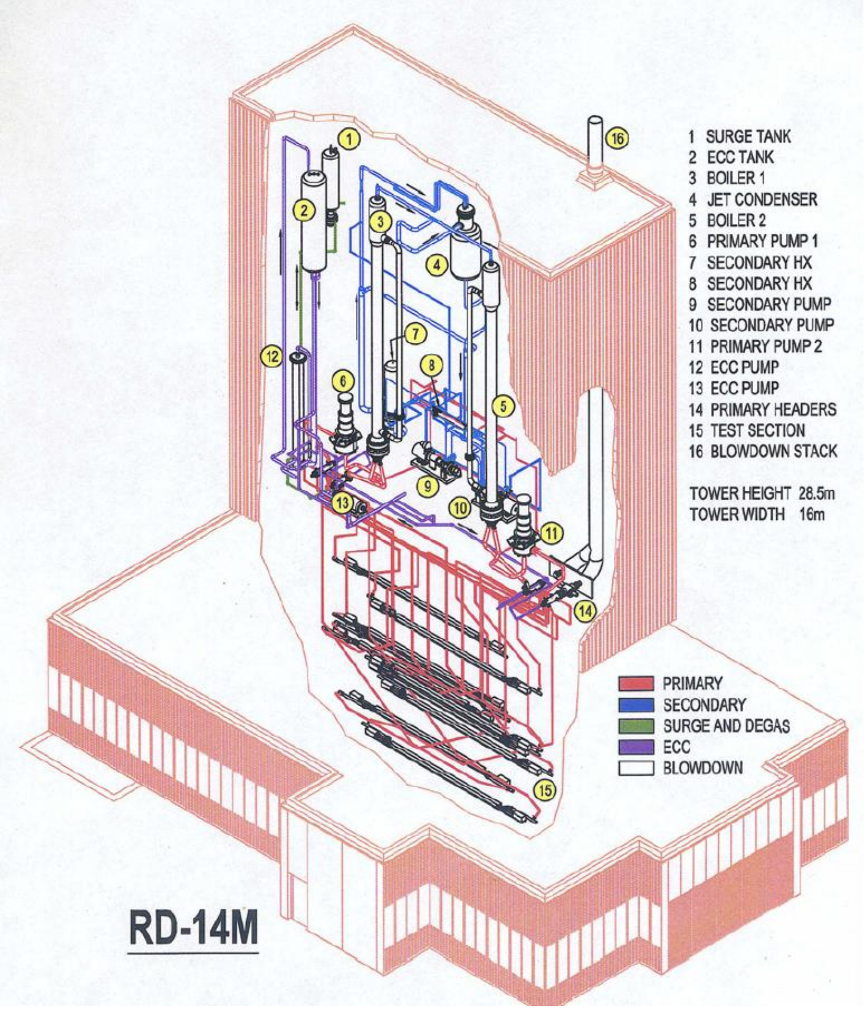


Figure 2: RD-14M facility schematic

The primary coolant loop consists of ten fuel channels of typical CANDU length, connected by end fitting simulators to full elevation feeder pipes. The end fitting simulators represent a metal mass and stagnant coolant volume similar to the end fittings in a CANDU reactor. The ten fuel channels are connected to two full elevation U-tube steam generators in a figure of eight arrangement via four headers, one of which is shown in **Figure 3**. Circulation is provided by two bottom suction centrifugal pumps scaled for reactor-typical head and flow rate. A surge tank provides pressure control.

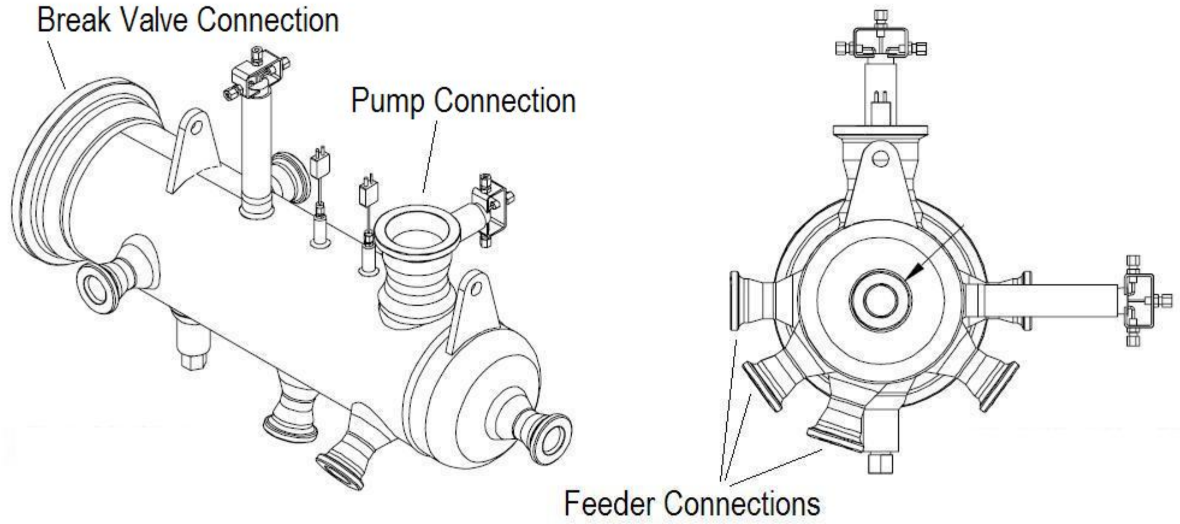


Figure 3: Diagram of Inlet Header 8 showing connections to pump and feeders

The secondary side of the steam generators includes an integral preheater and external downcomer pipe. Steam is directed from the steam separators to a jet condenser and cooling heat exchangers. Feedwater pumps return the cool feedwater to the steam generators. The jet condenser and feedwater pumps are treated as boundary conditions for modeling purposes.

The Fuel Element Simulators (FES) are 7 element, electrically heated assemblies designed for a power density, heat flux and heat capacity similar to that of 37 element CANDU fuel bundles. **Figure 4** shows an RD-14M FES. Each FES is divided into twelve 495 mm sections representing 12 fuel bundles. Each section is separated by an unheated section and a bundle restrain clip which simulates the endplates between adjacent fuel bundles.

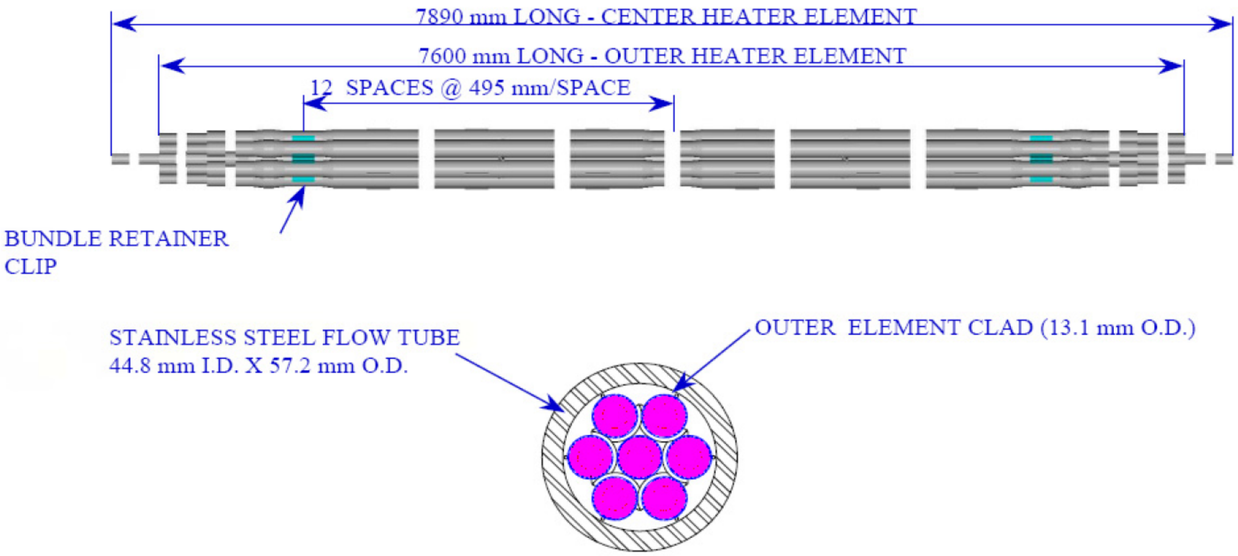


Figure 4: The Fuel Element Simulator (FES) used at RD-14M.

Loss of Coolant Accidents (LOCA) are simulated at RD-14M using a fast-acting valve (the break valve) connected to the end of either an inlet or outlet header. For this experiment the valve is connected to inlet header 8, shown in **Figure 5**. An interchangeable orifice plate installed between the header and the valve is used to control break size. Opening the valve connects the header to a 20 inch blowdown line which vents to the roof of the facility, simulating the break of a header into containment. It should be noted that flow through the blowdown line is not measured in RD-14M.

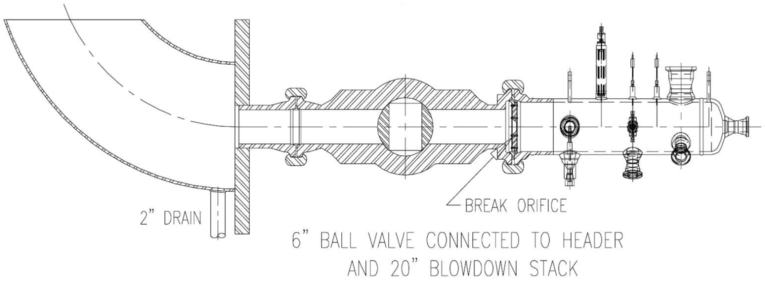


Figure 5: Blowdown valve used to simulate LOCA in RD-14M

An Emergency Core Cooling (ECC) system with high pressure and low pressure stages is proved in the RD-14M facility. This system was not used in the experiment described in this report and therefore was not modeled.

The RD-14M facility is extensively instrumented; during the test over 200 measurements were recorded at 20 ms intervals for pressures, temperature and flow rate. Void is measured in the inlet and outlet feeders, steam generator inlet and outlet and pump discharge using gamma densitometers. To measure channel voiding, a high sensitivity neutron scatterometer was installed on one of the simulated fuel channels (channel 14). This device utilizes a neutron source and eight detectors; it determines void fraction by measuring thermal neutrons scattered by the coolant in the channel.

Flow is measured during steady state conditions with turbine flow meters which are calibrated for single phase flow. During transient two-phase conditions flow direction and magnitude may be inferred from differential pressure measurements, [7].

3.2 B0106 Test

RD-14M experiment B0106 was conducted as part of a series of tests to investigate the rate of coolant voiding in fuel channels during a LOCA [8]. For these tests, orifice plates with various sized openings were installed between inlet header 8 and the break valve to simulate different break sizes. For experiment B0106 an orifice plate was used to simulate a critical break, where flow in the downstream channels reaches near-stagnation conditions following break opening.

After warming the loop and achieving the desired steady state conditions, data collection began. Shortly after isolation of the surge tank (within 5 seconds) the break valve was opened. Within 2 seconds the power was run down to decay heat levels and a rotation-controlled pump rundown began. Data collection lasted for approximately 3 minutes after break valve opening.

4. TRACE MODEL DEVELOPMENT

A TRACE nodalization of the RD-14M facility was developed using the Symbolic Nuclear Analysis Package (SNAP).

4.1 Nodalization

The entire RD-14M facility nodalization as represented by SNAP is show in **Figure 6**

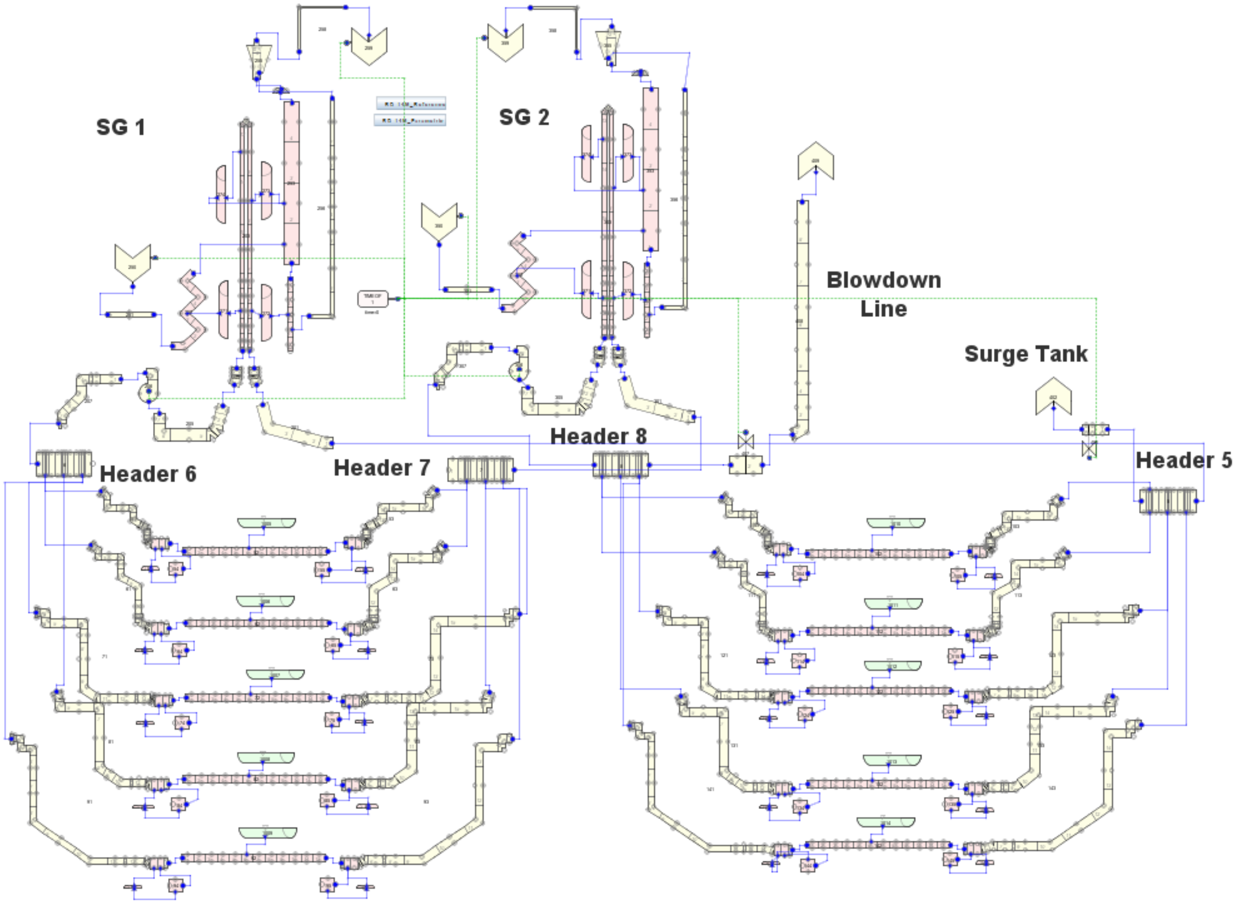


Figure 6: SNAP visualization of RD-14M nodalization

The below header section of the model, comprising the feeder pipes, end fitting simulators, and test sections is shown in **Figure 7**. Feeders are modeled as multi-cell PIPE components connecting to the headers via 90 degree side junctions. Bends and elevations in the feeders are represented as accurately as practicable. The three cells at the lower end of each feeder pipe represent the main flow path through the end fitting simulators. The dead space behind the end fitting shield plug is simulated by a separate, 1 cell PIPE connected by a side junction at an angle of 0 degrees. A heat structure representing the liner tube thermally connects the dead space to the main flow path.

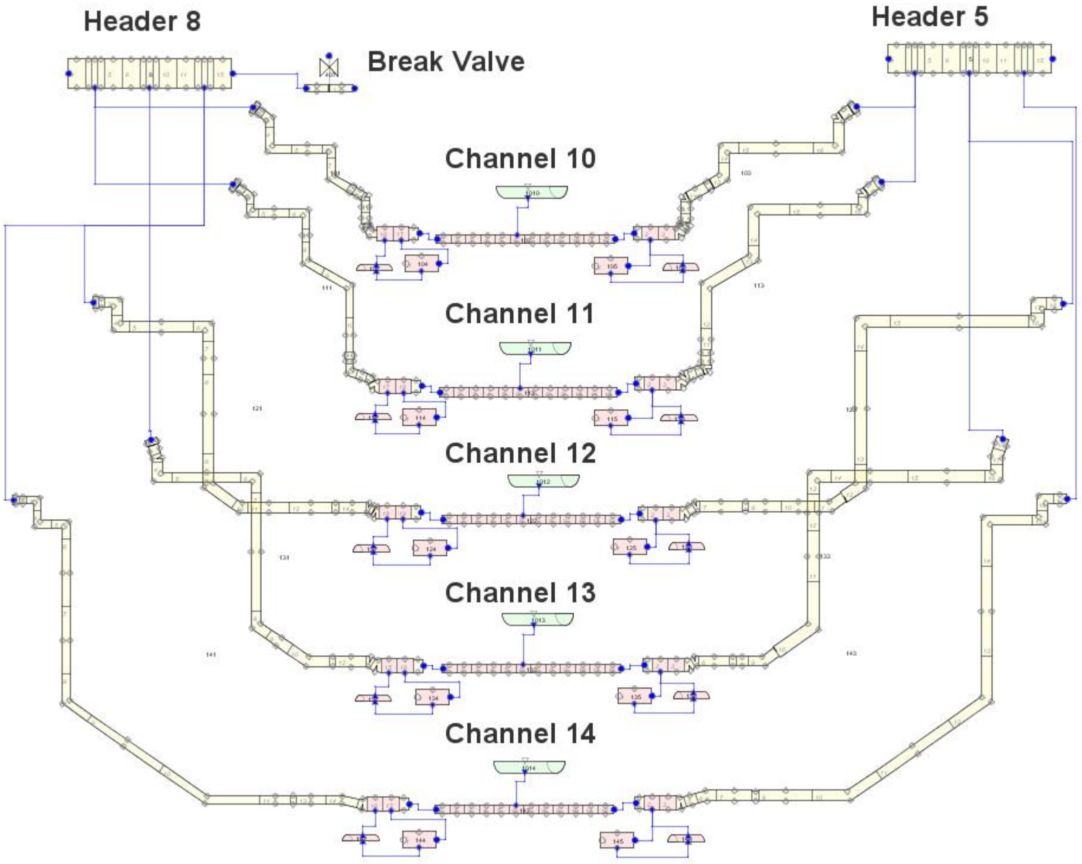


Figure 7: SNAP nodalization of one loop of the below header piping

Each fuel channel test section is modeled as a 12 cell PIPE. A heat structure with 9 radial nodes represents the different materials in the FES cross section. A unique POWER component is connected to each heat structure between radial nodes 3 and 4 which represents the Inconel-600 heater portion of the FES. The heat generated by the POWER component is controlled as a function of time to simulate initial power and subsequent reduction to decay power levels.

The headers are nodalized as a 15 cell PIPE component. Header nodalization is finer around the feeder connections to conform with the TRACE guideline that adjacent cells should have a volume ratio of 10:1 or less. Whereas in the physical design the connections to the above header piping are at 90 degrees to the header long axis, in the model these connections are made at the ends of the headers; this is because TRACE does not allow for PIPE components with only side junction connections. To work around this limitation a nodalization of the header as multiple connected pipes was trialed; however this model encountered significant convergence difficulties.

The surge tank is connected to header 5. The surge tank was isolated during this experiment, therefore it was modeled simply as a BREAK component set to the steady state pressure in header 5. Surge tank isolation is modeled with a time-controlled VALVE component.

The break valve is modeled as a 2 cell VALVE component attached to inlet header 8. The valve is set to open at problem time 60.1s with an opening time of 0.25s. A PIPE component models the blowdown stack, connecting the break valve to a BREAK component set to atmospheric pressure and temperature.

The above header section of the model consists to the Steam Generator primary side, HT pumps, associated piping, and the entire secondary side, shown in Figure 8

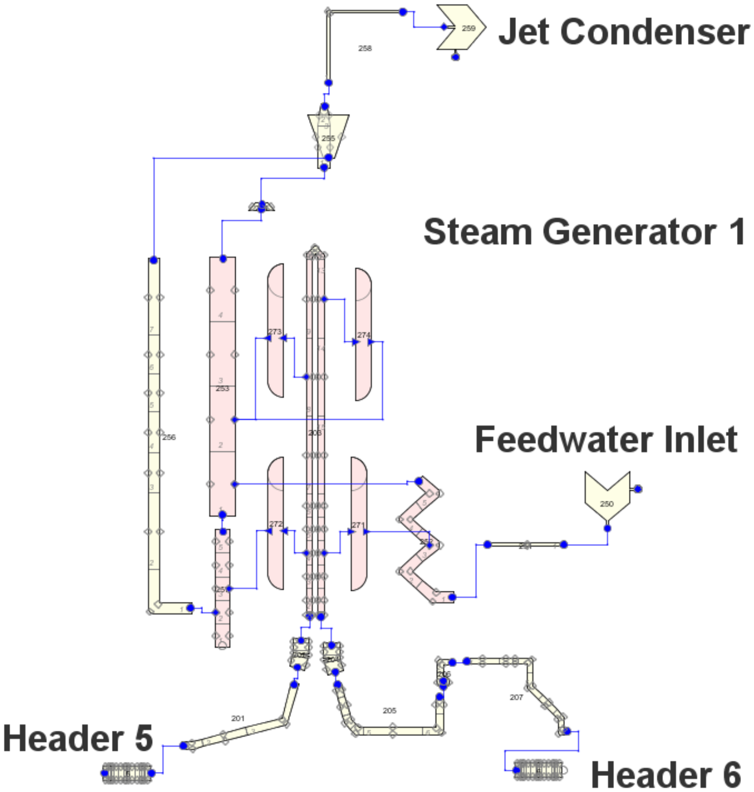


Figure 8: SNAP visualization of one of the steam generators

The U-tubes in the steam generators are modeled as a single PIPE component representing the combined flow area of all the tubes. Inlet and outlet plenums are also represented by PIPE components. The primary side pumps are modeled as 2 cell PUMP components with rated values and pump curves representing the RD-14M pumps. Rotation is controlled as a function of time, allowing the model to recreate the rotation controlled pump speed in the experiment.

The feedwater pumps are represented as a FILL boundary condition, which is time controlled to reproduce the flow rates in the experiment. The FILL is connected to an angled PIPE component representing the integral preheater. The steam separators are modeled as SEPERATOR components. The jet condenser is modeled as a BREAK component with pressure set to the jet condenser pressure as measured in the experiment. Four heat structures thermally connect the steam generator primary and secondary sides.

4.2 Model Options

4.2.1 Critical Flow Model

Prediction of choking or critical flow is very important for modeling LOCA because of the rapid depressurization in the early stages of the transient. The TRACE critical flow model is enabled using default multipliers at the junction between inlet header 8 and the break valve, which is the location of the orifice plate.

4.2.2 Maximum Time Step

To increase computational efficiency the maximum allowed time step size is varied over the course of the transient based on the expected rate of change of parameter. Allowed maximum time step size is shown in **Table 1**.

Table 1: Maximum time step size

Time Range	Max Allowed Time Step Size	Notes
0 – 54.0 s	1.0 s	
54.0 – 57.0 s	0.1 s	Surge tank isolated at 55.0 s
57.0 – 62.0 s	0.01 s	Break opens at 60.1 s
62.0 – 92.0 s	0.1 s	
92 – 296.0 s	0.5 s	

4.2.3 Wall Drag Coefficient Model

The fuel channels and headers are expected to experience stratified flow at some point during the transient. Therefore the wall drag dispersed/stratified model is activated. With this option TRACE determines if flow in horizontal components is stratified based on a critical relative velocity; if stratified conditions are predicted a special stratified flow wall drag coefficient is implemented. The limitations of this model with respect of modeling CANDU fuel channels are discussed in section 2.1.

4.2.4 Off-take Model

The TRACE off-take accounts for liquid entrainment and vapour pull-through in stratified flow through junctions in horizontal pipes. As discussed in Section 2.1.2 the off-take model is not applicable to the geometry of the RD-14M headers. Therefore the off-take model is not used in the reference nodalization of RD-14M. A separate study using the off-take model was performed which is detailed in Section 7.5.

4.3 Model Calibration

The TRACE nodalization was initially designed with K-factors given in the RD-14M facility description. When steady state was reached flow division between the test sections was found to deviate from the values measured at the beginning of the test. To correct channel flow rates the K-factors in each test section were calibrated in a trial and error process to give a correct channel mass flows and pressures, with particular attention paid to correct prediction of flows through heated section 14 where channel voiding is measured.

5. STEADY STATE CONDITIONS

Steady state was obtained by running the model for a period of 2000 seconds to check for oscillations. Model parameters at the end of the test were then saved as the initial conditions for subsequent transient calculations.

Pressure and temperature measurements in the headers are a good indication of the state of the heat transport system. Table 2 shows steady state pressure and temperature values in the headers, all of which are within 1% of experimental values.

Table 2: Steady state header conditions for experiment and TRACE model

Pressure (kPa)	***Experiment***	***TRACE***	***% Difference***
Header 5	10009.0	9999.8	-0.09
Header 6	11527.4	11535.5	0.07
Header 7	9971.5	10045.3	0.74
Header 8	11508.7	11531.3	0.20
Temperature (ºC)			
Header 5	298.1	295.6	-0.83
Header 6	265.7	264.1	-0.60
Header 7	298.1	298.4	0.11
Header 8	265.0	264.2	-0.32

Table 3 shows a summary of error in inlet and outlet feeder pressure, fuel channel outlet temperature and mass flow rate. As mentioned in Section 4.3, special attention was paid in calibration of the model to ensure channel 14 error was minimized, as this is the location of channel voiding measurements.

Table 3: Error in fuel channel parameters for TRACE model

Parameter	***Average % Error***	***Max Error***	***Channel 14 Error***
Pressures	0.48%	1.42%	0.30%
Outlet Temperature	-0.89%	1.40%	0.61%
Mass Flow	2.22%	5.49%	0.13%

6. TRANSIENT RESULTS

This section presents the results of the TRACE model in comparison with experimental values. Each data set is presented on two times scales: a 5 second scale to show the rapid changes occurring immediately after break opening, and a 60 second scale to show behavior as the system depressurizes. A discussion on measurement selection appears in Appendix A.

6.1 Channel Voiding

Void fraction in channel 14 is the key parameter in this experiment. **Figure 9** shows channel voiding results. The model predicts the timing of the onset of voiding correctly. Void predictions follow the trend of the experiment and are generally over predicted by 0.1 to 0.2. It should be noted that the maximum measurement error for the neutron scatterometer is 0.1.

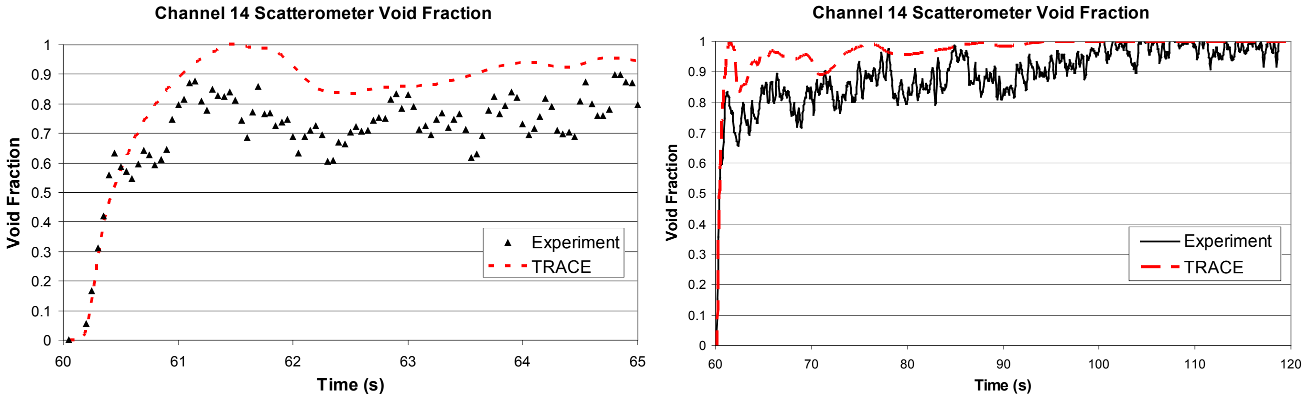


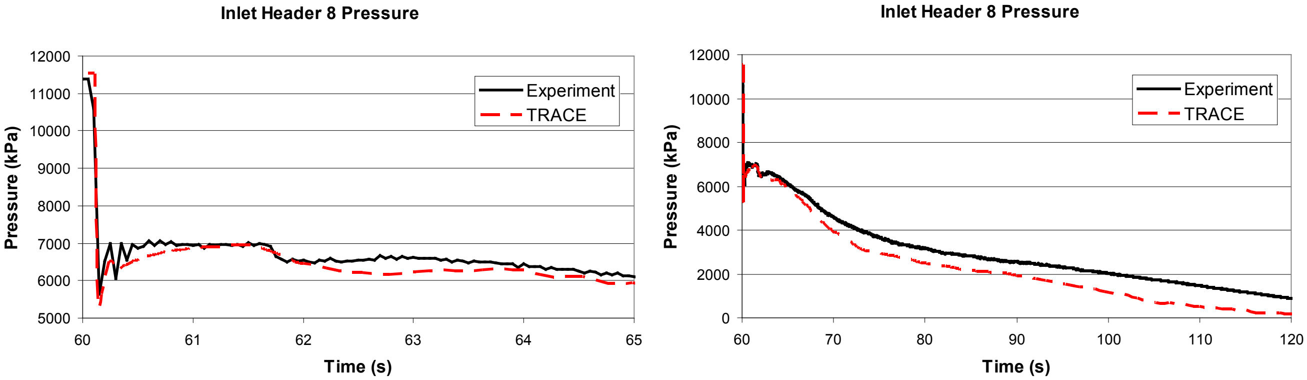
Figure 9: Channel void fraction predictions at location of scatterometer

As discussed in Section 2.1.1 there are inherent difficulties in modeling CANDU fuel channel heat transfer in TRACE. A likely contributor to the over prediction of voiding is that TRACE does not account for the reduction in heat transfer from the fuel to the liquid phase which occurs with stratification. The influence of stratification is also suggested by fuel sheath temperature predictions detailed in Section 6.4.

6.2 Header Pressure

Pressure in the headers is a key indication of the state of the heat transport system. Pressure in Header 8, the location of the break, is of particular significance as it is indicative of break mass flow. Note that mass flow from the break valve is not measured at the RD-14M facility.

Figure 10 through **Figure 13** show pressures in the headers during the transient.


Inlet Header 8 Pressure

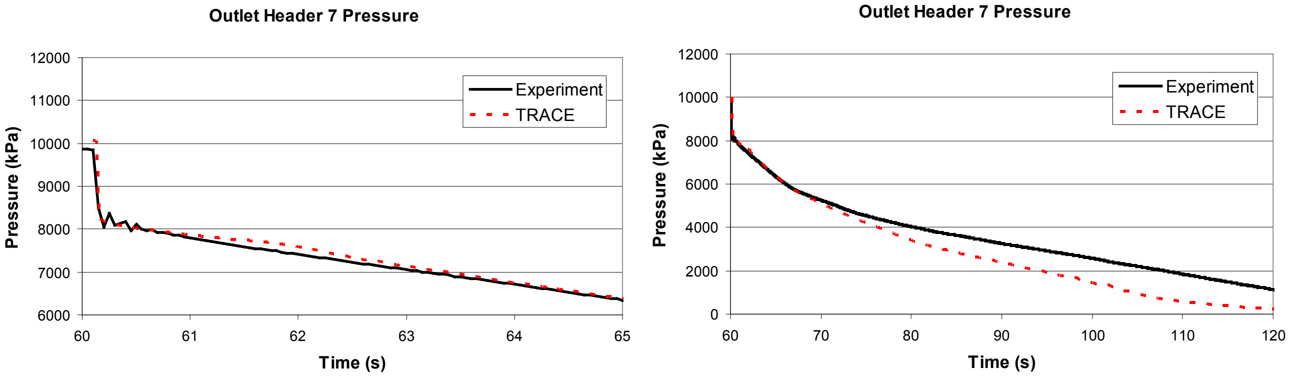
Inlet Header 8 Pressure

Figure 10: TRACE prediction of header 8 pressure

Pressure predictions in the headers over the first 5 seconds are in very good agreement with the experimental results. The maximum error during this period is a 0.5 MPa under prediction in header 8.

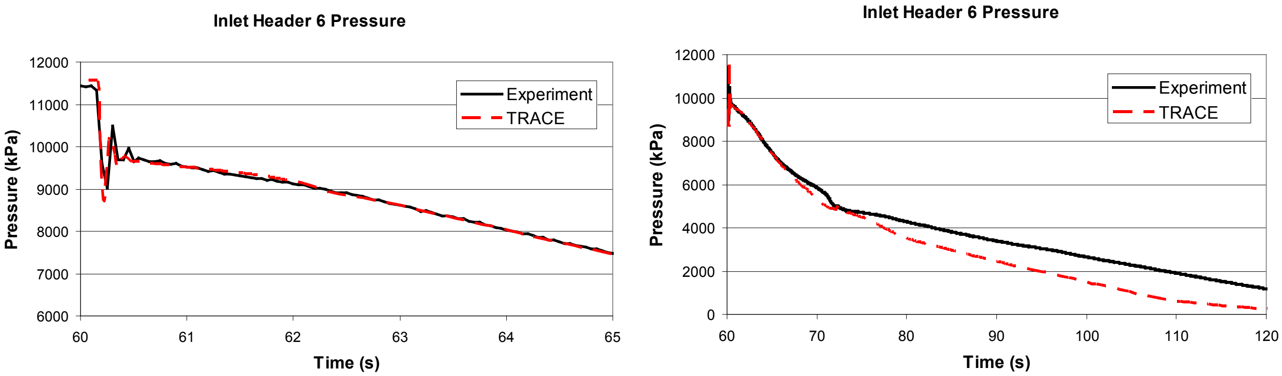
Beyond 5 seconds pressure predictions begin to diverge from the experimental values and pressures in all headers are under-predicted. This indicates that the predicted two-phase critical velocity is higher than in the experiment, resulting in a more rapid depressurization.

TRACE allows for manipulation of the critical flow velocity through user-defined multipliers, which are defined separately for the single-phase and two-phase models. This test used the default multiplier values of 1.0. Calibration of the critical flow model is explored in Section 7.2.


Outlet Header 7 Pressure

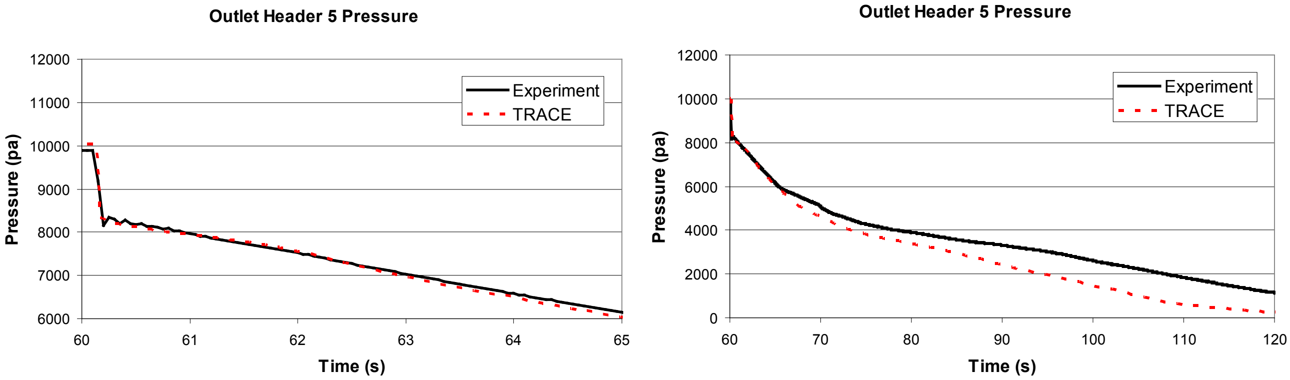
Outlet Header 7 Pressure

Figure 11: TRACE prediction of header 7 pressure


Inlet Header 6 Pressure

Inlet Header 6 Pressure

Figure 12: TRACE prediction of header 6 pressure


Outlet Header 5 Pressure

Outlet Header 5 Pressure

Figure 13: TRACE prediction of header 5 pressure

6.3 Differential Pressures

The turbine flow meters in the RD-14M facility are calibrated for single phase flow conditions [7] and therefore their precision degrades during the two-phase transient. Header to header pressure difference gives insight into the direction and magnitude of channel flow, which has a strong effect on channel voiding. Figure 14 and Figure 15 show differential pressures between inlet and outlet headers.

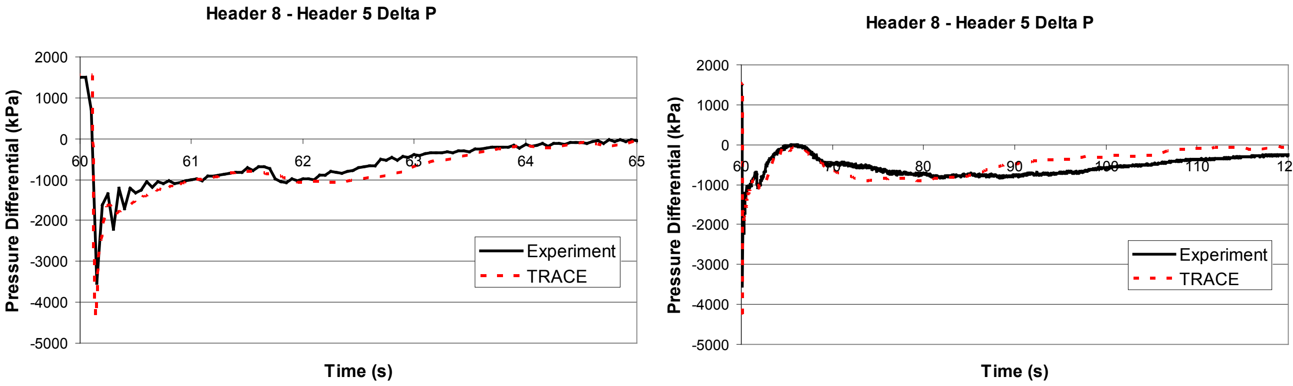


Figure 14: TRACE prediction of header 8 – header 5 differential pressure

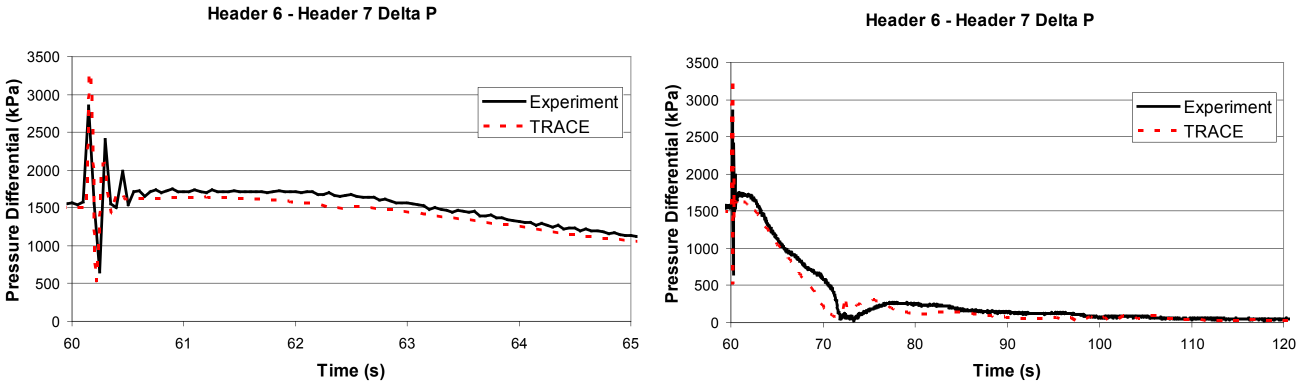


Figure 15: TRACE prediction of header 6 – header 7 differential pressure

As with absolute pressure, TRACE predicts differential pressure with very good accuracy over the first 5 seconds, beyond which predicted trends occur earlier than observed in the experiment. The low predicted differential pressure between header 8 and header 5 at around 90 seconds likely contributes to complete channel voiding occurring earlier in the TRACE results than in the experiment.

6.4 Fuel Sheath Temperature

Fuel sheath temperature is a critical parameter in safety analysis for prediction of fuel sheath integrity and potential fission product release.

Figure 16 shows sheath temperature at the location of the void fraction measurement. The thermocouple is located in the sheath of one of the upper fuel elements. The experimental data is corrected to give sheath surface temperature.

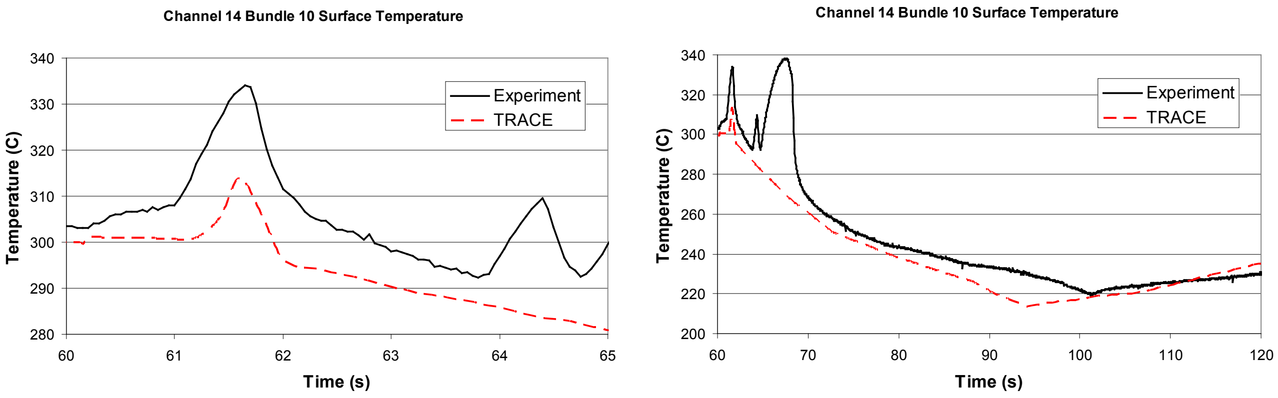


Figure 16: TRACE prediction of fuel sheath temperature in top pin of channel 14 bundle 10

TRACE captures the initial peak in temperature at 61.5 seconds but fails to capture the larger peak between 64 and 70 seconds. This second spike does not appear in measurements of elements at the bottom of the fuel channel, therefore it is likely due to stratification in the channel where the top pin is surrounded by vapour. As mentioned in section 2.1.1, the TRACE heat transfer model does not account for stratification effects.

Aside from stratification effects, TRACE predicts fuel sheath temperature with reasonable accuracy over the first 20 seconds of the transient. The timing of minimum fuel temperature corresponds to where TRACE predicts complete channel voiding. This occurs earlier in the TRACE predictions than in the experiment. After the minimum, TRACE predicts more rapid heat up of the fuel, indicating under prediction of heat transfer in the single phase vapour region.

7. SENSITIVITY STUDIES

Several analyses were performed to assess model sensitivity to nodalization and various input parameters. For brevity, studies which did not produce meaningful changes in results are summarized at the end of this section.

7.1 Time Step Sensitivity

TRACE internally calculates time step size based on the rate of change of system parameters. The user may control time step size by defining a maximum allowable size. To test time step sensitivity, the model was run with maximum time step sizes of 1.0, 0.1, 0.01 and 0.001s. By comparison, the reference maximum time step size was varied during the run with 0.01s immediately before and after break opening (see section 4.2.2)

Figure 17 compares header 8 pressure and channel 14 void fraction for the reference case and the various time step sizes. The results for the reference case and finest time step size are almost identical, indicating that the reference time step size is sufficiently small.

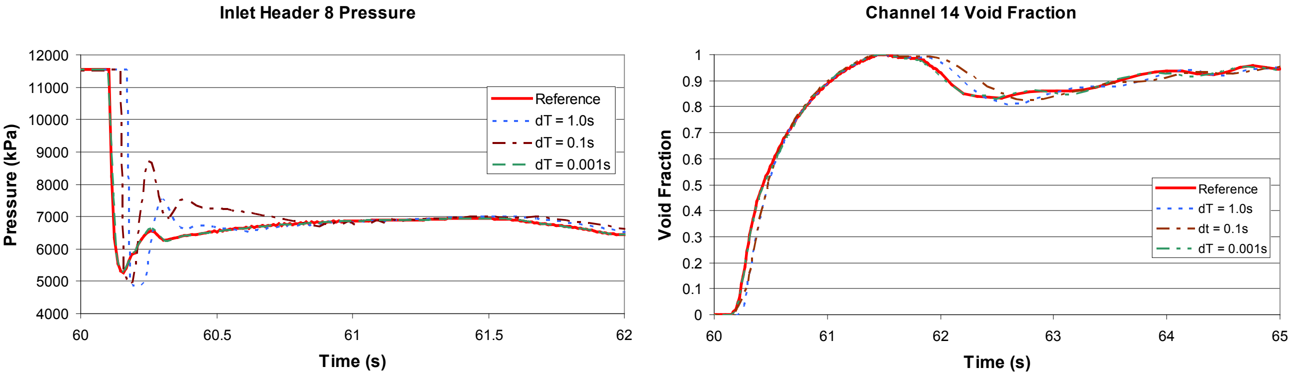


Figure 17: Comparison of Header 8 pressure and Channel 14 void for timestep size study

7.2 Critical Flow Model Sensitivity

The prediction of critical flow is important for determining the rate of depressurization during a LOCA. As seen in Section 6.2 system pressure is under predicted after the first 5 seconds of the transient using the default critical flow model, indicating an over prediction in break discharge. The critical flow model may be adjusted by modifying multiplying coefficients CHM1 and CHM2, which are applied to the predicted critical velocity for single phase and two phase flow, respectively. Reference results use the default value of 1.0 for both terms.

Reference model results diverge from experimental results after the first 5 seconds of the transient, where break discharge is two phase. Therefore the two phase critical flow multiplier CHM2 was adjusted to values less than 1.0 to lower critical velocity and reduce the rate of depressurization of the system.

Figure 18 shows header 8 pressures for different values of CHM2. Study results diverge from the reference case at about 5 seconds, with CHM2 = 0.7 showing much closer correlation with the experimental results.

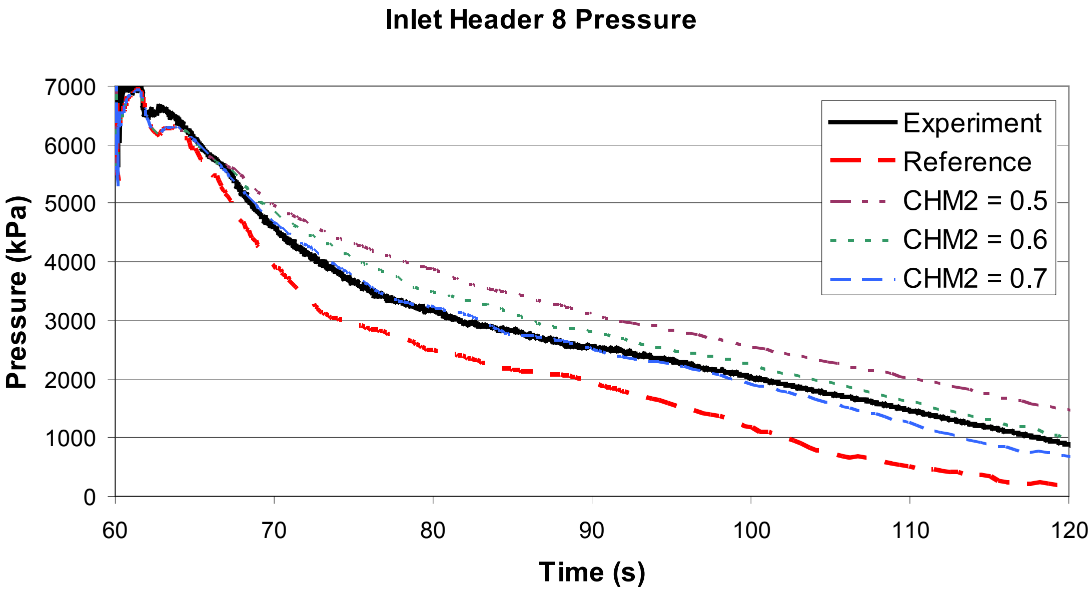


Figure 18: Header 8 pressure for CHM2 sensitivity study

Figure 19 shows study results for pressure in header 5. CHM2 = 0.6 provides the most accurate header 5 pressure results. The difference between header 5 and header 8 optimal CHM2 values may be impacted by the modeling of flow resistance through the fuel channels, which would appear to be too low in the early portion of the transient. This could possibly be addressed using Reynolds number dependent friction factors to more accurately predict resistance for the low flow portion of the transient, however this was not explored.

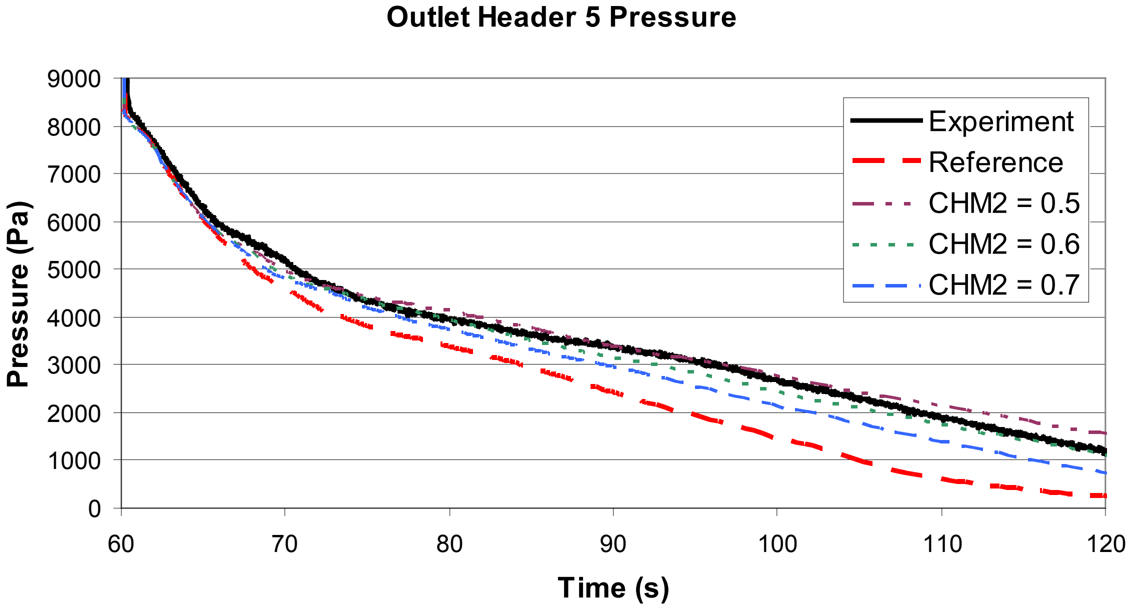


Figure 19: Header 5 pressure for CHM2 sensitivity study

Figure 20 shows that lower values of CHM2 results in lower differential pressure which would correspond to lower flow rates. This lower flow causes increased voiding predictions as shown in **Figure 21**.

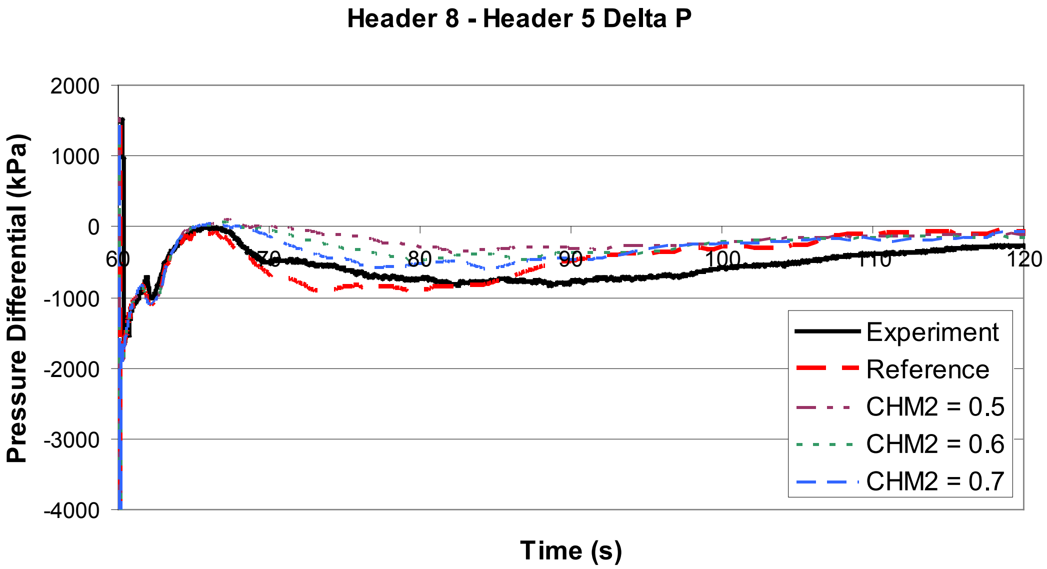


Figure 20: Header 8 – header 5 differential pressure for CHM2 sensitivity study

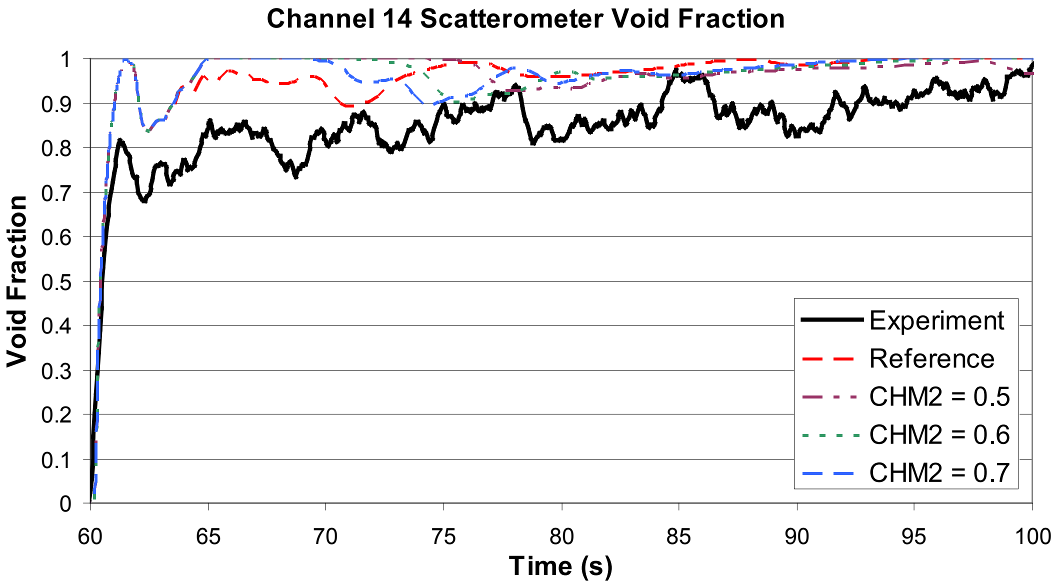


Figure 21: Void fraction for CHM2 sensitivity study

Selection of the correct critical flow multiplier values is clearly important to the prediction of system behavior. To investigate this effect further, a study extension modeling three additional RD-14M tests is detailed in Section 8.

7.3 Header Nodalization Sensitivity

There are 3 planes of feeder connections in the RD-14M headers, therefore a minimum of 3 cells is required to properly represent them. However, TRACE modeling guidelines recommend a maximum ratio of adjacent cell volumes of 10:1, therefore the header for the reference model was made finer at the feeder connections, resulting in a 15 cell header. To determine sensitivity to header nodalization, the model was run using the 3 cell and 27 cell header nodalizations shown in Figure 22.

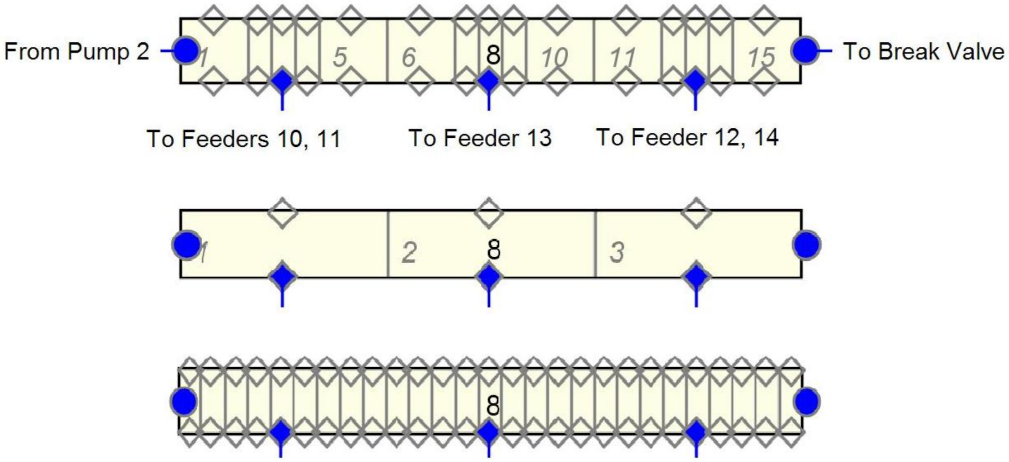


Figure 22: 15 cell, 3 cell and 27 cell header nodalizations used in study

Header 8 pressure for the 3 nodalizations is shown in Figure 23. The finer 27 cell nodalization shows no difference from the reference 15 cell model.

The 3 cell header shows a much slower rate of depressurization than the reference model. The notable difference in this nodalization is that the cell at the break location is also connected to two feeder outlet side junctions. This results in side junction flow being included in the momentum calculation for the break, which seems to have a detrimental impact on the evaluation of critical flow velocity. Based on these results, separation of break location from feeder connection cells is an important aspect of header nodalization in TRACE.

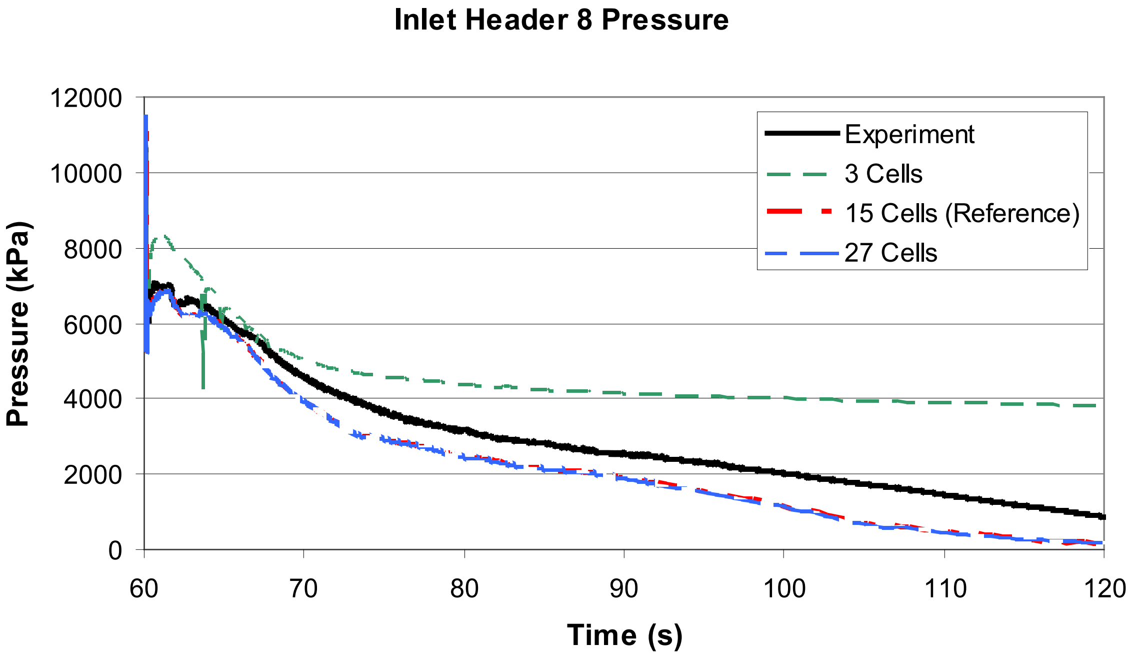


Figure 23: Header 8 pressure for header nodalization study

7.4 Fuel Channel Nodalization Study

As discussed in section 2.1, the TRACE heat transfer equations do not account for the effects of flow stratification in horizontal geometries, which is important to analysis of CANDU fuel channels. To try to capture the effects of stratification, a "quasi-2D" representation of fuel channel 14 was constructed, as proposed by Hummel [9].

The FES can be divided into three horizontal planes of elements, therefore the quasi-2D fuel channel model consists of 3 parallel pipes. Channel flow area is divided into 3 segments: one each for the flow area around the top 2, bottom 2 and middle 3 FES elements. Separate heat structures define the FES surface area in each pipe. The top and bottom pipe elevations are adjusted to account for the vertical distance between the fuel pin centerlines. Side junctions connect the pipes along their length allowing for fluid transfer between pipes. The quasi-2D representation is shown in Figure 24.

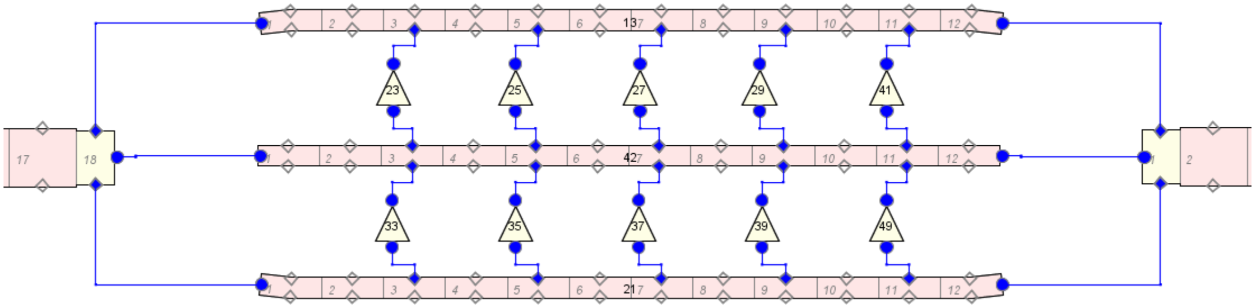


Figure 24: Parallel pipe nodalization of channel 14

Figure 25 shows the average void fraction across the three pipes compared with the reference case. The void fraction for the individual pipes is show in Figure 26.

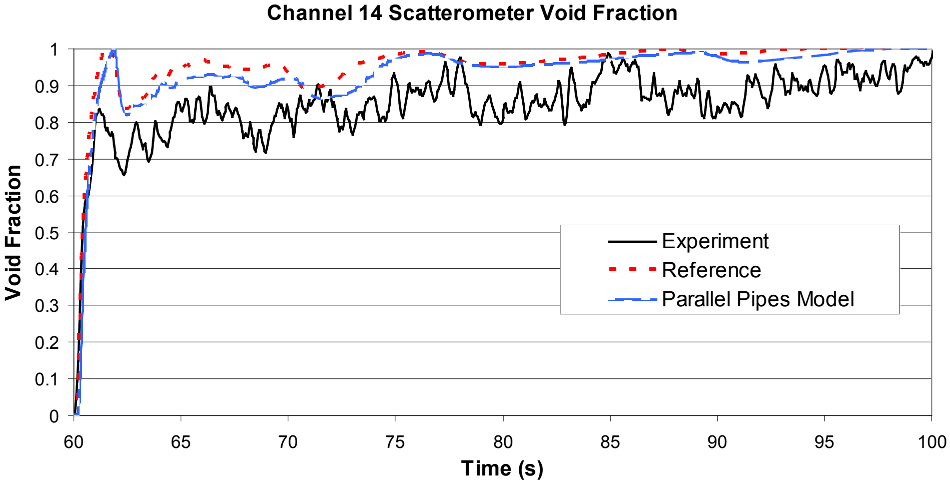


Figure 25: Void fraction for parallel pipes model

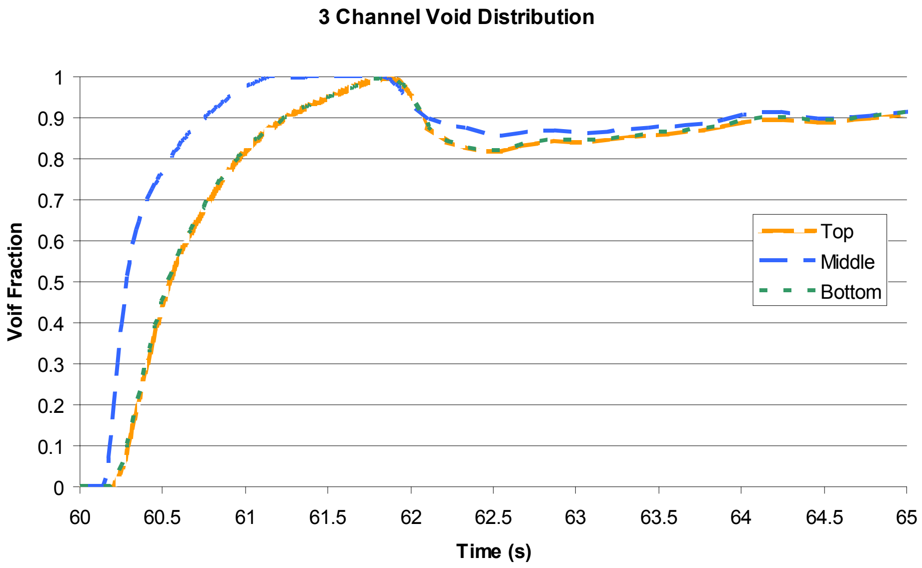


Figure 26: Void fraction in the three parallel pipes

Contrary to expectations, stratification did not occur between the three pipes. It appears that the TRACE momentum equations do not allow the vapour phase to rise to the top pipe through the junction connections. Small differences were observed between the conditions in the top/bottom pipes and the central pipe; these appear to be mostly due to differences in geometry: the 3 fuel elements in the central pipe have a smaller associated flow area relative to the reference case and thus produce a higher void fraction.

System pressure is unaffected by using the parallel pipes model. Prediction of the fuel sheath temperature is slightly less accurate.

Based on these results a quasi-2D representation of CANDU fuel channels is not able to resolve modeling difficulties related to fuel channel heat transfer and flow stratification in TRACE.

7.5 Further Sensitivity Studies

Several sensitivity studies were conducted which produced negligible changes in results. For completeness they summarized here.

7.5.1 Valve Opening Time

Adjusting the valve opening time between 0.15s and 1.0s showed minor pressure differences over the first 0.2s of the transient, after which results were identical to the reference case of 0.25s opening time.

7.5.2 Off-take Model

To test the impact of liquid entrainment and vapour pull-through on break flow the reference nodalization was modified so that the break valve was connected to the header as a side junction. This allowed the use of the off-take model. Model results are mostly unchanged, except for small oscillations in pressure between 63 and 70 seconds, corresponding to the period of low differential pressure between the headers.

7.5.3 Drag Coefficient Model

The reference model allows TRACE to apply a stratified flow drag coefficient if flow is predicted to be stratified. Disabling this option, TRACE only applies a dispersed drag coefficient. Disabling the stratified drag coefficient resulted in only minor changes in pressure. This indicates that TRACE predicts a very small period of flow stratification during the transient.

7.5.4 Fuel Element Thermal Diameter

By default, TRACE uses cell hydraulic diameters in wall heat transfer calculations. The user is able to define a separate thermal diameter for these calculations. A studied was performed to assess if manipulation of this value could improve fuel sheath temperature predictions. It was found that unrealistically large thermal diameter values were required to achieve small changes in sheath temperature, and overall trends could not be predicted more accurately.

7.5.5 Choking Plane Study

Choking is expected to occur at flow restrictions with large pressure differentials. TRACE requires the user to define cell edges were choking is expected to occur. A model was run with the choking model enabled for all three cell edges in the break valve. In this test TRACE did not predict the correct choking plane, which resulted in over prediction of pressure and voiding in the early transient.

7.5.6 Valve Internal Loss Model

No data was available for the minor loss through the break valve at intermediate stages of opening; therefore these losses were ignored in the reference model. The TRACE internal loss model automatically calculates valve internal losses; however enabling this option had a minimal impact on results.

8. EXTENSION STUDY: CRITICAL FLOW MULTIPLIERS

The selection of critical flow multiplier values was shown to have a strong impact on the rate of system depressurization. While no specific guidelines for selecting multiplier values were found in TRACE documentation, the User's Manual notes that:

> *"the choked-flow model allows [the user] to input subcooled and two-phase choked-flow multipliers … these multipliers allow [the user] to adjust the predicted liquid, steam/gas-mixture, or both, choking velocities to account for break or nozzle geometry effects." [10]*

To further investigate optimization of the TRACE critical flow model, RD-14M tests B0104, B0105 and B0108 were modeled. These tests simulate different sized inlet header breaks using an experimental setup nearly identical to the previously analyzed B0106.

8.1 Changes to Nodalization

For the B01XX test series different orifice plates were installed between inlet header 8 and the break valve to simulate different sized breaks, as shown in Table 4. In the TRACE nodalization, the flow area and hydraulic diameter of the junction between header 8 and the break valve were modified accordingly.

Table 4: Break Size of B01XX test series

Test	Break Orifice Plate Area Relative to Reference Case	Surge Tank Isolation
B0105	0.327	Header 7 < 5.5 MPa
B0104	0.462	Header 7 < 5.5 MPa
B0106 (reference case)	1.000	Before transient
B0108	1.173	Header 7 < 5.5 MPa

The surge tank was valved in for the start of these tests and isolated when header 7 pressure dropped to 5.5 MPa. Therefore a more detailed nodalization of the surge tank was added to the model.

Surge tank nodalization consists of 2 PIPE components: one representing the surge line and the other representing the volume of the surge tank itself. A control block closes the isolation valve when header 7 pressure drops to 5.5 MPa.

All boundary conditions were adjusted to the values recorded for each experiment, and new steady state calculations were performed prior to running transient cases.

8.2 Results

Figure 27 through Figure 29 show pressures for headers 5 and 8 for the various tests with a range of values of CHM2.

Test B0108 had the largest break size in the series and consequently the most rapid depressurization. For this test, optimal CHM2 values were similar to the reference test B0106: CHM2 = 0.7 gives better predictions for header 8 pressure, while CHM2 = 0.6 gives better predictions for header 5 pressure.

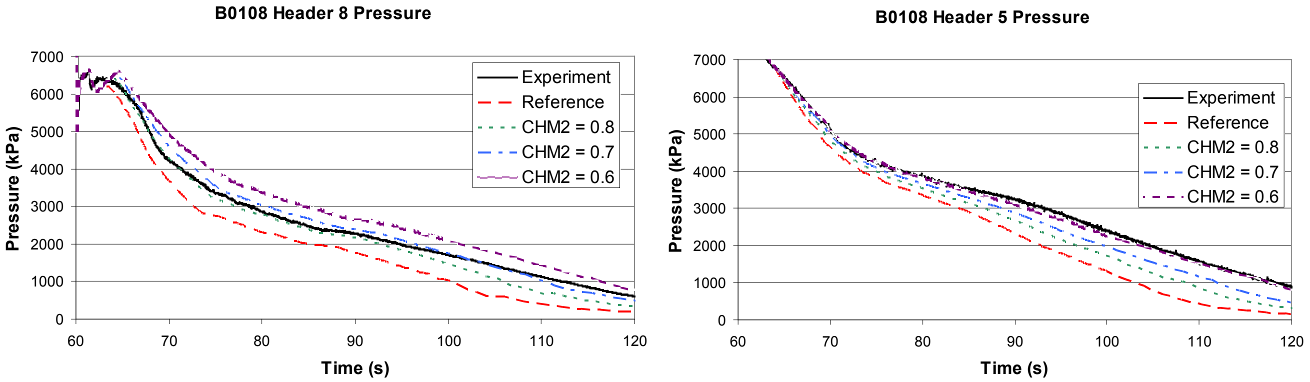


Figure 27: Header pressures for B0108 CHM2 study

Test B0104 had a break size with slightly less than half the area of the reference case. For this test CHM = 0.8 provides the best pressure results for both header 8 and header 5.

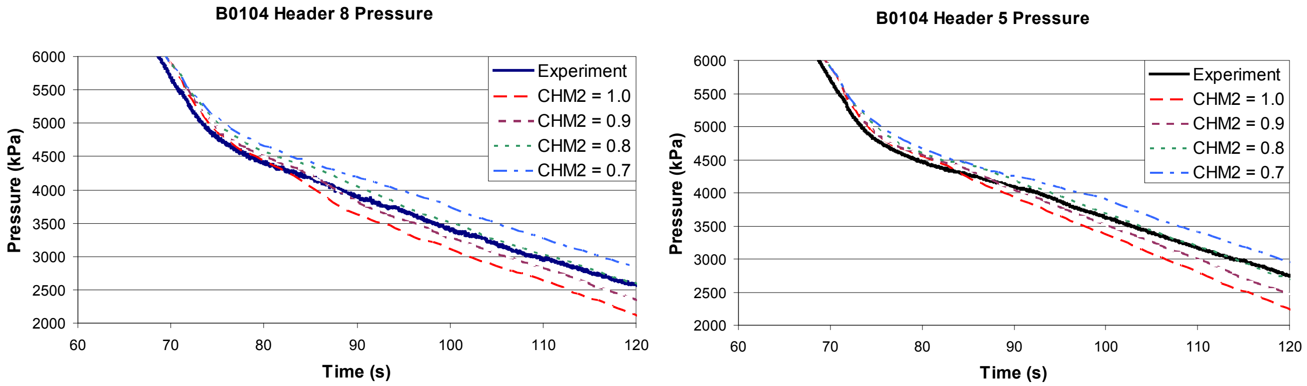


Figure 28: Header pressures for B0104 CHM2 study

Test B0105 had the smallest break size in the series. The default value of CHM2 = 1.0 provided the best results for this test, however in this test the pressures errors were larger in the early portion of the transient compared to other tests. The break is small enough that there is a significant period of single phase discharge, therefore full critical flow optimization for this test would involve modifying the single phase multiplier CHM1 as well.

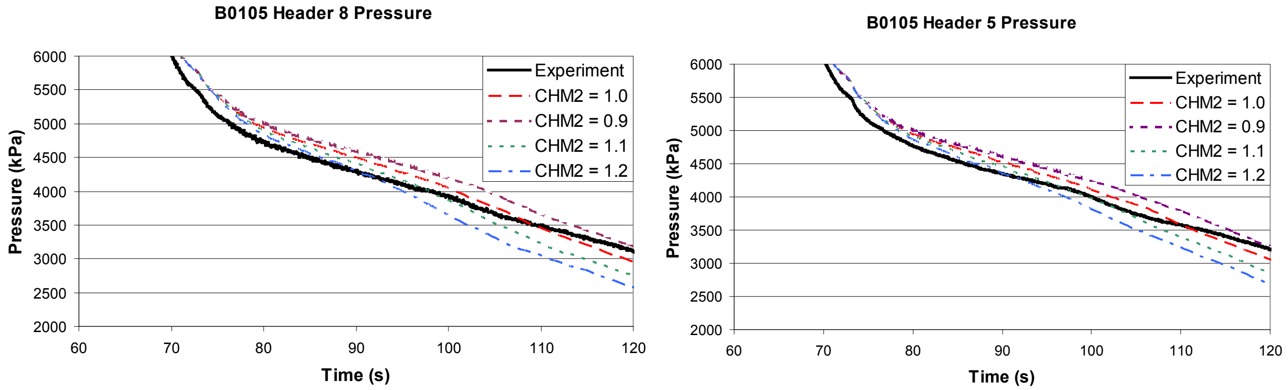


Figure 29: Header pressures for B0105 CHM2 study

8.3 Critical Flow Model Optimization

The results of this critical flow study show that, even between different breaks of the same shape, optimal critical flow multiplier values are geometry specific, and that larger break sizes tend to require lower multiplier values.

9. CONCLUSIONS

The TRACE model predicted experimental results with good accuracy. The timing of the onset of fuel channel voiding matches experimental observations, while the extent of voiding is generally over predicted. System pressure is very accurate over the first 5 seconds of the transient, while later in the transient pressure is under predicted. Fuel sheath temperature predictions followed the general trend of the experiment but failed to capture temperature peaks resulting from flow stratification.

The difference in results can mostly be attributed to the critical flow model and heat transfer in the fuel channels. The default critical flow model over predicts flow velocity at the break location for two phase break discharge. This can be corrected using the two-phase critical flow multiplier; further study modeling additional RD-14M tests indicates that the appropriate value is dependent on break size, with larger breaks tending to require a lower multiplier value. Error in heat transfer from fuel to coolant arises from modeling horizontal fuel channels using correlations developed for unobstructed pipes, particularly the inability to represent fuel pin location within a stratified flow regime.

To improve CANDU modeling capabilities in TRACE, modifications to the code could be made to better account for CANDU specific geometries. These could include implementing a special PIPE model which uses heat transfer and flow stratification correlations developed specifically for CANDU channels and a heat structure which accounts for fuel element position within a stratified flow regime. Alternatively the VESSEL component could be modified to allow 3D modeling of horizontal components. Improvements in header modeling could be made by expanding the off-take model to allow a range of connection angles to better account for feeder port location. Very similar modifications were previously made to the RELAP5 code by researchers in Korea as detailed in [4] and [11]

Overall, the TRACE model of the RD-14M facility predicts system response with good accuracy. TRACE appears to be able to account for most of the phenomena important to LOCA analysis in CANDU geometries.

10. REFERENCES

1. Morrison, Robert C., “Performance Improvement through Collaboration”, *Workshop on Best Practice in Heavy Water Reactor Operation* Buenos Aires, Nov 2013. <http://www.iaea.org/NuclearPower/Downloadable/Meetings/2013/2013-11-06-11-08-WS-NPTD/p1.pdf>
2. Canadian Nuclear Safety Commission, “Annual Canadian Nuclear Safety Commission Staff Report for 2005 on the Safety Performance of the Canadian Nuclear Power Industry”. September 2006. <http://publications.gc.ca/collections/collection_2007/cnsc-ccsn/CC171-1-2005E.pdf>
3. U.S. Nuclear Regulatory Commission, “TRACE V5.435 Theory Manual, Volume 1”, Division of Risk Assessment and Special Projects, Office of Nuclear Regulatory Research, U.S NRC, Washington DC, 2007.
4. Chung, B.D., Lee, W.J. and Bang, Y.S. “Improvements of RELAP5/MOD3.2.2 Models for the CANDU Plant Analysis” NUREG/IA-0189, October 2000.
5. Mysen, A., “TRACE Simulation of RD-14M B0104 LOCA Test”, *Fall CAMP Meeting,* Rockville, Maryland November 5-6, 2008.
6. Delja, A and Hawley, P., “Computer Codes Validation for Conditions of Core Voiding”, *14th International Topical Meeting on Nuclear Reactor Thermal Hydraulics (NURETH-14),* Toronto, Canada, Sept 25-29 2011,
7. Swartz, R.S. (ed.), “RD-14M Facility Description and Characterization” COG Report COG-00-034, January 2001.
8. Buell, J.R., Ingham, P.J. and Swartz, R.S. “RD-14M LOCA Tests with Channel Void Measurement: Phase I Tests. B0102-B0110”. COG-01-168, AECL Whiteshell Laboratories. March 2002.
9. Hummel, D.W., “Modeling an RD-14M LOCA Experiment with the TRACE Code”, Master of Applied Science Thesis, McMaster University, 2010.
10. U.S. Nuclear Regulatory Commission, “TRACE V5.435 User’s Manual, Volume 2: Modeling Guidelines”, Division of Safety Analysis, Office of Nuclear Regulatory Research, U.S NRC, Washington DC, Jan 20, 2011.
11. Chung, B.D., Lee, W.J., Hwang, M. “RELAP5/MOD3 Horizontal Off-Take Model for Application to Reactor Headers of CANDU Type Reactors” NUREG/IA 0238, June 2010.

APPENDIX A

Each header in RD-14M has two pressure measurement devices: a strain gauge transducer and a capacitance-type transducer. Differential pressures between headers are measured directly by two capacitance-type transducers for each set of measurements.

Examining the data, it is clear that the strain gauge transducers have a much higher response rate than the capacitance-type transducers. While pressure values after 1 second are consistent between devices, the timing of the initial pressure drop is recorded by the strain gauge transducers much closer to valve opening than the other devices. Therefore the strain gauge results are used for comparison in this report, with header differential pressure being calculated based on the difference between strain gauge measurements.

NRC FORM 335
(12-2010)
NRCMD 3.7

U.S. NUCLEAR REGULATORY COMMISSION

BIBLIOGRAPHIC DATA SHEET

(See instructions on the reverse)

1. REPORT NUMBER
(Assigned by NRC, Add Vol., Supp., Rev., and Addendum Numbers, if any.)
NUREG/IA-0446

2. TITLE AND SUBTITLE
Assessment of Channel Coolant Voiding in RD-14M Test Facility using TRACE

3. DATE REPORT PUBLISHED

MONTH	YEAR
July	2014

4. FIN OR GRANT NUMBER

5. AUTHOR(S)
Andrew Oussoren; Aleksandar Delja

6. TYPE OF REPORT
Technical

7. PERIOD COVERED (Inclusive Dates)

8. PERFORMING ORGANIZATION - NAME AND ADDRESS (If NRC, provide Division, Office or Region, U. S. Nuclear Regulatory Commission, and mailing address; if contractor, provide name and mailing address.)

Canadian Nuclear Safety Commission
280 Slater Street
P.O. Box 1046 Station B
Ottawa, Ontario, Canada

9. SPONSORING ORGANIZATION - NAME AND ADDRESS (If NRC, type "Same as above", if contractor, provide NRC Division, Office or Region, U. S. Nuclear Regulatory Commission, and mailing address.)

Division of Systems Analysis
Office of Nuclear Regulartory Research
U.S. Nuclear Regulatory Commission
Washington, DC 20555-0001

10. SUPPLEMENTARY NOTES
K. Tien , NRC Project Manager

11. ABSTRACT (200 words or less)

Coolant voiding in fuel channels of CANDU reactors during a Loss of Coolant Accident (LOCA) is important to reactor behaviour due to the power pulse arising from positive void reactivity. The prediction of voiding in fuel channels is therefore of fundamental importance to LOCA safety analysis. The CNSC is evaluating the applicability of the TRACE thermal hydraulics code to CANDU reactor simulation.

In this study, inlet header LOCA test B0106 from AECL's RD-14M thermal hydraulic test facility was modeled using TRACE. RD-14M is a scaled CANDU heat transport system containing 10 electrically heated fuel channels and full elevation feeders and boilers. In this test, a break in an inlet header is simulated using a fast opening valve. The size of the break is such that it creates near stagnation flow in the affected loop. A neutron scatterometer installed on one of the test channels measures void fraction in the channel during the transient.

The TRACE code was capable of predicting channel voiding trends with good accuracy, while the extent of voiding was generally over predicted. System pressure is predicted very well over the first several seconds of the transient; however pressure is under-predicted later in the transient. This under-prediction can be corrected through modifying the multiplying coefficients in the TRACE critical flow model. Fuel sheath temperature was under predicted for most of the test; this is due to limitations in the ability to represent a horizontal fuel channel in TRACE.

12. KEY WORDS/DESCRIPTORS (List words or phrases that will assist researchers in locating the report.)

Canadian Deuterium Uranium (CANDU) reactor
Canadian Nuclear Safety Commission (CNSC)
Atomic of Canada Limited (AECL)
Primary Heat Transport System (PHTS)
Pressurized Heavy Water Reactor (PHWR)

13. AVAILABILITY STATEMENT
unlimited

14. SECURITY CLASSIFICATION
(This Page)
unclassified
(This Report)
unclassified

15. NUMBER OF PAGES

16. PRICE

UNITED STATES
NUCLEAR REGULATORY COMMISSION
WASHINGTON, DC 20555-0001

OFFICIAL BUSINESS

NUREG/IA-0446 **Assessment of Channel Coolant Voiding in RD-14M Test Facility using TRACE** **August 2014**