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Assessment of Critical Subcooled Flow Through Cracks in Large and Small Pipes Using TRACE and RELAP5

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ABSTRACT

The thermal hydraulics system code TRACE has been used to predict subcooled critical flow in crack geometries. Three different experimental data sets were modelled in this study. The first experiment, performed at Purdue University, measured critical flow in slits with small section thicknesses similar to steam generator tubing. These results are also compared to model predictions using the RELAP5 code. The second experiment, conducted by Ontario Hydro (OH), measured critical flow rates in simulated circumferential cracks in thick-walled piping. The third experiment, from Atomic Energy of Canada Ltd. (AECL), measured critical flow through pressure cycling-induced fatigue cracks in thick walled vessels.

For the Purdue tests, TRACE predictions were similar to those obtained with RELAP5. For the thin walled samples in these tests a junction nodalization was found to be more suitable than explicitly modelling the section thickness of the samples. TRACE predictions for both the Purdue and OH tests were in reasonable agreement with measured leak rates, with calculated discharge coefficients of between 0.5 and 1.0 for most cases. However, the model of the OH tests showed a trend towards under prediction as pressure dropped below 8 MPa. There was no clear trend demonstrated with respect to subcooling. For the AECL experiments the flow rate was significantly over predicted, with discharge coefficients as low as 0.1. This result is consistent with the modelling performed by the original experimenters and is likely due to the complexity of the flow pathway in the fatigue cracks used in this test, as compared to the machined geometries of the other samples.

In general TRACE appears to be a suitable tool for prediction of critical flow rates in crack geometries. Comparison against additional experimental data is recommended.

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ACKNOWLEDGMENTS

The analysis in this report is based on the experimental work of Dr. Brian Wolf (formerly of Purdue University), the Ontario Hydro Research Division and Atomic Energy of Canada Limited.

ABBREVIATIONS

AECL	Atomic Energy of Canada Limited
ASTM	American Society for Testing and Materials
CAMP	Code Applications and Maintenance Program
CNSC	Canadian Nuclear Safety Commission
COD	Crack Opening Displacement
LOCA	Loss of Coolant Accident
NRC	United States Nuclear Regulatory Commission
OH	Ontario Hydro
RELAP	Reactor Excursion and Leak Analysis Program
SETS	Stability-Enhancing Two-Step
SG	Steam Generator
TRACE	TRAC/RELAP Advanced Computational Engine

SYMBOLS

A_t	throat area
A_{up}	upstream cell area
C_{NE}	non-equilibrium coefficient (default = 0.14)
$C_{p,v}$	vapour heat capacity
DP/Dt	substantial derivative of pressure
G_c	critical mass flux
N	non-equilibrium factor = $x_{eq,t} / C_{NE}$
P_{sat}	saturation pressure
P_t	throat pressure
P_{up}	pressure upstream of break
T	upstream fluid temperature
T_c	critical temperature
T_R	T / T_c
V_l	liquid specific volume
$V_{l,0}$	upstream liquid specific volume
V_v	vapour specific volume
$ds_{l,eq}/dP$	derived from liquid property tables
k_B	Boltzmann constant
$s_{l,0}$	upstream liquid entropy
$s_{l,eq}$	equilibrium liquid entropy
$s_{v,0}$	upstream vapour entropy
$s_{v,eq}$	equilibrium vapour entropy
v_t	throat velocity
x_0	upstream quality
γ	specific heat ratio of vapour
σ	surface tension
η	thermal equilibrium polytrophic exponent
ρ_l	liquid density

1 INTRODUCTION

Choked or critical flow is a phenomenon which occurs in a wide range of high pressure industrial systems. It is especially important in pressurized water-cooled nuclear reactors where high pressure subcooled water is used to generate steam. The discharge rate of coolant from a broken primary coolant pipe controls the rate of heat transfer in the core and determines the requirements for emergency core cooling and safety equipment as well as the containment structure design to remedy reactor loss of coolant accident [1]. Therefore, in the event of a Loss Of Coolant Accident (LOCA), choked flow determines the rate at which coolant inventory leaves the reactor cooling system. If choking were not to occur, the reactor water inventory would be depleted rapidly. This is not the case however because, as the pressurized subcooled water nears the break, it flashes to vapor which limits the mass flow rate. Therefore, the coolability and structural integrity of the core during a LOCA is strongly dependent on critical flow discharge.

A LOCA from a small or large break to the containment building is not the only place in a reactor where coolant could be escaping the primary side of the reactor. Steam generator (SG) tubes have a history of small cracks and even ruptures, which cause a loss of coolant from the primary to the secondary coolant loop and provide a pathway outside of containment. In the case of leakage through SG tubes to the secondary side of the plant, radiation detection measurements of the secondary flow are taken and calibrated to predict an increase or decrease of leakage through the SG tubes. If excessive leakage occurs, the plant must shut down or the operator must take appropriate action. It is therefore of great interest to be able to quantitatively predict such flow rates with great accuracy.

Reactor system safety codes were originally developed for simulation of single and two-phase flow of reactor coolant in nuclear power plants. Computer codes can be categorized in two broad groups: (i) one and limited three-dimensional system codes, and (ii) computational fluid dynamics codes. Computational fluid dynamics codes are generally based on commercial software and have the capability of modelling the flow in three dimensional space. Computational power and applicable models of turbulence are the main limitations of this type of code [2]. System codes, including TRACE and RELAP, are commonly used in nuclear industry for safety analysis of water-cooled reactors. These codes in general use non-homogeneous, non-equilibrium models to describe behaviors of single and two-phase flow. They have been validated against experimental data from separate effects tests and integral tests, and are generally accepted for accident simulations in light water reactors. Recently, there have been efforts to use these codes for order of magnitude smaller geometries such cracks in pipes and vessel walls [2] [3] [4] [5] [6]. Leak rate calculations on this scale are traditionally performed by purpose-built codes (e.g. LEAK_RATE [7], SQUIRT [8]) which are validated against critical flow leak rate experimental measurements for example [9] [10] [11]).

The Canadian Nuclear Safety Commission (CNSC), as a member of the Code Applications and Maintenance Program (CAMP), is evaluating the TRACE thermal hydraulic system code. This report details the modelling of three experiments measuring critical flow rates in crack geometries: one experiment recently sponsored by the CNSC as well as two earlier tests performed by Canadian researchers.

The first data set analyzed in this report comes from a CNSC sponsored research program conducted at Purdue University to measure critical subcooled flow through samples with a section thickness which approaches the wall thickness of steam generator tubing. The pressure drop across the samples was 6.9 MPa, which is close to the pressure difference between the primary and secondary coolant loops of a pressurized water reactor. Flow rates were measured for different levels of subcooling at constant pressure. Modelling results for RELAP5 were also available for this test; therefore, these results are compared against TRACE predictions.

The second set of data comes from tests conducted by Ontario Hydro involving prepared circumferential cracks in thick walled piping. Flow rates through flared and straight crack sections were measured over a range of temperatures and pressures.

The last set of data comes from tests conducted by Atomic Energy of Canada Limited (AECL) in which a vessel representing a large diameter pipe with a simulated internal defect was pressure cycled until a through wall failure occurred. Flow rates were measured through defects in five different test specimens at a pressure of 8.5 MPa and temperature of 260 °C. A unique aspect of these tests is the use of fatigue cracks, which are likely more representative of cracks which could potentially develop in operating reactors compared to the more stylized, machined geometries of cracks used in the other two tests.

The following chapters describe the critical flow models used in the TRACE and RELAP5 codes, the experimental setup and results for each of the three tests, the development of nodalization for those tests and comparisons of predicted flow rates against experimentally measured values.

2 CHOKED FLOW MODELS

2.1 Choked Flow

Pressurized systems with high fluid velocities have the potential for flow to become choked. This occurs when fluid's velocity is equal to its sonic velocity (speed of sound). The sonic velocity is the maximum speed at which pressure waves may propagate in a fluid, therefore when flow becomes choked pressure waves can no longer travel upstream. This causes the flow rate to become independent of the downstream pressure. In liquid systems such as water-cooled nuclear reactors, choked flow may occur due to localized vapour generation, which significantly reduces the mixture sonic velocity.

Consider a small hypothetical crack in the piping of a nuclear reactor cooling system where the coolant is at high pressure. If the coolant flowing out of the break is at sufficiently low temperature (highly subcooled), it will remain in a liquid state as it exits the break. The sonic velocity of liquid water is high enough that choked conditions will not occur.

If, however, the coolant is at high temperature (low subcooling), as is typically the case in an operating reactor, as the coolant exits the break and the pressure drops rapidly, the saturation temperature will fall below the temperature of the liquid. This causes some of the water to flash into steam. The sonic velocity of steam is much lower than that of water; therefore the speed of sound of the liquid/steam mixture will drop rapidly. This creates the conditions for flow exiting the break to become choked.

2.2 Choked Flow Models

Prediction of critical flow rates in an important component of any safety analysis system codes. Special process models are required in thermal hydraulic system codes to provide realistic estimates of flow rates in choked flow conditions.

The TRACE and RELAP5 model for critical flow employs a modified form of the Burnell model for critical flow of liquid which is initially subcooled. For initially two-phase mixtures the model developed by Ransom and Trapp is used. Since the tests described in this report consist only of initially subcooled flow, only the modified Burnell model will be described in detail.

RELAP5 also allows the user to select the Henry-Fauske model for critical flow; therefore this model is also described.

2.2.1 Modified Burnell Model

A modified version of the choked flow model originally proposed by Burnell [12] is used in both TRACE and RELAP5. In this model, subcooled critical flow is idealized using the Bernoulli equation. Because the choking flow rate is independent of the downstream pressure, the choking flow velocity at the throat is given as a function of the pressure difference between the upstream conditions, P_{up}, and the pressure at the choking plane, P_t. TRACE compares this velocity to the speed of sound for the homogeneous mixture; the velocity at the choking throat, v_t, is then given as:

$$v_t = \mathrm{Max}\left[\alpha_{HE}, v_{up}^2 + \frac{2(P_{up} - P_t)}{\rho}\right]^{\frac{1}{2}} \tag{1}$$

Where α_{HE} is the homogeneous equilibrium speed of sound and v_{up} is the upstream velocity. The pressure P_t is the pressure at the choking throat, where vaporization first occurs. Due to non-equilibrium effect P_t does not necessarily equal the local saturation pressure. The existence of superheated liquid results in a delay in the onset of nucleation at the throat, such that P_t may be significantly lower than the local saturation pressure [13]. A correlation is then required to determine the throat pressure at which vaporization will occur.

Both RELAP5 and TRACE employ the model described above for single phase critical flow; however they employ different correlations to derive P_t.

In RELAP5 P_t is given by a correlation developed by Alamgir and Lienhard [14] and Jones [15]:

$$\begin{aligned} P_t = P_{sat} - \mathrm{Max}\Bigg\{0\,, 0.258\frac{\sigma^{\frac{3}{2}}T_R^{13.76}}{\sqrt{k_B T_c}}\,\frac{V_v}{V_v - V_l}\left[1 + 2.078\mathrm{x}10^{-8}(\rho_l\frac{1}{A_t}\frac{dA_t}{dx}v_t^3)^{0.8}\right]^{0.5} \\ - \ 6.9984\mathrm{x}10^{-2}\left(\frac{A_t}{A_{up}}\right)^2 \rho_l v_t^2\Bigg\} \end{aligned} \tag{2}$$

where P_{sat} is saturation pressure, σ is surface tension, $T_R = T / T_c$, T is upstream fluid temperature, T_c is critical temperature, k_B is Boltzmann's constant, V_v is vapour specific volume, V_l is liquid specific volume, A_t is throat area, A_{up} is upstream cell area, and ρ_l is liquid density,.

In TRACE P_t is given by the correlation of Jones and Abuaf [13] [16]:

$$P_t = P_{sat} - \mathrm{Max}\left\{ 0\,, 0.258\frac{\sigma^{\frac{3}{2}}T_R^{13.76}}{\sqrt{k_B T_c}}\frac{V_v}{V_v - V_l}\left[1 + 13.25\left(\frac{-1}{1.01325x10^{11}}\frac{Dp}{Dt}\right)^{0.8}\right]^{0.5} - 27(0.072)^2\left(\frac{A_t}{A_{up}}\right)^2\frac{\rho_l v_t^2}{2}\right\} \tag{3}$$

where Dp/Dt = substantial derivative of pressure.

Equation (1) and equation (2) or (3) form a coupled set which are solved iteratively to determine the velocity which will result in choked flow. By comparison to the solution to the momentum equation the codes then determine whether choked flow conditions will occur.

2.2.2 Henry-Fauske Model

The Henry-Fauske model is the default model for choked flow in RELAP5. The model defines the critical mass flux at a choking plane as: [17]

$$G_c^2 = \left\{\frac{x_0 V_v}{\eta P} + (V_v - V_{l,0})\left[\frac{(1 - x_0)N}{(s_{v,eq} - s_{l,eq})}\frac{ds_{l,eq}}{dP} - \frac{x_0 C_{p,v}\left(\frac{1}{\eta} - \frac{1}{\gamma}\right)}{P_t\left(s_{v,0} - s_{l,0}\right)}\right]\right\}^{-1} \tag{4}$$

In the tests described in this report the test fluid is subcooled liquid. In this case the upstream quality $x_0 = 0$, and equation (4) reduces to:

$$G_c^2 = \left\{(V_v - V_{l,0})\left[\frac{N}{(s_{v,eq} - s_{l,eq})}\frac{ds_{l,eq}}{dP}\right]\right\}^{-1} \tag{5}$$

where $V_{v,eq}$ is the equilibrium vapour specific volume, $V_{l,0}$ is upstream liquid specific volume, N is the non-equilibrium factor = $x_{eq,t}$ / C_{NE}, $x_{eq,t}$ is equilibrium quality at the throat, C_{NE} is the non-equilibrium coefficient (default = 0.14), $s_{v,eq}$ is equilibrium vapour entropy, $s_{l,eq}$ is equilibrium liquid entropy, $ds_{l,eq}/dP$ is derived from liquid property tables.

2.2.3 Discharge Coefficients

In the implementation of these critical flow models, both RELAP5 and TRACE allow the user to specify a discharge coefficient (referred to in TRACE as a critical flow multiplier). This is a multiplier allowing the user to adjust the predicted flow rate to account for inconsistencies between model predictions and experimental observation. For the models described in this report, in all cases a discharge coefficient or critical flow multiplier of 1.0 was implemented.

Modelling results are presented in terms of a calculated discharge coefficient, defined as the experimental mass flow rate divided by the predicted mass flow rate. This value represents the multiplier which could be applied in the model to achieve perfect agreement with experimental results.

3 PURDUE THIN WALLED CRITICAL FLOW TESTS

3.1 <u>Facility Description</u>

This set of experiments was conducted to measure critical flow rates through slits with section thicknesses similar to steam generator tubes. The tests were sponsored by CNSC and conducted at Purdue University. Figure 1 shows a schematic of the test facility. It consists of a vertical pressure vessel, an outlet pipe leading to a test specimen holder and a water tank where discharge from the test specimen is condensed.

The vessel is pressurized using compressed nitrogen bottles connected via stainless steel piping. Ceramic band heaters are used to control the temperature of the pressure vessel inventory. Pressure and temperature are measured in the vessel as well as upstream of the test section.

A valve upstream of the test specimen is used to initiate the experiment. As the subcooled water is discharged from the test section it flashes and a two-phase critical flow develops. The outlet of test section is submerged in a cool water bath which condenses the discharged mixture. The condensed steam and discharged water are collected in the bath volume, the mass of which is measured using two high precision strain gauge type load cells. This allows for a time averaged mass flow rate to be measured.

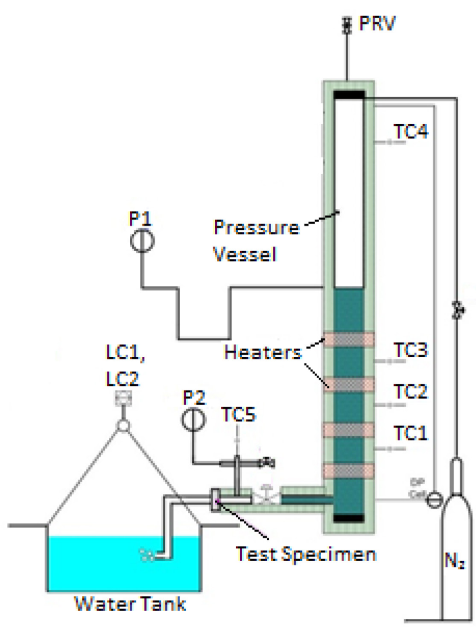

Figure 1 Schematic of test facility [18]

Flow rate tests were conducted using specimens consisting of a slit cut in a 3.175mm stainless steel disk.

The sample disks were mounted on a stainless steel nipple and attached to pressure vessel outlet pipe as shown in Figure 2.

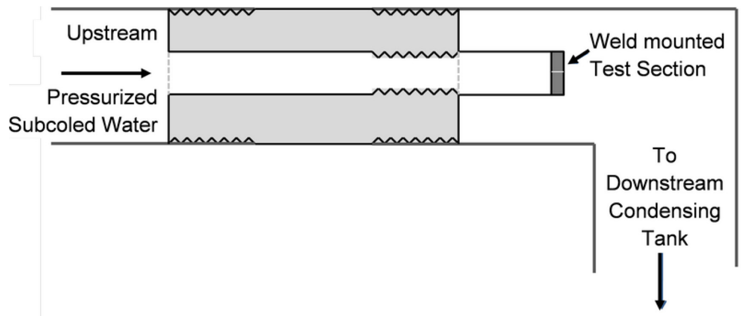

Figure 2 Sample mounting to test section [18]

The dimensions of the samples are presented below in Table 1. The use of laser cutting resulted in a non-uniform cross sectional area; the average flow area for each sample was determined by optical measurement of the front and back surfaces and averaging the values. Hydraulic diameter was also determined through optical measurement. Figure 3 shows the front and back surface of sample 2.

Table 1 Geometry of test samples [18]

Sample #	Area (m^2)	Dh (m)	Thickness (m)	L/D	Roughness (m)
2	9.736E-07	7.086E-04	3.175E-03	4.5	3.75E-05
3	1.269E-06	6.996E-04	3.175E-03	4.5	3.75E-05
4	1.333E-06	6.589E-04	3.175E-03	4.8	3.75E-05
5	1.359E-06	6.468E-04	3.175E-03	4.9	3.75E-05
6	1.833E-06	5.859E-04	3.175E-03	5.4	3.75E-05

The test matrix for each sample consisted of varying the subcooling at near constant pressure. Pressures for the tests ranged from 6.87 MPa to 6.60 MPa, with a range of subcooling between 48.1 and 24.7ºC. Measurement error for mass flux values was less than 2%.

As the experiments were designed to simulate choking flow through steam generator tube cracks, the tests were carried out at 6.9 MPa (1000 psi), which approaches the pressure differential across the walls of steam generator tubes under normal operating conditions. However, the pressure differential in actual steam generators is approximately 15 MPa to 5.8 MPa in PWRs (10 MPa to 4.7 MPa for CANDU reactors) as opposed to 7 MPa to 0.1 MPa in this experiment. Achieving prototype reactor conditions was not possible within the constraints of test apparatus.

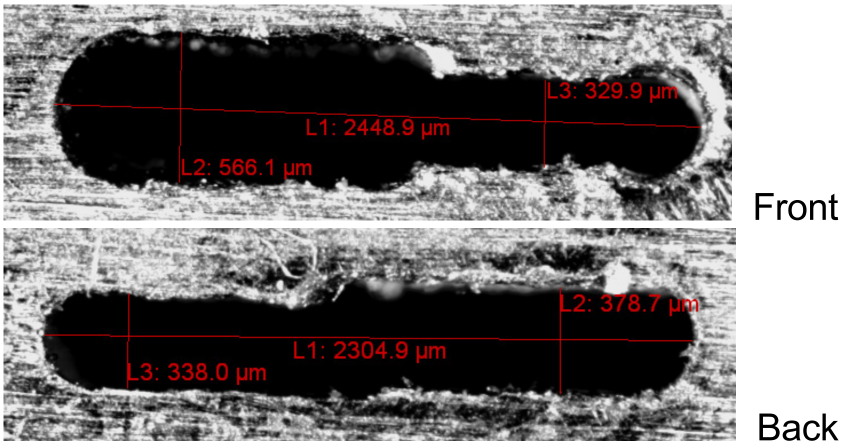

Figure 3 Slit crack test specimen # 2

3.2 Experiment Results

Figure 4 shows the measured mass flux as a function of subcooling for the 5 samples. In all cases the mass flux increases with subcooling; a more highly subcooled liquid results in less flashing at the choking plane and thus less restriction in flow rate. The mass flux does not show a clear trend with respect to the sample geometric parameters listed in Table 1.

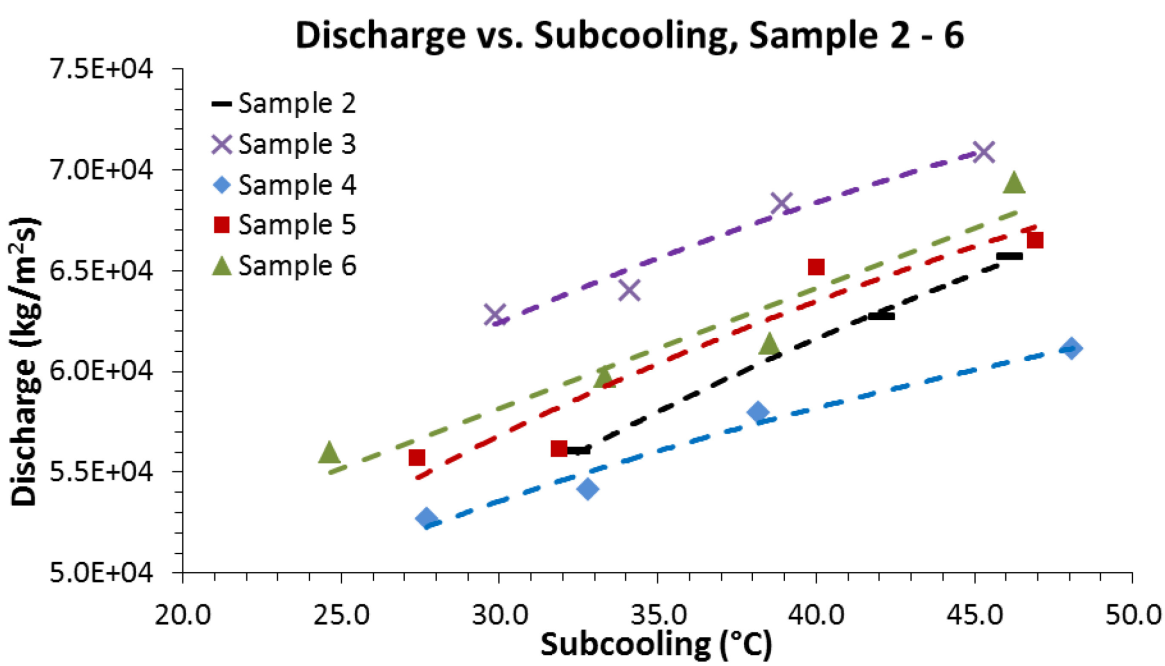

Figure 4 Critical mass flux as a function of subcooling

3.3 Modelling

The experiment was modelled using both RELAP5 and TRACE. Due to the very small section thickness of the samples, two nodalization schemes were investigated for each code:

1. Channel nodalization: The sample is modelled using discrete PIPE components with length equal to the section thickness (3.175mm), with cell and junction flow area and hydraulic diameters described as in Table 1.
2. Junction nodalization: The section thickness of the sample is not explicitly modelled; instead the junction between the upstream piping and the outlet boundary condition is assigned the flow area and hydraulic diameter of the test sample.

The nodalization for each code is described below.

3.3.1 RELAP5 Model

RELAP5/Mod3.3 Patch04 was used to model choked flow through the test specimens. The modelling was performed using the Symbolic Nuclear Analysis Package (SNAP) graphical interface. The SNAP representations of these two models are shown in Figure 5.

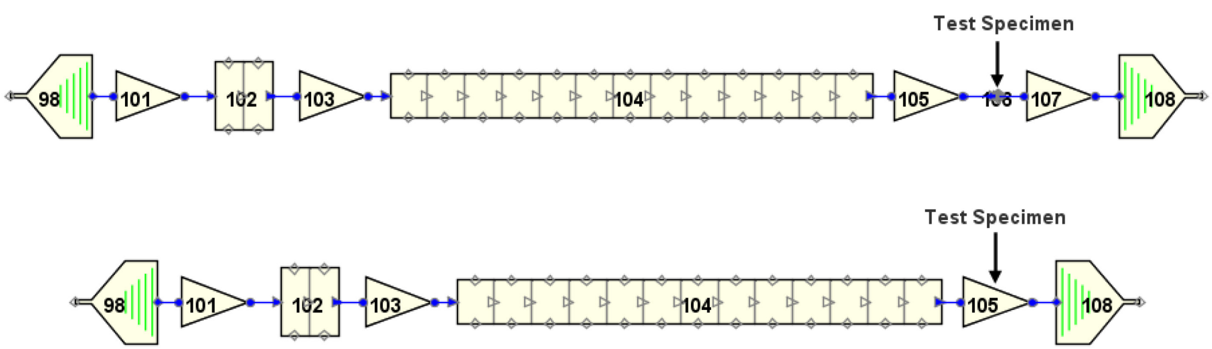

Figure 5 RELAP channel nodalization (top) and junction nodalization (bottom)

Components 101 through 104 represent the piping upstream of the sample. Components 98 and 108 are time dependent volumes which represent, respectively, the pressure vessel at test pressure and temperature and the condensing tank at standard atmospheric temperature and pressure.

In the channel nodalization the sample slit was represented by PIPE component 106 which consists of five hydraulic cells. Component 106, as well as junction components 105 and 107, was assigned the flow area and hydraulic diameter of the test specimen as given in Table 1.

For the junction nodalization components 106 and 107 are removed, and the flow area and hydraulic diameter of the test specimen are represented solely by junction component 105. In this nodalization the length of the flow path through the specimen is not explicitly modeled. No minor loss coefficients were assigned in the model.

In both models choking was enabled on the junction immediately upstream of the outlet boundary condition. The RELAP5 model was tested in four different configurations:

1. Channel nodalization using the modified Burnell critical flow model
2. Channel nodalization using the Henry-Fauske critical flow model
3. Junction nodalization using the modified Burnell critical flow model
4. Junction nodalization using the Henry-Fauske critical flow model

A critical flow discharge coefficient of 1.0 was used for all tests to facilitate comparison between models.

3.3.2 TRACE Model

TRACE V5.830 was used for the simulation. The TRACE nodalization was created using the 'Import RELAP' function available in SNAP which translated the RELAP input deck into a TRACE input file. As with the RELAP analysis, two nodalization were evaluated: Modelling the test specimen as a channel or as a junction. Note that unlike RELAP, TRACE does not utilize discrete junction components; the flow area and hydraulic diameter of cell junctions are instead defined at the edge of each PIPE component. The resulting nodalization are shown in Figure 6.

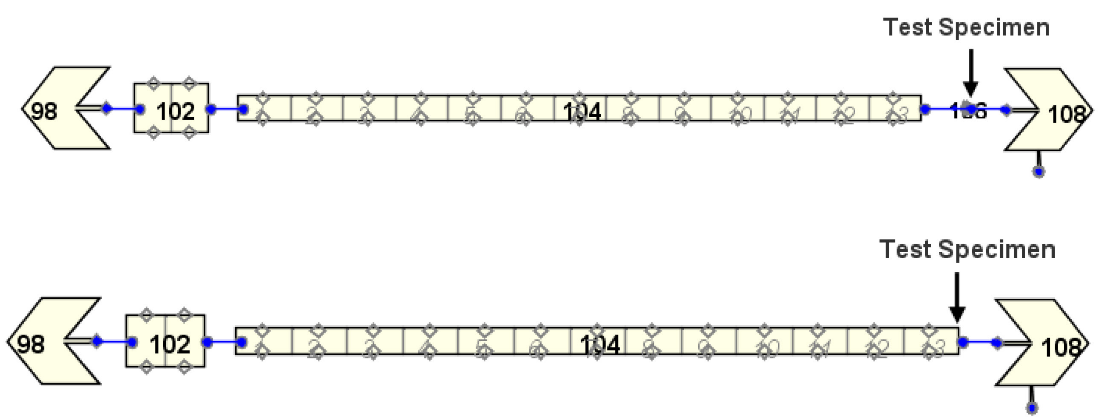

Figure 6 TRACE channel nodalization (top) and junction nodalization (bottom)

The TRACE model was tested for three different configurations:

1. Channel nodalization with critical flow enabled
2. Channel nodalization with critical flow disabled
3. Junction nodalization with critical flow enabled

Minor loss coefficients were calculated internally by TRACE by enabling the 'abrupt area change' model at the junctions between each component.

As with the RELAP runs, default critical flow multipliers of 1.0 were used. The default critical flow relaxation constant of 2.0 was found to produce oscillations; this value was reduced to 1.1 which produced more steady results.

3.4 Results

Figure 7 shows the Modelling results in terms of predicted vs. measured mass flux for both TRACE and RELAP.

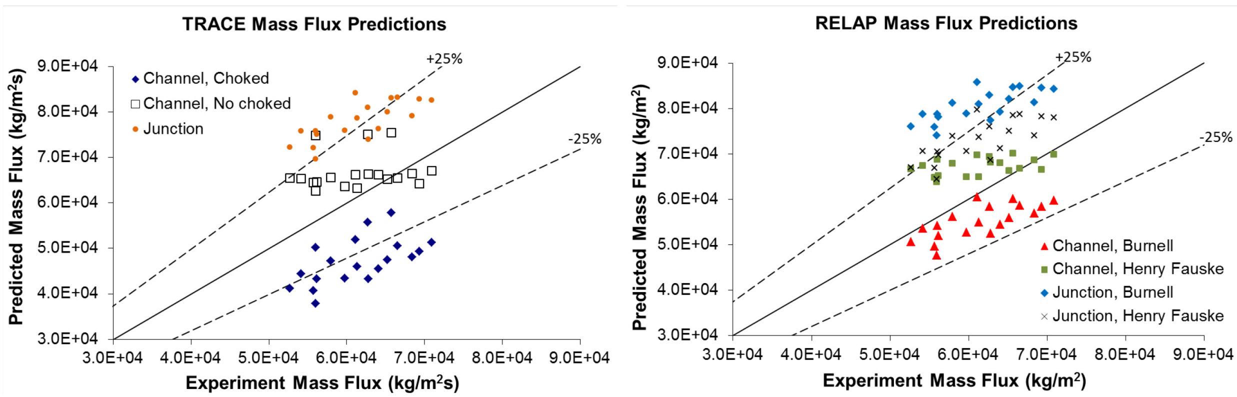

Figure 7 TRACE and RELAP mass flux predictions vs. measurements for Purdue tests

The channel nodalization for each model predicts lower mass flux rates compared to the junction nodalization. This is likely due to the added wall friction losses in the channel nodalization compared to the junction nodalization.

The modified Burnell models in RELAP and TRACE produce similar results for the junction nodalization. The Henry-Fauske model in RELAP is somewhat more accurate using the junction nodalization, however for the channel nodalization it does not appear to capture the trend. The TRACE model with choking disabled produces the results with the lowest absolute error, however the predicted flow rate is more or less constant; the most accurate data points correspond to tests with the highest subcooling, which approaches the un-choked condition.

A junction nodalization appears to be more suitable for Modelling critical flow through very thin walled samples such as the ones in this experiment: the junction models over predict flow, which is conservative in most cases, and a junction nodalization simplifies the model compared to a channel nodalization. This is particularly significant for RELAP5, where the numerical solving scheme is constrained by the Courant limit; the very short hydraulic cells of the channel nodalization result in a very small maximum time step and consequently long solving times.

From a Modelling perspective it is useful to present results in terms of a discharge coefficient, calculated as the measured mass flux divided by the predicted mass flux. These discharge coefficients are plotted as a function of subcooling in Figure 8. For the TRACE no choking model and the RELAP channel Henry-Fauske model the discharge coefficient increases with increasing subcooling, while the rest of the result are relatively consistent with respect to temperature.

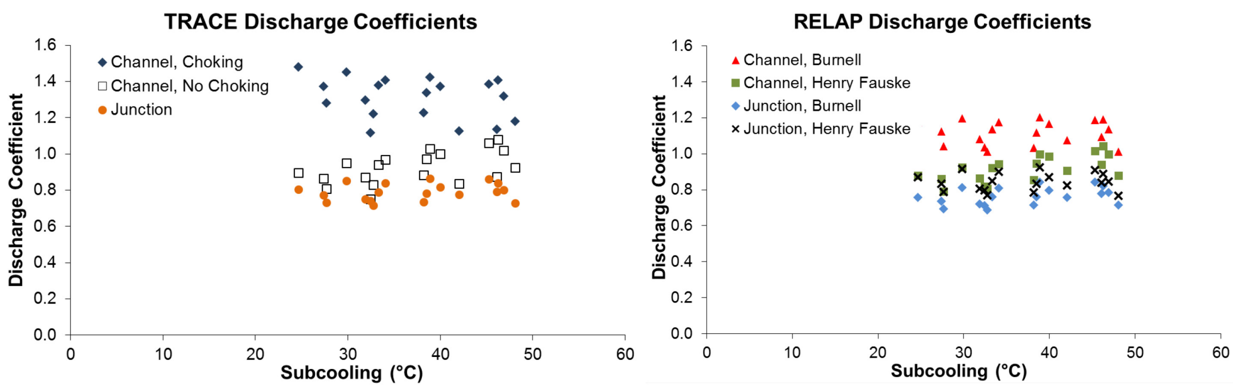

Figure 8 TRACE and RELAP calculated discharge coefficient for Purdue tests

3.5 Modelling Options and Sensitivity Studies

Several sensitivity studies were performed in both the TRACE and RELAP5 models to determine the impact of various modelling parameters. The results are detailed below.

3.5.1 TRACE Sensitivity Studies

Time Step Size: Reducing the time step from the 0.1s used in the analysis to 0.001s had no impact on results.
Numerical Scheme The default solver in TRACE is the SETS solver. Changing to the semi-implicit solver resulted in no appreciable change in predicted flow rates but produced some oscillations in the results.
Wall Roughness: Increasing wall roughness by 50% resulted in a decrease in predicted critical mass flow rate of less than 2%
Fineness of Nodalization: Doubling the number of hydraulic cells in the channel nodalization had a negligible impact on model results.
Critical Flow Relaxation Constant: As mentioned earlier, the relaxation constant for the critical flow model was reduced to 1.1. With the default 2.0 significant oscillations were observed in the flow rates.

3.5.2 RELAP

Time Step Size: The RELAP5 numerical solving scheme is subject to the material Courant limit, therefore the very short cell lengths in the channel nodalization results in a very small time step (on the order of 10^{-5} seconds). For the junction nodalization, reducing the time step from 0.1s to 0.001s had no impact on results.
Wall Roughness: Increasing the wall roughness by 50% reduced predicted critical mass flow rates by less than 3%.
Nodalization of Sample: Doubling the number of cells in the channel nodalization had a negligible impact on predicted mass flow rates.

4 ONTARIO HYDRO THICK WALLED CRITICAL FLOW TESTS

4.1 Facility Description

This series of tests was conducted by Ontario Hydro (OH) [7] in 1985 to support the use of a leak-before-break approach for pipe failure analysis in CANDU reactors. The tests were designed to measure flow rates through circumferential cracks in large diameter pipes.

The experiment used a test fixture consisting of two stainless steel cylinders. An aluminum wire shim was placed between the two cylinders, which were then bolted together. The wire crushed down to provide a leak tight seal. The thickness of the crushed wire determined the width of the crack or crack opening displacement (COD), while the positioning of the wire was used to produce either a rectangular or flared crack cross section.

Three tests were conducted using different parameters as outlined in Table 2.

Table 2 OH test fixture geometries [7]

Test ID	Crack Shape	COD (mm)	Crack Length at Outer Surface (mm)	Average Surface Roughness (μm)	Crack Depth (mm)
SS-A1	Flare 75.2°	0.102	98.6	2.03	38.1
SS-A2	Rectangular	0.109	48.8	2.03	38.1
SS-A3	Flare 75.2°	0.508	98.6	2.03	38.1

The measured change in COD before and after the test was less than 5%.

A pressure vessel with a capacity of approximately 200 kg was used to supply water to the test fixture. The entire apparatus of the pressure vessel, nitrogen tanks and supply lines was mounted on a weight balance platform. A load cell located under the opposite end of the platform measured the loss of water mass from the pressure vessel, which was correlated to mass flow rate from the test fixture. The nitrogen tanks were situated to eliminate the effects of mass shift from the tanks to the pressure vessel. Experimental error in leak rate measurement was within +/- 0.005 kg/s. The experimental apparatus and test fixtures are illustrated in Figure 9.

During testing the pressure vessel was filled with deionized water and heated using 40 kW immersion heaters. Nitrogen cover gas was used to maintain the desired pressure throughout the test.

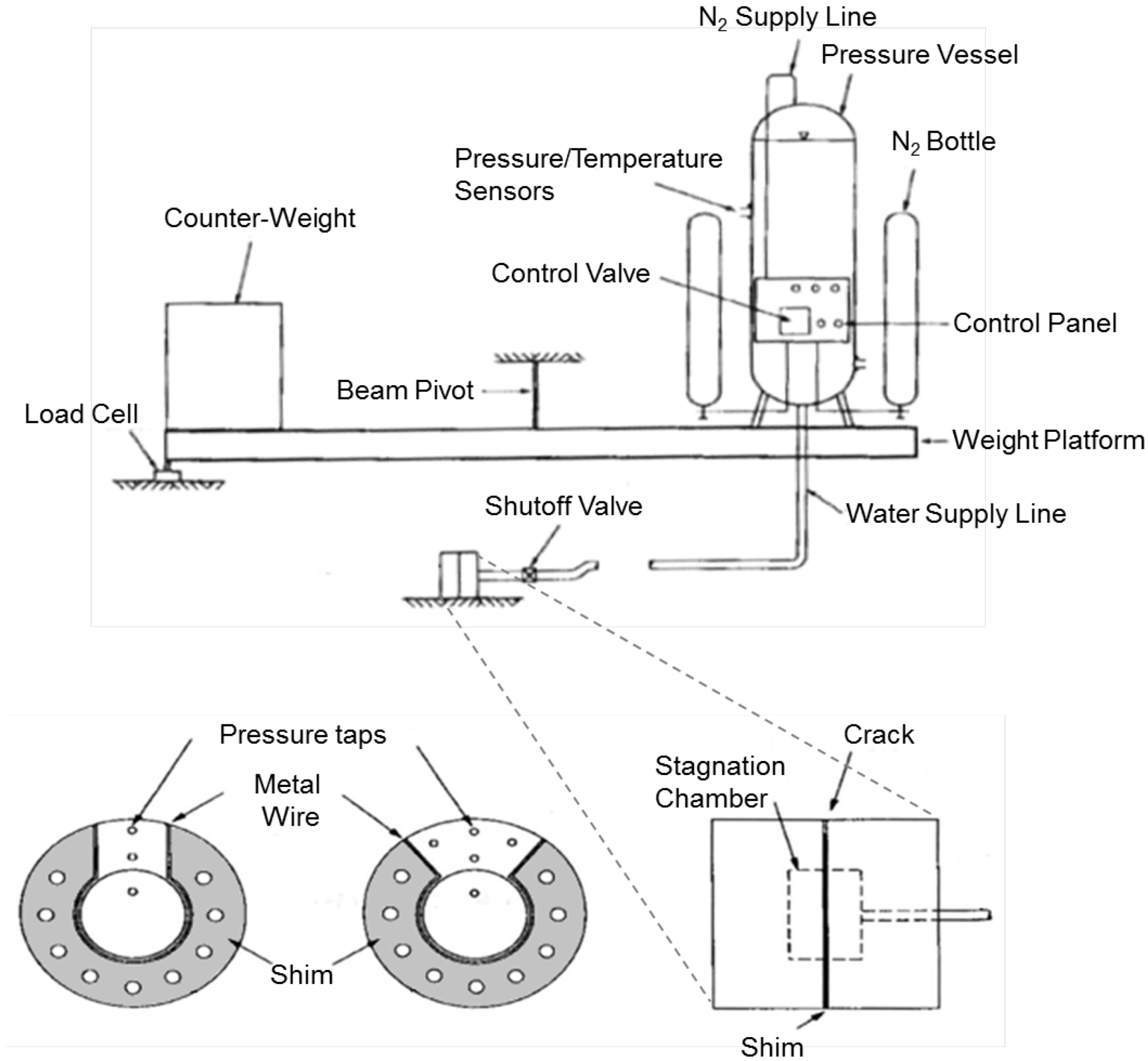

Figure 9 Test section showing shim and the flared and rectangular crack geometries [7]

4.2 Experimental Results

The measured flow rates for the three tests are shown in Figure 10. Flow rate was tested over a pressure range of 1 MPa to 12 MPa at temperatures between 177°C and 300°C. As the temperature increases (subcooling decreases) for each test the flow rate decreases. It is observed that for highly subcooled conditions the flow rate is strongly dependent on pressure, while at low subcooling the flow is less dependent on pressure.

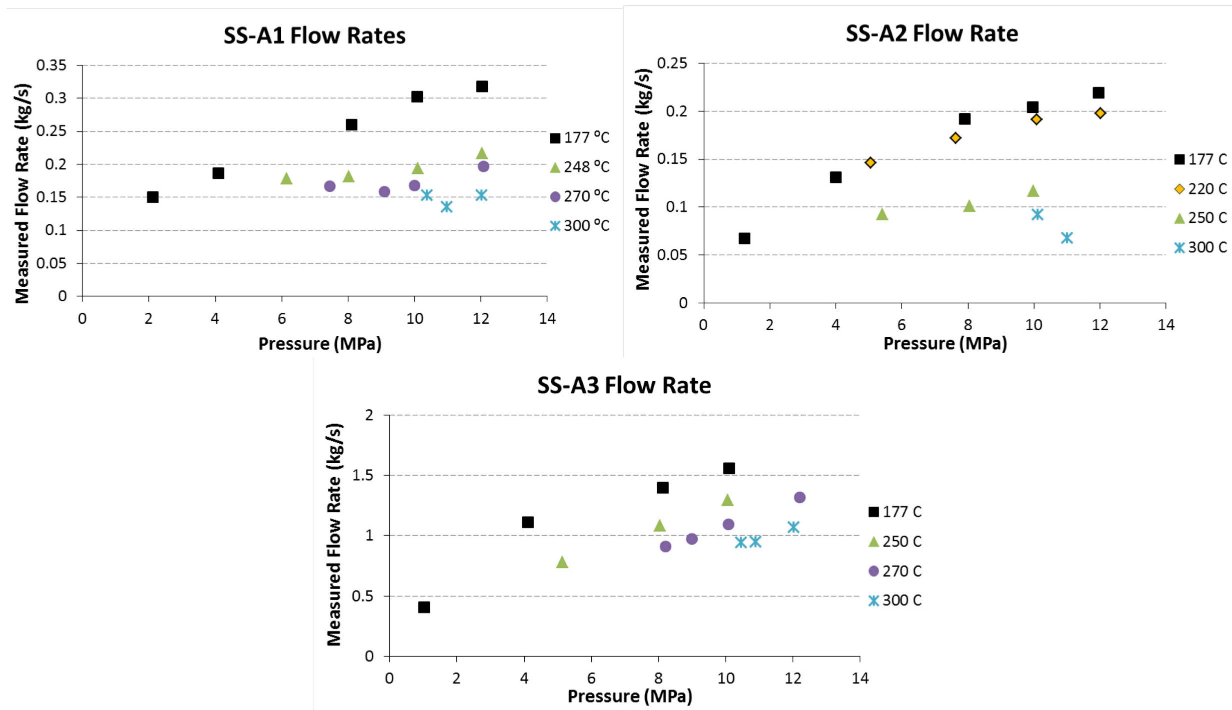

Figure 10 Measured flow rates for OH tests

4.3 Modelling

The experimental setup was modelled using TRACE V5.830. The SNAP representation of the nodalization is presented in Figure 11. The simulated crack is represented by a 3 cell PIPE (component 30). The internal volume of the test fixture is modelled with a single hydraulic cell (component 20). Boundary conditions 10 and 40 represent the test pressure and temperature and atmospheric conditions, respectively.

Choking was enabled at the interface between component 30 and boundary condition 40, with a default critical flow multiplier of 1.0 applied for all model runs. Minor losses at the inlet and outlet edge were calculated internally by TRACE using the ‘abrupt area change’ modelling option.

For the flared crack geometry the flow areas at the inner and outer edge of component 30 were calculated as the COD multiplied by the crack length along the pipe inner and outer circumference, respectively. Internal edge and cell centered flow areas were linearly interpolated between these values. Hydraulic diameter was calculated in a similar manner. For the straight crack geometry the flow area was calculated simply as the COD multiplied by the width of the flow path.

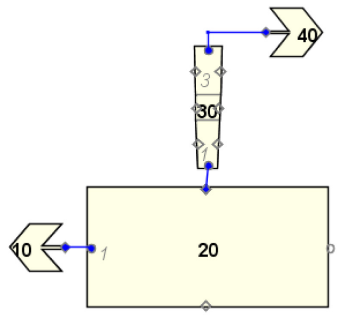

Figure 11 TRACE nodalization for OH tests samples (cell sizing not to scale)

4.4 Results

Figure 12 show the predicted vs. measured mass flow rate for the three test specimens. For samples 1 and 2 the flow rates are mostly predicted within ±25% and tend towards over prediction. Sample 3 results are over predicted to a greater degree, up to +75%.

The results in terms of calculated discharge coefficients are shown in Figure 13. Discharge coefficients trend towards higher values at lower pressures, indicating a tendency towards under prediction at low pressure; above 8 MPa results are more consistent. Under prediction of critical flow rates for the low pressure conditions have also been reported for the RELAP5 implementation of the modified Burnell/Ransom-Trapp critical flow model [17].

Samples 1 and 2 represent flared and rectangular crack geometries, respectively, which have a similar COD. For pressures above 8 MPa the discharge coefficients for these samples are similar, with a range of 0.7 – 1.05 for sample 1 and 0.6-0.9 for sample 2.

By comparison the discharge coefficients for sample 3 are both lower and fall in a narrower range of 0.52 – 0.64. The smaller range for sample 3 may be due to larger COD, which results in higher flow rates and thus lower relative error in experimental measurements.

Modelling results show no clear trend with respect to test temperature.

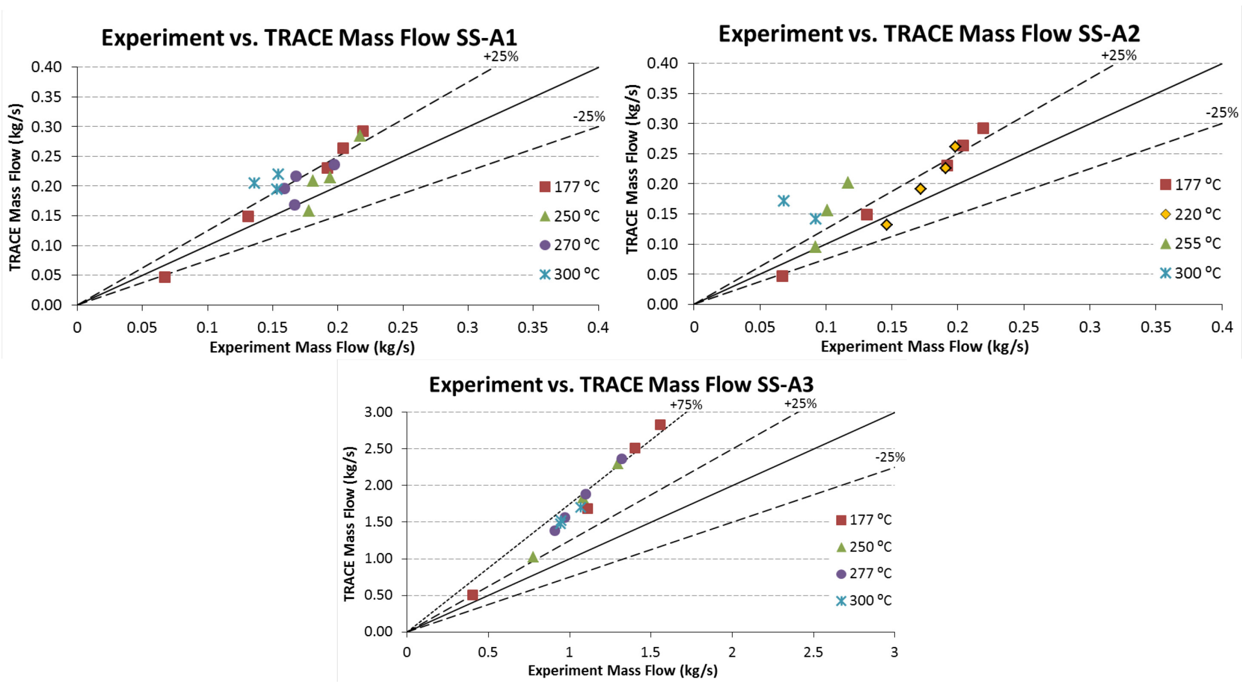

Figure 12 Model results for OH test samples

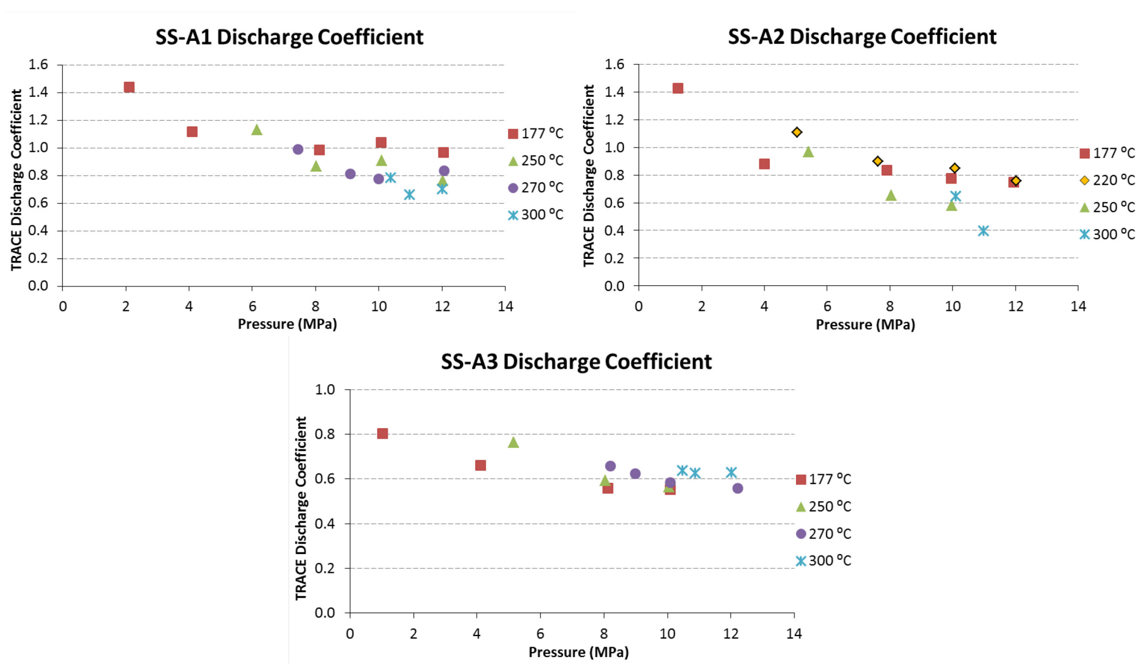

Figure 13 Discharge coefficients for the OH test samples

5 AECL FATIGUE CRACK CRITICAL FLOW TESTS

5.1 Facility Description

This series of tests was designed to measure flow rates through cracks in thick-walled pipes. A unique feature of these tests is the use of pressure cycling to produce fatigue cracks for flow rate measurements; the cracks produced by this method are expected to be more representative of through-wall defects which could potentially develop in reactors compared the machined, simulated crack geometries of the other tests.

A diagram of the pressure cycling rig used to produce cracks in the test specimens is shown in Figure 14. The pipe specimens consisted of 100 ASTM 106 Grade B pipes with diameters between 305 and 610mm and L/D of approximately 2, with end caps welded to each end. In order to assist the cracking process a notch was introduced on the inner surface using electric discharge machining (EDM). For samples 3 and 5 a flange was welded on the inside surface of the pipe to further increase stress. One end cap was connected with a pipe coupling to the pressure cycling rig.

Pressure cycling histories were different for each specimen; a typical regime involved cycling from 5 MPa up to 29 MPa. Between 30,000 and 91,000 pressure cycles were required to produce a through wall crack. During pressure cycling the outside of the pipe was sprayed with water to maintain ambient temperatures and to reduce the number of cycles required to form cracks.

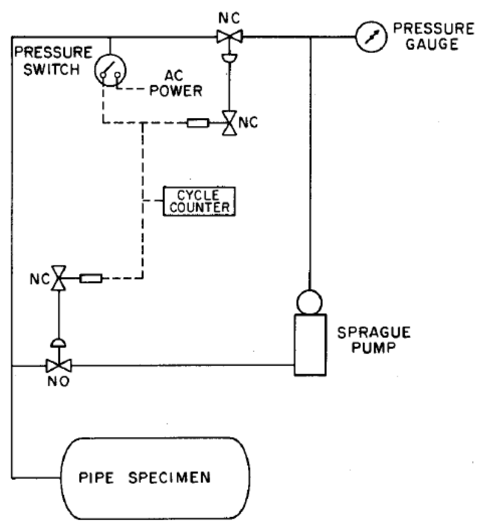

Figure 14 Pressure cycling rig [19]

Once a crack had been produced, the specimen was attached to a water supply at 260 ºC and 8.5 MPa. A single set of test pressure and temperature was used for the test series. Strap heaters and insulation were installed to maintain the temperature of the pipe at 260 ºC. Steam discharged from the crack was collected and condensed in a tube-to-tube heat exchanger. The condensate was collected in a bucket, the weight of which was recorded with a load cell to determine the leak rate.

Post testing, the cracks were examined by cutting out the crack section and measuring the crack length and crack opening displacement (COD) on both inside and outside surfaces. The section was then cooled with liquid nitrogen and cracked open to expose the leak path. The crack lengths were then re-measured and the surface roughness of the leak path was measured.

5.2 Experimental Results

The properties of the five test specimen are listed in Table 3. Several tests were performed for each sample using the same test conditions of 8.5 MPa and 260ºC; the range of flow rates observed during the different tests is reported. Note that the location of the crack, where the pipe failed during pressure cycling, varied and in the case of specimens 2 and 4 occurred not at the EDM notch but in the end cap weld.

Table 3 Test specimen properties and measured flow rates [19]

	Specimen 1	Specimen 2	Specimen 3	Specimen 4	Specimen 5
Pipe OD (mm)	324	457	324	324	610
Pipe Wall Thickness (mm)	21.2	26.7	19.7	21.4	38.9
Crack Location	EDM notch	Endcap weld	Flange	Endcap weld	Flange
Crack Length on ID (mm)	58	10	14	20.2	115
Crack Length on OD (mm)	13.5	65	14	12.6	10.5
Approximate COD (mm)	0.1	0.2	0.3-0.7	0.35	0.17
Crack Surface Roughness (μm)	10.2	13-16	5-20	3.8-7.6	20.3
Measured Leak Rate (kg/h)	0.5-7	8-11	15-30	65-115	8-24

For comparison to Modelling results the highest observed flow rate is used. Specimen 1 has a particularly wide range of flow rates; the researchers noted that the loop had not been used prior to testing of specimen 1, and leak rates measured closer to the lower end of the reported range where likely impacted by crud deposition in the crack [19].

5.3 Modelling

The experiments were modeled using TRACE V5.830. The nodalization appears in Figure 15 and is essentially the same model used for the Ontario Hydro tests detailed in section 4.3. Boundary conditions 10 and 40 represent the test fluid conditions and atmospheric conditions, respectively. Pipe 20 represents the volume of the test specimen, while the through-wall crack is represented by component 30.

The flow area and hydraulic diameter of the inlet and outlet of the crack are based on the crack length and COD values in Table 4.

For this set of tests the crack shape is not reported. For the fatigue cracks in this set of tests the COD is likely not consistent along the crack length. For development of the nodalization it was assumed that the reported COD is the maximum value at the crack center, which tapers linearly to zero at the crack ends. This assumption yields a diamond shaped crack whereby the flow area is equal to COD x crack length / 2. Flow area between the inner and outer surface of the crack was linearly interpolated. Minor losses at the inlet and outlet edge of the crack were calculated internally by TRACE using the 'abrupt area change' modelling option. Choking was enabled on the edge between component 30 and boundary condition 40.

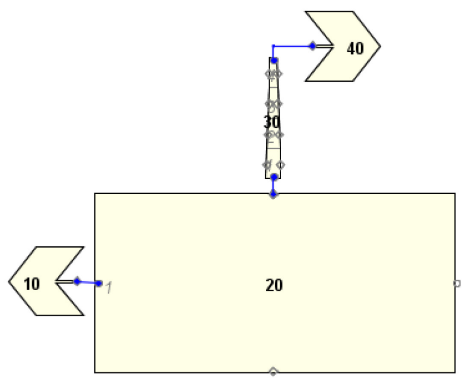

Figure 15 TRACE nodalization for the AECL tests (cell sizes not to scale)

5.4 Results

Modelling results are presented in Table 4 and Figure 16. The discharge coefficient is calculated as the measured mass flow rate divided by the predicted mass flow rate. For the measured rate the highest value reported in Table 3 is used.

In all cases TRACE significantly over predicts mass flow through the crack. Excluding specimen 4, the predictions are up to one order of magnitude higher than measured values. Specimen 4 prediction is closer to the experimental value; this test showed a significantly higher measured flow rate that the other tests. Based on the specimen geometry reported in Table 4 the major difference between sample 4 and the others samples is a lower surface roughness. The high relative roughness of the other samples with respect to their COD may contribute to the very low flow rates seen in those test.

Flow rate predictions for this experimental are significantly over predicted compared to the other two experiments. Notable difference between these tests and the OH tests, which also used thick walled sections, is the use of fatigue cracks as opposed to stylized, machined crack geometries. The irregularities in flow path resulting from the fatigue cracking process likely have a strong impact on the low flow rates seen in the test.

Table 4 TRACE predicted leak rates and calculated discharge coefficients

Specimen Number	Measured leak rate (kg/hr)	TRACE predicted leak rate (kg/hr)	Discharge coefficient
1	7	62	0.11
2	11	59	0.19
3	30	287	0.10
4	115	241	0.48
5	24	217	0.11

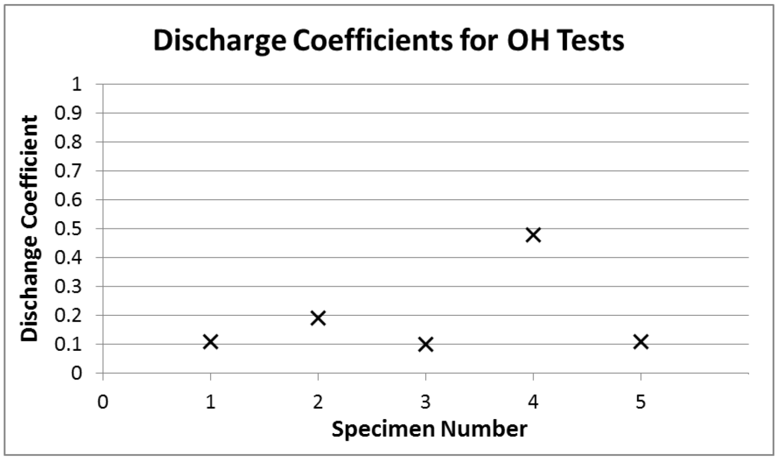

Figure 16 Discharge coefficients for the AECL tests

For specimen 4 a sensitivity study was conducted by changing the location of the choking plane. Table 5 shows that as the choking plane was moved away from the outside edge towards the inside surface of the pipe the flow rate increased until at edge 1 non-critical flow conditions were predicted.

Table 5 Predicted flow rate for sample 4, different edges selected as the choking plane

Location of Choking Plane	Predicted Flow Rate (kg/h)	Fluid Condition
Edge 5	241.2	Choked
Edge 4	257.4	Choked
Edge 3	273.2	Choked
Edge 2	282.6	Choked
Edge 1	322.9	Unchoked

6 DISCUSSION AND CONCLUSIONS

Based on the comparison of nodalization techniques for the Purdue tests, a junction nodalization appears more suitable for modelling of cracks with low wall thicknesses. When this nodalization scheme is employed, the TRACE implementation of the modified Burnell critical flow model gives similar results to the RELAP5 implementation of that model.

The Purdue tests and the OH tests both represent well defined, simulated crack geometries. The TRACE results for the OH tests at pressures above 8 MPa showed a range of discharge coefficients of 0.52 to 1.02, which bounds the results for the Purdue tests using the junction nodalization, where the range of discharge coefficients was 0.71 to 0.86. Modelling of the OH tests showed a tendency for TRACE to over-prediction critical flow at low pressures; in this case discharge coefficients began to rise at pressures below 8 MPa. There was no clear trend in model accuracy with respect to subcooling.

The OH and AECL tests both used thick walled samples with similar section thicknesses. However there is up to an order of magnitude difference in model predictions for these samples, with discharge coefficients for four of the five samples in the range of 0.10 – 0.19.

The major difference between the specimen sets is that the AECL tests have much higher surface roughness, on average 10-20 μm as opposed to 2 μm, for the AECL tests, likely due to production of the crack through a fatigue cracking process. For the very narrow cracks in these tests the surface roughness represents a significant fraction of the COD. This may introduce effects such as local changes in flow direction which are not accounted for in the model. It is notable that in the original report on the AECL tests a theoretical model for predicting leakage rate was described which produced good results only when a discharge coefficient of 0.07 was applied [19], indicating a more significant-over prediction of flow than the TRACE model.

In general, TRACE appears to be a suitable tool for modelling critical flow in thin and thick walled crack geometries. Modelling of additional leak rate tests should be performed to expand the code validation in this area.

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Kirk Tien, NRC Project Manager

11. ABSTRACT (200 words or less)

The thermal hydraulics system code TRACE has been used to predict subcooled critical flow in crack geometries. Three different experimental data sets were modeled in this study. The first experiment, performed at Purdue University, measured critical flow in slits with small section thicknesses similar to steam generator tubing. These results are also compared to model predictions using the RELAP5 code. The second experiment, conducted by Ontario Hydro (OH), measured critical flow rates in simulated circumferential cracks in thick-walled piping. The third experiment, from Atomic Energy of Canada Ltd. (AECL), measured critical flow through pressure cycling-induced fatigue cracks in thick walled vessels. For the Purdue tests, TRACE predictions were similar to those obtained with RELAP5. For the thin walled samples in these tests a junction nodalization was found to be more suitable than explicitly modeling the section thickness of the samples. TRACE predictions for both the Purdue and OH tests were in reasonable agreement with measured leak rates, with calculated discharge coefficients of between 0.5 and 1.0 for most cases. However, the model of the OH tests showed a trend towards under prediction as pressure dropped below 8 MPa. There was no clear trend demonstrated with respect to subcooling. For the AECL experiments the flow rate was significantly over predicted, with discharge coefficients as low as 0.1. This result is consistent with the modelling performed by the original experimenters and is likely due to the complexity of the flow pathway in the fatigue cracks used in this test, as compared to the machined geometries of the other samples.

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