STUDY OF TRACE DEPRESSURIZATION PREDICTIONS FOR THE MARVIKEN CRITICAL FLOW TEST

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Abstract

The TRAC/RELAP Advanced Computational Engine (TRACE) has been developed by the United States Nuclear Regulatory Commission as an advanced computational tool for best-estimate analyses of operational transients, loss-of-coolant accidents and other accident scenarios in light water reactors. As part of an effort to examine TRACE's predictions for depressurization transients with critical or choked flow, the Marviken Critical Flow Test of the rapid depressurization of a large vertical vessel has been modeled with TRACE. This paper details the TRACE model and presents a comparison between TRACE's prediction and the measured data from experiment. It is shown that TRACE's predictions when modeling this experiment were generally reasonable.

1. Introduction

The design, licensing and operation of nuclear power plants require advanced computational models to predict and foster an understanding of a system's response to perturbations as some systems are too complex to be accurately described by relatively simple theoretical models. The U.S. Nuclear Regulatory Commission (USNRC) has previously participated in the development of several system codes to model both the neutronic and thermal-hydraulic behaviour of reactors, including TRAC-P, TRAC-B, RELAP5 and RAMONA. As part of a continuous effort by the USNRC, power utilities and other organizations to provide advanced computational tools for simulating reactor systems, the capabilities of the aforementioned system codes have been combined into a single modernized tool, the TRAC/RELAP Advanced Computational Engine (TRACE) [1].

TRACE has been designed to analyse operational transients and accident scenarios in light water reactors as well as model experimental facilities that simulate reactor systems. Before TRACE can be accepted for its intended use it must be determined through a process of validation that its output compares favourably with measured data. Specifically, "separate effects" validation of TRACE refers to the modelling of experiments that capture a single thermal-hydraulic phenomenon of interest. This paper examines TRACE's predictions when modelling a rapid depressurization transient with critical or 'choked' flow.

In an accident scenario such as a Large Break Loss-Of-Coolant Accident (LB-LOCA) there is sudden depressurization as fluid under high pressure is exposed to a much lower pressure environment. As fluid rapidly depressurizes through the opening the fluid velocity may approach the sonic velocity (the maximum speed that pressure can propagate), in which case the flow becomes independent of the pressure differential. This phenomenon is called critical or choked flow [2]. To study TRACE's ability to accurately predict rapid depressurization with choked flow, the Marviken Critical Flow Test has been modeled with TRACE. This experiment consisted of the rapid blowdown of a large, pressurized vessel to atmosphere, with measurements of several fluid properties taken during the transient. This paper presents a detailed description of the experiment with how it was modeled in TRACE, and provides a comparison of some relevant measured data with the TRACE predictions.

2. The TRACE choked flow model

The partial differential equations that describe fluid flow and heat transfer are solved numerically in TRACE using finite volume methods. In TRACE, hydraulic components are discretized in to control volumes called cells, with quantities such as pressure, temperature and void fraction calculated at the cell centre. Velocities and mass flows are calculated at the cell edges.To determine if the flow is choked, TRACE calculates the conditions at which choking would occur at a given cell edge and then compares its momentum equation solution against these conditions. If the flow is judged to be choked, TRACE initiates its critical flow subroutine CHOKE to adjust the velocity and pressure derivatives of its solution. By default, TRACE will only check if a critical flow calculation is necessary at cell edges that are connected to user specified boundary conditions. The code can, however, be instructed to check any and all cell edges identified by the user as necessary. Since the conditions at which fluid choking will occur are dependent upon the nature of the flow at the cell edges and upstream cell-center, TRACE contains three different critical flow models: one each for subcooled-liquid, two-phase/two-component fluid, and single phase vapor [1]. Regardless of which model is used, the subroutine SOUND is first called by CHOKE to calculate the cell stagnation properties and homogeneous equilibrium sound speed. The method that SOUND uses to perform these calculations is dependent upon the length-to-hydraulic-diameter ratio of the cell and the presence or relative quantity of noncondensable gas in the flow.

A subcooled liquid choking calculation is initiated in TRACE when the cell-centered volumetric void fraction, α, falls in the range $\alpha \leq 1.0\times10^{-8}$. The model used by TRACE for this calculation is a modified form of the Burnell model, the same used in TRACE progenitor RELAP5 [1, 3]. In this region, fluid choking occurs when a subcooled liquid depressurizes rapidly through a break. If the downstream pressure is lower than the saturation pressure the fluid will change phase at the break, resulting in a large discontinuity in the sound speed. TRACE uses the Jones nucleation delay model to find the nucleation pressure at the cell edge, which it then substitutes into Bernoulli's equation with the cell-centre pressure to find the cell-edge velocity [1, 4]. The choking velocity is then taken to be the maximum of this calculated velocity or the homogeneous equilibrium sound speed returned by SOUND. The user is able to specify a multiplicative coefficient to the fluid choking velocity, which is labeled CHM1 in the code and has a default value of 1.0.

In the region $1.0\times10^{-5} \leq \alpha \leq 0.999$ TRACE performs a two-phase/two-component fluid choking calculation. The model in this region is an extension of that developed by Ransom and Trapp and assumes that thermal equilibrium exists between the phases [1, 5]. Since the model has been developed from first principles, the complexities of the computational method are such that they preclude a concise summary being included in this paper. Succinctly, a two-phase mixture choking velocity is calculated from the conditions returned by SOUND, and based on this velocity both liquid and gas choking velocities are determined. As was the case in the subcooled region, the user is able to specify a coefficient to the fluid choking velocity, labeled CHM2, with a value of 1.0 by default. A special case exists in the region $1.0\times10^{-8} \leq \alpha \leq 1.0\times10^{-5}$ where an interpolation is performed between the subcooled and two-phase models. This interpolation is linear with a slope dependent upon the value of α.

If $\alpha > 0.999$ a single-phase vapour choked flow calculation is done. The model used in this region is based upon the isentropic expansion of an ideal gas, wherein the fluid choking velocity is calculated as a function of the specific-heat ratio and the upstream stagnation temperature. The coefficient CHM2 also acts on the choking velocity in this region.

In each case above, if the velocity determined by the solution of the momentum equation is equal to or greater than the calculated choking velocity, then the fluid velocity is set explicitly to the choking velocity. Otherwise, the flow is determined to not be choked and calculation in CHOKE is terminated. Finally, the newly calculated choking velocities are relaxed with the previously calculated choking velocities as shown below:

$$V^{n+1} = 0.1 \; V^{p} + 0.9 \; V^{n} \qquad (1)$$

where V^{n+1} is the new-time choking velocity to be returned by CHOKE, V^p is the choking velocity just calculated, and V^n is old time choking velocity. The weights are chosen so that the choking model purposely lags behind any pressure transients in the main model.

3. Methodology

3.1 Facility and test description

The Marviken test facility, located in Sweden, used the pressure vessel of the cancelled Marviken power reactor project for a large series of full-scale thermal-hydraulics tests. The Critical Flow Test (CFT) program examined critical flow as functions of nozzle geometry and varying levels of fluid subcooling. The experiment chosen for modeling in this study was the 11th in the series [6].

The pressure vessel consisted of a cylindrical section 16.91 m tall with inner diameter of 5.22 m, which was capped on both the top and bottom by hemispherical domes of 2.63 m inner radius. A cupola or neck was welded to the top of the vessel as well, for a total height of 24.55 m. The vessel was made of low alloy steel 76 mm thick through the cylindrical section and between 40 to 65 mm in the domes. The vessel contained several vortex mitigators to prevent the formation of vortices during the tests, as well as elements of the original reactor vessel internals that could not be removed.

A discharge pipe extended axially from the bottom of the vessel. Fluid entered the discharge pipe through a bell mouth collector with an inlet diameter of 1 300 mm that contracted to the 752 mm inner diameter of the pipe proper. The total length of the pipe was 6 308 mm, including 740 mm inside the vessel for the collector. A nozzle containing a rupture disc was connected to the bottom of the pipe. For Test 11, this nozzle was 1 589 mm long and had a diameter of 509 mm. The discharge pipe contained two instrumentation rings to measure properties of the fluid, which were supplemented by pressure and temperature measurements at the vessel top and bottom.

For Test 11, the initial water level inside the pressure vessel was 17.63 m high relative to the vessel bottom. The remaining volume contained steam at 4.97 MPa. The saturation temperature of the steam was approximately 264 °C, with the temperature at the vessel bottom 226 °C. At the beginning of the transient the rupture disc at the bottom of the discharge pipe was broken, rapidly discharging the contents of the vessel to atmosphere.

3.2 TRACE model

The pressure vessel, discharge pipe and nozzle were modeled in TRACE V5.0 using 23 PIPE components, each comprised of a single cell. The rupture disc was modeled with a VALVE component that opened instantaneously at the beginning of the transient run, discharging to a BREAK component set to atmospheric pressure and temperature. This is shown graphically in Figure 1. K-factors were applied at select cell edges to capture the minor pressure losses associated with the vessel internals, the bell mouth collector, and some flow obstructions in the discharge pipe.

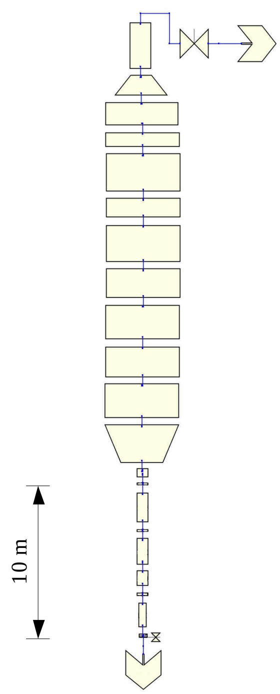

Figure 1 Nodalization of the Marviken CFT as it appears in the Symbolic Nuclear Analysis Package (SNAP) graphical user interface for creation TRACE input files (image to scale).

To ensure a realistic pressure and temperature distribution in the vessel before the start of the transient, a steady-state run was first executed based on initial guesses of temperature, pressure and void at each cell. For the steady-state run the discharge VALVE component at the bottom was closed, and a second VALVE component of zero volume at the top of the vessel was opened. This VALVE connected the top of the vessel to a BREAK set to 4.97 MPa at 264 °C, the saturated steam conditions stated for Test 11, to serve as a boundary condition for the steady-state calculation. Once the steady-state conditions were determined, a restart run was initiated for the transient calculation. At the beginning of the transient, the top VALVE was closed instantaneously to isolate the BREAK used for the steady-state boundary, and the bottom VALVE was opened. The transient was allowed to continue for 60 seconds, after which the vessel was mostly discharged.

4. Results

Figure 2 shows the mass flow measured and predicted by TRACE at Instrumentation Ring 2 on the discharge pipe. The uncertainty shown is the maximum uncertainty quoted for the pitot-static mass flux measurement at Instrumentation Ring 2 (10.4%) in the Marviken CFT report [6]. Both the measured and predicted plots show three stages to the transient. In the first stage the mass flow decreases in time from its initial maximum value as subcooled liquid from the bottom of the vessel passes through the discharge pipe. The second stage begins between 15 and 20 seconds into the transient, where two-phase fluid begins to pass through and the mass flow decreases at a much slower rate. Finally, approximately 50 seconds in to the transient the initial liquid inventory is almost completely discharged and the mass flow decreases rapidly.

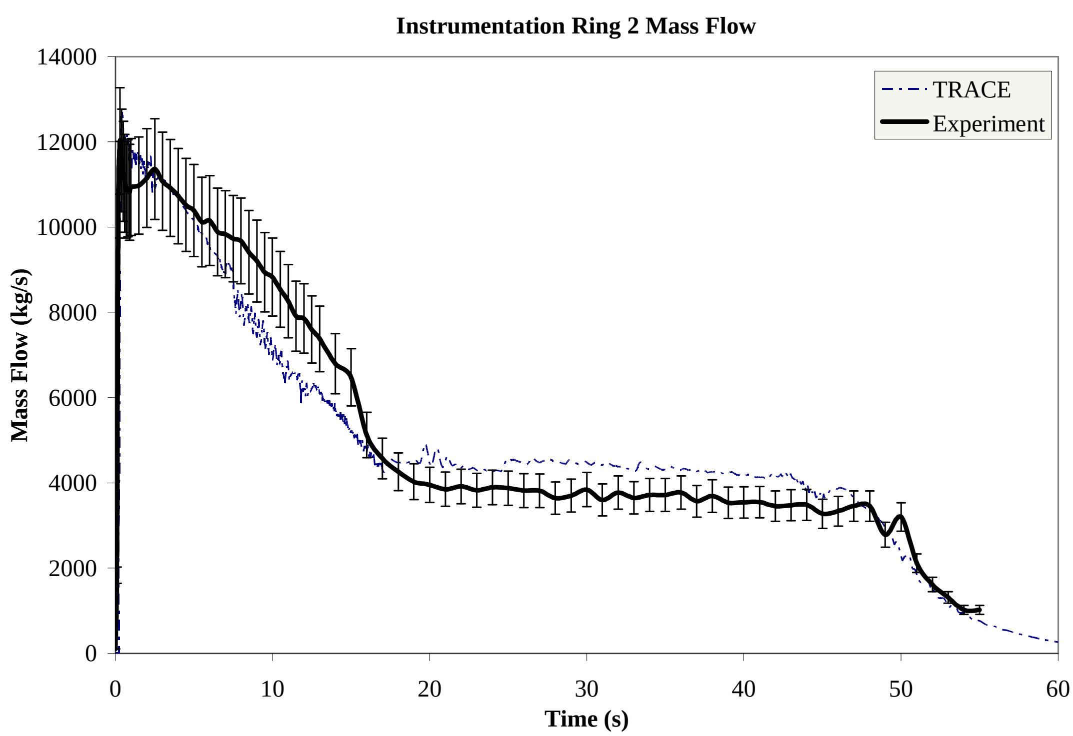

Figure 2 Marviken CFT Test 11 mass flow.

In the first stage of the transient, TRACE's prediction for mass flow begins within the measurement uncertainty but then decreases more rapidly than measured. The TRACE prediction then enters the second stage (two-phase discharge) at a higher mass flow than measured, before entering the final stage again within measurement uncertainty. Figure 3 shows the integrated discharge with time, where it is evident that the predicted value is within the 10.4% relative measurement uncertainty of mass flow for the entire duration of the transient.

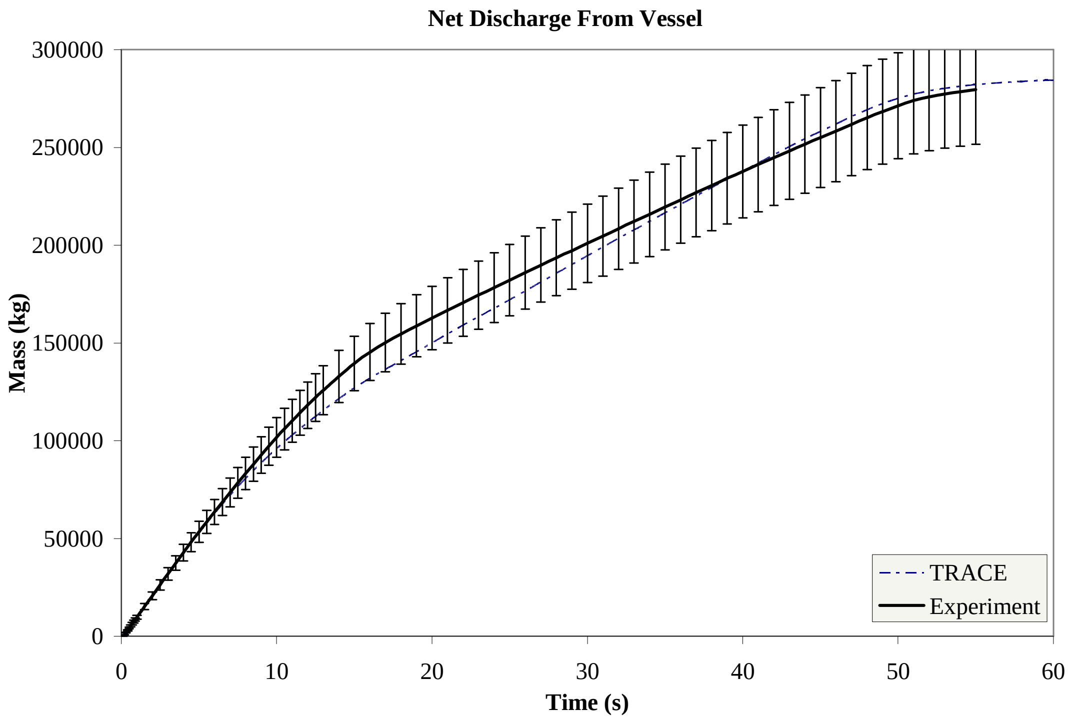

Figure 3 Marviken CFT Test 11 integral mass discharge.

Figure 4 shows the measured and predicted void at the same location as the mass flux measurement. The uncertainty shown is that quoted in the Marviken reports for the gamma-densitometry measurements used for determining void (10%) [6]. TRACE's prediction after 25 seconds shows a rapid increase in void to a higher level than measured. This is likely a result of two underlying phenomena, the first being the difference in TRACE's prediction of the integrated mass discharge (i.e. the amount of total mass remaining) as shown in Figure 3. The second is the earlier onset of void in the experimental data as a result of non-thermal equilibrium voiding effects which are not modeled in TRACE.

TRACE allows tuning of its predicted critical velocity via the adjustment of coefficients CHM1 and CHM2. In this case, decreasing the value of the two-phase multiplier CHM2 would proportionally decrease the prediction for the choking velocity in the second phase of the discharge transient. Optimization of the values for CHM1 and CHM2 for specific geometries, rather than just adjusting the values so that the prediction matches the measured data, is worthy of further study.

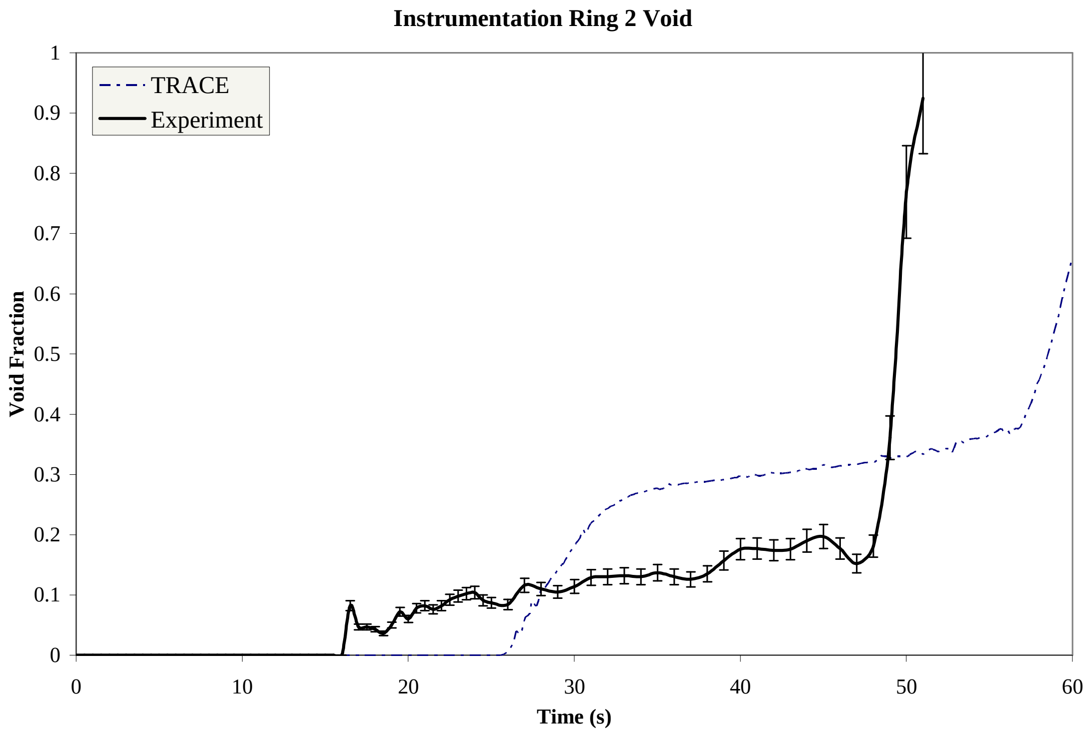

Figure 4 Measured void fraction and volumetric void fraction predicted by TRACE.

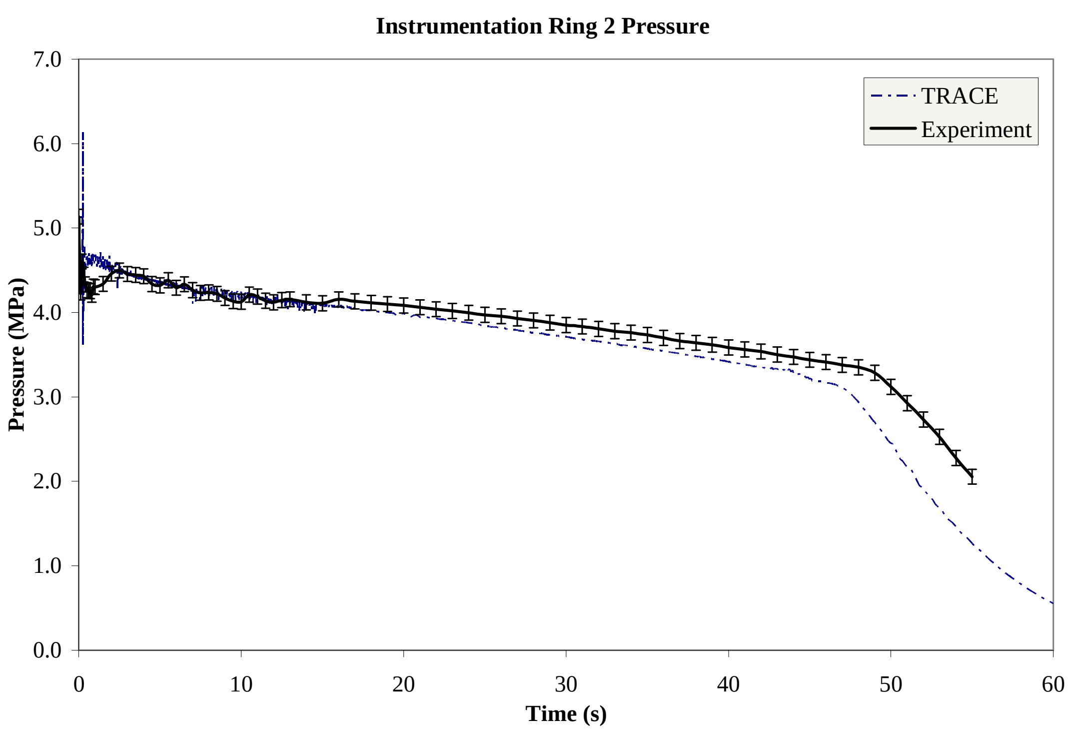

Figure 5 Pressure transient during discharge.

Finally, Figure 5 shows both the measured and predicted pressures at the same location. The measurement uncertainty shown is ± 90 kPa, quoted as the maximum error for the pressure measurement in the Marviken report [6]. In the first few seconds, the initial pressure loss and recovery is not predicted by TRACE. After this point, however, TRACE predicts the pressure within the measurement uncertainty up until the second stage of the discharge. The pressure is then under predicted, which is consistent with the faster rate of discharge in this region as shown in Figures 2 and 3.

4. Conclusions

The Marviken CFT has been modeled with TRACE to study TRACE’s predictions of rapid depressurization transients with choked flow. It was found that TRACE’s predictions for mass discharge and pressure with this nodalization were within the measurement uncertainty for much of the initial stage of the transient. Further into the transient, however, TRACE over predicted the mass flow and rate of depressurization. It was evident that TRACE had over predicted the choking velocity in the two phase discharge region with default values for the critical velocity multipliers CHM1 and CHM2. Optimization of the values of these coefficients is a subject for further study. Nevertheless, given that the predicted the mass flow and pressure for the first stage of the transient were within the measurement uncertainty, and that the prediction of the integral mass discharge for the entire transient was equally good, TRACE’s predictions when modeling this experiment were generally reasonable.

5. Acknowledgements

The author would like to thank the University Network of Excellence in Nuclear Engineering (UNENE) for their support as well as AMEC NSS for access to TRACE.

6. References

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