NUREG/IA-0007

International Agreement Report

Assessment of RELAP5/MOD 2 Against Critical Flow Data From Marviken Tests JIT 11 and CFT 21

Prepared by
Ö. Rosdahl, D. Caraher

Swedish Nuclear Power Inspectorate
P.O. Box 27106
S102 #52 Stockholm, Sweden

Office of Nuclear Regulatory Research
U.S. Nuclear Regulatory Commission
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Prepared as part of
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Swedish Nuclear Power Inspectorate

Östen Rosdahl
David Caraher*

ICAP
Assessment of RELAP5/MOD Against Critical Flow Data from Marviken Tests JIT 11 and CFT 21

ABSTRACT

RELAP5/ MOD2 simulations of the critical flow of saturated steam are reported together with simulations of the critical flow of subcooled liquid and a low quality two-phase mixture. The experiments which were simulated used nozzle diameters of 0.3 m and 0.5 m. RELAP5 overpredicted the experimental flow rates by 10 to 25 percent unless discharge coefficients were applied.

* Software Engineering Consulting

Approved by

Eric Hellstrand

EXECUTIVE SUMMARY

RELAP5/MOD2 simulations have been conducted to assess the critical flow model in RELAP5. The experiments chosen for the simulations were Marviken Jet Impingement Test (JIT) 11 (saturated steam flow) and Marviken Critical Flow Test (CFT) 21 (subcooled and two-phase flow).

The experimental facility consisted of a large vessel 5.2 m in diameter and 22 m high having a total volume of 420 m^3. A discharge pipe containing a valve, a nozzle, rupture discs and assorted transducers was attached to the bottom of the vessel. For JIT 11 a standpipe, 1 m in diameter and 18 m tall, was mounted within the vessel to prevent any liquid from entering the discharge pipe. The nozzle used for the saturated steam flow test (JIT 11) had a diameter of 0.3 m and a length of 1.18 m. The nozzle used for the subcooled critical flow test (CFT 21) had a 0.5 m diameter and was 0.96 m in length.

For all the RELAP5 simulations the experimentally measured fluid conditions in the vessel were used as boundary conditions. This technique allowed the simulations to focus on the flow in the discharge pipe.

The simulations of saturated steam flow overpredicted the experimental discharge flow rate by 20 to 25 percent. Explicity representing the nozzle region by up to five computational cells had little effect on computed results. It was concluded that, when simulating saturated steam critical flow with RELAP5, a discharge coefficient of ~ 0.8 needs to be applied. Furthermore, short lengths of pipe (L/D < 4) at the discharge should not be explicitly modeled.

Numerical discontinuities in calculated critical flow rate were found to occur in some of the saturated steam flow simulations. The cause of the discontinuities was traced to an approximation made in the equation used for determining the internal energy at a junction in subroutine JCHOKE.

When simulating CFT 21 RELAP5 was found to overpredict critical flow rates of subcooled liquid by 18 to 20 percent when the nozzle was not explicitly included in the RELAP5 model (only its flow area was included). Good agreement with experimental results was attained by using a discharge coefficient of 0.85.

When the nozzle was included in the RELAP5 model RELAP5 underpredicted the measured flow rates. Applying discharge coefficients greater than unity did little to improve computed results but greatly increased computational times. It was concluded that when modeling discharge regions using RELAP5 explicit representation of short lengths of piping near the discharge location should be avoided.

For low quality two phase flow RELAP5 was in good agreement with experimental data when the vessel fluid state (RELAP5 boundary condition) was based upon gamma densitometer measurements. When the fluid state was based upon dP measurements RELAP5 overpredicted the measured flow rate by up to 30 percent. Since the actual fluid state in the vessel probably lies between those used as boundary conditions it was concluded that RELAP5 would generally need a discharge coefficient of between 0.80 and 0.95 when used to simulate low quality critical flow.

Application of a discharge coefficient to the RELAP5 simulation of low quality two-phase flow did not achieve an expected result. Using a discharge coefficient of 0.85 instead of 1.0 resulted in only a 8 percent reduction in flow rate rather than the 15 percent expected.

It was discovered that, because of the logic used in subroutine JCHOKE to select between the subcooled and saturated flow calculations and because of an apparent dependency of local equilibrium quality on discharge coefficient, the sonic velocities used in the RELAP5 choking criterion could increase when a discharge coefficient was applied, thus partially offsetting the velocity reduction represented by the discharge coefficient.

LIST OF CONTENTS

1 INTRODUCTION

The International Thermal-Hydraulic Code Assessment and Applications Program (ICAP) is being conducted by several countries and coordinated by the USNRC. The goal of ICAP is to make quantitative statements regarding the accuracy of the current state-of-the-art thermal-hydraulic computer programs developed under the auspices of the USNRC.

Sweden's contributions to ICAP relate both to TRAC-PWR (1) and RELAP5 (2). The assessment calculations are being conducted by Studsvik Energiteknik AB for the Swedish Nuclear Power Inspectorate. The assessment matrix is shown in Table 1.

In this report the results of an assessment of the RELAP5's critical flow model is presented. The ability of RELAP5 to simulate the critical flow of saturated steam is assessed by comparison to data from Marviken Jet Impingement Test (JIT) number 11 (5). The subcooled critical flow model is assessed by comparison to data from Marviken Critical Flow Test (CFT) number 21 (6).

This report is organized as follows: Section 2 describes the experimental facility and section 3 describes the RELAP5 model used to simulate the experiments. In section 4 results from the simulations are presented and discussed. Computational efficiency of RELAP5 and numerical problems encountered during the simulations are given in section 5. Conclusions are presented in section 6.

Table 1

ICAP Assessment Matrix - Sweden.

Code	Facility	Type Sep. effect	 Integral	Description
RELAP5	Marviken21	X		Subcooled Critical Flow
RELAP5	Marviken11	X		Critical Flow, level swell
RELAP5	FIX-II		X	Recirculation Line (10 %) break
RELAP5	FIX-II		X	Recirculation Line (31 %) break
RELAP5	FIX-II		X	Recirculation Line (200 %) break
RELAP5	LOFT		X	Cold Leg Break (4") pumps off
RELAP5	LOFT		X	Cold Leg Break (4") pumps on
RELAP5	FRIGG	X		Subcooled Void Distribution
RELAP5	FRIGG	X		Critical Heat Flux
RELAP5	RIT	X		Post Dryout Heat Transfer
TRAC/PF1	Ringhals		X	Loss of Load

2. FACILITY AND TEST DESCRIPTION

The Marviken Power plant was built as a boiling heavy water direct cycle nuclear reactor but was never commissioned. The nuclear steam supply system was left intact and an oil fired boiler was built to provide steam for the turbine.

During 1978 and 1979 Marviken was the site of the Critical Flow Test (CFT) program. This test program generated full scale critical flow data for subcooled liquid and low quality two-phase mixtures.

Subsequent to the CFT program, Marviken became the site of the Jet Impingement Test (JIT) program. This program, which focused on measuring loads due to a fluid jet impinging upon a flat plate, also generated full scale critical flow data. One of the tests, JIT 11, allowed only saturated steam to be discharged.

Figure 2-1 depicts the Marviken pressure vessel and the location of the differential pressure measurements. For JIT 11 a standpipe (dotted line) was inserted into the vessel to ensure that only steam flowed out of the vessel. In other tests no standpipe was used; the fluid entered the discharge pipe at the bottom of the vessel directly. The nozzle was located beneath the pressure vessel. The piping leading to the nozzle and the nozzle are depicted in Figures 2-2 and 2-3. Initial and boundary condition for JIT 11 and CFT 21 are summarized in Table 2-1. Complete descriptions of the experimental facility for the JIT program and for the CFT program are given in References 3 and 4 respectively. A description of JIT 11 is presented along with test results in Reference 5 and a description of CFT 21 is given in Reference 6. The probable error (one standard deviation) in the measured differential pressure values shown in this report is 0.6 kPa; the 99 % confidence error is 1.5 kPa.

Table 2-1

Important parameters for Marviken JIT 11 and CFT 21

	JIT 11	CFT 21
Vessel volume (net internal)	420 m^3	420 m^3
Vessel inside diameter	5.22 m	5.22
Standpipe: height	18 m	-
outside diameter	1.04 m	-
wall thickness	8.8 mm	-
Disharge nozzle: diameter	0.299 m	0.500 m
area	$702 \times 10^{-4} m^2$	0.1963 m^2
length	1.18 m	1.5 m
Initial pressure	5.0 MPa	4.9 MPa
Final pressure	1.88 MPa	2.5 MPa
Initial water level	10.2 m	19.9 m
Final water level	8.0 m	<0.8 m
Initial inventory: water	145×10^3 kg	330×10^3 kg
steam	5×10^3 kg	6×10^2 kg
Maximum subcooling	< 3 K	33 K

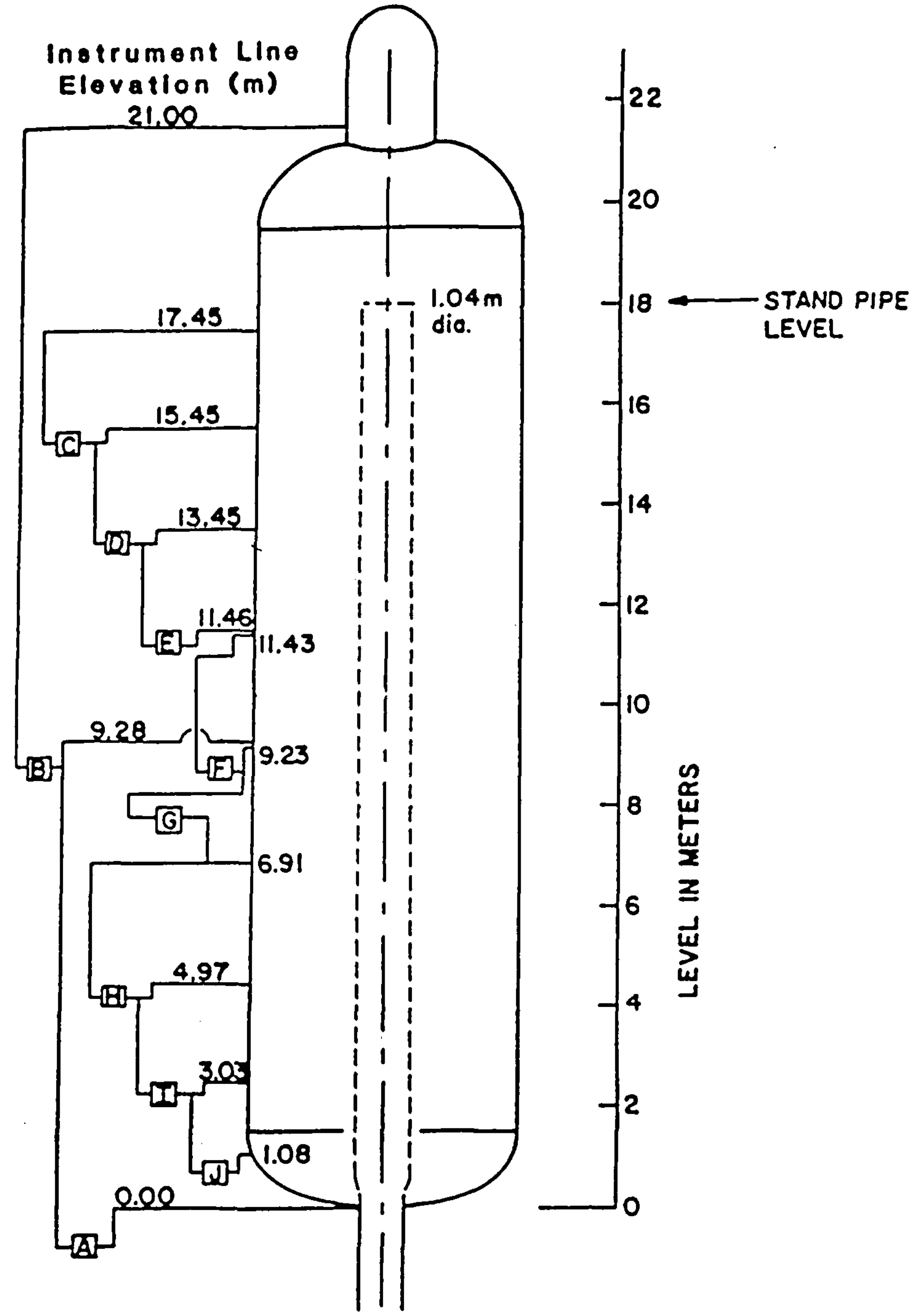

Figure 2-1

Marviken test vessel. Differential pressure transducers A through J.

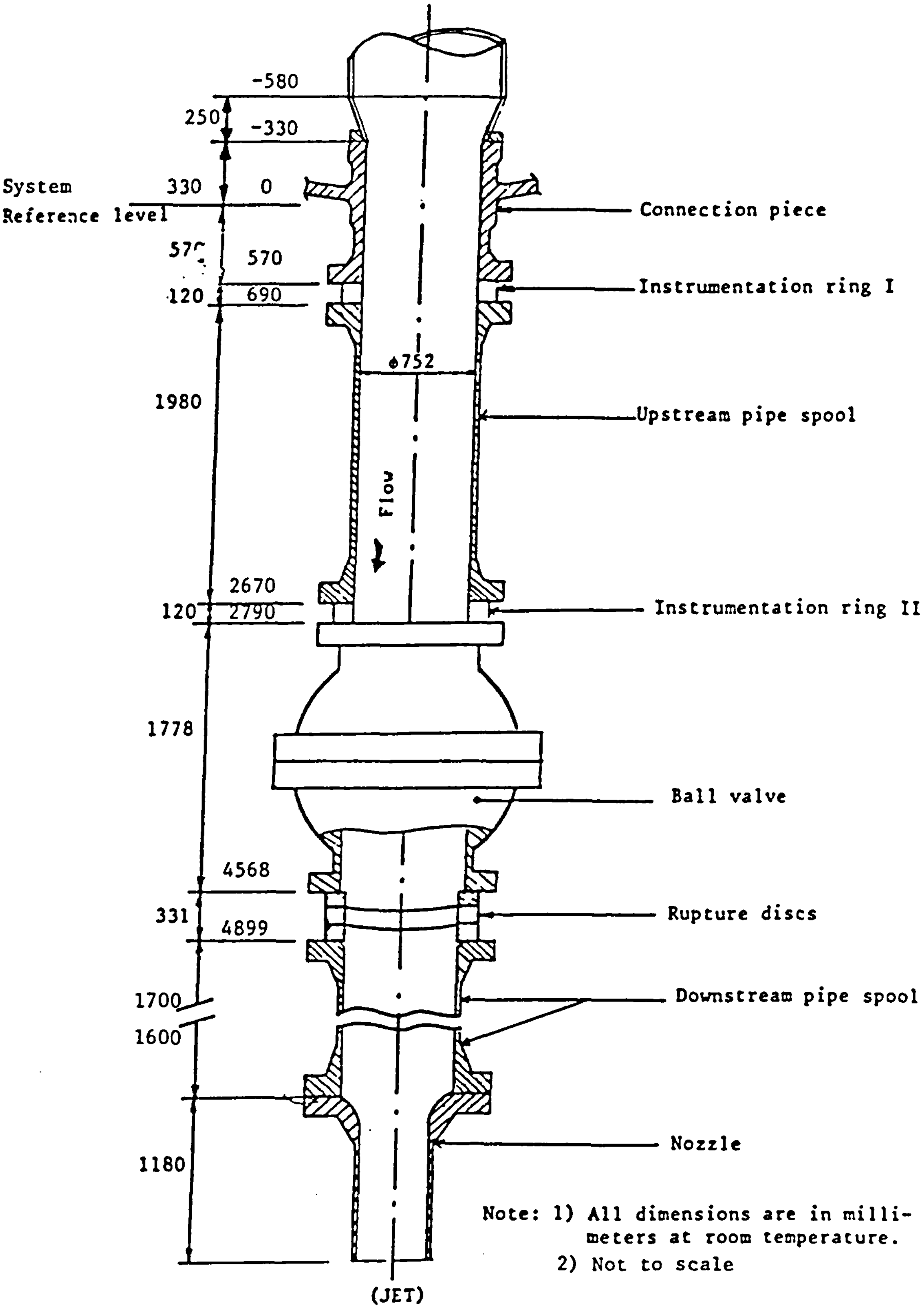

Figure 2-2

Arrangement of components in the discharge pipe for Jet Impingement Test 11.

Note: All dimensions are in millimeters at room temperature.

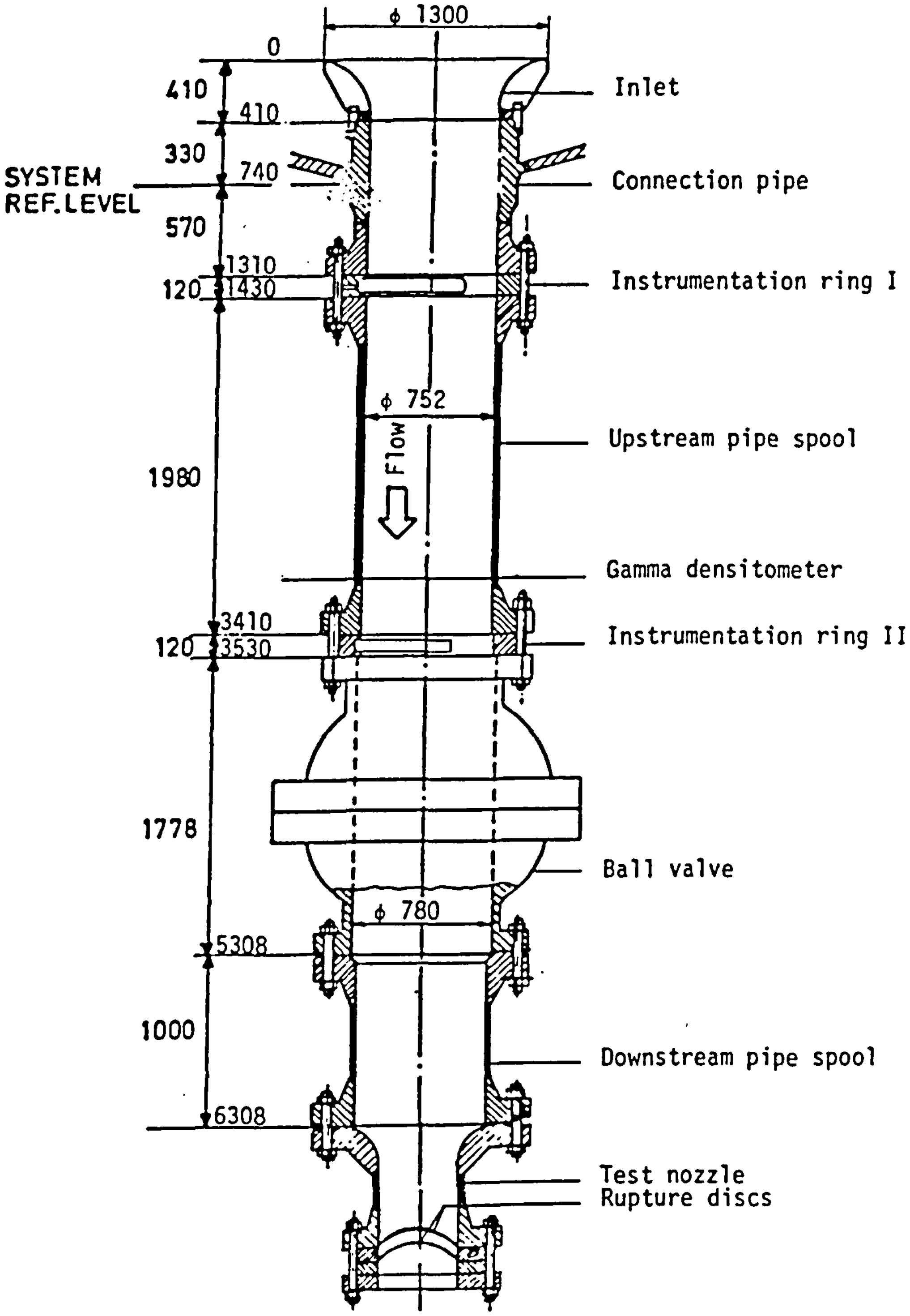

Figure 2-3

Arrangement of components in the discharge pipe for Critical Flow Test 21.

3 CODE AND MODEL DESCRIPTION

The critical flow simulations of JIT 11 and CFT 21 were performed with RELAP5/MOD2, cycle 36.02.

3.1 Input description - JIT 11 simulations

In order to focus on the critical flow model in RELAP5 it was decided to drive RELAP5 with vessel boundary conditions determined from the experimental data. A TMDPVOL component was used to represent the vessel for all the simulations of JIT 11. The containment was also represented by a TMDPVOL component (with constant P = 0.1 MPa). The piping between the vessel and the containment (see Figures 2-1, 2-2) was represented several different ways, as described in Table 3-1.

Table 3-1
Description of the JIT 11 simulation cases

Case	Description
0 node	Vessel modeled as time dependent volume. Standpipe and discharge pipe not modeled. A single junction component used to represent the discharge area.
7 node	Vessel model as time dependent volume. Standpipe modeled as pipe component (4 cells). Discharge pipe modeled as pipe component (3 cells). Single junction component used to represent the discharge area.
9 node	Same as 7 node model except nozzle included. Nozzle modeled by pipe component (2 cells).
12 node	Same as 9 node model except nozzle now represented with 5 cells.

3.2 Input description - CFT 21 simulations

For the simulations of CFT 21 a TMDPVOL component was used to represent the fluid conditions at the bottom of the vessel. For the simulations of subcooled flow the pressure and temperature measured at the vessel bottom were fed to RELAP5. For the simulations of saturated liquid or two-phase flow the pressure and fluid quality at the vessel bottom were fed to RELAP5. The fluid quality history was determined from experimental measurements of density, pressure, and differential pressure combined with the assumption of adiabatic flow between the vessel bottom and the gamma densitometer location (refer to Figure 2-3).

The RELAP5 simulations are described in Table 3-2. For simulations CFT01 to CFT06 the discharge pipe was modeled by a PIPE component with three cells. The discharge area was represented by a SNGLJUN component but the nozzle was not explicitly modeled. For simulations CFT07 and CFT08 the nozzle was modeled as a PIPE component having one cell.

The saturated flow simulations (CFT04, CFT05, CFT06) all began at 26.7 seconds into the blowdown. Each of these simulations was initiated by restarting case CFT03 and inputting a new (saturated conditions) set of boundary conditions representing the experimental measurements made between 26.7 and 60 seconds.

Table 3-2

Description of the CFT 21 simulation cases.

RELAP5 case	Description
CFT01	Subcooled boundary conditions. No discharge coefficients. Nozzle not modeled.
CFT02	Subcoooled boundary conditions. Subcooled discharge coefficient (C_D) = 0.85. Nozzle not modeled.
CFT03	Subcooled boundary conditions. C_D = 0.85. Boundary condition temperature reduced 2K for t>18 s. Nozzle not modeled.
CFT04	Saturated boundary conditions. Restarted from CFT03 at 26.5 s. No discharge coefficient for two-phase flow.
CFT05	Saturated boundary conditions. Restarted from CFT03 at 26.5 s. No discharge coefficient. Boundary condition quality limited to upper value of 0.003.
CFT06	Same as CFT05 except C_D = 0.85.
CFT07	Subcooled boundary conditions. No discharge coefficient. Nozzle modeled with one node.
CFT08	Same as CFT07 except C_D = 1.09 for subcooled flow and 1.13 for two-phase flow.

4 RESULTS AND DISCUSSION

RELAP5 simulations of the critical flow of saturated steam (JIT 11) are reported in section 4.1. Simulations of the subcooled critical flow and the low quality two-phase critical flow of CFT 21 are discussed in sections 4.2 and 4.3, respectively.

4.1 Critical flow of saturated steam - JIT 11

For the RELAP5 simulation of the critical flow in JIT 11 the experimentally measured pressure in the vessel was used as a boundary condition. Calculated discharge flow rate was then compared to the measured flow rate. The pressure history and the discharge mass flow rate history for JIT 11 are given in Figures 4-1 and 4-2.

The results of all the RELAP5 simulations of JIT 11 are shown together with the experimental data in Figure 4-3. Error bounds on the measured mass flow rate are also indicated.

Regardless of the nodalization used, RELAP5 overpredicted the discharge flow rate. Except for anomalous flow increases in the 0 node, and 9 node cases, the 0 node, 7 node, and 9 node cases yielded nearly the same flow rate. The 12 node calculation yielded a slightly better prediction of the measured flow rate.

The anomalous (and incorrect) increases in flow rate for the 0 node and the 7 node cases have been traced to an approximation made in the calculation of the internal energy at a junction experiencing choked flow. This is discussed further in section 5.

Figure 4-3 indicates that there is little incentive to nodalize discharge piping extensively in RELAP5. Computational costs rise rapidly as nodes are added in the nozzle region (due to the material Courant limit on time step size) yet little improvement is obtained in computed results.

The computed results shown in Figure 4-3 can be brought into fairly good agreement with the experimental results by application of a 0.83 multiplier. This suggests that when using RELAP5 for calculating the discharge of saturated steam through a nozzle having a well rounded entrance, a discharge coefficient of 0.83 should be applied.

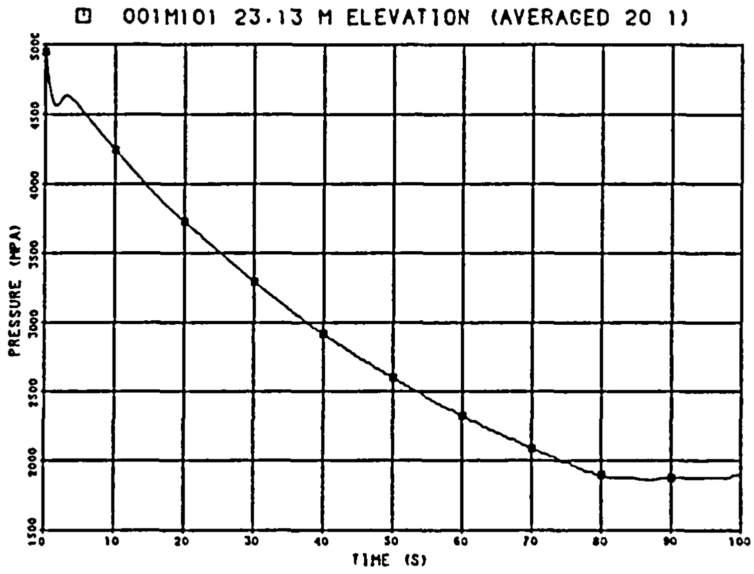

Figure 4-1

Measured vessel pressure for Marviken JIT 11.
RELAP5 boundary condition.

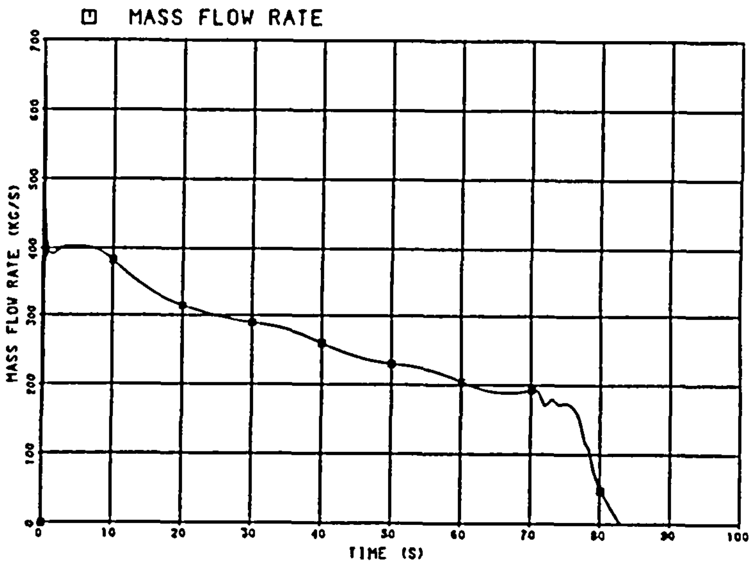

Figure 4-2

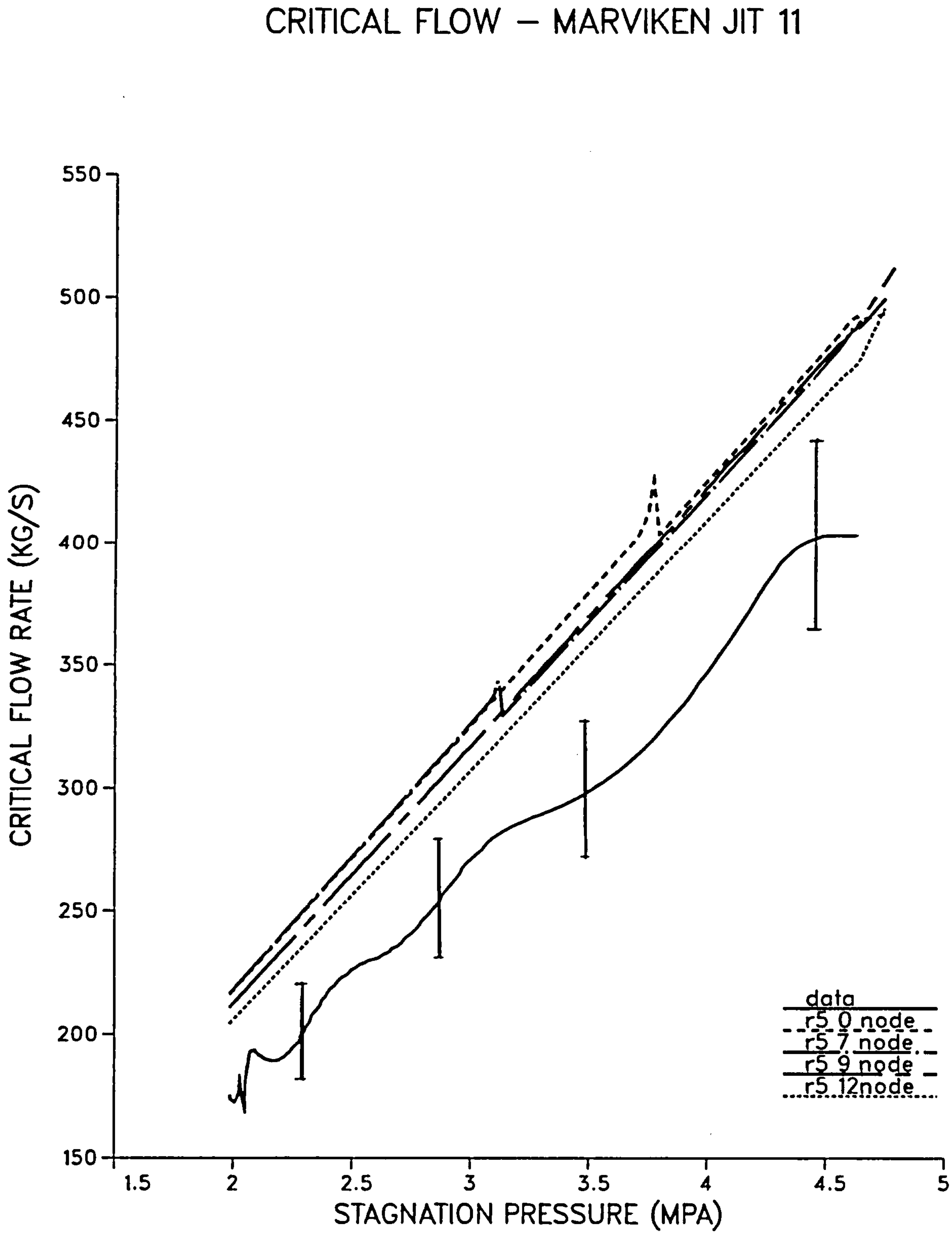

Figure 4-3

Critical flow of saturated steam.
RELAP5 simulations and JIT 11 data.

4.2 Subcooled critical flow - CFT 21

The subcooled critical flow model in RELAP5 was assessed against Marviken experiment CFT 21 by driving a RELAP5 model of the discharge piping with boundary conditions (pressure and temperature) measured near the inlet to the discharge piping. Calculated values of discharge flow rate, pressure drop across the discharge pipe inlet, and fluid quality in the discharge pipe were compared to measured values.

In CFT 21 the subcooled blowdown lasted for the first 25-30 seconds of the 60 second test period.

The pressure boundary condition used in RELAP5 was taken from pressure transducer 001M106 (Figure 4-4). The temperature boundary condition was taken as the average reading from thermocouples 001M521 and 001M402. These thermocouples are located at the 0.74 m elevation and 0.75 m from the vessel axis. The amount of subcooling (saturation temperature minus liquid temperature) in the boundary conditions is shown in Figure 4-5.

Figure 4-6 compares the RELAP5 base case (CFT01) calculated discharge flow rate history to the measured one. RELAP5 overpredicted the discharge flow rate. The gradual decline in the measured flow rate beginning at 22 s is associated with vapour formation in the discharge piping. Figure 4-7 shows the experimentally determined fluid quality in the discharge pipe based upon a gamma densitometer measurement. RELAP5 calculated only a brief period of two-phase flow in the discharge pipe. The calculated flow rate dropped sharply when bubbles were calculated to exist.

In Figure 4-8 the differential pressure from the discharge pipe to the vessel interior is shown. The calculated pressure loss across the discharge pipe inlet agrees well with the measured pressure loss. It is slightly larger than the measured loss but this may be the result of calculated velocities in the discharge pipe being higher than measured ones. The good agreement between calculated and measured pressure loss rules out pressure discrepancies in the discharge pipe as a cause of the flow rate discrepancies seen in Figure 4-6.

Rerunning the RELAP5 calculation and using a discharge coefficient of 0.85 (case CFT02) brought the calculated and measured flow rates into agreement for the first 22 seconds of the transient (Figure 4-9). For this RELAP5 calculation the pressure loss across the discharge pipe inlet was slightly less than the measured loss (Figure 4-10). The difference between the calculated and measured loss is probably due to no form loss coefficient being used in the RELAP5 model. A form loss coefficient of 0.15, if used in the RELAP5 model, would bring the calculated pressure loss into very good agreement with the measured loss.

The inability of RELAP5 to calculate the decline in flow rate after 22 s is due to the fact that RELAP5 calculated essentially no vapour formation in the discharge pipe. The experimental data indicate vapour formation beginning at 22 s.

One possible reason for the discrepancy between calculated and measured flow rates after 22 s is that the fluid temperature boundary condition used in RELAP5 is not a true measure of the temperature at the entrance to the discharge piping. The thermocouples whence the boundary condition is taken are 0.75 m from the vessel central axis. Moreover a radial temperature distribution did exist during the experiment (6).

In order to test the hypothesis that the RELAP5 overprediction of flow rate after 22 seconds was partly due to uncertainty in the boundary temperature, a RELAP5 simulation (case CFT03) was conducted in which the boundary fluid temperature was reduced 2K for t > 18s (the discharge coefficient was left at a value of 0.85). Two degrees Kelvin corresponds to the maximum error associated with the temperature measurements (the 1σ error is 0.6K) and is believed to be encompass the probable radial temperaure variation.

The good agreement between calculated and measured flow rates (Figure 4-11) which resulted when the boundary temperature was changed proved the hypothesis. The calculation ended at 26.7s when the boundary condition subcooling vanished.

4.2.1 Nodalization study

In the RELAP5 simulations discussed thus far the nozzle was not included in the model and a discharge coefficient of 0.85 was required to bring the calculated flow rate into agreement with the experimental flow rate. To explore the sensitivity of calculated results to nodalization a RELAP5 simulation (case CFT07) was performed in which the nozzle was modelled by one computational cell. It was thought that this simulation might yield computed flow rates which agreed with experimental ones without using any discharge coefficient. Choking was allowed only at the nozzle outlet for this simulation.

The results of the one-node-nozzle simulation are depicted in Figures 4-12 and 4-13.

The discharge mass flow was underpredicted by RELAP5 and the pressure in the nozzle was overpredicted. From these results one concludes that, if a complete description of the experimental geometry is included in the RELAP5 model a discharge coefficient greater than 1.0 is required to bring computed flow rates into agreement with measured ones.

The one-node-nozzle simulation was rerun (case CFT 08) using values of 1.09 and 1.13 for the subcooled and saturated critical flow coefficients. This simulation did not improve calculated discharge flow rate (Figure 4-14). The computed flow rate exhibited erratic behaviour generally associated with numerical problems and, indeed, this RELAP5 simulation was very inefficient, taking 2 947 time steps and repeating 1 416 time steps for the 30s transient. When no discharge coefficients were used the simulation required only 1 242 time steps and repeated 620.

4.3 Low quality critical flow - CFT 21

In order to study the RELAP5 critical flow model's response to low quality two phase flow the subcooled flow simulation which gave the best agreement with experimental data (case CFT 03) was restarted (at 26.7 s) and saturated boundary conditions were imposed at the discharge pipe inlet. The boundary condition pressure was taken from pressure transducer 001M106. The boundary condition fluid quality was calculated (6) based upon the gamma densitometer reading and the assumption of an adiabatic fluid expansion between the vessel bottom and the location of the densitometer in the discharge pipe. The boundary conditions as depicted in Figure 4-16 and 4-17.

The flow rate history from the saturated boundary condition base simulation (case CFT 04) is shown together with the measured flow rate in Figure 4-18. For completeness, the subcooled portion of the transient (case CFT 03) has also been included. The computed and measured mass flow rates agree well with one another. These results imply that RELAP needs no discharge coefficient when simulating low quality two phase critical flow through large pipes.

Subsequent to the CFT 04 simulation it was discovered that the experimental data offered conflicting indications of what the boundary condition fluid quality was during the 30 to 60 s time range. While the gamma densitometer indicated a fluid quality history as shown in Figure 4-17, the differential pressure measurement 007M246 indicated that the fluid quality never rose beyond 0.003. Thus, the rapid increase in quality occurring around 40 s may not have been real.

To explore the effect which the uncertainty in the boundary condition quality had upon computed results, the RELAP5 CFT 04 simulation was rerun with the boundary condition quality limited to a value of 0.003 (case CFT 05). This change only affected the condition for t > 35 seconds.

The flow rate calculated by case CFT 05 was higher than the measured flow rate (Fig 4-19). The results suggested that a two-phase discharge coefficient value simular to that used for the subcooled blowdown might be applicable. For t > 40 s the average value of the ratio of measured to calculated flow rate is 0.85.

RELAP5 simulation CFT 06 was a rerun of CFT 05 but utilized a two phase flow discharge coefficient of 0.85. It was thought that CFT 06 would give a flow rate wich was in much better (relative to CFT 05) agreement with the experimental data. In fact, this was not the case, as can be seen by comparing Figures 4-19 and 4-20. In spite of applying a discharge coefficient which should have reduced the calculated flow rate so that it fell upon or below the experimental data, the calculated flow rate remained greater than the measured flow rate. This result implied a feedback existed between the flow solution and the discharge coefficient - an unexpected feedback.

Having feedback between a critical flow discharge coefficient and the flow solution is undesirable because one wants to use discharge coefficients as free parameters - ones which can be used to reduce the discharge flow by a predictable amount.

In order to explain the feedback between the discharge coefficient and the flow solution a degression - a brief review of the mechanics of choking in RELAP5 - is needed.

The RELAP choking criterion is (Eq 333 of Ref 2)

$$\frac{\alpha_f \rho_f V_f + \alpha_g \rho_g V_g}{\alpha_f \rho_f + \alpha_g \rho_g} = C_D \, a_{HE} \qquad \text{(Eq 4-1)}$$

The discharge coefficient, C_D, is the two phase discharge coefficient (input by the user) whenever the void fraction, α_g, is greater than 0.02. Otherwise C_D is the subcooled discharge coefficient.

For subcooled choking the quantity a_{HE} is the maximum of the local homogeneous equilibrium (HE) sound speed and a speed calculated by applying Bernoulli's flow equation together with the Alamer-Lienhard-Jones correlation.

Detailed examination of the RELAP5 simulations CFT 05 and CFT 06 showed that the sonic velocity being used for subcooled flow calculations in JCHOKE was generally six to eight percent greater than that used for saturated calculations in JCHOKE.

Two-phase choking is applied if choking is indicated and the local void fraction is greater than 10^{-7} <u>and</u> the local <u>equilibrium</u> quality is greater than 2.5×10^{-4}. If these criteria are not met then single phase liquid choking is applied.

Underrelaxation is applied to the choked flow model velocities as long as the local equilibrium quality is less than 2.5×10^{-3} and the local void fraction is greater than 10^{-7}. For the cases being considered the underrelaxation was always applied. The underrelaxation algorithm ($V^{n+1} = 0.9\ V^{n} + 0.1\ V^{n+1}$) is heavily weighted to old time values. Thus, once a junction velocity is established a large change in velocity resulting from the solution of Eq 4-1 will not show up in the choked junction velocity unless the change persists for several time steps.

With the above points in mind one can return to the RELAP5 cases. The discharge junction velocities and void fractions from the RELAP5 simulations are illustrated in Figures 4-21 and 4-22. The discharge velocity was the same for cases CFT 04 and CFT 05 but the discharge void fraction was much larger after 40 s in case CFT 04. Thus the difference in discharge flow rate between case CFT04 and CFT05 can be attributed to a changing void fraction. On the other hand, the discharge void fraction was nearly the same for cases CFT05 and CFT06 but the discharge velocity was lower - but not 15 percent lower in case CFT06.

The reason the application of $C_D = 0.85$ did not reduce the discharge velocity by 15 % is contained in Figures 4-23 and 4-24. These figures illustrate the fluid equilibrium quality at the discharge junction. For completeness the static quality has also been plotted. Recall that the equilibrium quality value determines whether the saturated or subcooled critical flow model is active.

Comparing Figure 4-23 to Figure 4-24 one sees that when the discharge coefficient was applied, the equilibrium quality at the discharge junction was depressed - on the average, it remained less than 2.5×10^{-4} more time than it did when no discharge coefficient was used. Thus the choked flow velocities coming from the subcooled critical flow model played a stronger role (because of the under-relaxation algorithm, the model, subcooled or two phase, which is selected for most of the time steps dominates the calculation of the local junction velocity) in CFT06 compared to CFT05.

Because sonic velocities (a_{HE} in Eq 4-1) used in the subcooled critical flow logic were six to eight percent greater than those in the two-phase critical flow logic the longer time which case CFT 06 spent in the subcooled flow logic led to a value of a_{HE} which was greater than that seen in CFT 05, enough greater to offset half of the 15 % reduction represented by the discharge coefficient.

The above analysis has revealed why application of a discharge coefficient may not reduce computed flow rates in a predictable manner during low quality flow simulations. The next question to address is how the situation might be rectified.

The undesirable feedback could be eliminated by introducing logic into subroutine JCHOKE to ensure that the velocity a_{HE} used in the RELAP5 choking criterion is continuous at the interface between the subcooled choking model and the two-phase flow choking model.

The feedback could also probably be eliminated by eliminating the erratic behavior of the equilibrium quality evident in Figures 4-21 and 4-22 or else having the critical flow model selection logic depend more upon static rather than equilibrium quality. Since the erratic behaviour of the equilibrium quality is undoubtably of numerical origin, it would appear to be a likely candidate for improvement.

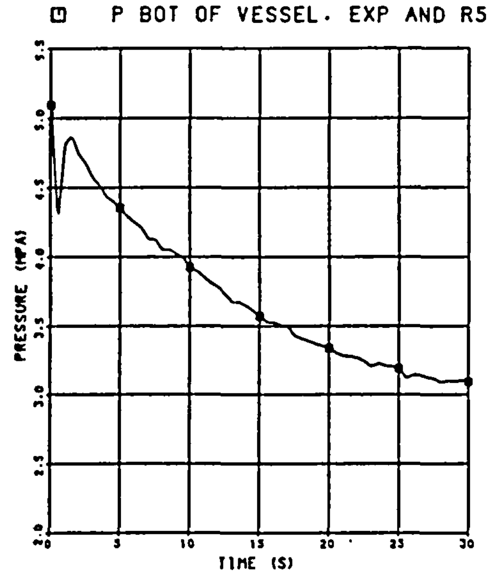

Figure 4-4

Pressure Boundary Condition for Case CFT 01.

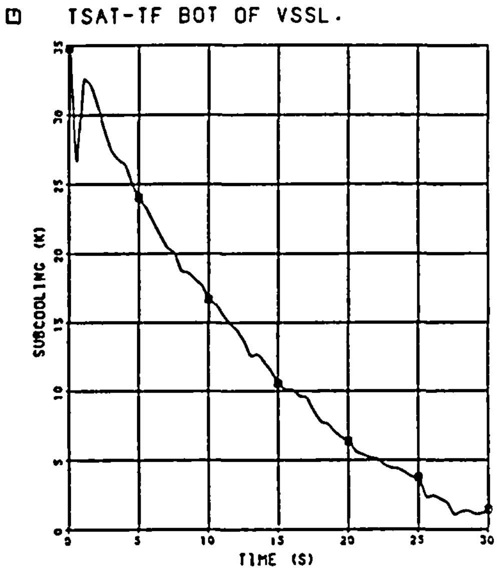

Figure 4-5

Subcooling Boundary Condition for Case CFT 01.

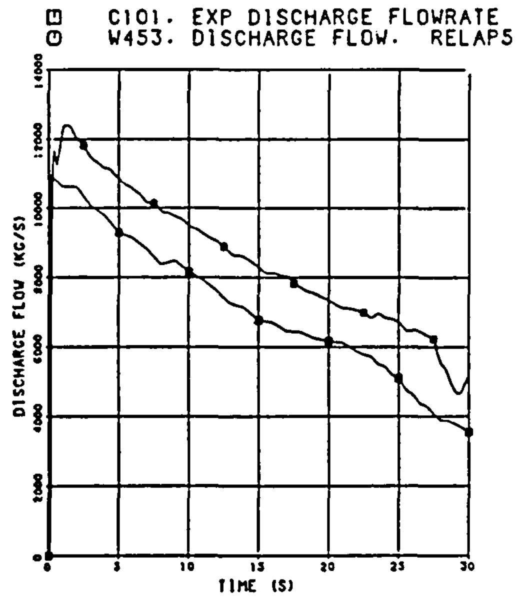

Figure 4-6

Discharge Flow Rate. Measured and Case CFT 01.

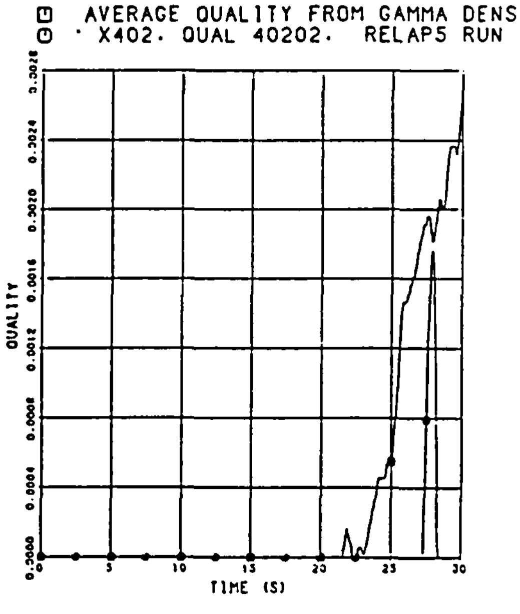

Figure 4-7

Fluid Quality in the Discharge Pipe.

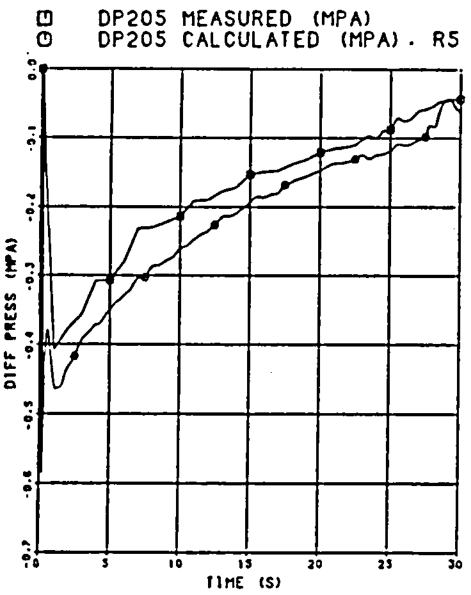

Figure 4-8

dP Across the Vessel Outlet. Measured and Case CFT 01.

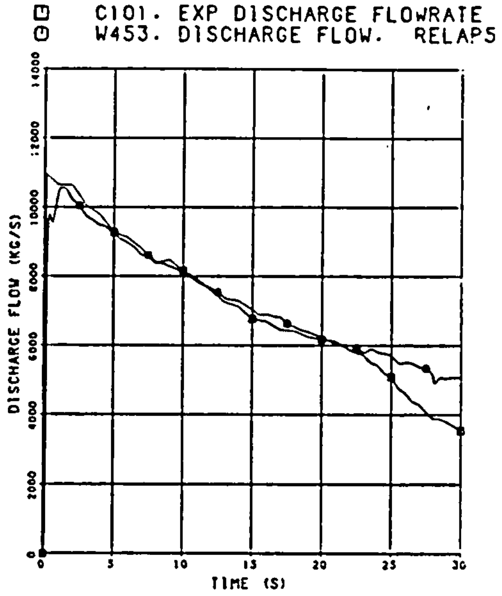

Figure 4-9

Discharge Flow Rate. Measured and Case CFT 02.

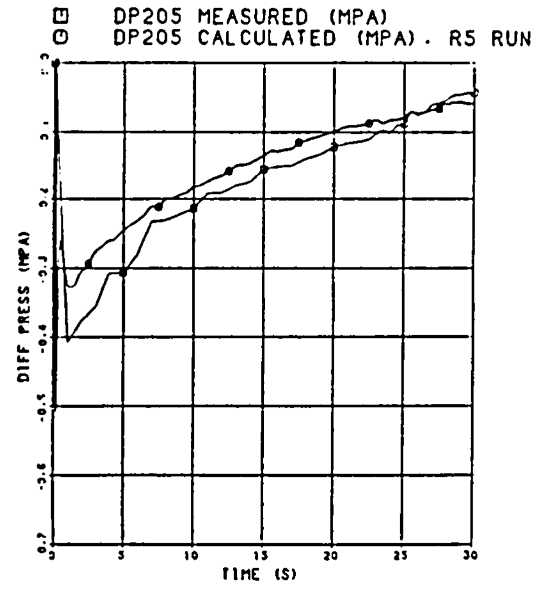

Figure 4-10

dP Across the Vessel Outlet. Measured and Case CFT 02.

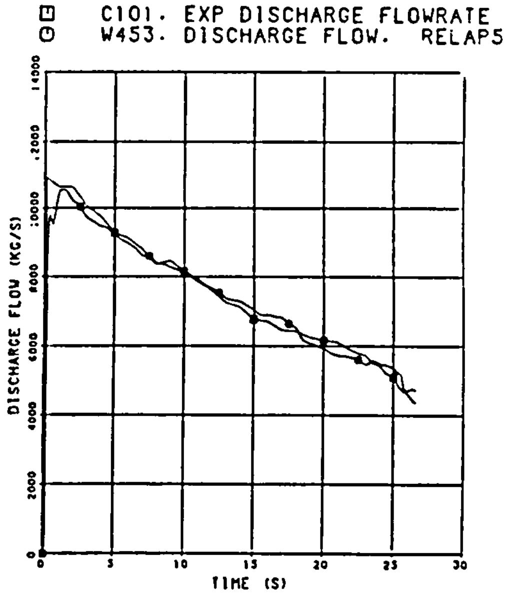

Figure 4-11

Discharge Flow Rate. Measured and Case CFT 03.

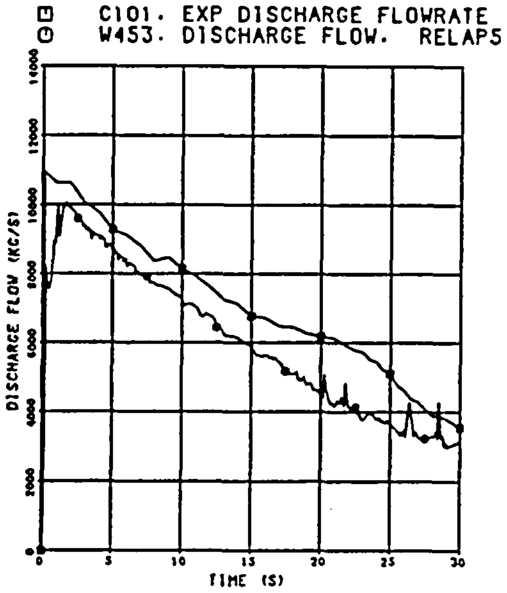

Figure 4-12

Measured and Calculated (Case CFT 07) Discharge Flow Rate.

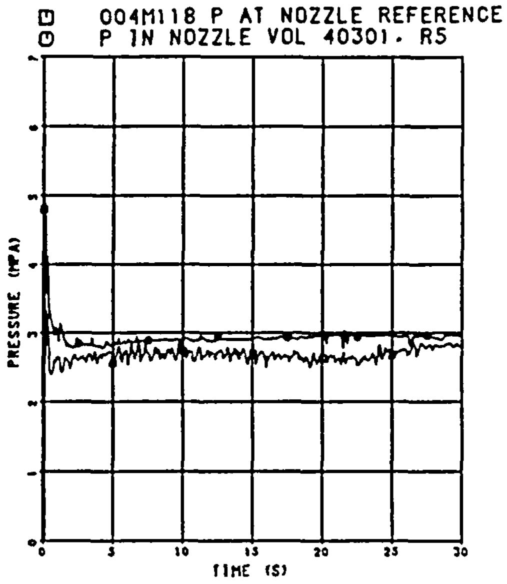

Figure 4-13

Measured and Calculated (CFT 07) Pressure in the Nozzle.

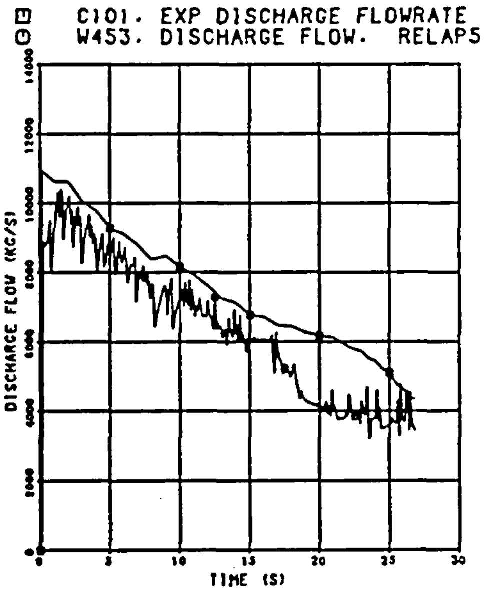

Figure 4-14

Measured and Calculated (CFT 08) Discharge Flow Rate.

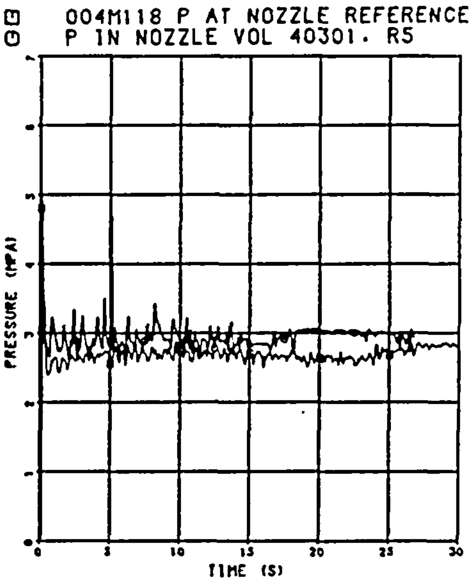

Figure 4-15

Measured and Calculated (CFT 08) Pressure in the Nozzle.

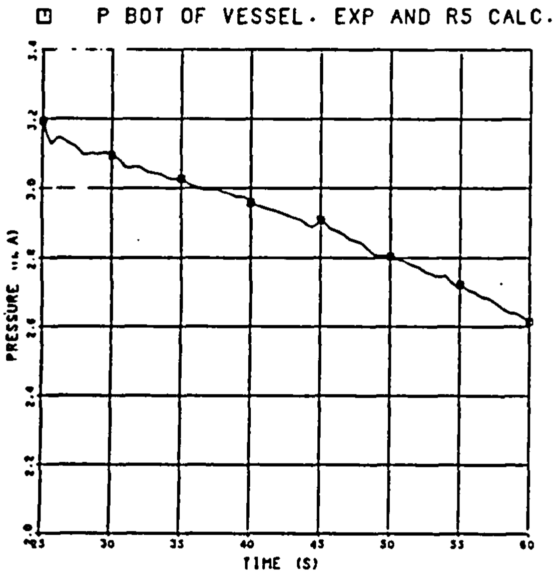

Figure 4-16

Pressure Boundary Condition of Saturated Flow Simulations.

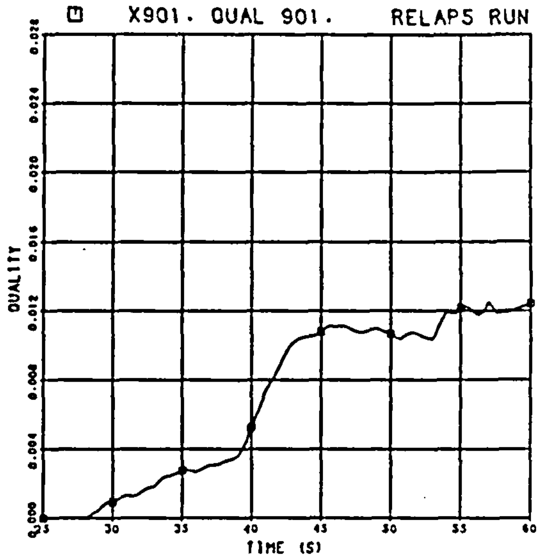

Figure 4-17

Fluid Quality Boundary Condition for Saturated Flow simulations.

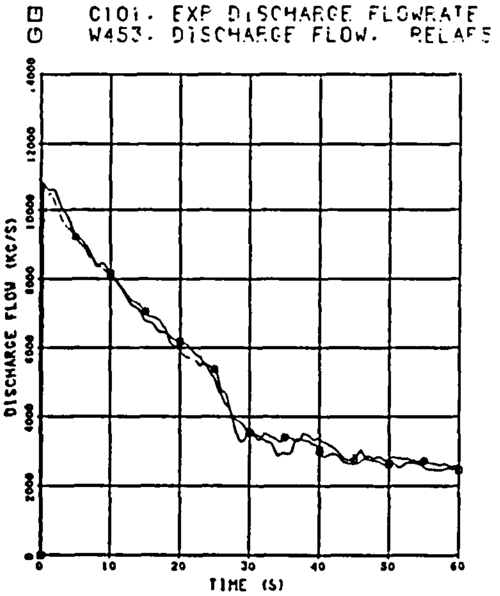

Figure 4-18

Discharge Flow Rate. Measured and Calculated (CFT 03 + CFT 04).

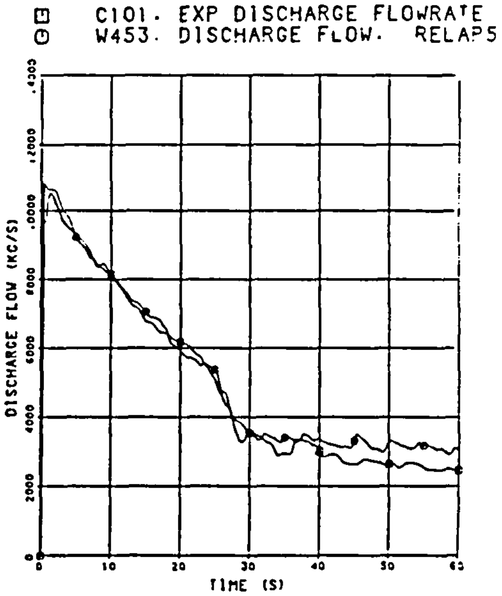

Figure 4-19

Discharge Flow Rate. Measured and Calculated (CFT 03 + CFT 05).

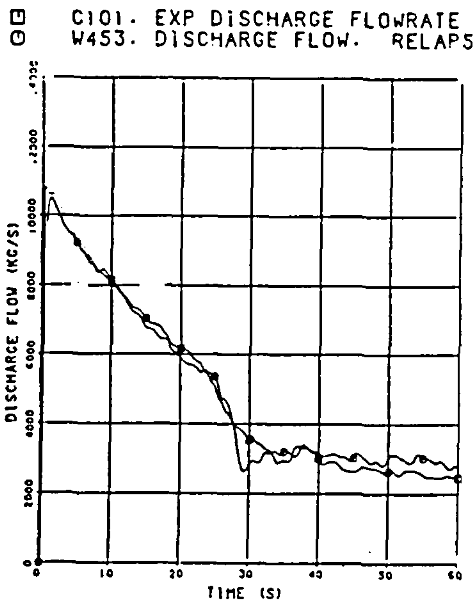

Figure 4-20

Discharge Flow Rate. Measured and Calculated (CFT 03 + CFT 06).

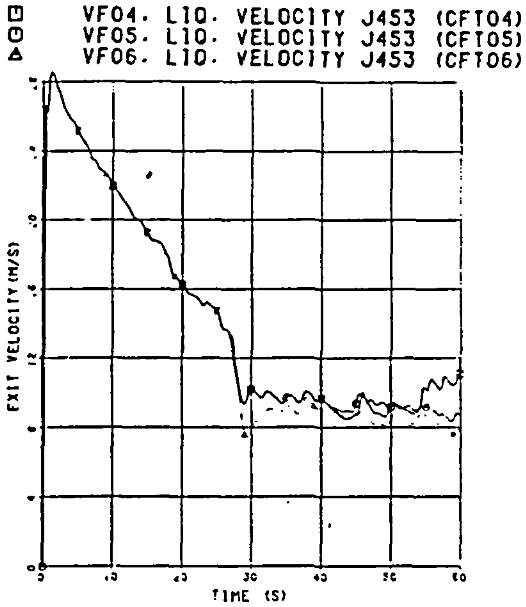

Figure 4-21

Liquid Velocity at the Discharge Junction. RELAP5 Cases CFT 04, CFT 05 and CFT 06.

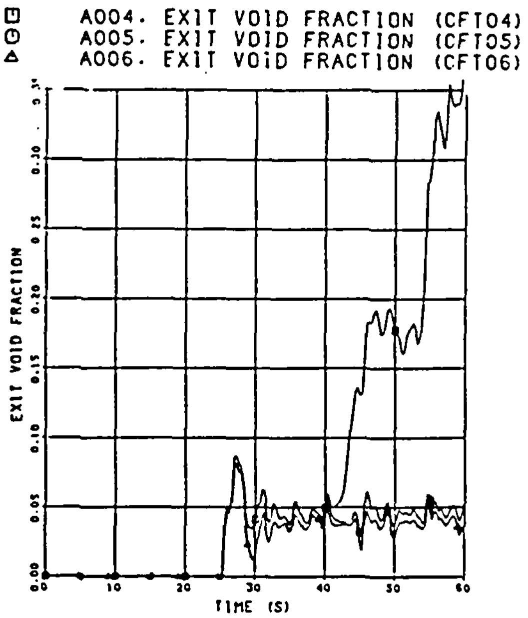

Figure 4-22

Void Fraction at the Discharge Junction. RELAP5 Cases CFT 04, CFT 05 and CFT 06.

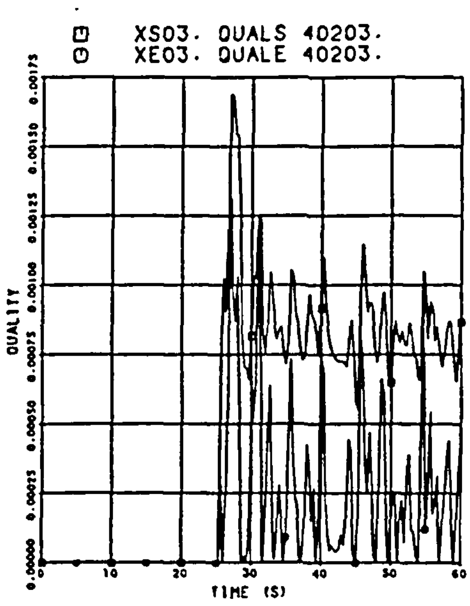

Figure 4-23

Static and Equilibrium Quality at the Discharge Junction. Case CFT 05.

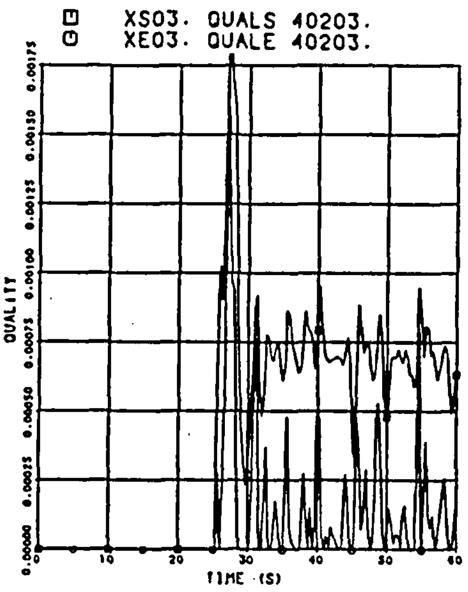

Figure 4-24

Static and Equilibrium Quality at the Discharge Junction. Case CFT 06.

5 COMPUTATIONAL EFFICIENCY AND NUMERICAL PROBLEMS

The computational efficiency of the RELAP5 simulations are summarized in Tables 5-1 and 5-2. The simulations were conducted on a CYBER 180-810 computer.

The simulations of JIT 11 were limited by the material Courant limit except for the case in which the standpipe and discharge pipe were not included in the model. Simulation times increased dramatically when the nozzle was introducted into the model (9 mode and 12 mode simulations). Considering the similarity of computed results amongst the various simulations it is apparent that including the nozzle in the RELAP5 model was not cost effective.

The simulations of CFT 21 proceeded at the maximum allowed time step size when the saturated portion of the test was being simulated (CFT 04, CFT 05, CFT 06). For the simulations of the subcooled portion of the test the time step size was restricted to 0.05 s for the first 15 s due to the material Courant limit. Simulations CFT 07 and CFT 08 in which the nozzle was modeled proceeded quite slowly and had to repeat a large number (about 50 % of the total shown in the table) of time steps.

Table 5-1

Run Statistic For The JIT 11 Simulations.

Case	DT Max	Actual time steps	CPU (s)	CPU/Cell/ Step
0 Node	0.001 (t < 0.01) 0.01 (0.01 < t < 0.5) 0.10 (0.5 < t < 75.)	808	43.	0.05
7 Node	0.001 (t < 0.01) 0.01 (0.01 < t < 0.5) 0.10 (0.5 < t < 75.)	1 552	296.	0.03
9 Node	0.001 (t < 0.01) 0.01 (t > 0.01)	60 002	13 995.	0.03
12 Node	0.001 (t < 0.01) 0.01 (t > 0.01)	239 969	70 481.	0.02

Table 5-2

Run Statistics for the CFT 21 Simulations.

Case	Transient	DT Max	Actual time steps	CPU (s)	CPU/Cell/ Step
CFT01	0 - 30 s	0.1	481	60.	0.04
CFT02	0 - 30 s	0.1	419	47.	0.04
CFT03	0 - 26.7 s	0.1	386	42.	0.04
CFT04	26.7 - 60 s	0.1	334	36.	0.04
CFT05	26.7 - 60 s	0.1	334	37.	0.04
CFT06	26.7 - 60 s	0.1	334	37.	0.04
CFT07	0 - 30 s	0.1	1 242	211.	0.06
CFT08	0 - 30 s	0.1	2 947	484.	0.05

5.1 Critical Flow Model numerical problems

Two of the RELAP5 simulations of JIT11 exhibited nonphysical jumps (see Figure 4-1). An investigation showed that the jumps occurred because the thermodynamic state at the discharge junction was calculated to switch from two phase to single phase vapor. Physically the junction should have remained in a two-phase state throughout the transient.

It was discovered that the erroneous thermodynamic state was calculated because of the approximation being used to find the internal energy at a choked junction (subroutine JCHOKE).

Assuming a quasi-steady, adiabatic flow, the internal energy at a junction may be calculated from (j = junction; up = upstream):

$$e_j = e_{up} + \frac{P_{up}}{\rho_{up}} - \frac{P_j}{\rho_j} - \frac{V_{up}^2 - V_j^2}{2}$$

In RELAP5, the term P_j/ρ_j is replaced by P_j/ρ_{up}. This approximation can result in an e_j value corresponding to vapor when the true value would correspond to two-phase. Because the sound speed (determined from (P_j, e_j)) is discontinous at the two phase/vapor interface a jump in the calculated choked flow velocity occurs when the approximation for P_j/ρ_j leads to an incorrect value of e_j.

6 CONCLUSIONS

1. RELAP5 critical flow model overpredicts the critical flow of saturated steam. For the JIT 11 simulations the calculated critical flow could be brought into agreement with the measured flow by applying a discharge coefficient of 0.82.

2. Computed results for JIT 11 were not substantially improved by modeling the nozzle. Considering the empirical nature of the RELAP5 choked flow model it is concluded that there is no benefit in modeling discharge piping having L/D < 4 when steam is being discharged.

3. An approximation made in the calculation of junction internal energy in subroutine JCHOKE is responsible for nonphysical jumps in computed discharge mass flow rate evident in two of the JIT 11 simulations.

4. RELAP5 overpredicted the subcooled critical mass flow rate for CFT 21 when the nozzle was not explicitly modeled. Calculated mass flow rates could be made to agree with measured ones by using a discharge coefficient of 0.85 in RELAP5.

5. When the nozzle geometry was explicitly modeled in RELAP5 mass flow rates for CFT 21 were underpredicted. Application of discharge cofeficients (greater than unity) did not improve computed results; on the contrary, doing so gave rise to a very numerically noisy solution. It is concluded that short discharge nozzles or pipes (L/D < 2) should not be modeled explicitly in RELAP5.

6. For the saturated blowdown portion of CFT 21 RELAP5 simulated the discharge flow quite accurately when the bounding condition fluid quality was based upon the gamma densitometer measurement. No discharge coefficient was needed to achieve agreement with the experimental data.

7. When the fluid quality boundary condition was lowered (based upon vessel differential pressure measurements) RELAP5 overpredicted the discharge flow rate.

8. The RELAP5 simulation of the discharge of low quality two-phase fluid did not respond in a predictable manner when discharge coefficients were applied. It was determined that a feedback exists for low quality flow such that application of a discharge coefficient may increase the value of the sonic velocity used in the choking criterion (Eq 4-1) partially offsetting the sonic velocity reduction represented by the discharge coefficient. Application of a discharge coefficient of say, 0.85, will reduce computed flow by only 7 or 8 percent instead of the 15 percent one might expect.

REFERENCES

1. TRAC-PF1/MOD1:
   An Advanced Best-Estimate Computer Program for Pressurized Water Reactor Thermal-Hydraulic Analysis.
   NUREG/CR-3858.

2. RANSOM, V et al.
   RELAP5/MOD2 Code Manual.
   NUREG/CR-4312.
   August 1985.

3. The Marviken Full Scale Jet Impingement Tests. Facility Description.
   MXD-101.
   February 1982.

4. The Marviken Full Scale Critical Flow Tests. Description of the Test Facility.
   MXC-101.

5. The Marviken Full Scale Jet Impingement Tests. Test 11 Results.
   MXD-211.
   March 1982.

6. The Marviken Full Scale Critical Flow Tests. Results from Test 21.
   MXC-221.
   September 1979.

7. The Marviken Full Scale Critical Flow Tests. Summary Report.
   MXC-301.
   December 1979.

APPENDIX A

INPUT FOR RELAP5 FOR JIT 11 SIMULATION

```
*  CRITICAL FLOW TEST MARVIKEN TEST 11
*  HIGH QUALITY STEAM.
*
*  INPUT PREPARED BY \STEN ROSDAHL
*                     STUDSVIK ENERGITEKNIK AB,SWEDEN
*
*
0000100   NEW  STDY-ST
0000101   RUN
0000102   SI   SI
0000105   30.       40.
*
*           REF VOL     LEVEL   FLUID
0000120     200010000   18.33   WATER   MARVIKEN
*
***** TIME STEP CONTROL CARDS
*          END-TIME  DTMIN     DTMAX     OPT      MINOR   MAJOR  RESTART
0000201     0.01     1.0-6     .001     00003        1     100      200
0000202     0.5      1.0-6     .01      00003        5     100      200
*0000203    10.0      1.0-6     .01      00003       50    1000     1000
*0000204    75.0      1.0-6     .01      00003       50    1000     1000
0000203    10.0      1.0-6     .1       00003       50    1000     1000
*
***** MINOR EDIT REQUESTS
301    MFLOWJ   450000000
302    MFLOWJ   451000000
303    MFLOWJ   452000000
304    MFLOWJ   453000000
*
***** TRIP INPUT DATA
0000501   TIME     0          GT  NULL     0     10000.0   L  *
*
*
*
*****   HYDRAULIC COMPONENTS
*
*=====================================
*
2000000  VESSEL      SNGLVOL                    * 18.330 TO  18.830
4010000  STPIPE      PIPE                       * 18.330 TO   0.330
4020000  DCPIPE      PIPE                       *  0.330 TO  -7.599
4030000  NOZZLE      PIPE                       * -7.599 TO  -8.779
9010000  P-CONST     TMDPVOL
9020000  ATMOS       TMDPVOL
*
*
*   JUNCTIONS
*
2510000  VESSFILL     SNGLJUN
4500000  STAND-IN     SNGLJUN
4510000  DISCH-IN     SNGLJUN
```

```
4520000  NOZZ-IN      SNGLJUN
4530000  NOZZ-OUT     VALVE
*
*
*****  COMPONENT INFORMATION CARDS
4010001  4
4020001  3
4030001  2
*
*****  SNGLVOL, BRANCH AND TMDPVOL GEOMETRY CARDS
*
*        AREA LENGTH VOLUME  HA  VANG ELEVCH  ROUGH   DIAH    FE
2000101 0.   0.5  10.79     0.   90.  0.5     0.     .0      00
9010101 20.  1.    0.       0.  -90.   .000  20.-6  .0      00
9020101 0.   1.    1.       0.  -90.   .000  20.-6  .0      00
*
*****  PIPE AND ANNULUS GEOMETRY CARDS
*
*          VOLAREA   NR
4010101  0.7854      4                        * D = 1.000
4020101  0.4441      3                        * D = 0.752
4030101  0.07022     2                        * D = 0.299
*
*          LENGTH    NR
4010301  4.5         4                        * 18.000/4
4020301  2.643       3                        *  7.929/3
4030301  0.59        2                        *  1.180/2
*
*          VOLUME    NR
4010401  0.00000     4
4020401  0.00000     3
4030401  0.00000     2
*
*          VANG      NR
4010601  -90.        4
4020601  -90.        3
4030601  -90.        2
*
*          ROUGH     DIAH      NR
4010801  20.E-6    0.0         4
4020801  20.E-6    0.0         3
4030801  20.E-6    0.0         2
*
***  PIPE JUNCTION LOSS COEFFICIENTS
*         FORWARD  REVERSE  NR
4010901     0.00     0.00   3
4020901     0.00     0.00   2
4030901     0.00     0.00   1
*          FE         NR
4011001    00         4
4021001    00         3
4031001    00         2
*
*****  PIPE JUNCTION CONTROL FLAGS
*          CAHS     NR
4011101    0000     3
4021101    0000     2
4031101    0000     1
*
*****  SNGLJUN, VALVE AND TMDPJUN GEOMETRY CARDS.
```

```
*          FROM        TO           JUNAREA    FJUNF  FJUNR    CAHS
2510101  901000000  200010000  0.         0.0    0.0      0000
4500101  200000000  401000000  0.         0.0    0.0      0100
4510101  401010000  402000000  0.         0.0    0.0      0000
4520101  402010000  403000000  0.         0.0    0.0      0000
4530101  403010000  902000000  0.         0.0    0.0      0100
*
*****  SNGLVOL AND PIPE VOLUME INITIAL CONDITIONS
*
*          CW     PRESSURE    QUAL                            NR
2000200     2     5.0000E6   1.00
4011201     2     5.0000E6   1.00        0.    0.    0.       4
4021201     2     5.0000E6   1.00        0.    0.    0.       3
4031201     2     5.0000E6   1.00        0.    0.    0.       2
*
*****  TMDPVOL DATA CONTROL CARD
*          CW    TRIP    ALPHA     NUM
9010200     2    501
9020200     2
*****  TMDPVOL DATA CARD
*            TIME          PRESS     QUAL
9010201     0.000         4981900.  1.000
9010202      .100         4927880.  1.000
9010203      .200         4866110.  1.000
9010204      .300         4829747.  1.000
9010205      .400         4794753.  1.000
9010206      .500         4747376.  1.000
9010207      .600         4718367.  1.000
9010208      .700         4691854.  1.000
9010209      .800         4657311.  1.000
9010210      .900         4637825.  1.000
9010211     1.000         4613516.  1.000
9010212     1.100         4600787.  1.000
9010213     1.200         4589881.  1.000
9010214     1.300         4575948.  1.000
9010215     1.400         4569016.  1.000
9010216     1.500         4565032.  1.000
9010217     1.600         4563218.  1.000
9010218     1.700         4563401.  1.000
9010219     1.800         4567248.  1.000
9010220     1.900         4572064.  1.000
9010221     2.000         4576934.  1.000
9010222     2.100         4584592.  1.000
9010223     2.200         4591024.  1.000
9010224     2.300         4600115.  1.000
9010225     2.400         4606497.  1.000
9010226     2.500         4613723.  1.000
9010227     2.600         4620684.  1.000
9010228     2.700         4623998.  1.000
9010229     2.800         4628821.  1.000
9010230     2.900         4634576.  1.000
9010231     3.000         4635503.  1.000
9010232     3.100         4636305.  1.000
9010233     3.200         4636456.  1.000
9010234     3.300         4635035.  1.000
9010235     3.400         4630834.  1.000
9010236     3.500         4626632.  1.000
9010237     3.600         4622737.  1.000
9010238     3.700         4619639.  1.000
```

```
9010239    3.800          4616288.  1.000
9010240    3.900          4608276.  1.000
9010241    4.000          4603496.  1.000
9010242    5.000          4550326.  1.000
9010243    6.000          4483077.  1.000
9010244    7.000          4427020.  1.000
9010245    8.000          4362641.  1.000
9010246    9.000          4303644.  1.000
9010247   10.000          4248200.  1.000
9010248   11.000          4189435.  1.000
9010249   12.000          4132475.  1.000
9010250   13.000          4075548.  1.000
9010251   14.000          4020970.  1.000
9010252   15.000          3963155.  1.000
9010253   16.000          3918553.  1.000
9010254   18.000          3815226.  1.000
9010255   20.000          3727483.  1.000
9010256   22.000          3643477.  1.000
9010257   24.000          3556808.  1.000
9010258   26.000          3469451.  1.000
9010259   28.000          3381221.  1.000
9010260   30.000          3299092.  1.000
9010261   32.000          3218463.  1.000
9010262   34.000          3133862.  1.000
9010263   36.000          3058316.  1.000
9010264   38.000          2985187.  1.000
9010265   40.000          2921124.  1.000
9010266   42.000          2853242.  1.000
9010267   44.000          2784410.  1.000
9010268   46.000          2717872.  1.000
9010269   48.000          2663770.  1.000
9010270   50.000          2601918.  1.000
9010271   52.000          2538747.  1.000
9010272   54.000          2490818.  1.000
9010273   56.000          2430753.  1.000
9010274   58.000          2372546.  1.000
9010275   60.000          2326299.  1.000
9010276   62.000          2283809.  1.000
9010277   64.000          2223326.  1.000
9010278   66.000          2178751.  1.000
9010279   68.000          2135757.  1.000
9010280   70.000          2092031.  1.000
9010281   72.000          2050116.  1.000
9010282   74.000          2008471.  1.000
9010283   76.000          1965180.  1.000
9010284   78.000          1922647.  1.000
9010285   80.000          1901403.  1.000
9010286   82.000          1880158.  1.000
9010287   84.000          1880158.  1.000
9010288   85.000          1876141.  1.000
9010289   86.000          1868512.  1.000
9010290   87.000          1865495.  1.000
9010291   88.000          1872848.  1.000
9010292   89.000          1879907.  1.000
9010293   90.000          1880158.  1.000
9010294   95.000          1880158.  1.000
*
9020201   0.      0.100E6       1.
*
*****  SNGLJUN AND VALVE INITIAL CONDITION CARD
```

```
2510201    1        0.0       0.        0.
4500201    1        0.0       0.        0.
4510201    1        0.0       0.        0.
4520201    1        0.0       0.        0.
4530201    1        0.0       0.        0.
*
*****  PIPE JUNCTION CONDITIONS CONTROL CARD
4011300    1
4021300    1
4031300    1
*
*****  PIPE AND BRANCH JUNCTION INITIAL CONDITION CARD
4011301     0.0       0.        0.      3
4021301     0.0       0.        0.      2
4031301     0.0       0.        0.      1
*
*****  VALVE TYPE CARD
4530300     TRPVLV
*
*****  VALVE DATA
4530301   501
*
.
```

APPENDIX B

LISTING OF INPUT DATA FOR CASE CFT01

```
=  MARVIKEN CFT 21. SUBCOLD CRIT FLOW. P,T BC AT VSL BOT.
*
*
0000100   NEW  TRANSNT
0000101   RUN
0000102   SI   SI
0000105   30.        40.
*
*
***** TIME STEP CONTROL CARDS
*         END-TIME  DTMIN     DTMAX     OPT     MINOR    MAJOR  RESTART
0000201   30.00     1.0-6     .100     00003        1       50       50
*
***** MINOR EDIT REQUESTS
301         P   901010000
303   CNTRLVAR 105      * RATIO  (MEAS FLOW / CALC FLOW)
304  CNTRLVAR  110   *  QUAL  RING II EXP
305   QUALE  402020000   * CALC QUAL RING II
306  CNTRLVAR  122   * DP205  CALC-EXP
307  CNTRLVAR  130   * T - TSAT IN VOL 901
*
***** TRIP INPUT DATA
0000501   TIME     0          GT  NULL     0     0.0   L  *
0000502   CNTRLVAR   130    GE  NULL     0      -0.1   L  *
*
*     STOP SUBCOOLED TRANSIENT WHEN T-TSAT GT -0.1K
*
600   502
*
*
*
*****  HYDRAULIC COMPONENTS
*
*=====================================
*
4020000  DCPIPE      PIPE                      * -0.690 TO  -5.570
*4030000  NOZZLE      PIPE                      * -5.570 TO  -6.565
9010000  P-T(BC)     TMDPVOL
9020000  ATMOS       TMDPVOL
*
*
*   JUNCTIONS
*
4510000  DISCH-IN     SNGLJUN
*4520000  NOZZ-IN      SNGLJUN
4530000  NOZZ-OUT     VALVE
*
*
*****  COMPONENT INFORMATION CARDS
4020001  3
```

```
*4030001  5
*
*****  SNGLVOL, BRANCH AND TMDPVOL GEOMETRY CARDS
*
*        AREA LENGTH VOLUME  HA  VANG ELEVCH  ROUGH   DIAH    FE
9010101 19.6  0.5  0.0   0.  -90.   .000  20.-6  .0        00
9020101 0.   1.    1.       0.  -90.   .000  20.-6  .0        00
*
*****  PIPE AND ANNULUS GEOMETRY CARDS
*
*          VOLAREA   NR
4020101  0.4441      3                        * D = 0.752
*4030101  0.07022     5                        * D = 0.299
*
*          LENGTH    NR
4020301  2.100       3                        *  6.3  /3
*4030301  0.236       5                        *  1.180/5
*
*          VOLUME    NR
4020401  0.00000     3
*4030401  0.00000     5
*
*          VANG      NR
4020601  -90.        3
*4030601  -90.        5
*
*          ROUGH     DIAH      NR
4020801  20.E-6    0.0         3
*4030801  20.E-6    0.0         5
*
***  PIPE JUNCTION LOSS COEFFICIENTS
*        FORWARD  REVERSE  NR
4020901     0.00     0.00   2
*4030901     0.00     0.00   4
*          FE          NR
4021001   00          3
*4031001   00          5
*
*****  PIPE JUNCTION CONTROL FLAGS
*          CAHS      NR
4021101   0000      2
*4031101   0000      4
*
*****  SNGLJUN, VALVE AND TMDPJUN GEOMETRY CARDS
*
*        FROM        TO           JUNAREA   FJUNF  FJUNR    CAHS
4510101  901000000  402000000  0.          0.0    0.0      0000
*4520101  402010000  403000000  0.          0.0    0.0      0000
4530101  402010000  902000000  0.1963    0.0    0.0      0100
*
*****  SNGLVOL AND PIPE VOLUME INITIAL CONDITIONS
*
*          CW     PRESSURE    QUAL                            NR
4021201    3     4.2131E6   508.54     0.   0.   0.       3
*4031201    2     5.0000E6   1.00       0.   0.   0.       5
*
*****  TMDPVOL DATA CONTROL CARD
*          CW    TRIP    ALPHA     NUM
*
*********  CFT21 PRESSURE AND TEMPERATURE AT BOTTOM OF VESSEL  *****
```

```
***** PRESSURE FROM 001M106.   TEMP FROM AVG OF 001M521 AND 001M402
*
9010200  3  501
9010201    .00  .509680E+07  503.46
9010202    .50  .425960E+07  501.31
9010203   1.00  .481560E+07  502.01
9010204   1.50  .487560E+07  503.31
9010205   2.00  .474530E+07  503.11
9010206   2.50  .467900E+07  504.01
9010207   3.00  .457190E+07  504.11
9010208   3.50  .451670E+07  504.01
9010209   4.00  .443460E+07  503.21
9010210   4.50  .439870E+07  504.21
9010211   5.00  .435300E+07  504.61
9010212   5.50  .429500E+07  504.46
9010213   6.00  .425320E+07  504.86
9010214   6.50  .421590E+07  505.31
9010215   7.00  .413030E+07  505.01
9010216   7.50  .412930E+07  505.26
9010217   8.00  .405310E+07  505.56
9010218   8.50  .405760E+07  505.71
9010219   9.00  .402270E+07  505.71
9010220   9.50  .399420E+07  505.71
9010221  10.00  .391990E+07  505.71
9010222  10.50  .390030E+07  505.71
9010223  11.00  .385400E+07  505.76
9010224  11.50  .381230E+07  505.71
9010225  12.00  .378470E+07  505.71
9010226  12.50  .373310E+07  505.71
9010227  13.00  .367460E+07  506.01
9010228  13.50  .367360E+07  505.76
9010229  14.00  .364710E+07  505.96
9010230  14.50  .361170E+07  506.06
9010231  15.00  .357140E+07  506.36
9010232  15.50  .353010E+07  506.06
9010233  16.00  .352910E+07  506.01
9010234  16.50  .350600E+07  506.16
9010235  17.00  .350400E+07  506.16
9010236  17.50  .343420E+07  506.01
9010237  18.00  .340910E+07  506.41
9010238  18.50  .339340E+07  506.26
9010239  19.00  .337180E+07  506.51
9010240  19.50  .335560E+07  506.66
9010241  20.00  .333930E+07  506.66
9010242  20.50  .330200E+07  506.76
9010243  21.00  .328360E+07  506.66
9010244  21.50  .327840E+07  506.76
9010245  22.00  .326950E+07  506.66
9010246  22.50  .324540E+07  506.71
9010247  23.00  .320660E+07  506.26
9010248  23.50  .323270E+07  506.76
9010249  24.00  .321400E+07  506.71
9010250  24.50  .320710E+07  506.96
9010251  25.00  .319280E+07  506.71
9010252  25.50  .312160E+07  506.96
9010253  26.00  .314810E+07  507.21
9010254  26.50  .314610E+07  507.46
9010255  27.00  .312890E+07  507.41
9010256  27.50  .311980E+07  508.16
9010257  28.00  .308910E+07  507.31
```

```
9010258 28.50  .310730E+07  507.56
9010259 29.00  .309650E+07  507.66
9010260 29.50  .310880E+07  507.81
9010261 30.00  .309500E+07  507.26
*
*
*
9020200  2
9020201   0.      0.100E6        1.
*
*****  SNGLJUN AND VALVE INITIAL CONDITION CARD
4510201    1        0.0       0.        0.
*4520201    1        0.0       0.        0.
4530201    1        0.0       0.        0.
*
*****  PIPE JUNCTION CONDITIONS CONTROL CARD
4021300    1
*4031300    1
*
*****  PIPE AND BRANCH JUNCTION INITIAL CONDITION CARD
4021301     0.0      0.        0.      2
*4031301     0.0      0.        0.      4
*
*****  VALVE TYPE CARD
4530300     TRPVLV
*
*****  VALVE DATA
4530301   501
*
*
*        CONTROL COMPONENT 101, EXPERIMENTAL MASSFLOW
20510100   NOZZFLOW-X   FUNCTION   1.   0.  0
20510101   TIME   0   801
*
*        CONTROL COMPONENT 102, CALC - EXP CRITICAL FLOW
20510200   FLOWERR      SUM        1.   0.  0
20510201   0.    1.   MFLOWJ    453000000
20510202        -1.   CNTRLVAR  101
*
*        CONTROL COMPONENT 103, REL.ERR. OF CRITICAL FLOW
20510300   CF-REL-ERR   DIV       100.   0.  0
20510301   CNTRLVAR  101      CNTRLVAR  102
*
*        CONTROL COMPONENT 104, COMPUTED MASSFLOW
20510400   NOZZFLOW-C   SUM       1.   0.0001  0
20510401   0.0001   1.   MFLOWJ    453000000
*
*        CONTROL COMPONENT 105, RATIO
20510500   CF-RATIO     DIV        1.   1.  0
20510501   CNTRLVAR  104      CNTRLVAR  101
*
*        GENERAL TABLE USED BY CONTROL COMPONENT 101
*      MASS FLOW FROM CFT 21 ( FROM FILE T21EVAL, VARNAM=FAVE)
*
*         GENERAL TABLE 801.  MEASURED DISCHARGE FLOW RATE  (FAVE)
*
20280100   REAC-T
20280101    .00 11000.00
20280102  1.00 10634.00
20280103  2.00 10632.00
```

231	20280104	3.00	10063.00
232	20280105	4.00	9791.20
233	20280106	5.00	9281.40
234	20280107	6.00	9125.90
235	20280108	7.00	8815.60
236	20280109	8.00	8377.10
237	20280110	9.00	8493.10
238	20280111	10.00	8162.90
239	20280112	11.00	7937.20
240	20280113	12.00	7622.30
241	20280114	13.00	7262.10
242	20280115	14.00	7138.30
243	20280116	15.00	6771.10
244	20280117	16.00	6718.70
245	20280118	17.00	6468.00
246	20280119	18.00	6439.30
247	20280120	19.00	6261.30
248	20280121	20.00	6175.60
249	20280122	21.00	6127.90
250	20280123	22.00	5880.20
251	20280124	22.50	5789.90
252	20280125	23.00	5737.50
253	20280126	23.50	5519.70
254	20280127	24.00	5443.80
255	20280128	24.50	5212.50
256	20280129	25.00	5106.70
257	20280130	25.50	4774.20
258	20280131	26.00	4632.10
259	20280132	26.50	4381.10
260	20280133	27.00	4299.60
261	20280134	27.50	4075.40
262	20280135	28.00	3887.80
263	20280136	28.50	3896.40
264	20280137	29.00	3800.80
265	20280138	29.50	3685.00
266	20280139	30.00	3555.90
267	20280140	30.50	3652.90
268	20280141	31.00	3450.10
269	20280142	31.50	3450.00
270	20280143	32.00	3359.50
271	20280144	32.50	3253.00
272	20280145	33.00	3272.70
273	20280146	33.50	3133.70
274	20280147	34.00	2832.30
275	20280148	34.50	2926.90
276	20280149	35.00	3005.70
277	20280150	35.50	2900.70
278	20280151	36.00	2962.60
279	20280152	36.50	3359.50
280	20280153	37.00	3373.30
281	20280154	37.50	3381.90
282	20280155	38.00	3297.10
283	20280156	38.50	3338.60
284	20280157	39.00	3204.70
285	20280158	39.50	3251.80
286	20280159	40.50	2812.30
287	20280160	41.50	2940.70
288	20280161	42.50	2936.30
289	20280162	43.50	2694.00
290	20280163	44.50	2646.10

```
20280164 45.50  2634.00
20280165 46.50  2823.30
20280166 47.50  2745.90
20280167 48.50  2728.10
20280168 49.50  2604.40
20280169 50.50  2715.10
20280170 51.50  2500.30
20280171 52.50  2695.40
20280172 53.50  2692.30
20280173 54.50  2634.60
20280174 55.50  2481.00
20280175 56.50  2491.70
20280176 57.50  2458.00
20280177 58.50  2542.70
20280178 59.50  2467.70
*
*   CONTROL COMPONENT 110.  EXPERIMENTAL CALCULATED QUAL AT RING II
20511000  X-RINGII  FUNCTION  1.  0.  0
20511001   TIME  0  803
*
*
*  GENERAL TABLE 803.   QUALITY AT RING II   (XGAV)
20280300  REAC-T
20280301   .00  .00000
20280302  1.00  .00000
20280303  2.00  .00000
20280304  3.00  .00000
20280305  4.00  .00000
20280306  5.00  .00000
20280307  6.00  .00000
20280308  7.00  .00000
20280309  8.00  .00000
20280310  9.00  .00000
20280311 10.00  .00000
20280312 11.00  .00000
20280313 12.00  .00000
20280314 13.00  .00000
20280315 14.00  .00000
20280316 15.00  .00000
20280317 16.00  .00000
20280318 17.00  .00000
20280319 18.00  .00000
20280320 19.00  .00000
20280321 20.00  .00000
20280322 21.00  .00000
20280323 22.00  .00013
20280324 22.50  .00000
20280325 23.00  .00005
20280326 23.50  .00016
20280327 24.00  .00037
20280328 24.50  .00046
20280329 25.00  .00055
20280330 25.50  .00099
20280331 26.00  .00147
20280332 26.50  .00161
20280333 27.00  .00176
20280334 27.50  .00193
20280335 28.00  .00182
20280336 28.50  .00206
20280337 29.00  .00223
```

```
20280338 29.50  .00237
20280339 30.00  .00263
20280340 30.50  .00237
20280341 31.00  .00247
20280342 31.50  .00262
20280343 32.00  .00267
20280344 32.50  .00282
20280345 33.00  .00316
20280346 33.50  .00348
20280347 34.00  .00365
20280348 34.50  .00377
20280349 35.00  .00400
20280350 35.50  .00381
20280351 36.00  .00416
20280352 36.50  .00430
20280353 37.00  .00445
20280354 37.50  .00443
20280355 38.00  .00468
20280356 38.50  .00473
20280357 39.00  .00474
20280358 39.50  .00605
20280359 40.50  .00793
20280360 41.50  .00979
20280361 42.50  .01141
20280362 43.50  .01181
20280363 44.50  .01193
20280364 45.50  .01251
20280365 46.50  .01245
20280366 47.50  .01217
20280367 48.50  .01228
20280368 49.50  .01205
20280369 50.50  .01175
20280370 51.50  .01213
20280371 52.50  .01152
20280372 53.50  .01274
20280373 54.50  .01293
20280374 55.50  .01364
20280375 56.50  .01369
20280376 57.50  .01316
20280377 58.50  .01347
20280378 59.50  .01358
*
*
*    CONTROL COMPONENT 120.  EXPERMENTAL DP205.  RINGI TO VESL BOT
*
20512000   DP205MEAS   FUNCTION  1.  0.  0
20512001   TIME  0  802
*
*    CONTROL COMPONENT 121.  CALC DP 205.
20512100   DP205CALC  SUM  1.  0.  0
20512101   0.   1.   P   402020000
20512102        -1.   P   901010000
*
*
*     CONTROL COMPONENT 122.  CALC MINUS MEAS DP205
20512200   DIFFDP205  SUM  1.  0.  0
20512201   0.   1.  CNTRLVAR  121
20512202        -1.  CNTRLVAR  120
*
*
```

```
*     GENERAL TABLE 802.  DP205 (RING1 TO VESSEL BOTTOM)  001M205
*
20280200   REAC-T
20280201   .00  .596140E+04
20280202  1.00 -.407560E+06
20280203  2.00 -.376360E+06
20280204  3.00 -.355610E+06
20280205  4.00 -.306570E+06
20280206  5.00 -.305870E+06
20280207  6.00 -.279860E+06
20280208  7.00 -.231390E+06
20280209  8.00 -.229750E+06
20280210  9.00 -.221960E+06
20280211 10.00 -.213740E+06
20280212 11.00 -.190830E+06
20280213 12.00 -.189630E+06
20280214 13.00 -.177610E+06
20280215 14.00 -.172230E+06
20280216 15.00 -.153120E+06
20280217 16.00 -.148750E+06
20280218 17.00 -.147300E+06
20280219 18.00 -.137490E+06
20280220 19.00 -.131160E+06
20280221 20.00 -.120660E+06
20280222 21.00 -.115030E+06
20280223 22.00 -.112490E+05
20280224 22.50 -.109900E+06
20280225 23.00 -.102120E+06
20280226 23.50 -.962950E+05
20280227 24.00 -.101420E+06
20280228 24.50 -.891450E+05
20280229 25.00 -.876260E+05
20280230 25.50 -.697820E+05
20280231 26.00 -.759200E+05
20280232 26.50 -.711110E+05
20280233 27.00 -.602270E+05
20280234 27.50 -.581390E+05
20280235 28.00 -.540890E+05
20280236 28.50 -.465590E+05
20280237 29.00 -.457360E+05
20280238 29.50 -.432690E+05
20280239 30.00 -.427620E+05
20280240 30.50 -.383330E+05
20280241 31.00 -.404840E+05
20280242 31.50 -.368140E+05
20280243 32.00 -.399780E+05
20280244 32.50 -.350430E+05
20280245 33.00 -.327650E+05
20280246 33.50 -.342200E+05
20280247 34.00 -.364350E+05
20280248 34.50 -.379530E+05
20280249 35.00 -.356750E+05
20280250 35.50 -.360550E+05
20280251 36.00 -.358020E+05
20280252 36.50 -.381430E+05
20280253 37.00 -.378270E+05
20280254 37.50 -.372570E+05
20280255 38.00 -.376370E+05
20280256 38.50 -.375100E+05
20280257 39.00 -.378270E+05
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20280258 39.50 -.361820E+05
20280259 40.50 -.393450E+05
20280260 41.50 -.377000E+05
20280261 42.50 -.370040E+05
20280262 43.50 -.363080E+05
20280263 44.50 -.353590E+05
20280264 45.50 -.355490E+05
20280265 46.50 -.345360E+05
20280266 47.50 -.364350E+05
20280267 48.50 -.373210E+05
20280268 49.50 -.365610E+05
20280269 50.50 -.355490E+05
20280270 51.50 -.349160E+05
20280271 52.50 -.343460E+05
20280272 53.50 -.340300E+05
20280273 54.50 -.347260E+05
20280274 55.50 -.346630E+05
20280275 56.50 -.367510E+05
20280276 57.50 -.341570E+05
20280277 58.50 -.320050E+05
20280278 59.50 -.319420E+05
*   CONTROL COMP 130.   T901-TSAT901
*     USE THIS CONTROL VARIABLE TO END SUBCOOLED B.C TRANSIENT
20513000    T-TSAT901  SUM  1.  -34.  1
20513001   0.   1.   TEMPF   901010000
20513002        -1.  SATTEMP  901010000
*
.
```

APPENDIX C

LISTING OF INPUT DATA FOR CASE CFT04

```
*
=  MARVIKEN CFT 21. SAT CRIT FLOW. P,X BC AT VSL BOT.
*  R88TARMEOFGCFT818( SUBCOOLED RUN WITH CD=0.85, AND T901 INCRESED 2K
*
*
*
0000100   RESTART  TRANSNT
0000101   RUN
0000102   SI   SI
103   387
0000105   30.        40.
*
*
***** TIME STEP CONTROL CARDS
*            END-TIME  DTMIN      DTMAX     OPT     MINOR   MAJOR  RESTART
2000201 6030.00  1.E+50-6 0.1 .020 00008003      315     1800     1800
*
***** MINOR EDIT REQUESTS
301         P   901010000
303   CNTRLVAR 105      * RATIO  (MEAS FLOW / CALC FLOW)
304  CNTRLVAR  110   *  QUAL  RING II EXP
305   QUALE  402020000   * CALC QUAL RING II
306  CNTRLVAR  122   * DP205  CALC-EXP
*
***** TRIP INPUT DATA
0000502   TIME          0    GE  NULL     0      60.0   L  *
*
*  INPUT P,X BC AT VOL 901.
9010000  P-X(BC)   TMDPVOL
9010101  19.6  0.5  0.0  0.  -90.  0.000  20.-6  0.  00
*
*
*
***********  CFT 21  PRESSURE AND QUALITY AT BOTTOM OF VESSEL  ****
*       P FROM 001M106    X FROM XVGB
*
*
***********  CFT 21  PRESSURE AND QUALITY AT BOTTOM OF VESSEL  ****
*       P FROM 001M106    X FROM XVGB
*
9010200  2  501
9010201  0.0   3.13406E6  0.0
9010202 25.00  .313406E+07  .00000
9010203 25.50  .313406E+07  .00000
9010204 26.00  .313406E+07  .00000
9010205 26.50  .313406E+07  .00000
9010206 27.00  .312890E+07  .00000
9010207 27.50  .311980E+07  .00000
9010208 28.00  .308910E+07  .00000
9010209 28.50  .310730E+07  .00028
9010210 29.00  .309650E+07  .00046
```

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 56    9010211 29.50  .310880E+07  .00096
 57    9010212 30.00  .309500E+07  .00095
 58    9010213 30.50  .308760E+07  .00118
 59    9010214 31.00  .305270E+07  .00140
 60    9010215 31.50  .306430E+07  .00122
 61    9010216 32.00  .306350E+07  .00151
 62    9010217 32.50  .304710E+07  .00179
 63    9010218 33.00  .304440E+07  .00183
 64    9010219 33.50  .304190E+07  .00238
 65    9010220 34.00  .302770E+07  .00245
 66    9010221 34.50  .302620E+07  .00259
 67    9010222 35.00  .303010E+07  .00282
 68    9010223 35.50  .301040E+07  .00277
 69    9010224 36.00  .300600E+07  .00267
 70    9010225 36.50  .299620E+07  .00290
 71    9010226 37.00  .299570E+07  .00316
 72    9010227 37.50  .300060E+07  .00304
 73    9010228 38.00  .298830E+07  .00332
 74    9010229 38.50  .298640E+07  .00340
 75    9010230 39.00  .297460E+07  .00359
 76    9010231 39.50  .298190E+07  .00423
 77    9010232 40.00  .295440E+07  .00543
 78    9010233 40.50  .295190E+07  .00628
 79    9010234 41.00  .294410E+07  .00747
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 82    9010237 42.50  .292540E+07  .00975
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 99    9010254 51.00  .279070E+07  .01062
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112    9010267 57.50  .267070E+07  .01181
113    9010268 58.00  .265550E+07  .01195
114    9010269 58.50  .263880E+07  .01193
115    9010270 59.00  .264170E+07  .01217
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116     9010271 59.50  .262850E+07  .01226
117     9010272 60.00  .261370E+07  .01245
118     .
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13. ABSTRACT *(200 words or less)*

RELAP5/MOD2 simulations of the critical flow of saturated steam are reported together with simulations of the critical flow of subcooled liquid and low-quality two-phase mixture. The experiments which were simulated used nozzle diameters of 0.3 m and 0.5 m. RELAP5 overpredicted the experimental flow rates by 10 to 25 percent unless discharge coefficients were applied.

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SEPTEMBER 1986