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International Agreement Report

Review and Summary of TRAC Assessment from the International Code Assessment and Application Program (ICAP)

Prepared by
N. M. Schnurr

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Office of Nuclear Regulatory Research
U.S. Nuclear Regulatory Commission
Washington, DC 20555

April 1992

Prepared as part of
The Agreement on Research Participation and Technical Exchange
under the International Thermal-Hydraulic Code Assessment
and Application Program (ICAP)

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ABSTRACT

TRAC-PF1/MOD1 has been exercised by several international users as a part of the ICAP Program. Participants are requested to prepare a report summarizing the results of their work. These assessment reports contain discussions of the code accuracy, errors and deficiencies, new user guidelines, and recommendations for code upgrades and modifications.

CONTENTS

LIST OF FIGURES

FIGURE PAGE

LIST OF TABLES

TABLE PAGE

ACRONYMS

AEEW	Atomic Energy Establishment at Winfrith, United Kingdom
ANS	American Nuclear Society
CCFL	Countercurrent-flow limitation
CEGB	Central Electricity Generating Board, United Kingdom
CERL	Central Electricity Research Laboratories, UK
CHF	Critical heat flux
COBRA-TF	Coolant boiling in rod arrays, the two-fluid version
ECC	Emergency core cooling or coolant
ECCS	Emergency core cooling system
HPIS	High-pressure injection system
HTC	Heat-transfer coefficient
ICAP	International Code Assessment and Applications Program
INEL	Idaho National Engineering Laboratory
ISM	Interface-sharpener model
LANL	Los Alamos National Laboratory
LBLOCA	Large-break loss-of-coolant accident
LOBI	LWR Off-Normal Behavior Investigation
LOCA	Loss-of-coolant accident
LOFT	Loss-of-Fluid Test, a PWR experiment facility at INEL
LPIS	Low-pressure injection system
LWR	Light-water reactor
OECD	Organization for Economic Cooperation and Development
QOBV	Quick-opening break valve
PWR	Pressurized water reactor
RELAP5	Reactor Leak and Power Safety Excursion code, the fifth major version of the code
SBLOCA	Small-break loss-of-coolant accident
SETS	Stability-enhancing two-step numerical technique
TRAC	Transient Reactor Analysis Code
USNRC	US Nuclear Regulatory Commission

1. INTRODUCTION

The Office of Nuclear Regulatory Research, United States Nuclear Regulatory Commission (USNRC) has sponsored the development of the Transient Reactor Analysis Code (TRAC) at Los Alamos National Laboratory (LANL) for the past several years. TRAC is an advanced best-estimate systems code for analyzing transients in thermal-hydraulic systems. It performs best-estimate analyses of loss-of-coolant accidents (LOCAs) and other transients in pressurized light-water reactors and of thermal-hydraulic experiments in reduced-scale facilities. The TRAC code has been under development since 1976, when the first version was developed. Since that time it has evolved through a number of versions until TRAC-PF1/MOD1 (Ref. 1) was released in 1984. The major part of the developmental effort was completed with the release of TRAC-PF1/MOD2 in June 1990 (Ref. 2).

An important part of the code development has been assessments of the code. These assessments, both internal and external, are necessary to ensure the adequacy, accuracy, and applicability of the code in performing the safety analyses for which it was intended. As part of the assessment activities of TRAC and other thermal-hydraulic safety analysis codes, the USNRC organized an international cooperative effort to exercise the codes and compare calculated results with experimental data. These assessment studies were undertaken based on a mutual agreement between the USNRC and participating countries and are part of an overall assessment plan organized by the USNRC. The formal title of this program is the International Code Assessment and Applications Program (ICAP). The intent of the program (Ref. 3) is to

- support the efforts of the USNRC to determine the ability of the code to represent important physical phenomena appropriately and support the quantitative determination of code accuracy,
- share user experience on code assessment and to present a well-documented data base,
- share experience on code errors and inadequacies and cooperate in removing the deficiencies to maintain a single, internationally recognized code version, and
- establish and improve user guidelines for applying the code

TRAC-PF1/MOD1 has been exercised by several international users as a part of the ICAP program. The code has been used to simulate several different test facilities in which a variety of different reactor-safety-related tests were performed. Code predictions were compared with the data obtained from these tests. Participants are requested to prepare a report summarizing the results of their work. These assessment reports should contain discussions of the code accuracy, errors and deficiencies, new user guidelines, and recommendations for code upgrades and modifications.

The Engineering and Safety Analysis Group (N-6) at LANL also is involved in the ICAP effort. A portion of the Los Alamos contribution to this program is the review of TRAC assessment reports prepared by external participants. Twenty-five assessment reports have been received in the past two years. Eight of these assessments were reviewed during FY 1989 (Ref. 4). The remaining 17 reports have been reviewed during FY 1990 and are summarized in this report. The following assessments were reviewed this year:

- K. H. Ardron and A. J. Clare, "Assessment of Interface Drag Correlations in the RELAP5/MOD2 and TRAC-PF1/MOD1 Codes," GD/PE-N/557 (March 1987).
- F. Pelayo, "TRAC-PF1/MOD1 Post-Test Calculations of the OECD-LOFT Experiment LP-SB-2," ICSP-LP-SB-2-T, AEEW-R 2002 (April 1987).
- C. G. Richards, "Pre-Test Calculation of LOBI Test BL-02 Using TRAC-PF1/MOD1," AEEW-M 2416 (February 1987).
- J. C. Birchley, P. Coddington, and C. R. Gill, "Analysis of LOFT Experiment LP-02-6 Using the TRAC-PF1/MOD1 Computer Code," AEEW-R 2288 (November 1987).
- R. O'Mahoney, "A Study of the Reflood Characteristics of TRAC-PF1/MOD1," AEEW-M 2305 (April 1986).
- J. Blanco, V. Lopez Montero, and J. Rivero, "Analysis of LOFT Experiment LP-02-6 Using TRAC-PF1/MOD1," ICSP-LP-02-06 (January 1988).
- F. J. Barbero, "TRAC-PF1 Code Assessment Using OECD-LOFT LP-FP-1 Experiment," ICSP-LP-FP-1 (July 1988).

- B. Spindler and M. Pellissier, "Assessment of TRAC-PF1/MOD1 Version 14.3 Using Components Separate Effects Experiments," SETh/LEML/89-165 (March 1989).
- W. M. Dempster, A. M. Bradford, T. M. S. Callender, and H. C. Simpson, "An Assessment of TRAC-PF1/MOD1 Using Strathclyde 1/10 Scale Model Refill Tests," Strathclyde-SB291, Phase 1.
- D. M. Turner, "Discretization Effects in TRAC-PF1/MOD1 on the Prediction of Low Subcooling Counter Current Flow in a PWR Downcomer," CEGB report no. RD/L/3455/R89 (February 1989).
- P. Coddington, "OECD-LOFT LP-LB-1 Comparison Report," AEEW-R 2478 (February 1989).
- P. Coddington, "Analysis of the Blowdown of the Accumulator B Line in the OECD-LOFT Fission Product Experiment LP-FP-1," AEEW-R 2328 (February 1988).
- R. O'Mahoney, "A Study of Axial Effects in the TRAC-PF1/MOD1 Heat Conduction Solution During Quenching," AEEW-M 2552 (June 1989).
- A. Sjoberg, "Assessment of TRAC-PF1/MOD1 Against an Inadvertent Feedwater Line Isolation Transient in the Ringhals 4 Power Plant," STUDSVIK/NP-88/101 (S) (November 1988).
- F. Pelayo and A. Sjoberg, "Assessment of TRAC-PF1/MOD1 Against an Inadvertent Steam Line Isolation Valve Closure in the Ringhals 2 Power Plant," ICSP-R2MSIV-T (February 1988).
- R. O'Mahoney, "Time Step and Mesh Size Dependencies in the Heat Conduction Solution of a Semi-Implicit, Finite Difference Scheme for Transient Two-Phase Flow," AEEW-M 2590 (July 1989).
- W. M. Dempster, "An Assessment of TRAC-PF1/MOD1 Using Strathclyde 1/10 Scale Model Refill Tests, 2nd Report," submitted to CERL, Phase 2 of Contract RK: 1642 Job No. SB291, Strathclyde-SB291, Phase 2 (July 1989).

Some of these reports do not meet all of the requirements of an assessment as defined by Ref. 3. The Ardron and Clare work (GD/PE-N/557), for example, did not use the TRAC code directly but used an auxiliary code to test some of the correlations used in TRAC. The Coddington report (AEEW-R 2478) is a comparison study of several different reactor analysis codes. Nevertheless, all of the reports listed above provide valuable information concerning the strengths and weaknesses of TRAC-PF1/MOD1 and are therefore included in this summary report.

Each of the reports has been reviewed using the guidelines of Ref. 3. These reviews serve not only to identify the key findings of the assessment and ensure feedback to code developers but also to assess the degree to which ICAP guidelines are adhered to by international users. Complete reviews of the 17 ICAP assessment reports are included in the appendix to this report.

This report summarizes the results of the ICAP assessment report reviews. Brief summaries of the ICAP reports are presented. Any deficiencies or errors in TRAC identified by the assessment report authors are summarized. Suggested code improvements and new user guidelines are listed.

2. TRAC-ICAP ASSESSMENT MATRIX STATUS

TRAC is an advanced best-estimate computer code for analyzing transients in thermal-hydraulic systems. Its primary use is the simulation of transients in pressurized water reactor (PWR) power plants. The value of the code is determined by the accuracy of these simulations and the practicality of performing them. Assessments performed by ICAP members help to evaluate both the accuracy and computational efficiency of the code.

Because of the complexity of PWR systems and the large number of different accident scenarios, there are many different thermal and hydraulic phenomena that may occur. The goal of a code assessment program is to test the ability of the code to simulate all of the important phenomena accurately. A completely comprehensive assessment may not be practical. The approach taken in the ICAP program has been to give highest priority to the phenomena judged to be of greatest importance because of the severity of their effect on plant safety or their probability of occurrence. Several of these phenomena have been been identified in Ref. 3 and are listed in Table I. Also included in Table I are the numbers of ICAP assessment reports reviewed during the past two years that have addressed each of these phenomena. This table constitutes the TRAC assessment matrix.

The key parameters dealt with in ICAP reports are listed in Table II. It should be noted that most of the important phenomena have been simulated, and several of the most important, such as emergency core cooling (ECC) bypass and penetration, break-flow rates, and core heat transfer, have been addressed in several assessment reports.

In several cases, the ICAP code users found areas in which the results of their simulations did not agree well with experimental data. In some of these cases, they provided specific suggestions for improving the code. The following list summarizes the phenomenological areas where improvements were suggested in the 1990 assessment reports.

- Interphase drag
- Condensation models
- Heat structure and reflood models
- Horizontal pipe offtake model
- Minimum film-boiling temperature correlation
- Interface-sharpener logic
- Conservative discretization of the momentum equation

TABLE I
TRAC ASSESSMENT MATRIX

PWR Phenomena	ICAP Assessments 1989	 1990
Break flow and valve-leak flow	6	10
Phase separation in T-junction and effect on break flow	1	2
Liquid-inventory distribution	2	5
Phase separation	2	3
Mixing and condensation during ECC injection		5
ECC bypass and penetration	2	7
Steam binding		
Core-wide void and flow distribution	5	5
Entrainment and deentrainment in core		3
Entrainment and deentrainment in upper plenum		2
CCFL at upper tie plate and pool formation in upper plenum		
Mixture level in core	2	6
Mixture level in downcomer	2	5
Core heat transfer including partially covered core	5	11
Quench-front propagation	4	9
Single-phase natural circulation	1	1
Two-phase natural circulation	1	
Natural circulation through vent valves		
Stratification in horizontal pipes	4	2
Reflux-condenser mode and CCFL		1
Boiler-condenser mode		
Noncondensable-gas effects		3
Asymmetric-loop behavior		3
Loop-seal clearance	1	1
Primary-side steam-generator heat transfer	1	3
Secondary-side steam-generator heat transfer	1	3
Mixture level and entrainment in steam generator	1	3

TABLE I (cont.)

PWR Phenomena	ICAP Assessments 1989	 1990
One- and two-phase pump behavior	1	2
Pressurizer thermal hydraulics	1	3
Surge line hydraulics		
Refill of loops	1	1
Thermal-hydraulic nuclear feedback	1	1
Boron mixing and transport		
Separator hydraulics		

TABLE II
KEY PARAMETERS

Core temperature	Fuel surface, cladding
Liquid temperature	Hot and cold legs, break flows, lower plenum, downcomer
Pressure	Primary side, secondary side, hot and cold leg, upper plenum, pressurizer
Pressure difference	Pump, steam generator, vessel, intact and broken loops
Fluid density	Hot and cold leg, break line, pump inlet and outlet
Void fraction	Hot and cold legs
Fluid velocity	Hot and cold leg, downcomer, core inlet and outlet, break line

TABLE II (cont.)

Momentum flux	Hot and cold leg
Mass-flow rate	Break, bypass, accumulator, LPIS, HPIS, main feedwater, auxiliary feedwater, hot and cold legs
Mass inventory	Primary system, downcomer, lower plenum
Liquid level	Accumulator, steam generator, pressurizer
Time of event	Control signals, trips, maximum clad temperature during blowdown and reflood, loop-seal clearing, ECC initiation, pressurizer empty
Miscellaneous	Condensation rate, pump speed, core power

The authors of the ICAP reports have proposed several new user guidelines, and other guidelines can be inferred from discussions in the reports. These guidelines will be helpful to both new and experienced TRAC users. They are discussed in detail in Chap. 6.

The ICAP TRAC assessment reports have contributed significantly to the development of the code. They have helped to identify weak areas in the code and have led to to several corrections and improvements in the latest version of the code, TRAC-PF1/MOD2. Some of the user guidelines have been included in the latest version of the TRAC User's guide.

3. BRIEF SUMMARIES OF ASSESSMENT REPORTS

The following discussions briefly summarize each of the 17 ICAP reports reviewed. This chapter is organized into the broad categories of integral and separate-effects assessments. The integral assessments are subdivided into large-break loss-of-coolant accidents (LBLOCA), small-break loss-of-coolant accidents (SBLOCA), and transients. The separate-effects assessments are subdivided into countercurrent flow, condensation during ECC injection, U-tubes in steam generators, and fuel-rod heat transfer.

3.1. Integral Assessments

All five of the LBLOCA integral assessments were based on tests conducted in the Loss-of-Fluid Test (LOFT) Facility at the Idaho National Engineering Laboratory (INEL). These reports are summarized in Sec. 3.1.1. The two SBLOCA integral assessments simulated tests conducted in the LOFT and LWR Off-Normal Behavior Investigation (LOBI) facilities. Those reports are discussed in Sec. 3.1.2. There were also two integral assessments summarizing simulations of inadvertent transients that occurred in the Ringhals 2 and Ringhals 4 nuclear power plants in Sweden. They are discussed in Sec. 3.1.3.

3.1.1. Large-Break LOCA Experiments

The LOFT facility is a 50-MWt PWR designed to simulate the major components and system response of a commercial PWR during a LOCA or operational-transient accident. It has a single active intact loop that simulates the three intact loops of a commercial four-loop PWR. The intact loop contains a steam generator, pressurizer, two primary-coolant pumps in parallel, a Venturi meter, and the connecting pipework. The emergency core coolant system (ECC) injection line intersects the intact-loop cold leg between the pumps and the reactor vessel. The broken loop is an inactive loop that simulates the broken loop of the commercial reactor during a LBLOCA. It consists of separate hot and cold legs that are each connected to the reactor vessel and a blowdown-suppression-tank header. The hot leg contains pump and steam-generator simulators. Each broken leg contains a quick-opening valve to initiate the transient. A SBLOCA can be simulated by the LOFT facility by attaching the required additional piping and valving to the primary-system hot or cold leg and not operating the quick-opening valves in the broken legs.

3.1.1.1. LOFT Experiment LP-02-6. Experiment LP-02-6 was a 200% double-ended cold-leg LOCA test carried out at full power (47 MW). The transient was initiated by opening the quick-opening blowdown valves. The reactor was scrammed on indication of loss of pressure in the intact-loop hot leg, and the coolant pumps were tripped within 0.1 s and allowed to coast down. The system pressure fell rapidly to the saturation pressure corresponding to the temperature of fluid in the hot leg. The rapid discharge of liquid in the broken loop caused voiding of the core, a large reduction of heat transfer from the fuel rods, and a rapid rise in cladding temperatures. Saturated conditions in the broken-loop cold leg were reached at about 4 s, accompanied by a reduction in cold-leg break flow. This reduced flow, accompanied by a partial sustaining influence from the pumps, produced a partial bottom-up flow through the core and quenching of rods in the bottom 30% of the core. The intact-loop cold leg also began to void from about 5 s onward so that the break flow again exceeded the flow into the vessel, and the core reemptied, and the fuel rods heated up again. At about 15 s, a top-down flow of liquid through the core began. This quenched the top 25 in. of the central fuel assembly. Flow from the accumulator began at 17.5 s, and the high- and low-pressure injection systems (HPIS and LPIS) were activated at 21.8 and 34.8 s, respectively. Quenching of the fuel rods, which began at about 30 s, was completed very rapidly by the filling of the core, with all the fuel quenched at about 56 s.

J. C. Birchley, P. Coddington, and C. R. Gill, "Analysis of LOFT Experiment LP-02-6 Using the TRAC-PF1/MOD1 Computer Code," AEEW-R 2288 (November 1987). This assessment was performed using TRAC-PF1/MOD1, Version 12.2. The input deck was similar to that used at Winfrith in previous simulations of LOFT experiments. The model contained 343 cells, of which 192 were in the vessel.

The simulation accurately reproduced most of the characteristics of the primary system and vessel-hydraulic response. The calculations of flows and fluid conditions are in quite good agreement with data for most of the transient. Agreement is best in the early part of the blowdown when the flow is more strongly influenced by the subcooled break-flow model rather than conditions in the vessel. Calculations of accumulator flow are also in good agreement with the data.

Calculations of reactor-vessel flows and rod temperatures do not agree with the experimental data as well as the pressures, temperatures, and flow rates computed for the hot and cold legs of the intact and broken loops. Nevertheless, the agreement is qualitative and moderately good considering the uncertainties in initial conditions (energy content of the heat structures, pump characteristics, etc.) and uncertainties in some of the experimental data.

Calculated fuel-rod cladding temperatures are not in good agreement with experimental data. During the first few seconds there was a rapid heat-up following departure from nucleate boiling. The time for the first temperature peak was well predicted. The size of the peak was overpredicted, however. The major cause of the discrepancy appeared to be a significant overprediction of the initial stored energy of the fuel. There was also some question concerning the size of the fuel-cladding gap. The fuel rods had experienced numerous power escalations, scrams, temperature transients, and quenches prior to this test. It is possible that the gap had been substantially reduced. More recent calculations using a zero gap gave much closer agreement with the data for the initial temperature peak. The bottom-up flow of liquid caused a rapid decrease in temperature at about 7 s, but as the water level in the core decreased, the rod heated up again. After the onset of the reflood quench at 34 s, cooling and quenching gradually moved upward in the core, reaching the 11-in. elevation at slightly above 40 s. The calculation did not show the second quench until nearly 80 s because the temperatures were too high.

The authors concluded that most of the primary loop and vessel hydraulic responses were accurately simulated. The hydraulic behavior in the vessel downcomer and the effect of the discharge of accumulator nitrogen in promoting reflood were also accurately simulated. The major discrepancies were in the rod temperature calculations. The adequacy of TRAC's post-CHF heat-transfer package could not be evaluated with confidence from this analysis, partly because of the excessive initial fuel-stored energy and partly because of the probable effect of the thermocouples on the quenching process.

J. Blanco, V. Lopez Montero, and J. Rivero, "Analysis of LOFT Experiment LP-02-6 Using TRAC-PF1/MOD1," ICSP-LP-02-06 (January 1988). The input deck used for the simulation of experiment LP-02-6 was similar to an input deck produced at INEL and used for a TRAC-PD2/MOD1 calculation. The simulation accurately reproduced most of the general thermal-hydraulic behavior. Predictions of rod temperatures were not as accurate, however. The calculated centerline temperatures were in fair agreement with the data although there were differences in excess of 300 K at late times. The cladding temperature predictions failed to simulate either the initial of secondary quench accurately. This may have been caused partly by the effect of the external thermocouples on the quenching process. TRAC did not include an external thermocouple model to simulate this effect.

3.1.1.2. LOFT Experiment LP-FP-1. Experiment LP-FP-1 was a fission-products-release test. It simulated a large-break LOCA in the cold leg with ECC injection delayed long enough to allow pin rupture and fission-product release from 24 fuel rods that were enriched to 6% U^{235} and prepressurized at cold conditions. The transient phase of the experiment started with reactor scram followed by the opening of the quick-opening break valves (QOBVs). The primary-coolant system quickly depressurized to saturation pressure. A bottom-up partial core quench occurred between 6 and 7 s followed at 12 to 18 s by a total top-down quench of the central fuel assembly. The cold-leg QOBV was closed at 68 s, forcing all break flow out the cold leg and core flow from bottom to top. A sustained heat-up of most of the core started at 90 s, resulting in the rupture of some of the enriched fuel rods beginning at 325 s. The ECCS was initiated at 344 s and the entire core was quenched by 365 s.

F. J. Barbero, "TRAC-PF1 Code Assessment Using OECD-LOFT LP-FP-1 Experiment," ICSP-LP-FP-1 (July 1988). The simulation of the LOFT LP-FP-1 experiment accurately reproduced the thermal-hydraulic behavior during the blowdown phase. There was also good agreement between calculated and measured cladding temperatures for the 4%-enriched rods in the central fuel assembly. The predicted temperatures of the 6%-enriched rods that were quenched during the blowdown phase were in fair agreement with experimental data. For the remaining 6%-enriched rods, the predicted temperatures were too high. The author suggests that quenching may be prevented by the minimum stable film boiling temperature (MSFBT) used in the code.

An attempt was made to predict paths the fission products might follow based on flow directions in the vessel during the rod-rupture period. There was some question about the accuracy of the flow calculations in this region, however, because the code does not account for the severe changes in flow-channel dimensions caused by swelling of the rods. The code does not have the direct capability to track fission products.

P. Coddington, "Analysis of the Blowdown of the Accumulator B Line in the OECD-LOFT Fission Product Experiment LP-FP-1," AEEW-R 2328 (February 1988). The purpose of this study was to use TRAC to help in determining the cause of an unintended injection of ECC water into the upper plenum during LOFT experiment LP-FP-1. This study was confined to the behavior of the accumulator B line in the LOFT facility during experiment LP-FP-1. During that experiment, most of the water in the accumulator B line was unintentionally injected into the upper plenum during blowdown. The cause of this injection was attributed to a noncondensable gas (N_2) trapped in the injection line prior to the experiment from an earlier test that had been prematurely aborted. During the time period between the two tests the injection lines of the accumulators were not vented or flushed with water so that gas left from the first experiment remained until the beginning of the second experiment. This noncondensable gas was then pressurized in the injection line to the system pressure during the pretransient phase of the experiment. As a result, the system blowdown triggered a second blowdown in the injection line through the expansion of the noncondensable gas.

Two series of TRAC simulations were carried out in an effort to better understand the phenomenon and to verify the proposed explanation. The first series of runs used the model of a direct line connecting the accumulator to the upper plenum. Initially a single nitrogen bubble was trapped in this line at the system pressure. A total of 10 simulations were performed for this configuration using five different initial bubble sizes and two different expressions for the upper-plenum system pressure. The general profile of the initial flow from the accumulator line into the upper plenum was in good agreement with the flow measurements. The range of nitrogen masses used for these calculations was believed to be consistent with the actual mass. One of the runs in this series gave flow rates that approximately coincided with the flow measurements.

A second series of simulations were performed using an accumulator-line configuration that included an additional length of pipe that allowed two possible locations for the compressed nitrogen to be trapped. Six runs were made, four using the plenum-pressure history thought to be more probable and the other two runs using the other distribution. The calculated flow was found to be similar to results from the first set of calculations. The multiple-bubble calculations confirmed but did not particularly enhance the information obtained from the single-bubble calculations.

In general, it was concluded that the observed and calculated flows exhibited the same general behavior. Experiment and calculation showed reasonable agreement in the general shape of the volumetric flow and the peak flow rate. This almost certainly confirmed the assumption that the expansion of one or more bubbles of trapped nitrogen was the mechanism that produced the unintentional upper-plenum injection in LOFT experiment LP-FP-1.

A detailed flow behavior study was also carried out as part of this analysis. A series of graphics were produced (using the SMART program) at various times during the transient that clearly showed the void-fraction distribution within the pipe by using colored shading.

3.1.1.3. LOFT Experiment LP-LB-1. OECD-LOFT experiment LP-LB-1 simulates a large-break (200% double-ended cold-leg) LOCA. The transient was initiated by opening the blowdown valves in the broken loop. The reactor was scrammed on indication of low pressure in the intact-loop hot leg and the primary pumps were tripped and decoupled from their flywheels, all within 1 s. The upper-plenum and hot-leg fluid began to flash as liquid flowed rapidly out of the broken-loop hot and cold legs. The voiding in the core resulted in the initial departure from nucleate boiling of the core fuel rods at a time just less than 1 s. After this the fuel-rod cladding temperatures rose rapidly. As a result of the decoupling of the primary-coolant pumps from their flywheel systems the flow in the intact-loop cold leg fell rapidly. After 3.5 s, saturated conditions were reached in the broken-loop cold leg and the break flow fell. Initially the fuel-rod cladding temperatures rose rapidly as the stored heat in the center of the fuel was distributed across the entire fuel pin. Once this was complete, the rate of the temperature rise fell as the source of heat became the core decay heat.

At about 13 s, a top-down flow of liquid through the core began. This caused a quenching of the top 18 in. of the fuel rods. The ECCS injection was initiated at 17.5 and 32 s from the accumulator and the LPIS, respectively. The liquid from the accumulator flowed into the vessel downcomer and down into the lower plenum with a minimal amount bypassing the vessel and flowing across the top of the downcomer and out the broken-loop cold leg. The lower plenum filled rapidly and fluid entered the core at about 33 s. A complete core reflood was accomplished at about 48-50 s.

P. Coddington, "OECD-LOFT LP-LB-1 Comparison Report," AEEW-R 2478 (February 1989). This report presented a comparative analysis of six posttest calculations performed by five different organizations in five different countries for the LOFT experiment LP-LB-1. The organizations and computer codes used were

(1) UKAEA/UK using TRAC-PF1/MOD1,
(2) GRS/Germany using DRUFAN/FLUT,
(3) VTT/Finland using RELAP5/MOD2,
(4) EIR/Switzerland using RELAP5/MOD2 (2 calculations), and
(5) University of Bologna/Italy using RELAP5/MOD1.

Only the TRAC-PF1/MOD1 results will be discussed in this report summary. The input description used for the TRAC calculations was similar to earlier TRAC-PD2 descriptions of LOFT used in the analysis of experiments L2-3 and L2-5 as well as LP-LB-1 at various laboratories. It was also similar to the input deck used at Los Alamos in the analysis of experiments L2-3 and LP-02-6. The input deck contained a total of 112 loop and 192 vessel cells.

The TRAC simulation gave satisfactory agreement with test data for thermal-hydraulic phenomena in both the intact and broken loops. The calculated parameters that were compared to experimental data included pressure, momentum flux, fluid density, and fluid temperatures in the intact- and broken-loop hot and cold legs. The pressure, density, momentum flux, and fluid temperatures were in fairly good agreement with experimental data in both the broken and intact loops. It should be noted that the data errors quoted on all of these measurements were relatively large. In the broken-loop hot leg, for example, TRAC predicted a maximum flow rate of 140 kg/s compared to a measured value of 180 kg/s but was still within the experimental error band. The intact-loop cold-leg mass-flow rate calculated by TRAC was in good agreement with the test data and was well within the large experimental error range.

One area where TRAC did not give accurate predictions was the calculation of steady-state pump speed. The calculated pressure drop through the 3D vessel was greater than the experimental value so that a larger-than-measured pump speed was needed to obtain the required steady-state mass-flow rate. During the rapid coastdown of the pump following trip and decoupling from the flywheels, however, the TRAC predictions accurately followed the experimental data.

The most difficult phenomena to predict accurately in this type of simulation were the hydraulic effects in the vessel and the core heat transfer during blowdown and refill. The accuracy of the calculations during the refill and reflood stages was difficult to determine. The error in the measurement of flow out of the vessel along the broken-loop cold leg was large and the momentum-flux instruments on which the mass-flow data were based were, after about 25 s, operating at a level below the minimum of their range. The time for initiation of reflood in the TRAC calculation was in very good agreement with experimental data. However, an underestimation of the broken-loop cold-leg flow during the refill period helped to compensate for an equivalent overestimation during blowdown.

The central fuel assembly fuel-rod cladding temperatures predicted by TRAC were in very good agreement with the experimental data up to the time of reflooding of the core at 40 to 45 s (See Fig. A-27). After 45 s the calculations overpredicted liquid fractions in the core fluid cells which produced an overestimate of the clad-to-coolant heat transfer. The fuel-rod center-line temperatures predicted by TRAC were in good agreement with the experimental data (Fig. A-28). Agreement was not as good for the peripheral fuel assemblies. An examination of the experimental data from the peripheral fuel assemblies showed that there was a significant azimuthal variation in the thermocouple transients across the core during the blowdown period. The TRAC predictions for each of the instrumented assemblies showed a much smaller azimuthal variation of the cladding temperature.

In general, one may conclude that TRAC does an adequate job of predicting thermal-hydraulic behavior in both the intact and broken loops. Hydraulic behavior in the vessel was not as well predicted although the large error bands on the experimental data makes assessment of TRAC performance difficult. Maximum core temperatures were fairly well predicted but the quench times for cladding did not agree well with data. The large azimuthal temperature variations measured in the peripheral fuel assemblies were not predicted by the calculations.

3.1.2. Small-Break LOCA Experiments

F. Pelayo, "TRAC-PF1/MOD1 Post-Test Calculations of the OECD-LOFT Experiment LP-SB-2," ICSP-LP-SB-2-T, AEEW-R 2002 (April 1987). The LOFT test facility is described in Sec. 3.1.1. Experiment LP-SB-2 studied the effect of a delayed pump trip in a small-break LOCA scenario with a 3-in.-equivalent-diameter break in the hot leg of a commercial PWR operating at full power. During this experiment the accumulators and LPIS were not used and scaled-HPIS flow was directed into the intact cold leg. The experiment started with the opening of the break valve in the hot leg of the intact loop. After 1.8 s the pressurizer pressure fell below the reactor-scram set point value. Simultaneously the main feedwater valve started to close and, with a 1-s delay, the main steam control valve began to close. At 4.3 s the main feedwater valve was isolated, and the main steam control valve was fully closed at 4.8 sec. As a consequence of the subsequent pressure increase, the steam bypass valve was actuated. Meanwhile, at 42 s, the HPIS was initiated and at 50.3 s the subcooled blowdown ended. At 63.8 s the steam-generator auxiliary feedwater was manually initiated. At 582.2 s pump degradation was observed, and at around 600 s the onset of partial phase separation in the hot leg was detected. At around 1200 s the break started to uncover, increasing the depressurization rate and, after 1290 s, the secondary pressure exceeded the primary pressure. After 1864 s the auxiliary feedwater was shut off and at about 2853 s the primary coolant pumps were tripped after reaching their pressure set point.

The input deck used for the numerical simulations was an adaptation of a deck previously used at the Atomic Energy Establishment of Winfrith (AEEW) to simulate LOFT experiment LP-SB-1. The major changes included replacing the 3D vessel with a 1D model, removing an accumulator and line, and adding nodalization of the broken loop, pump injection, and nodalization of the hot-leg break. The model included 36 components with 142 cells and 42 junctions.

The results of two different simulations were discussed. The base case, called Run A, used the frozen version of TRAC-PF1/MOD1, Version 12.7. A second run, Run B, was made with a Winfrith version of TRAC with modifications. Run A was a 3000-s simulation of the SB-2 test that required about 1.63 h of CPU time on a Cray X-MP computer. The stability-enhancing two-step (SETS) numerical technique was used so the Courant time limit could be exceeded and time steps as large as 0.5 s could be used for a large part of the calculation. The TRAC-PF1/MOD1 (Version 12.7) code was able to predict reasonably well the evolution of the SB-2 transient. The flow-regime map performed well in identifying fully stratified conditions. The main discrepancy between the experiment and the calculation was the overprediction of mass loss from the primary system. The author concluded that for transients where phase separation upstream of the break affects the break density, the predictive capability of the code could be improved by incorporating a model relating quality in a branch to the thermal-hydraulic conditions in the main pipe. An offtake model should be used that considers the geometric relationship between the break junction and the main line.

Run B was made in an attempt to improve the accuracy of the break-flow calculation and to determine whether a better prediction of that parameter would improve the predictions of primary pressure, hot- and cold-leg densities, and vessel inventory and subsequent heat-up. The most important modification for Run B was the use of a method which could control the quality in the break line as a function of the void fraction in the hot leg. The pump-head multipliers were modified to force a sharp degradation at an inlet void fraction of 0.35 and the multipliers for Pump No. 1 were further modified to try to reproduce the asymmetrical pump behavior after degradation. The equation for calculating the critical gas velocity in the stratified model was corrected by including a missing factor.

These changes did indeed greatly improve the accuracy of the break-flow-rate calculation (Fig. A-5). The density in the break line matched the experimental data much more closely for the entire transient. There were also significant improvements in the predictions of primary pressures and temperatures, primary-mass inventory, and vessel inventory and rod temperatures.

One difficult aspect of the simulation was the accurate prediction of pump behavior. The velocities predicted by the code after the pump degradation were not entirely satisfactory and the steady fall in the velocities observed in the experiment were not reproduced. One area of uncertainty was the performance of the pumps under two-phase conditions. The intact loop of the facility contained two similar pumps working in parallel. The strong coupling between those pumps constituted a potential source of instability when asymmetric perturbations in flow conditions were felt at the pump inlets. The use of a 1D vessel did not allow reproduction of the asymmetrical flow distribution in the downcomer and its influence on the flow distribution in the bypasses. It was not possible, therefore, to determine whether the poor predictions of flow rates in some instances were caused by the pump-characteristic curves and multipliers or by the lack of accurate predictions of pump inlet conditions.

C. G. Richards, "Pre-Test Calculation of LOBI Test BL-02 Using TRAC-PF1/MOD1," AEEW-M 2416 (February 1987). The LOBI two-loop test facility simulated the cooling system of a four-loop, 1300-MWe PWR. One test loop, having three times the capacity in water volume and mass flow of the other, represented the three intact primary loops. The other represented the broken primary loop. Both loops contained an active steam generator and coolant pump. An active secondary-loop system contained two condensers, a cooler, and a feedwater pump. The power input, the primary-circuit coolant mass flow, and the volume were scaled from reactor values by a factor of 712, leading to a heating power of 5.3 MW in the 8 x 8 heater rod bundle and to a core mass flow of 28 kg/s. The absolute heights and relative elevations of the individual system components have been kept at reactor values to preserve the gravitational heads. The broken-loop steam generator had 8 full-size active U-tubes while the intact-loop steam generator had 24. Both the primary and secondary side of the LOBI rig were extensively instrumented. ECC was provided by high-pressure injection and accumulator flow to the intact loop.

Experiment BL-O2 was a 3% cold-leg break at full power. The break nozzle was at the center of the cold leg. The secondary side underwent a controlled cooldown at the rate of 56 K/h. At the beginning of the test the break valve was opened and the pressurizer heaters were turned off. When the primary-side pressure reached a set point of 131 bar, the steam-line valve was closed and the main-coolant pumps began coastdown. The auxiliary feedwater was turned on 60 s after the 131-bar set point was reached and the main-coolant pumps reached zero speed 141 s later. The high-pressure injection system began to operate 35 s after a 117-bar set point was reached. The accumulators began injection when the primary-loop pressure dropped to 41 bar.

The input deck was a revision of a deck developed at AEEW for participation in the ISP18 exercise. Changes were made in the control system and boundary conditions to reflect the specification of BL-02. A control system was used to model the accumulator.

The calculation was run to 900 s before being terminated because of slow running. Only a short portion of the refill phase of the transient was modeled. Numerical predictions of primary- and secondary-side pressures were in reasonably good agreement with experimental data. The measured secondary-side pressure dropped somewhat more rapidly than the calculated value but this was partly caused by the fact that the secondary-side cooldown was larger than was specified in the test. Given the slight differences between the effective boundary conditions in the experiment and those assumed in the calculation, the TRAC pretest calculation gave a reasonable prediction of the pressure behavior experienced in the test.

The early break flow was reasonably well predicted by TRAC, but after about 200 s, TRAC incorrectly predicted an increase in break flow. This increase was probably caused by the upstream void fraction decreasing at 200 s. This took the critical flow model into the interpolation region between void fractions of 0.0 and 0.1. The overprediction of the break flow resulted in a premature loop-seal clearance. The reason for the overprediction of the broken-loop cold-leg density that gave rise to this error in break flow has not yet been determined. It should be noted that there was some uncertainty attached to the experimental primary-mass measurement. A significant qualitative difference between the experimental and calculated behavior was the failure of the intact-loop seal to clear in the calculation.

3.1.3. Operational Transients

A. Sjoberg, "Assessment of TRAC-PF1/MOD1 Against an Inadvertent Feedwater Line Isolation Transient in the Ringhals 4 Power Plant," STUDSVIK/NP-88/101 (S) (November 1988). A TRAC-PF1/MOD1 simulation has been conducted to assess the capability of the code to predict feedwater-line isolation. The measured data were obtained from an inadvertent feedwater-line isolation at full-power operation in the Ringhals 4 power plant. Ringhals 4 is a 915-MWe Westinghouse PWR with three loops and two turbines. It is equipped with three Westinghouse steam generators with a feedwater-preheater section located at the cold-leg side of the U-tube bundle and a division is made of the feedwater flow between this lower feedwater inlet and the top inlet at the upper part of the downcomer. During the pretransient stationary phase the total feedwater was apportioned so that about 10% of the flow was delivered to the top inlet and the rest to the preheater. The circulation ratio at this condition was about 2.43.

The transient was initiated by a failure in an electronic logical circuit causing the feedwater-line isolation valves to close in all three loops. Following the closure of the feedwater valves the steam flow through the feedwater-preheater train ceased with a corresponding increase of flow through the turbine. This was automatically compensated for by the throttling of the turbine valves. As a consequence, the impulse-chamber pressure of the turbine was decreased by about 10%. This was felt by the control logic of the turbines as a corresponding load rejection resulting in deblocking of 25% steam-dumping capacity.

Because of the loss of main-feedwater flow, the average temperature of the primary coolant increased while the reference temperature was decreased due to reduced impulse-chamber pressure. This deviation resulted in a dump demand signal and about 14 s after the feedwater isolation, steam dumping from the turbines was initiated. The continued steam flow resulted in depletion of steam-generator liquid inventory and reactor scram was obtained on low downcomer-level signal. Isolation of the turbines was activated and auxiliary feedwater supply was initiated. The level then slowly increased and finally reached the normal value.

In the TRAC simulation, only a single-loop representation was used, and the core was modeled by the TRAC neutron point kinetics specified with middle-of-cycle conditions. The complete model comprised 37 components made up of 144 nodes. The boundary conditions were either taken directly from the recordings of the plant computer or were inferred from those data.

Prior to the transient simulations, a steady-state analysis was run and conditions were adjusted to replicate the actual pretransient conditions. A heat-balance calculation of the plant during the stationary phase provided information of recirculation-pump power and primary-coolant mass flow which were not known from measurements. The model steady-state conditions were saved for later use as initial conditions for transient simulations.

The base-case transient was simulated for 300 s including 10 s of pretransient steady-state condition. At 10 s the feedwater isolation started with feedwater flow being ramped down to zero in 2.5 s. The calculated flow, taken from the differential pressure between the steam generator dome and the steam line, did not agree well with the direct flow when the flow was reduced and the pressure increased. The reason for this discrepancy was the omission of pressure dependence in the flow algorithm. When this compensation was introduced, a favorable comparison with measured steam flow was obtained.

As the steam-generator level was decreasing, there was an oscillation in the narrow-range level signal predicted by the calculations that was not measured during the actual transient. A denser nodalization of the upper part of the downcomer helped to alleviate this problem. The primary temperature in the base-case model was too low compared to measurements. An increase in the initial stored energy of the fuel would have raised the coolant temperature. An increase in stored energy was obtained by decreasing the gap conductance of the fuel. A sensitivity analysis showed that a gap conductance of 5.0 kW/m^2·K (half the base-case value) resulted in a reasonable response of the reactor system when compared to measurements.

F. Pelayo and A. Sjoberg, "Assessment of TRAC-PF1/MOD1 Against an Inadvertent Steam Line Isolation Valve Closure in the Ringhals 2 Power Plant," ICSP-R2MSIV-T (February 1988). The Ringhals 2 power plant is a three-loop, two-turbine PWR of Westinghouse Stal-Laval design with. The nominal thermal power is 2440 MW and the electrical net output is 800 MW. The plant is equipped with three Westinghouse steam generators of the vertical U-tube design. Because of problems with U-tubes in the steam generators, the core power has been reduced to about 80% of normal.

A transient in the system operation was initiated by an interruption of power to the electrical coil in the magnetic pilot valve of the steam-line isolation valve in loop 3. The isolation valve closed and the steam flow decreased by 1/3 quite rapidly. This caused a rapid pressure decrease in the other two steam lines and a corresponding steam flow increase. The steam flow in loops 1 and 2 increased to the trip set point, resulting in a closure signal for the steam-line isolation valves in the two intact loops, activation of safety injection, isolation of main feedwater, scram signal generation, and termination of letdown and charging flows. The auxiliary-feedwater flow was automatically activated. Because of the isolation of the steam generators, the circulation flow on the secondary side ceased and a stagnant condition occurred. The steam-generators downcomer level quickly decreased. The core decay heat and the stored energy in the structures on the primary side caused the secondary-side pressure to slowly increase. Throughout the transient, important plant signals were monitored and stored on the plant computer. Unfortunately the plant signal follower, which records the time sequence of trips and control signals, was not functioning properly and thus no true sequence of events could be established. The sequence of events was inferred from the time plots of relevant signals.

The simulation of the transient was made with TRAC-PF1/MOD1, Version 14.0. A two-loop representation of the plant was used. A 1D representation of the vessel made up of seven components was used. A lumped-parameter model and adiabatic walls represented the vessel and its externals. The axial heat-flux shape and hot-rod peaking factors were derived from in-core measurements. The pressurizer was modeled by a TEE containing six cells and the bottom of the pressurizer was a PIPE component divided into four cells. The pressurizer walls were simulated by heat structures with four radial nodes. All the pressurizer valves were sized to their rated capacities under choked-flow conditions. The steam generators were modeled in detail. Each steam generator comprised a number of components where the STGEN component included the primary side of the U-tube bundle and the secondary-side riser and separator parts. The downcomer was nodalized so as to permit adequate tracing of the water level as well as correct placement of level pressure taps. The steam flow was measured by means of a differential pressure between the steam-dome pressure tap in the relief and safety-valve header. Control system and trip logic modeling was extensive. Boundary conditions for the simulations were either taken directly from the recordings of the plant computer or were inferred from them.

Prior to the transient simulation, the TRAC model was adjusted to replicate the plant stationary pretest conditions. The measured steam flows and corresponding feedwater flows were found not to balance during the pretransient phase, indicating that some of the flows were miscalibrated. A heat balance for the steam generator revealed that the steam flows were erroneously recorded. Therefore, the steam flows were assumed to match the feedwater flows.

The transient simulations were made using both a single- and double-loop representation. Measured thermal-hydraulic data were obtained for each loop and an averaging procedure was used to provide data for the double loop. The main heat source during the transient was the core power and decay heat. The default kinetic parameters were used. The speed of the reactor coolant pumps was assumed constant throughout the transient. The feedwater flow was specified using a trip-controlled FILL component with tabulated data as a function of time taken from recorded data.

The single-loop steam generator pressure, water level, and flow behavior were well reproduced in the calculation. The calculated transient-pressure decrease in the double-loop steam line prior to the reactor and turbine trip was slightly overestimated. This was believed to be caused by the omission of most of the structural materials in the secondary side of the steam generator model. Following the reactor trip, the average temperature on the primary side decreased more rapidly than the measured data indicated. This may have been due to overestimating primary-to-secondary heat transfer and underestimating the stored energy in the fuel. The calculations were rerun with a modified gap conductance which produced more stored energy in the fuel during steady state and better results were obtained.

For this fairly mild transient, no problems with the thermal-hydraulic calculations were encountered. Instead the control-system performance was a source of difficulty. No time-step control was imposed in the input deck and TRAC was allowed to use as big a time step as the solution method permitted. This resulted in some unstable behavior for some of the controls having relatively small time constants.

3.2. Separate-Effects Assessments

The separate-effects assessments are divided according to the specific phenomenon they address. These include countercurrent flow, ECC injection, behavior of a U-tube of a steam generator during accident conditions, and fuel-rod heat transfer.

3.2.1. Countercurrent Flow

K. H. Ardron and A. J. Clare, "Assessment of Interface Drag Correlations in the RELAP5/MOD2 and TRAC-PF1/MOD1 Codes," GD/PE-N/557 (March 1987). An assessment was carried out to compare the interphase-drag correlations used in the RELAP5/MOD2 and TRAC-PF1/MOD1 codes. Both codes use a two-fluid model in which separate momentum equations are solved for the gas and liquid phases. Flow-regime-dependent constitutive equations are used to model interphase momentum transfer. The assessment was performed by using models from these codes to calculate void fractions in steam/water flows and comparing those results with predictions of standard correlations and with test data. The assessment is confined to bubbly- and slug-flow conditions ($\alpha_g < 0.75$).

There are extensive data available for cocurrent upflow of steam/water and air/water mixtures, and a number of void-fraction correlations have been proposed in the literature. The "best-estimate" model used in this assessment was developed by combining the correlations of Wilson et al. (Ref. 5) and Rooney (Ref. 6). The Wilson correlation is based on steam/water data for pressures in the range 2.0 - 13.8 MPa and pipe diameters between 100 and 914 mm. The Rooney correlation was used for flow rates high enough to fall outside the range of validity of the Wilson correlation. The "best-estimate" correlation of void fraction for upward flow combines these two correlations according to

$$\alpha_g = \min(\text{Wilson, Rooney}) .$$

These correlations are expected to give results with RMS errors in the two-phase-mixture density in the range of 17-30 %.

For cocurrent downflow very little void fraction data are available and there are no well-established correlations. Therefore, the performance of the code models was assessed against the data of Petrick (Ref. 7).

To assess the interphase-drag models in the codes, the drag equations were first used to develop relationships between the void fractions and the phase flow rates for the case of steady, fully developed steam/water flow in a uniform-area vertical pipe. The void fractions obtained from these relationships were then compared with predictions of the best-estimate empirical correlation for upflow and with the available data for downflow.

Results of the calculations show reasonably good agreement between both RELAP5 and TRAC results and the Wilson-Rooney correlation for moderate and high liquid flow rates and small hydraulic diameters. Discrepancies are largest for low pressures, large pipe diameters, small liquid flows, and large vapor flows. Discrepancies between the code predictions and the correlations, measured in terms of density, are comparable for the two codes and are within the quoted experimental accuracy for most of the range of parameters covered in this assessment.

Results for upflow at a pressure of 7.0 MPa and a hydraulic diameter of 49 mm give very good agreement for both RELAP5 and TRAC. Comparisons were also made with data at pressures of 4.1 and 10.3 MPa and similar conclusions were reached.

The conclusions from this assessment are the following:

1. The interphase-drag models in RELAP5/MOD2 and TRAC-PF1/MOD1 perform comparably well in modeling vertical flows.
2. Errors in the two-phase mixture density increase with decreasing liquid flow, increasing vapor flow, increasing pipe size, and decreasing pressure.
3. For upflow, at the pressures of interest in modeling small-break LOCAs, the errors in two-phase mixture density are not grossly different from errors normally expected in applying standard correlations for void fraction.
4. For downflow, the code models perform very well in comparison with the limited void fraction data available.

W. M. Dempster, A. M. Bradford, T. M. S. Callender, and H. C. Simpson, "An Assessment of TRAC-PF1/MOD1 Using Strathclyde 1/10 Scale Model Refill Tests," Strathclyde-SB291, Phase 1. The Strathclyde test facility was designed for operation with steam/water and steam/air as the working fluids and incorporates a closed-loop recirculation system. The reactor-vessel test section was a 1/10-scale model of a Westinghouse PWR, with particular emphasis on the downcomer annulus. Two test sections were available, one with a transparent exterior, restricting operation to pressures less than 1.7 bar but allowing visual observation, and the other, made of stainless steel, permitting pressures up to 5 bar. The reactor-vessel simulation included the provision of four hot legs, connected through the annulus to the core, and four cold legs connected to the annulus. Two of the hot legs were used to supply steam/air to the core; three of the cold legs were used as ECC-injection points, while the fourth represented the broken leg.

The main measurements taken during the tests included inlet steam/air flow rate, injected-water flow rate, water penetrating to the lower plenum, and various temperatures, pressures, and pressure differences. Two types of tests were performed. In the "water first" tests a particular water flow rate was set and then the steam flow rate was increased in steps until complete bypass occurred. In "steam first" tests the steam flow rate was set and the water flow rate was increased until bypass ceased.

The nodalization scheme used was similar to that used in TRAC large-plant calculations that had been previously carried out in the UK. The vessel nodalization included 13 axial levels, 4 sectors, and 1 radial ring to represent the downcomer. The core also had 13, 4, 1 noding and simply acted as a flow path for the flow of steam or air. The ECC-injection flow rates were modeled using FILL components injecting into PIPE components. A BREAK component was used to specify the experimental break pressure in the nozzle of the broken cold leg.

It was not possible to directly model the heat transfer between hydrodynamic cells separated by solid structures using TRAC PF1/MOD1. Therefore the 1D conduction slab model was adapted in an attempt to include wall heat-transfer effects. The first node of the heat structure modeled the core steam temperature which remained at an approximately constant value throughout the test. An artificial material with very high thermal capacity was used to maintain a constant temperature boundary condition at the first node. The thermal conductivity associated with this material corresponded to a value determined using the Dittus-Boelter convective-heat-transfer correlation.

Four tests were chosen from the Strathclyde data bank that covered the entire range of available conditions from total penetration to total bypass at moderately high subcooling. Test A was a steam/water total-penetration test, tests B and C were partial-penetration tests with steam/water and air/water respectively, and test D was a high-subcooling steam/water bypass test. All four tests were simulated using TRAC and calculations for tests B and D were repeated using an upgraded code that used a more conservative form of the momentum equations.

Test A was a high-subcooling total-penetration test in which a high degree of thermal equilibrium was reached. Results of the simulation showed that TRAC calculated the correct situation with all the injected liquid flowing to the lower plenum. The amount of steam condensed in the vessel was slightly underpredicted, however. Overall, TRAC predictions agreed well with experimental results for this case.

Test B was a partial-penetration test with approximately 45% of the inlet water flow bypassing the lower plenum. The TRAC comparisons with the experimental results showed a far greater amount of liquid predicted to penetrate the downcomer than in the test. There was poor agreement between TRAC predictions and the experimental measurements and (visually) observed flow patterns in the downcomer.

Test C was an air/water penetration test in which 75% of the inlet liquid flow rate was bypassed across the downcomer and out of the break. Again, the results were in very poor agreement with the experimental values, with the majority of the inlet liquid flow being calculated by TRAC to penetrate the lower plenum.

Test D consisted of a total bypass condition at a relatively high subcooling. TRAC calculated that approximately 55% of the steam flow condensed in the downcomer, comparing well with the measured value of nearly 57%. TRAC correctly predicted that the majority of liquid flowing into the downcomer was held up and bypassed the downcomer.

Simulations of tests B and D were repeated using a modified version of TRAC in which the momentum equations were set in conservative form. Calculations for case B showed very little improvement in the overall predictions. However, noticeable differences were seen when comparing the overall distribution of liquid fractions and velocities. The most dramatic difference occurred when recalculating test D. It was now found that TRAC correctly predicted total bypass.

A computer program was written at Strathclyde to carry out sensitivity calculations on the annular-mist model used in TRAC. Conditions typical of the test simulated in this assessment were used. The results of the calculations showed that the mist drag coefficient was many magnitudes larger than the annular-film-drag coefficient across the whole void fraction range. The consequence of this was that the entrainment fraction played an important role in determining if the annular-film coefficient has any significance in the total drag coefficient. It was found that the entrainment was negligible and the interfacial-drag coefficient was dominated by the annular-film-drag coefficient for velocities up to 10 m/s. For higher velocities, the increasing entrainment caused the total drag to be quickly dominated by the droplet drag. Velocities in the Strathclyde tests were generally larger than 10 m/s. Deficiencies in the modeling were attributed to the Wallis correlation. A correlation by Bharathan which is more appropriate to countercurrent flow than the Wallis correlation was found to produce better results. This was attributed to the fact that this correlation produces interfacial-film drag coefficients approximately 5 times higher than those predicted by the Wallis correlation.

The authors conclude that TRAC consistently underpredicted the amount of bypass. This, in addition to the underprediction of the amount of steam being condensed, suggested that deficiencies existed in the interfacial-drag modeling. The use a conservative form of the momentum equations produced better results and is a more correct formulation. This form of the momentum equation should be used together with suitable experimental data to determine the validity of the interfacial closure relations.

W. M. Dempster, "An Assessment of TRAC-PF1/MOD1 Using Strathclyde 1/10 Scale Model Refill Tests, 2nd Report," Submitted to CERL, Phase 2 of Contract RK: 1642 Job No. SB291, Strathclyde-SB291, Phase 2 (July 1989). This is the second and final phase of the work discussed in a previous assessment report. Comparisons of calculated results with experimental data for several tests were reported in the Phase 1 report. This report discusses the results of some nodalization and sensitivity studies.

The effect of the hydraulic diameter selected for the downcomer was investigated. There is a thermal shield in the downcomer that divides it into two separate flow paths. The downcomer was modeled, however, with only one ring, and the two channels were combined into a single flow path. There was some question concerning what hydraulic diameter should be specified for the resulting cells. Two limiting values were used, producing slightly different results. Agreement with experimental data, however, was not markedly different for the two cases.

A study was also carried out to assess the accuracy of the condensation-rate heat-transfer calculations in TRAC. Comparison of TRAC predictions with values deduced from experimental data showed that TRAC condensation-rate heat transfer can be an order of magnitude higher than the experimentally derived values. This is apparently caused by the use of interfacial areas based on a uniform flow distribution in cases where the flow is actually stratified.

Nodalization studies were performed for a case in which total bypass occurred. This study was primarily restricted to changing the number of azimuthal sectors in the vessel. The authors conclude that using only four azimuthal sectors is not sufficient for good accuracy. They also find that it is important to correctly model the position of the cold-leg/vessel connections. TRAC's inability to predict the circumferential redistribution of liquid injected into the downcomer is attributed to the lack of appropriate terms in the momentum equations at the pipe/vessel junction.

D. M. Turner, "Discretization Effects in TRAC-PF1/MOD1 on the Prediction of Low Subcooling Counter Current Flow in a PWR Downcomer," CEGB report no. RD/L/3455/R89 (February 1989). The CREARE experimental rig consists of a 1/5-scale vessel with superheated steam injected at a constant rate at the top. When equilibrium conditions prevail, subcooled water is injected into the top of the downcomer from three pipes simulating cold legs. There is no structure equivalent to hot legs in this vessel. An outlet pipe, simulating a broken cold leg, has a larger diameter than the other cold legs to prevent a significant buildup of pressure within the rig. Unless complete bypass occurs, the lower plenum gradually fills up with water during the experiment as a steam/water mixture issues from the outlet pipe. The results from the CREARE experiments are presented as a flooding curve with a dimensionless countercurrent steam flux on one axis and a dimensionless liquid flux delivered to the lower plenum on the other axis.

The nodalization scheme used for the TRAC calculations used three, four, and seven nodes in the radial, azimuthal, and axial directions, respectively. Only one radial node was used in the downcomer. Later calculations were performed with eight azimuthal nodes. Calculations were performed for a given liquid flow rate and five different steam flow rates for four different versions of TRAC. These were the standard version, the modified cross-derivative version, a conservative scheme, and a version including both modifications. An asymptotic filling rate for the liquid flow into the lower plenum was calculated for each run. This filling rate was converted to a nondimensional flow rate for comparison to experimental data. In general, the lower plenum filling rates were underpredicted. The conservative scheme gave slightly worse agreement but the original TRAC scheme had been tuned to predict the CREARE data and any changes made to the code would be expected to produce worse agreement. It should be noted that the scatter in the experimental data was quite large so that the comparisons of calculated and experimental results was inconclusive.

The major thrust of this assessment was a comparison of results produced by the standard version to those predicted by the modified versions. Calculated void fractions and liquid and vapor velocities are shown for several cells using all four versions of the code. These results show that the conservative scheme significantly reduces the flow variability, both locally node-to-node and during the transient. The solutions produced by the conservative scheme are much less oscillatory than those produced by the original scheme.

A series of simulations were performed using eight azimuthal nodes for comparison to the four-node results. With the eight-node downcomer model, the original scheme produced flows with an alternating pattern in the downcomer. This pattern was strongly linked to nodalization and the geometry of the ECC-water input and was thought to be nonphysical. The conservative scheme with the eight-node downcomer model did not exhibit the alternating flow pattern. Predictions for the conservative scheme for the eight-node downcomer were similar to the four-node downcomer results with water flow up around the break-flow side of the vessel and down elsewhere.

A series or curves are presented showing the magnitude of the various terms in the momentum equation. These terms include the time derivative, interfacial friction, convective derivative, pressure gradient, and velocity head. These data suggest that in general the pressure gradients will be lower with the conservative scheme. This is believed to be the reason for the lower liquid velocities observed with the conservative scheme. For the conservative scheme, when the time derivative is small, the flow in the downcomer is very similar to a classical vertical countercurrent flow except that the convective derivative in the vapor equation remains significant.

Run-time information for each scheme is presented for the same conditions. The conservative scheme is able to perform more time steps per unit time than the original scheme.

3.2.2. ECC Injection

B. Spindler and M. Pellissier, "Assessment of TRAC-PF1/MOD1 Version 14.3 Using Components Separate Effects Experiments," SETh/LEML/89-165 (March 1989). EPIS-2 simulates the ECC-injection system in the cold leg of a pressurized water reactor. The cold leg is simulated by a horizontal pipe 9.13 m long with an inside diameter of 28 mm. Two pipes connected to the cold leg are used to simulate accumulator injection and pump injection. During a test, vapor flows through the cold leg at a given rate and water is injected at a specified rate which may vary with time. Pressures, temperatures, and void fractions are measured at various locations along the test section and steam and water flow rates are measured as functions of time.

Tests were performed within four series covering a wide range of parameters. The tests selected for the TRAC simulations were chosen from the last series of tests, which is the most reliable. Test 81.23 corresponds to a stable regime. Test 80.19 corresponds to a large-oscillation regime with a liquid plug passing alternately upstream and downstream of the injection point. Test 85.14 is in a small-oscillation regime with the liquid front not passing upstream of the injection point.

The cold leg was modeled with the primary side of a TEE component with the secondary side modeling the injection pipe. The upstream end of the primary side was connected to a PLENUM simulating the volume preceding the cold leg. The downstream end of the TEE was connected to a BREAK simulating the outlet of the test section where the back pressure is imposed. A FILL component, connected to the secondary side of the TEE, was used to provide the liquid injection rate.

The experimental pressure distribution at steady state was compared to that predicted by TRAC for Test 81.23. The measured pressure exhibits an increase near the injection point caused by condensation and vapor deceleration followed by an increase attributed to liquid acceleration downstream of the injection point. The predicted pressure shows only the sharp decrease. The code does, however, accurately predict the liquid and vapor temperatures.

In Test 80.19 a plug immediately formed and oscillated with a period of about 0.6 s. The code predicted an oscillating plug with a period of 0.7-1.0 s but the simulation eventually failed because the minimum-time-step limitation was reached caused by a water-packing effect.

Test 85.14 had a liquid-injection flow rate about 3 times that of test 80.19. The results of the simulations for this case showed oscillations with a period much larger than shown by the data. The amplitude of the oscillations was approximately twice that of the data.

The authors conclude that the condensation model in TRAC was not satisfactory for these tests. This is probably due to an overprediction of interfacial area for a case in which liquid injection is in the form of a jet. They also note that the use of the water-packing option sometimes causes a sharp reduction in the time step. Nodalization studies show little difference in results for the range of cell lengths from 0.1 to 3.0 m. They recommended a relatively coarse mesh. A study of the sensitivity of the pressure distribution to the volume of the upstream plenum indicated that the period of the oscillations increases and the amplitude decreases as the upstream volume size is increased. This is qualitatively in agreement with the experiments.

3.2.3. Transient Effects In U-Tube of a Steam Generator

B. Spindler and M. Pellissier, "Assessment of TRAC-PF1/MOD1 Version 14.3 Using Components Separate Effects Experiments," SETh/LEML/89-165 (March 1989). The PATRICIA experiments simulate the U-tube of a steam generator. Water flowing in the tube simulates the primary circuit. The secondary circuit is simulated by the flow of an organic fluid in the annulus around the tube. The test section is divided into four sections, each having an independent secondary circuit. Pressure drops across the test section are measured with a manometer. Temperatures in the primary circuit are measured with thermocouples located in the connection pieces between segments.

About 600 tests were performed. Six series of tests (a total of 85 tests) were selected for TRAC simulations. Twenty-nine of these tests included the injection of a noncondensable gas. Each part of the test section is modeled with a PIPE component. Four nodes are used in the walls and experimentally measured power is extracted at the external node to simulate the secondary side of the steam generator. The first PIPE component is connected to a FILL where the inlet conditions are imposed and the last PIPE is connected to a BREAK component where the back pressure is specified. An entire series of tests was simulated in one run using a 10 s ramp in the boundary conditions. These conditions were then maintained for 250 to 1000 s to reach an equilibrium state. Steady state was reached for most of the runs although oscillations with small pressure-drop variations occurred in some cases. For the series of tests with a noncondensable gas, steady state was not reached and this series was abandoned.

The TRAC predictions WERE reasonably good for most calculations except for a series of runs at high void fractions. This was attributed to the fact that TRAC uses a homogeneous wall-shear-stress model whereas the flow was rather annular at large void fractions. In cases with countercurrent flow, the pressure drops were too low in the first and second segments but good in the third and fourth parts of the test section where there is little liquid. Thermal resistances calculated by TRAC were in poor agreement with measured values. These discrepancies are attributed to the poor accuracy of the temperature measurements.

A nodalization study for this apparatus indicates little effect for the range of cell sizes studied. The sensitivity of pressure drops to the friction factor option was also studied. Most calculations were performed using NFF = 1. Calculations using NFF = 2 were found to largely overpredict the pressure drops. The use of that option was not recommended.

3.2.4. Fuel-Rod Heat Transfer

R. O'Mahoney, "A Study of the Reflood Characteristics of TRAC-PF1/MOD1," AEEW-M 2305 (April 1986). The purpose of this assessment was to determine the accuracy of the hydraulics model in TRAC-PF1/MOD1 for reflood conditions. The accuracy of the TRAC simulations was determined by comparison of calculated results with experimental data from forced-reflooding tests in the THETIS experimental rig at Winfrith. The THETIS facility consists of a single cluster of rods in a shroud tube housed in a pressure vessel. Water may be introduced into the bottom of the cluster through a penetration of the pressure vessel wall. The top of the shroud tube is open to the pressure vessel via a steam separator. The vessel is then vented to the atmosphere through a pressure-control valve.

The cluster consists of a 7 x 7 square array of electrically heated, Inconel-clad fuel-rod simulators. Before an experiment is begun, a low power level is applied to the test section to heat the rods to a selected temperature. The experiment is then initiated by increasing the power input to a specified level and, a few seconds later, closing a fast-acting drain valve to force the reflood water to rise in the test section. Simulations were performed for two THETIS experiments, Run 65 with a reflood rate of 2.0 cm/s and power of 99 kW, and Run 75 having a reflood rate of 5.7 cm/s and a power of 200 kW.

The base case was run with TRAC-PF1/MOD1 Version 11.9. This version of the code contains an interface-sharpener model (ISM) which attempts to compensate for the fact that the interfacial-shear package is not necessarily representative of the physical processes occurring during reflood. The model operates by explicitly attempting to limit the upward flow of liquid at a liquid/vapor interface according to an entrainment correlation. Results of the base-case simulation are compared with data from Run 65. The integrated liquid carryover calculated by TRAC is in fair overall agreement with the experimental data but the calculated curve is a series of steps instead of the smooth curve one would expect. This effect is also clearly evident in the liquid-volume-fraction predictions which show alternating periods of filling and emptying producing a sawtooth effect.

A series or modifications were made to TRAC in an effort to improve the results. The first modification was a reduction of the lower bound on liquid velocity for which the ISM was used. The limit was changed from 3/4 to 1/20 of the vapor velocity. The second modification replaced the entrainment correlation with the COBRA-TF model, modified the interfacial-shear model to allow upflow of droplets, and further decreased the lower bound on the liquid velocity to 0.001 m/s. The third modification changed the test for invoking the cubic-spline model (used to interpolate the liquid fraction value using a cubic equation) to one based on height above the interface rather than void fraction. The results of the first modification had a limited effect. The second modification had a rather significant effect in smoothing out the predictions of the integrated core-outlet liquid flow. The third modification had little additional effect.

A detailed examination of the calculations indicated that the timing of the discontinuities was largely coincident with the quenching of the heat slabs used to represent the shroud. A heat slab is used in each fluid cell but the heat-slab model does not allow any axial subdivisions within a slab. This means that a particular heat slab will quench all at once rather than in a smooth axial progression. This has the effect of causing spikes in the liquid and vapor flow rates above the slab. A simulation was therefore performed with the slabs replaced by rods. An error found in the equation for calculating the liquid film coefficient during film boiling was also corrected. The results of a simulation of Run 65 with a code containing these modifications (as well as those discussed in the previous paragraph) gives improved results. The core-outlet liquid mass flow for this case has oscillations with greatly decreased amplitudes.

Finally a sensitivity study was performed to determine the effect of the ISM. Simulations were performed, with and without the ISM, for the case with slabs replaced with rods and the error correction included. These calculations were performed with a later version of TRAC, Version 12.2. The results are somewhat better for the calculation with no ISM. The prediction of vapor fractions is significantly improved although some oscillation is still predicted as the cells fill. There is also significant improvement in the overall cladding-temperature history, particularly in the time to quench.

Two sets of simulations were also performed for Run 75, an experiment with a much higher reflood rate. The first set compares the base version of TRAC (Version 11.9) with a version containing the basic modifications but slabs representing the shroud. Both versions give good agreement with experimental data up to 100 s but become increasingly poor after that time. The modified version shows no improvement over the base case other than being slightly smoother. The second set compares the TRAC base case (Version 12.2) and TRAC with no ISM. These results show a significant change in both the hydraulic and thermal predictions when the ISM is excluded. The change in hydraulic predictions is toward the experimental trends although an early spike in the flows causes too much liquid to be carried out. The change in heat-transfer predictions is also toward the experimental trend up until the time of quenching in the experiment. The lower quench temperature in the calculations causes rather late quenching in the no-ISM calculation.

The author concludes that TRAC-PF1/MOD1 with the ISM included is not adequate to predict the detailed hydraulic behavior observed during the THETIS reflood tests. The predictions display an oscillatory and discontinuous behavior dominated by the movement of a sharp liquid interface. Modifications of the ISM and the interfacial-shear model, in line with published entrainment correlations, removes much of the unphysical behavior. A significant amount of stored metalwork heat cannot be adequately represented by heat slabs in TRAC. Replacing the slabs by heated rods improves the accuracy of the calculation. The lack of any axial subdivisions leads to unphysical discontinuities in the heat transfer and related fluid behavior. Excluding the ISM significantly improves the overall hydraulic predictions although some oscillation is still predicted.

The author recommends that the interface-sharpener model not be used. Some code deficiencies were identified. Using rods rather than slabs to represent stored heat in the core for a reflood situation will largely eliminate oscillations in fluid flow. An error in the calculation of a film coefficient for liquids in film boiling was uncovered.

R. O'Mahoney, "A Study of Axial Effects in the TRAC-PF1/MOD1 Heat Conduction Solution During Quenching," AEEW-M 2552 (June 1989). The model for which all simulations were performed consisted of a CORE component containing a single rod of typical PWR construction, a FILL component to provide reflood water, and a BREAK component providing a back pressure at the outlet. The CORE component was subdivided into 20 equal hydraulic cells. The calculations are initiated with all but the bottom cell in dryout. The bottom cell is initially quenched. The quench front then advances as the reflood water flows in.

A series of simulations was performed for each of the two extremes likely to be encountered. These were (1) high temperature ahead of the quench front combined with a low reflood rate, and (2) low temperatures ahead of the quench front combined with a high reflood rate. For each series of simulations the parameter DZNHT was varied from 5.0 to 0.1. The results for the low-temperature/high-flow case are in the form of cladding temperature histories at successive elevations for four separate values of DZNHT (Fig. A-29). There are small differences in the quench time at elevations up to 50 cm. There are also small differences in the apparent quench temperatures. Overall, the changes are not very significant. The results of a similar series of calculations for the high-temperature/low-flow case (Fig. A-30) show a much larger effect of DZNHT. Reducing the value of DZNHT leads to an earlier quench time at each elevation and a higher apparent quench temperature. These results strongly suggest that a choice of 5 mm for DZNHT will produce a rather poor representation of the quench front. The author suggests a value in the range of 0.2 to 0.5 mm.

Additional simulations were performed for the high-temperature/low-flow case to determine the effect of the axial conduction term on the quench-front speed. This was done with a version of the code having the axial term removed from the conduction equation. The quench-front speed was reduced 35-45% when the axial term was removed. The dependence of the solution on time-step size and mesh size disappears almost completely for this case. The absence of the axial conduction term also has a significant effect on the distance over which the temperature rise occurs at the quench front. That distance was about 1.5 mm with no axial conduction term and closer to 2.5 mm with that term included.

Additional calculations are performed using a version of the code that does not use the smoothing/limiting techniques applied to the calculation of the surface-to-coolant HTC. The author concludes that at least a part of the effect seen in going to a small time step is attributable to heat-transfer smoothing. He suggests that the heat-transfer smoothing be done on a per-second rather than a per-time-step basis. It is also recommended that the conduction solution in TRAC be changed to a fully-implicit formulation.

Run-time data is presented for eight simulations. Grind times are in the range of 2.18 - 2.82 s based on the typical minimum time step.

R. O'Mahoney, "Time Step and Mesh Size Dependencies in the Heat Conduction Solution of a Semi-Implicit, Finite Difference Scheme for Transient Two-Phase Flow," AEEW-M 2590 (July 1989). This report is not intended primarily as an assessment of the TRAC code. Its purpose is to establish the cause of time-step and mesh-size dependencies identified in a previous report (AEEW-M 2552) by the same author. These dependencies are related to the coupling between the hydrodynamic equations and the heat conduction equations used to calculate the temperature distribution in fuel rods. The coupling takes place via the surface heat transfer between the rod and the surrounding fluid. The convective conductance at the surface depends on the surface temperature and fluid properties. It provides a surface boundary condition for the heat conduction equation and contributes to the energy- and mass-conservation equations for the fluid.

The finite-difference representation of the conduction equation is implicit in the radial direction but explicit in the axial direction. Of particular significance is the explicit treatment of the convective boundary condition. The heat transfer coefficient is calculated using surface temperature and fluid conditions from the previous time step. The author shows that this explicit evaluation, taken together with the smoothing that is applied to the HTC, is the major cause of the time-step-size dependency. Sensitivity studies show that reducing the time step causes the solution to asymptotically approach the numerically correct result. However, the time step required for good accuracy, particularly for reflood calculations, may be significantly smaller than that determined by the Courant limit and may severely increase CPU time.

Additional calculations showed there was also an axial-mesh-size dependency. This was found to be much smaller than the time-step-size dependency. The author suggests that some computation method should be found to improve or replace the explicit heat transfer coefficient evaluation and that the time-step-size dependency be removed from the heat-transfer-smoothing technique.

4. CODE PREDICTIONS AND COMPARISONS WITH DATA

The FY 1990 ICAP assessments covered a large number of important phenomena (Table I, Chap. 2) and calculated several key parameters (Table II, Chap. 2). These assessments were written during the period from April 1986 to July 1989 and used TRAC-PF1/MOD1 Versions 11.0 to 14.3 (see Table III). The code has been continually upgraded over the past several years so that some of the difficulties encountered with earlier versions of the code may have been corrected in later versions. The upgrades made in later versions of TRAC are discussed in Chap. 7.

TABLE III
PUBLICATION DATES AND TRAC VERSIONS FOR ASSESSMENTS

Assessment	Date	TRAC-PF1/MOD1 Version
GD/PE-N/557	March, 1987	13.2
ICSP-LB-SB-2-T	April, 1987	12.7
AEEW-M 2416	February, 1987	12.2
AEEW-R 2288	November, 1987	12.2
AEEW-M 2305	April, 1986	11.9
ICSP-LP-02-06	January, 1988	11.0
ICSP-LP-FP-1	July, 1988	11.0
SETh/LEML/89-165	March, 1989	14.3
Strathclyde-SB291-1	Not given	14.3
RD/L/3455/R89	February, 1989	13.0
AEEW-R 2478	February, 1989	11.0
AEEW-R 2328	February, 1988	13.0
AEEW-M 2552	June, 1989	13.0
STUDSVIK/NP-88/101	November, 1988	14.0
ICSP-R2MSIV-T	February, 1988	14.0
AEEW-M 2590	July, 1989	13.0
Strathclyde-SB291-2	July, 1989	13.0*

* Modified

This chapter presents the most significant results of the assessment calculations and compares those results with experimental data. The discussions that follow are organized according to key phenomena of interest to PWR applications. These are divided into the three major categories of secondary system behavior, primary-loop phenomena, and vessel phenomena.

4.1. Secondary-System Behavior

4.1.1. Secondary-Side Pressure

The simulation of the feedwater-line isolation transient in the Ringhals 4 Power Plant (STUDSVIK/NP-88/101) includes a calculation of the secondary-side pressure distribution. Those results are compared with experimental data in Fig. 1. The pressure increased 50 s after the beginning of the transient coincident with a sharp decrease in steam flow rate. The measured pressure profile was reasonably well predicted by the calculations.

4.1.2. Secondary-Side Steam-Generator Heat Transfer

A comparison of calculated and measured primary-side average temperatures for STUDSVIK/NP-88/101 is shown in Fig. 2. The temperature increased prior to reactor trip because of less efficient heat removal on the secondary side when the feedwater flow ceased and the throttling of the turbine valves was activated. The author suggests that the difference between the measured high average temperature and the calculated value exists because the measurement represents the highest value from the three loops whereas the calculated value represents an average value for the three loops. Nevertheless, the agreement is satisfactory.

The PATRICIA-SG1 tests simulated a U-tube steam generator for a wide range of mass-flow rates. Spindler and Pellissier (SETh/LEML/89-165) performed simulations of several of these tests. Their calculated profiles of thermal resistance vs inlet quality for the first two sections of the tube are compared to experimentally measured values in Fig. 3. In the first part of the test section, the experimental thermal resistance values are much higher than the calculated values but agreement is much better in the second segment of tube. The discrepancies are attributed to the low accuracy of the temperature measurements.

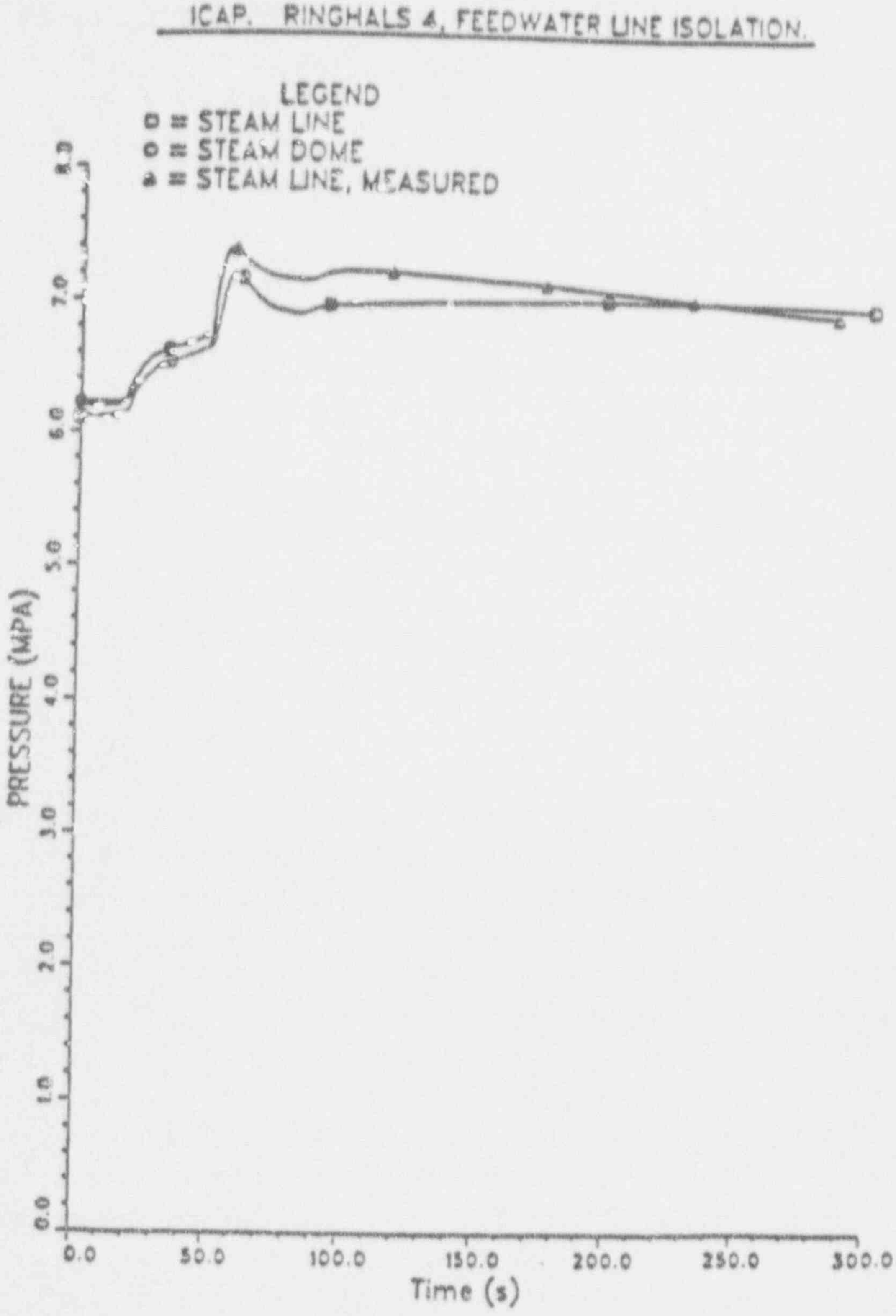

Fig. 1. Secondary-side pressure profile (STUDSVIK/NP-88/101).

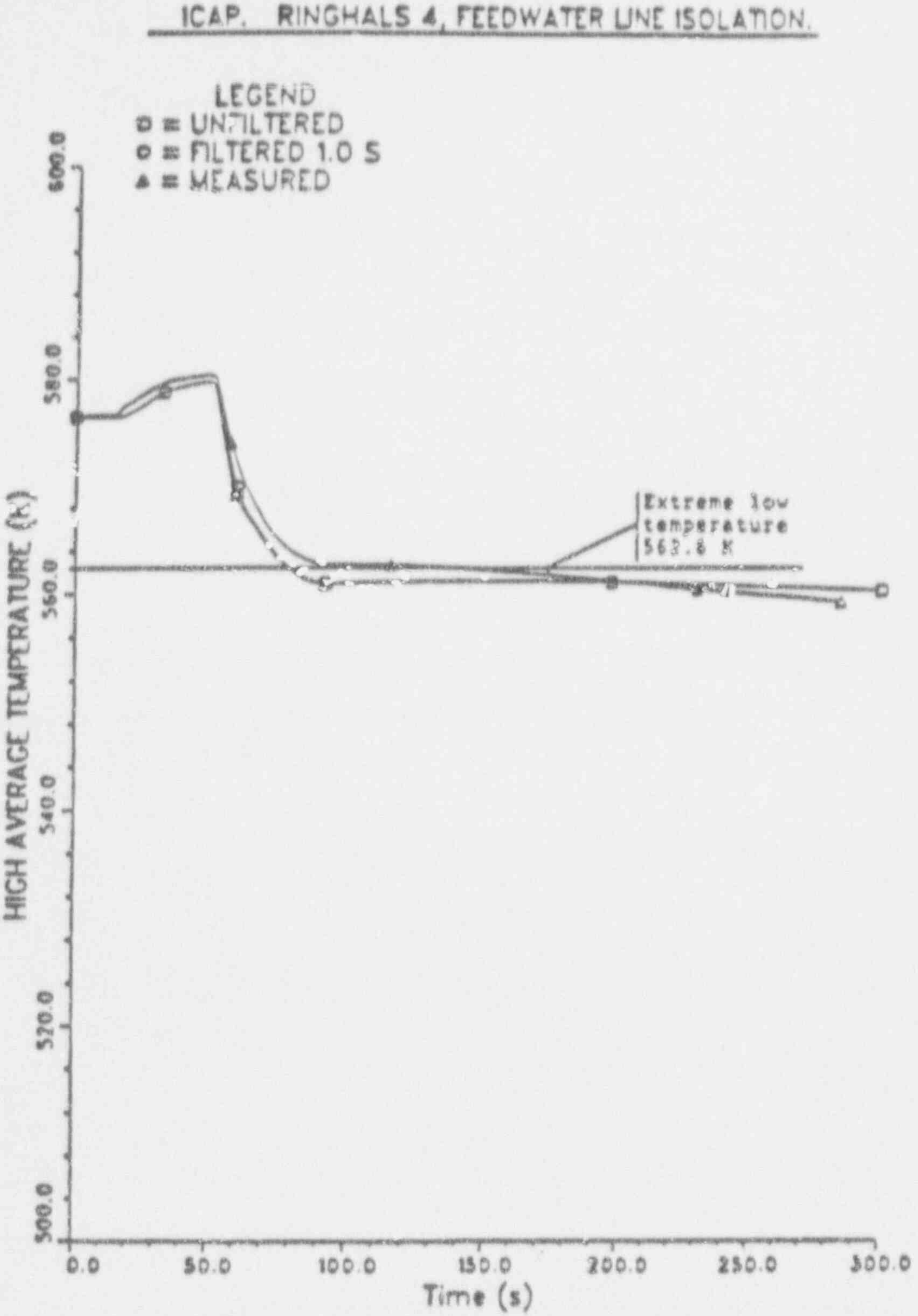

Fig. 2. Primary-side average temperature profile (STUDSVIK/NP-88/101).

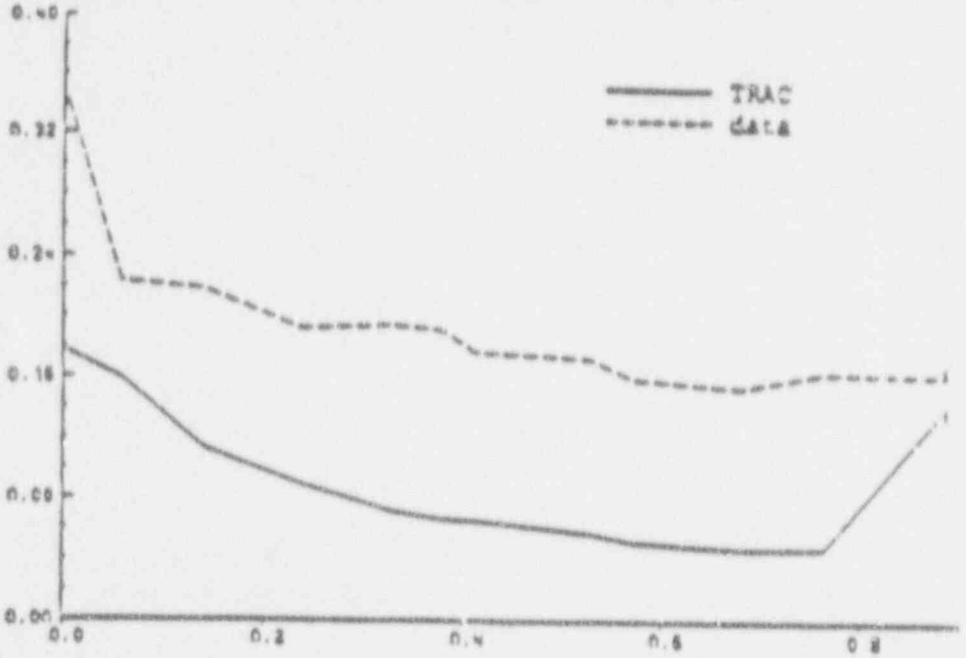

Fig. 3a. PATRICIA-SG1, Series 1, thermal resistance in the first part vs inlet quality (SETh/LEML/89-165).

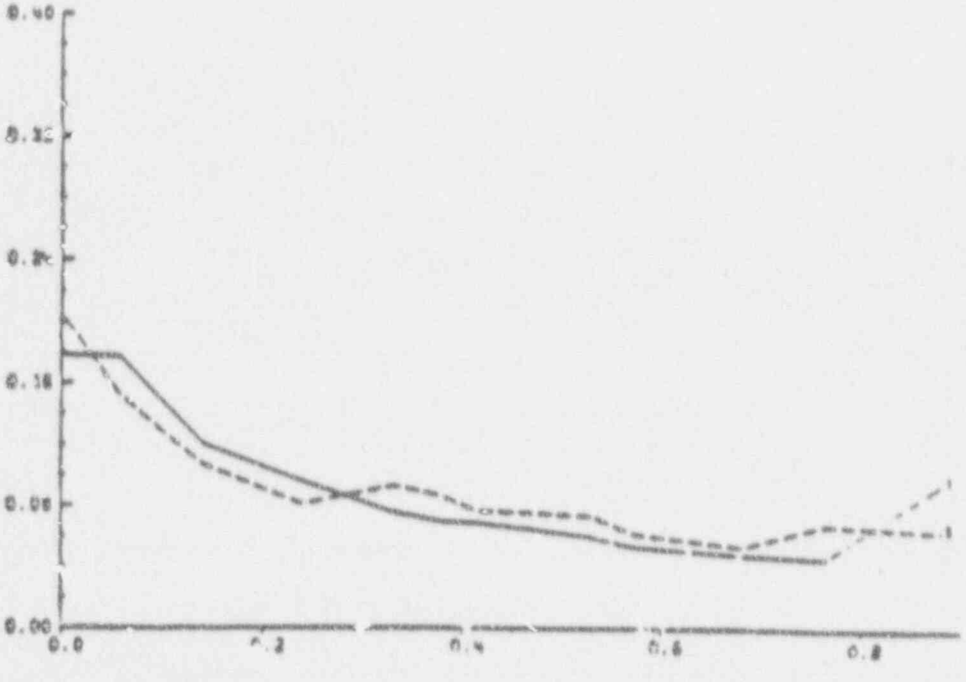

Fig. 3b. PATRICIA-SG1, Series 1, thermal resistance in the second part vs inlet quality (SETh/LEML/89-165).

4.1.3. Mixture Level and Entrainment in the Steam Generator

The calculated steam-generator level for the transient in the Ringhals No. 4 power plant (STUDSVIK/NP 88/101) is compared to measured values in Fig. 4. The agreement was satisfactory until the low-level-trip set point (33%) was reached. At that time an oscillation in the calculated level signal was encountered that had no correspondence in the collapsed level nor in the measurements. These oscillations, however, were not present in a later calculation that used smaller node spacing in the downcomer of the steam generator.

An assessment of a transient in the Ringhals 2 power plant caused by an inadvertent steam-line isolation valve closure (ICSP-R2MSIV-T) gave somewhat similar results. Agreement of calculated results with measured data was similar to that found in the STUDSVIK/NP-88/101 report.

4.2. Loop Phenomena

4.2.1. Mixing and Condensation During ECC Injection

The separate-effects assessment of the EPIS-2 tests by Spindler and Pellissier (SETh/LEML/89-165) simulates the behavior of an ECC injection system. A comparison of the experimental pressure distribution to that predicted by TRAC is shown in Fig. 5 for Test 81.23. The measured pressure exhibits an increase near the injection point caused by condensation and vapor deceleration followed by an increase attributed to liquid acceleration downstream of the injection point. The predicted pressure shows only the sharp decrease. The authors conclude that the condensation model was not satisfactory for these tests.

4.2.2. Break Flow

Break flow was calculated for the SBLOCA of LOFT experiment LP-SB-2 by Pelayo (ICSP-LP-SB-2-T). A comparison of these results with experimental data showed an overprediction of mass loss from the primary system. The author concluded that for transients where phase separation upstream of the break affects the break density, the predictive capability of the code could be improved by incorporating a model relating quality in a branch to the thermal-hydraulic conditions in the main pipe. A second simulation was made with a modified version of TRAC that included an algorithm to control the quality in the break line as a function of the void fraction in the hot leg. These results were in better agreement

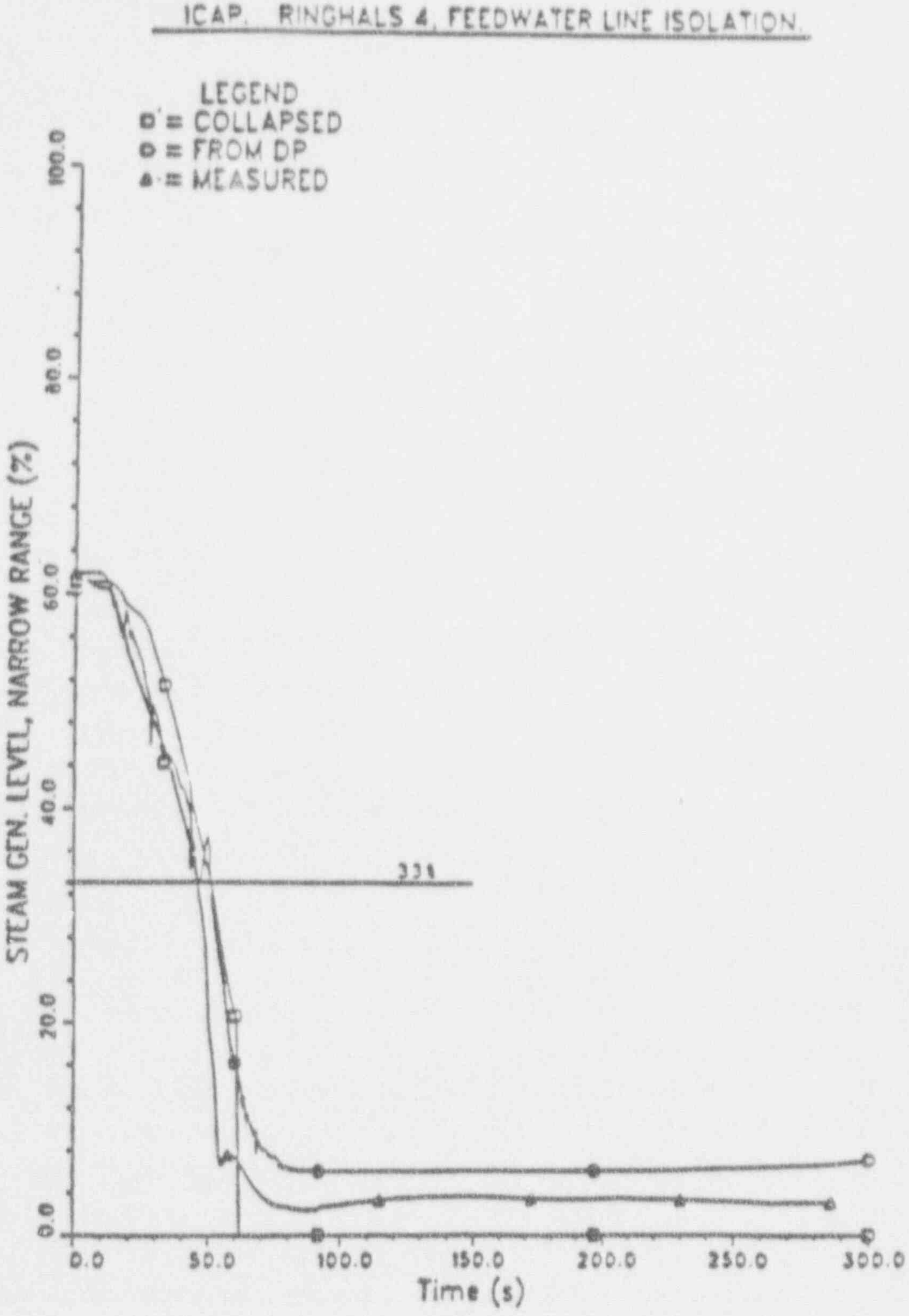

Fig. 4. Steam-generator level vs time (STUDSVIK/NP-88/101).

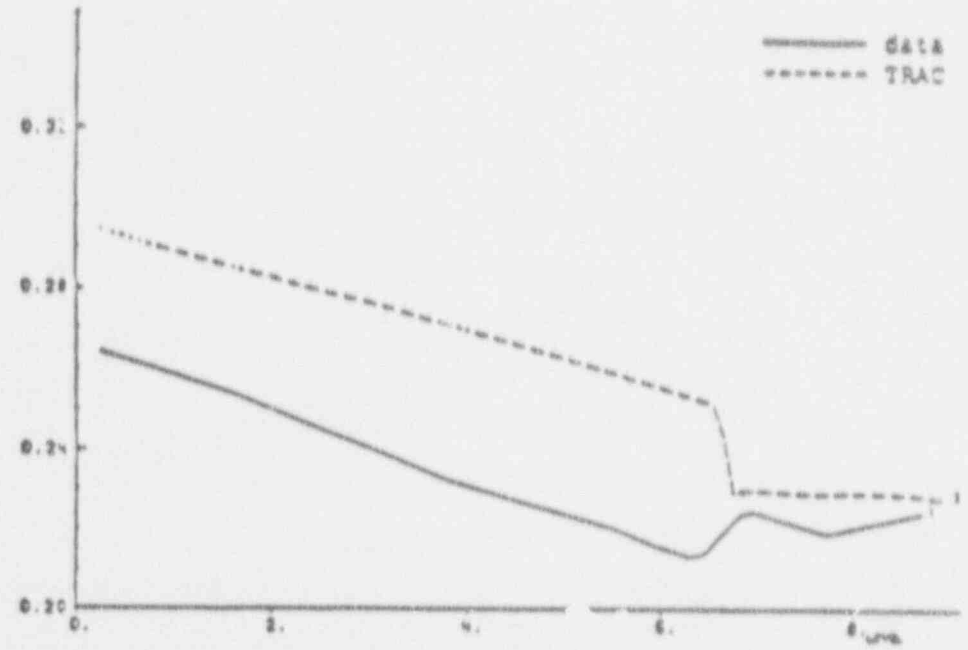

Fig. 5. Steady-state pressure distribution for EPIS-2, Test 81.23 (SETh/LEML/89-165).

with experimental data. The results of these calculations are shown in the complete assessment review in the Appendix.

The LBLOCA test LP-02-6 performed in the LOFT facility was simulated in the AEEW-R 2288 assessment report. A comparison of calculated and measured profiles of the broken-loop hot-leg flow rates is shown in Fig. 6. The mass flow are accurately predicted during the first 10 s. The calculation appears to underpredict the hot-leg break flow toward the end of reflood, although it is difficult to assess to what extent this is a result of the instrument uncertainty.

A similar comparison for LOFT LP-LB-1 (AEEW-R 2478) is shown in Fig. 7. The TRAC predictions underestimate the initial flow rate (a peak value of 140 compared to the measured value of 180 kg/s) and also underestimate the flow rate between 3 and 10 s. Overall agreement is relatively good, however, and is within the experimental data error band.

4.2.3. Stratification in Horizontal Pipes

The break flow in LOBI Test BL-02 (AEEW-M 2416) is somewhat overpredicted. The author speculates that this may be partially caused by the lack of an offtake model in TRAC that accounts for stratified flow in a horizontal pipe. This led to the development at Winfrith of an improved offtake model that was added to a later version of TRAC.

The author also notes that if a small break LOCA occurs near a pump the mechanical mixing in the pump could noticably affect the onset of stratification downstream of the pump. The code does not simulate this effect.

4.2.4. Loop-Seal Clearance

A result of the overprediction of the break flow in LOFT Test SB-2 (ICSP-LP-SB-2-T) is premature loop-seal clearance in the broken loop. A significant qualitative difference between the experiment and calculated behavior is the failure of the intact-loop seal to clear in the calculation. The author gives a rather detailed discussion of the phenomena that contribute to differences between numerical predictions and experimental data. He suggests some areas in the code that may contribute to these differences. These include underprediction of interphase friction, inadequacy of the heat-structure modeling, and possible overprediction of condensation rates.

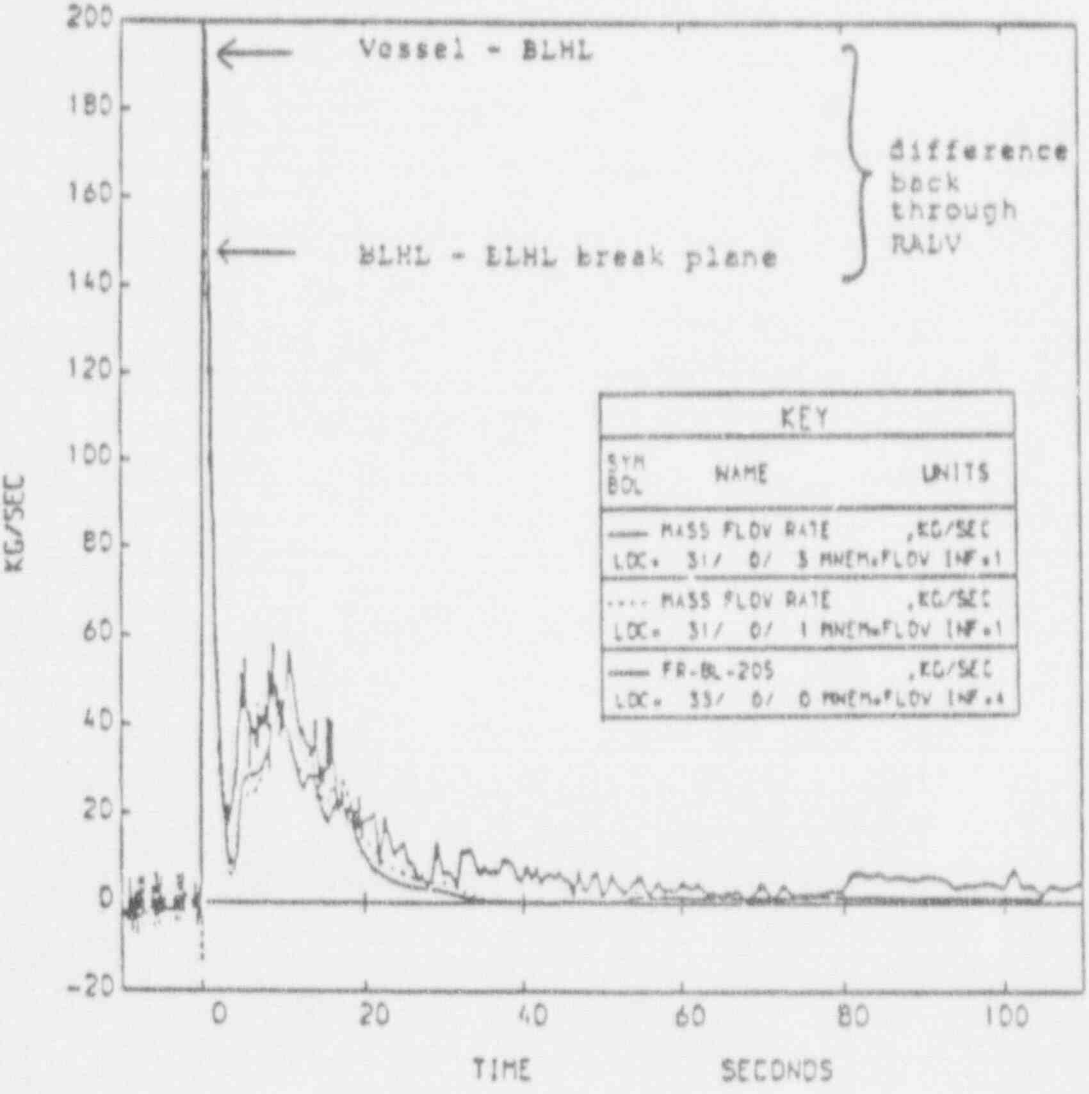

Fig. 6. Broken-loop hot-leg flow (AEEW-R 2288).

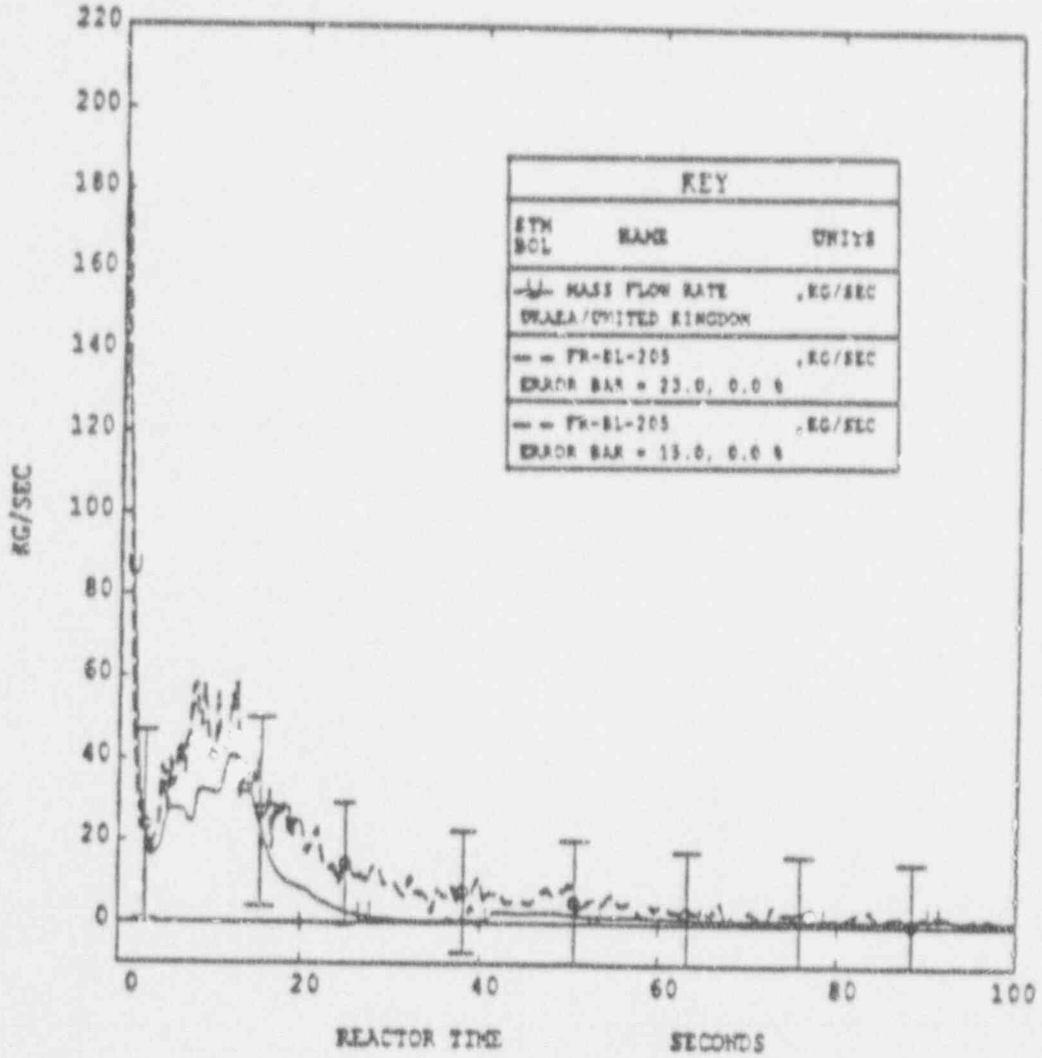

Fig. 7. Broken-loop hot-leg mass-flow (AEEW-R 2478).

4.2.5. One- and Two-Phase Pump Behavior

An important aspect of LOBI Test BL-02 (AEEW-M 2416) was the behavior of the pumps. The velocities predicted by the code after the pump's degradation werenot entirely satisfactory and the steady fall in the velocity observed in the experiment was not reproduced by the calculations. One area of uncertainty was the performance of the pumps under two-phase conditions. The intact loop of the facility contains two similar pumps working in parallel. The strong coupling between these pumps constitutes a potential source of instability when asymmetric perturbations in flow conditions are felt at the pump inlets.

4.2.6. Pressurizer Thermal Hydraulics

The pressurizer pressure profile was calculated for the Ringhals 4 power-plant transient (STUDSVIK/NP-88/101). A comparison of those results with experimental data is shown in Fig. 8. Agreement is good for the first 200 s. At times greater than 200 s, the calculated cooling of the primary side was less than the measurements, causing temperatures and pressures higher than those measured.

Similar results are shown for the Ringhals 2 power plant transient (ICSP-R2MSIV-T) in Fig. 9. The initial calculation was rerun with a modified gap-conductance value. That modification was made in an attempt to more accurately represent the energy stored within the fuel during steady state. The results of that calculation were in better agreement with measurements. The author noted, however, that during the insurge period excessive vapor superheat was observed and that contributed to the excessive pressurization rate.

4.2.7. Primary-System Pressure

Both primary- and secondary-loop pressures were compared with experimental data (see Fig. A-7) for LOBI Test BL-02 in the assessment report AEEW-M 2416. In general, the agreement is reasonable. The primary side pressure initially drops rapidly but levels out somewhat when high-pressure injection begins. The pressure drop becomes steeper again after loop-seal clearance in the broken loop.

A comparison of calculated and measured pressures in the broken-loop cold leg for LOFT LP-LB-1 (AEEW-R 2478) is shown in Fig. A-26. The calculations show a reasonably good agreement up to about 12.5 s. After 24 s the absolute pressure is lower in the TRAC calculation because of a more rapid fall in pressure between

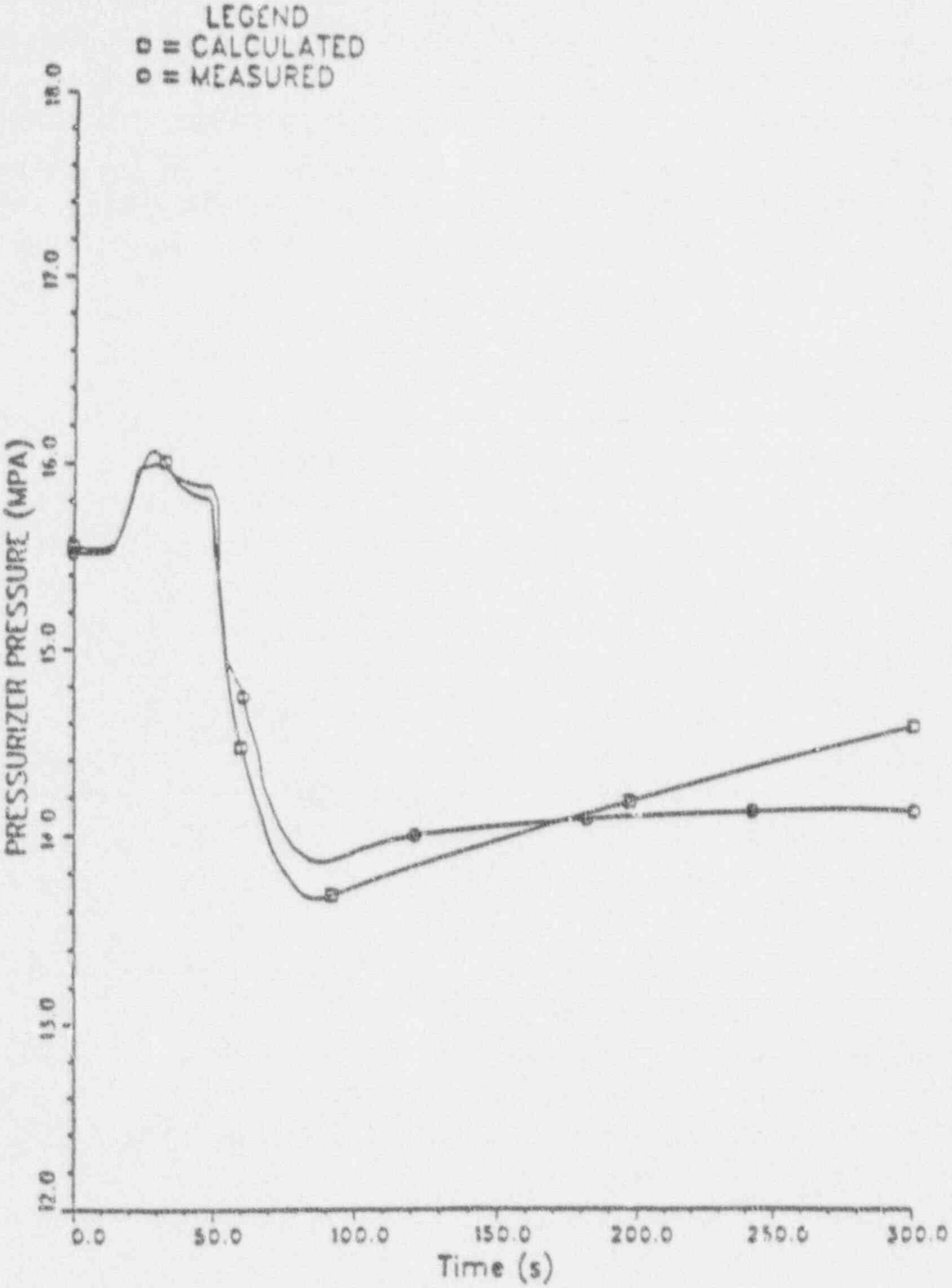

Fig. 8. Pressurizer pressure profile (STUDSVIK/NP-88/101).

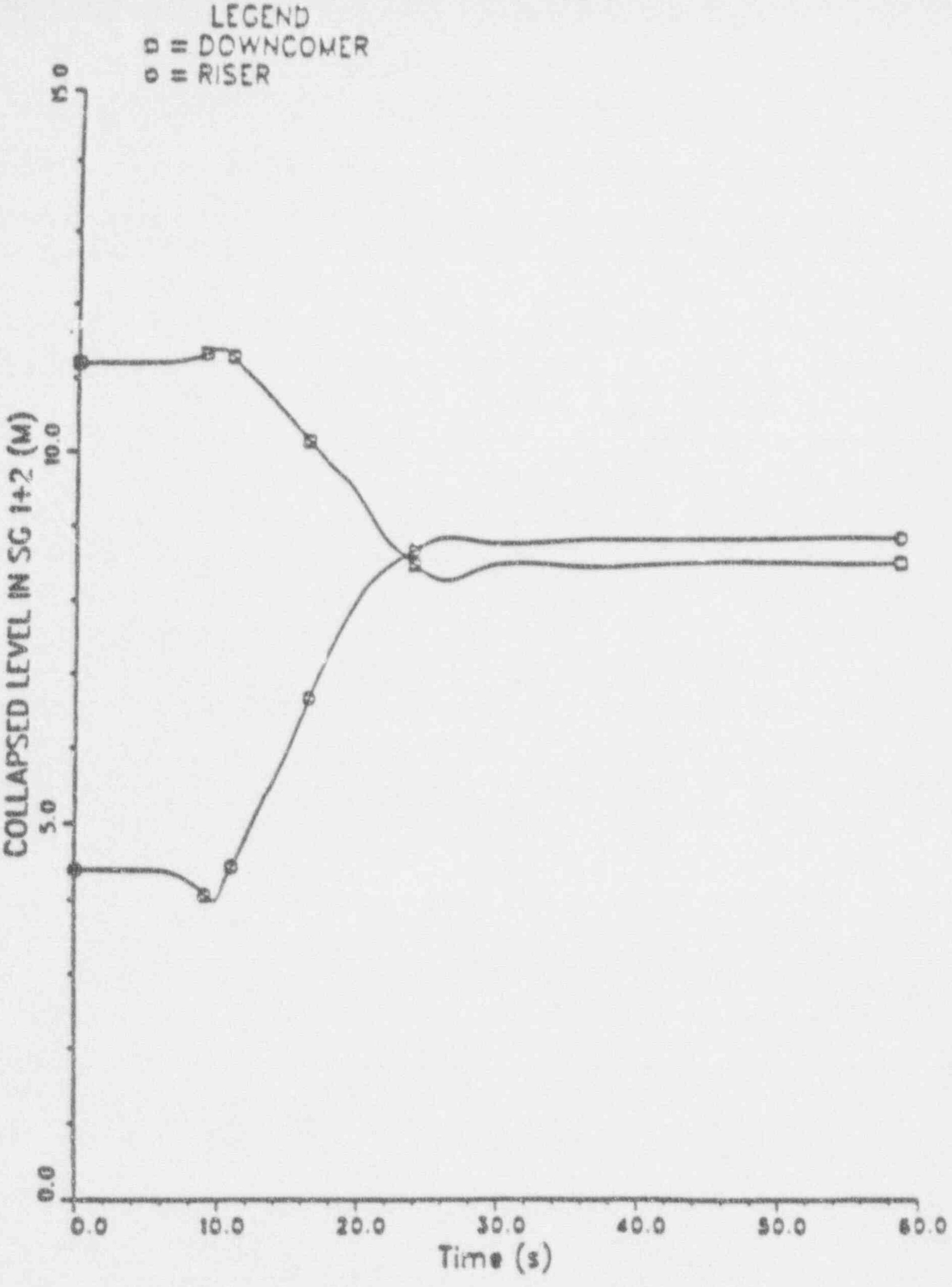

Fig. 9. Collapsed level in steam generator (ICSP-R2MSIV-T).

about 10 and 15 s, so that the TRAC and experimental pressures do not begin to fall into line until after about 30 s. The agreement between the calculated and experimental pressures after 40 s is very good.

4.2.8. Primary-System Flow Rate

The mass-flow rate in the hot leg calculated for LOFT LP-SB-2 (ICSP-LP-SB-2-T) is compared with experimental data in Fig. 10. Agreement is quite good up to 1500 s.

Mass-flow rates were also calculated for the intact loop for LOFT LP-LB-1 (AEEW-R 2478). Those results fell within the error bands for the experimental data.

4.3. Vessel Phenomena

4.3.1. Core-Wide Void and Flow Distribution

A detailed 3D model of the vessel was used in the LOFT-LP-LB-1 calculations (AEEW-R 2478). The fluid velocity and fluid momentum flux in the lower plenum are shown in Figs. 11 and 12. The fluid velocity measurement shows absolute values only, so that the level of agreement is difficult to judge. The calculation does accurately predict a downflow of liquid during the blowdown phase (0 to 20 s) as can be seen from the negative value of the lower-plenum momentum flux. The amplitude of the oscillations calculated for the momentum flux is somewhat larger than the measured values during the time period between 40 to 45 s, when subcooled liquid from the accumulator is flowing into the downcomer from the intact loop.

4.3.2. ECC Bypass and Penetration

The assessment performed by Dempster et al. (Strathclyde-SB291, Phases 1 and 2) compared calculated results for bypass in a vessel downcomer to data from the Strathclyde 1/10-scale facility. TRAC was found to underpredict the amount of bypass. They concluded that the interfacial-drag modeling in TRAC and the entrainment correlations were unlikely to be appropriate for the conditions that exist in the vessel downcomer. Additional calculations, performed using a modified version of the code that used a conservative form of the momentum equations, produced better results. Only four sectors were used in the vessel nodalization. A study showed that this nodalization was not sufficient to produce a converged solution. The effect this may have had on the results of the calculations is not clear.

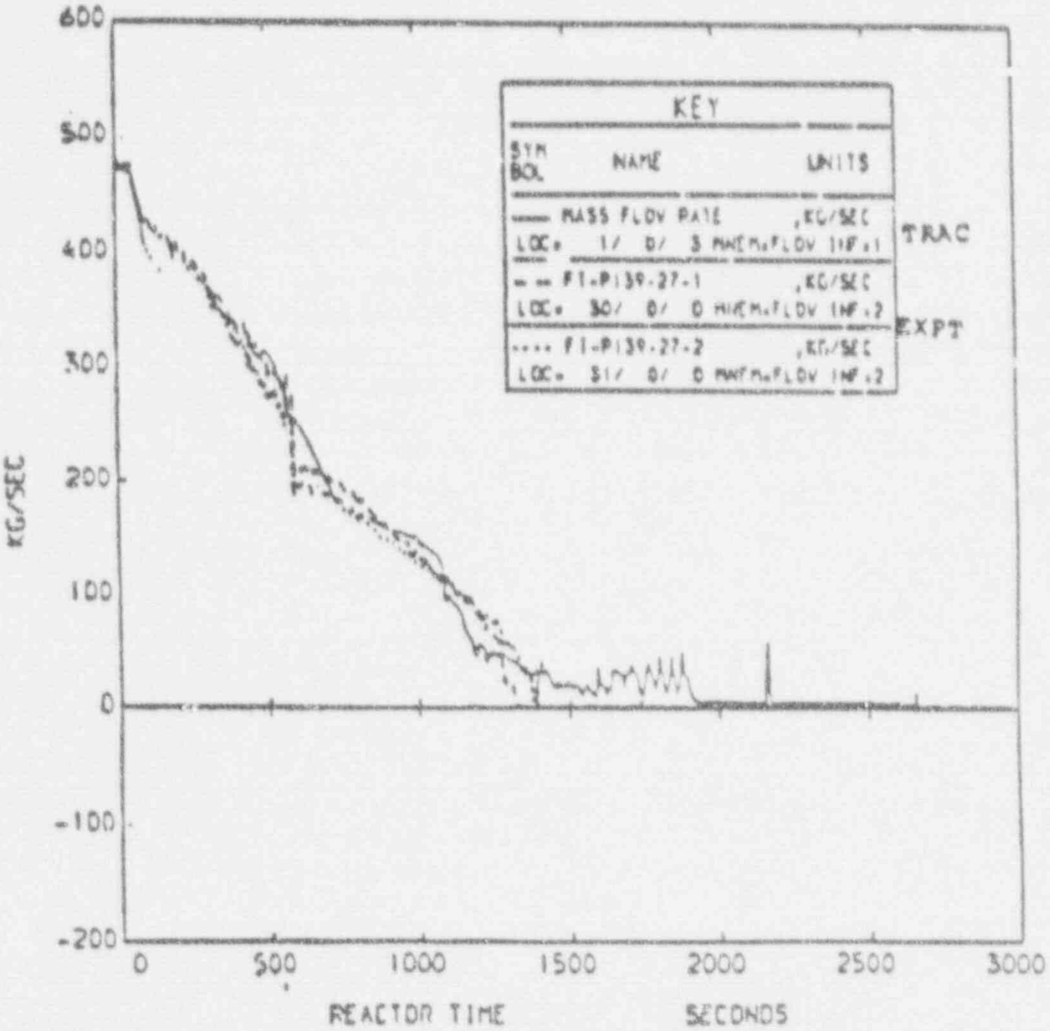

Fig. 10. Hot-leg mass-flow rate (ICSP-LP-SB-2-T).

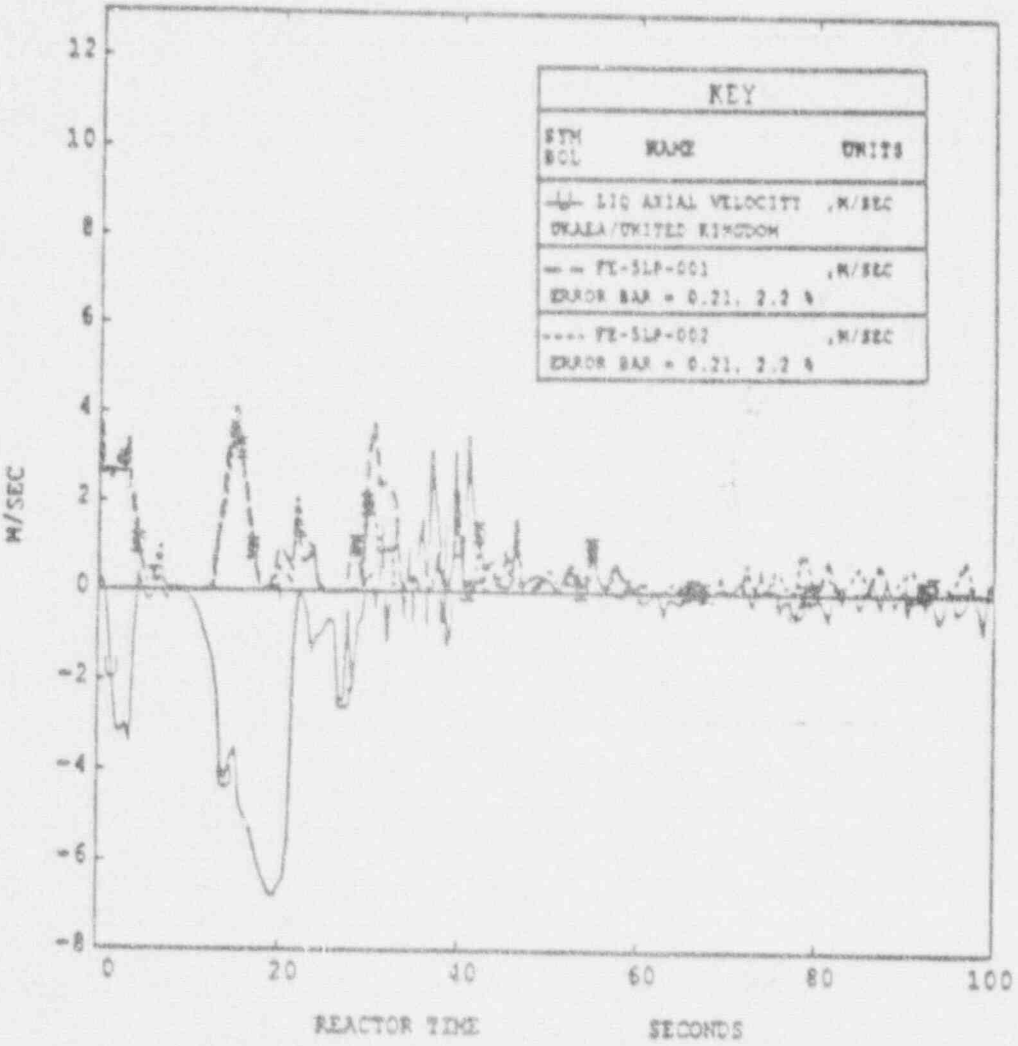

Fig. 11. Liquid axial velocity profile (AEEW-R 2478).

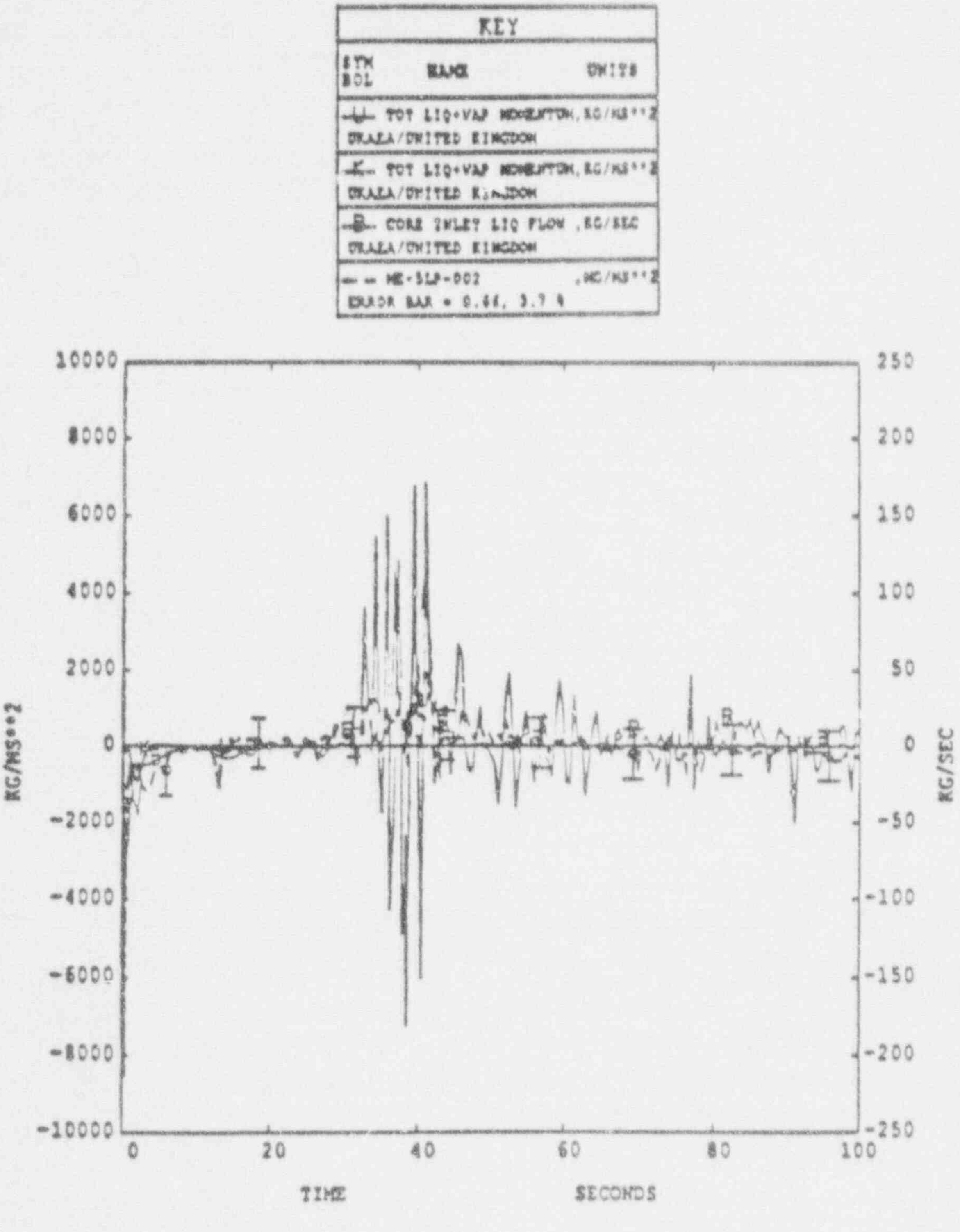

Fig. 12. Lower-plenum momentum flux (AEEW-R 2478).

Turner also studied countercurrent flow in a PWR downcomer (RD/L/3455/R89). The results of his calculations were compared to data taken from the CREARE countercurrent flow experiment. In general, the lower-plenum filling rates were underpredicted. This is the opposite of the results obtained at Strathclyde. A major thrust of this assessment was a comparison of results produced by modified versions of the code to those produced by the standard version. The use of a more conservative form of the momentum equation gave somewhat better results. A nodalization study showed that an eight-sector grid gave better (less oscillatory) results than the four-node grid.

4.3.3. Core Heat Transfer Including Partially Covered Core

Fuel-rod cladding temperatures were calculated for the highest-power fuel rods for LOFT LP-02-6 (AEEW-R 2288) at several axial locations. A comparison of TRAC predictions with experimental data for one axial location is shown in Fig. 13. The magnitude of the initial peak was overpredicted by about 200°C. The author believes the major cause of this discrepancy is a significant overprediction of the initial stored energy in the fuel. There was some question as to the size of the fuel-cladding gap. A more recent calculation using a zero gap gave much closer agreement for the initial temperature peak. The predicted quench time is significantly later than the measured time. It is not possible to determine whether this is the result of a poor reflood model or whether the fluid-level profile lags behind the actual values. There are no measurements of water levels within the core. An additional uncertainty is the effect of the thermocouples themselves on the local temperature history.

A separate-effects assessment carried out by O'Mahoney (AEEW-M 2305) simulated the THETIS experimental rig at Winfrith. The facility consists of a single cluster of powered rods in a shroud tube housed in a pressure vessel. Reflood is simulated by the upflow of water through the assembly. Cladding temperatures are measured with thermocouples at various axial locations. A comparison of calculated and measured temperatures at an elevation of 2 m for Run No. 65 is shown in Fig. 14. The TRAC prediction is reasonable up to 180 s. After that time the predicted temperature falls too fast, leading to an early quench. A series of modifications were made in an effort to improve the reflood calculations. The prediction of liquid entrainment in reflood was improved but the cladding-temperature calculations were not greatly improved.

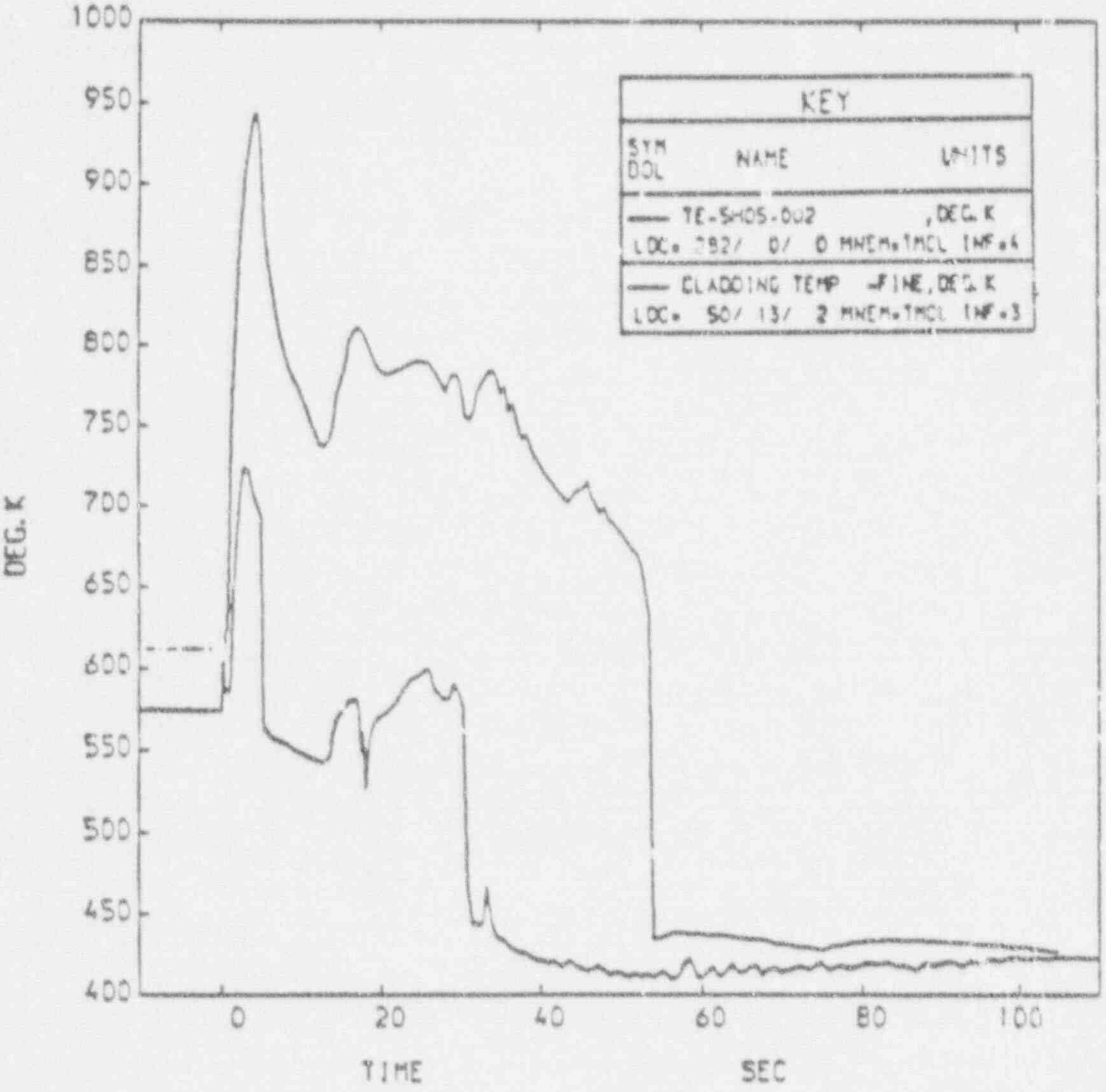

Fig. 13. Cladding temperature profile at 2-in. elevation (AEEW-R 2288).

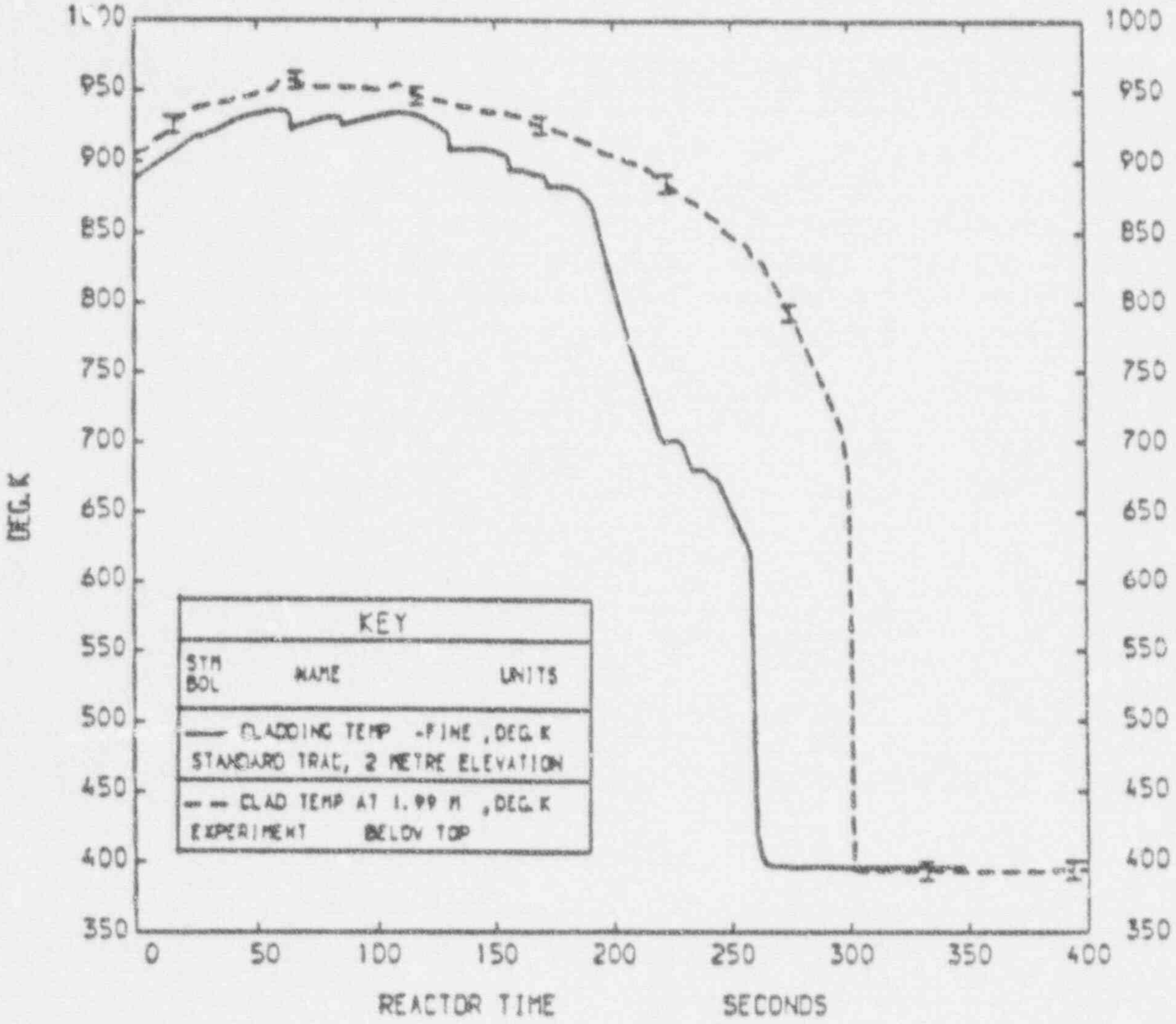

Fig. 14. Cladding temperature profile at 2-m elevation (AEEW-M 2305).

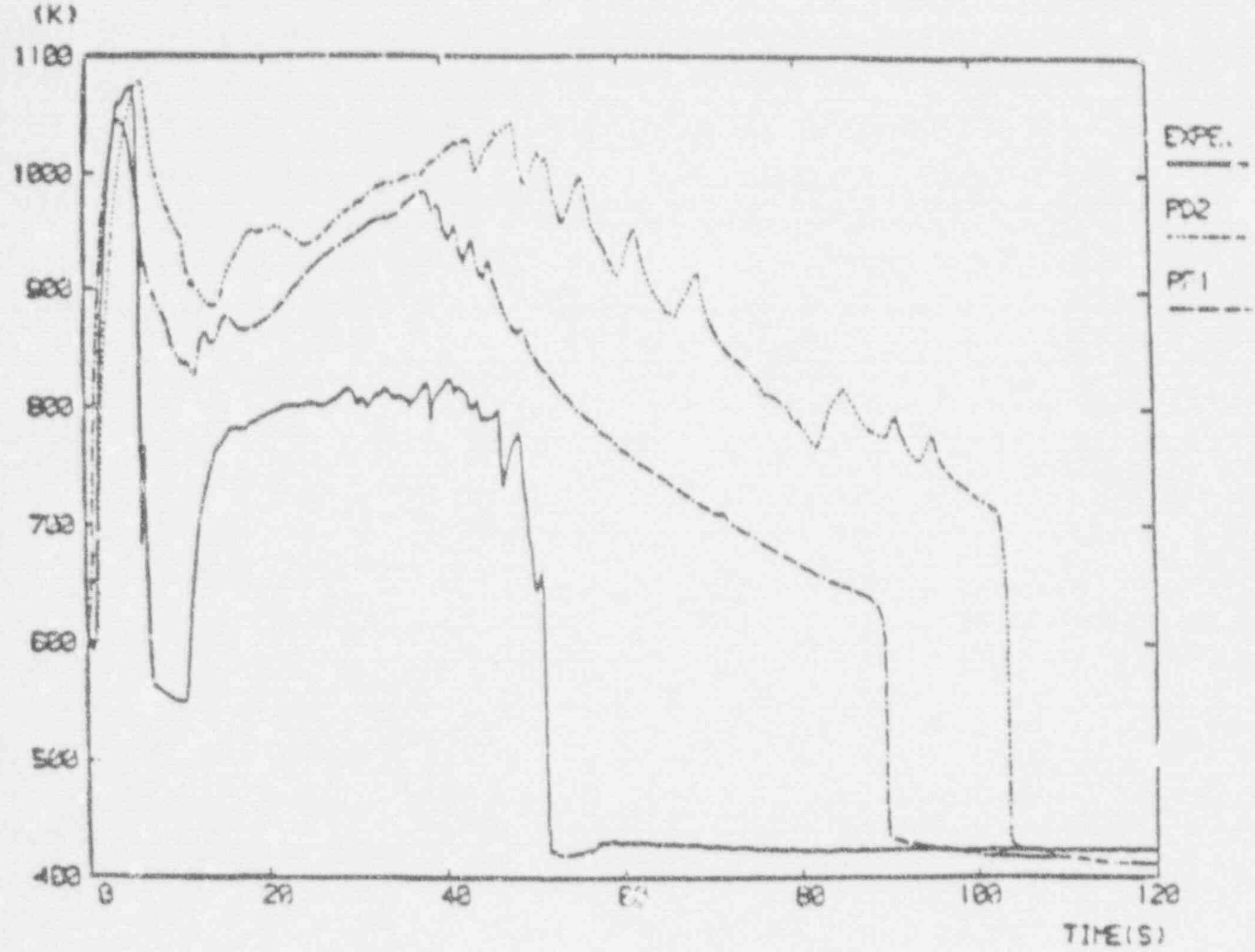

Fig. 15. Cladding temperature profile at 0.647-m elevation (ICSP-LP-02-06).

A comparison of calculated and measured cladding temperatures for LOFT LP-02-6 (ICSP-LP-02-06) is shown in Fig. 15. The peak temperature was accurately predicted by the code but the time of quench was not.

Cladding temperatures for LOFT LP-LB-1 (AEEW-R 2478) are shown in Fig. 16. The agreement is very good up to the time of reflooding of the core at 40 to 45 s. After 45 s the code predicts that the cells adjacent to the rod contain a large fraction of liquid, which produces an overestimate of the clad-to-coolant heat transfer so that initially the simulated fuel rods cool faster than those in the experiment. Subsequently, however, the quench progression in the actual fuel rods is significantly faster than the predictions.

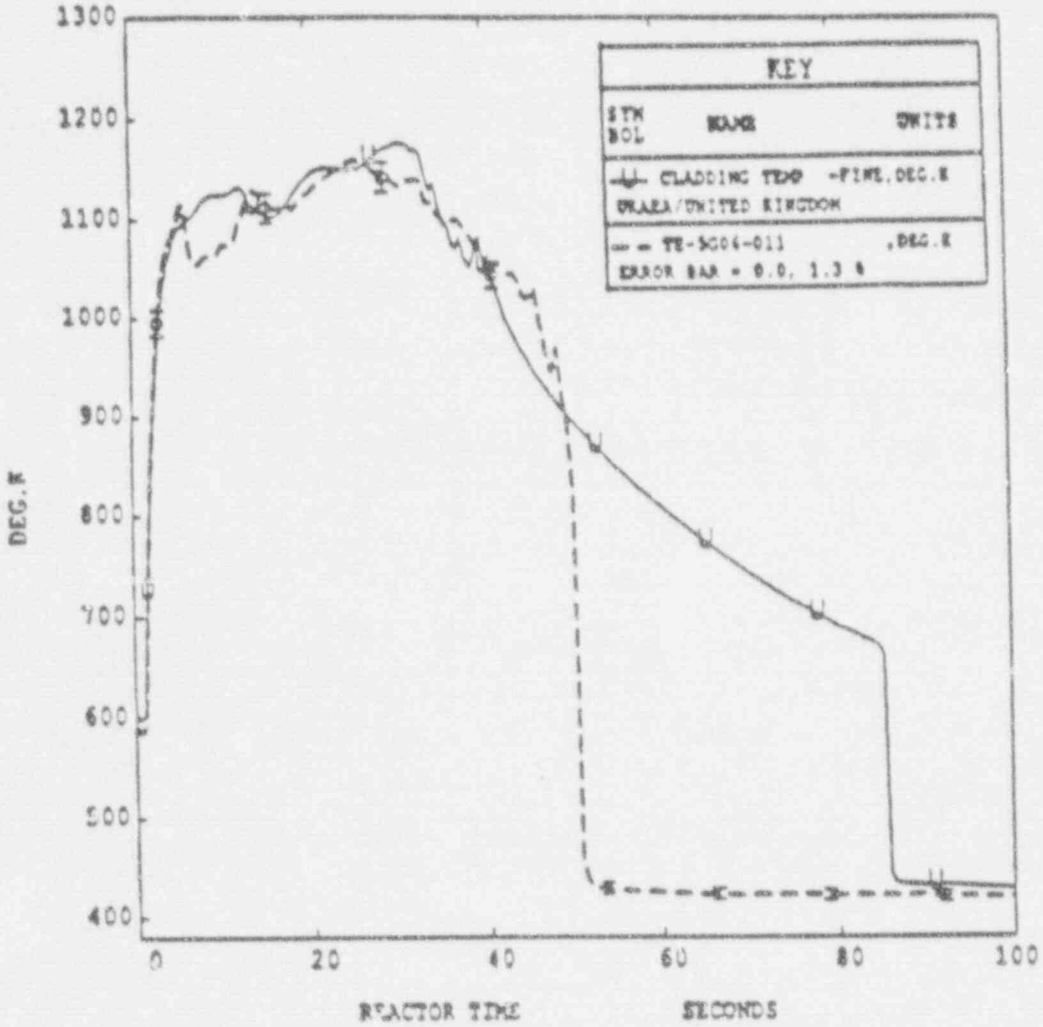

Fig. 16. Cladding temperature profile at 11-in. elevation (AEEW-R 2478).

5. SYNOPSIS OF NODALIZATION AND SENSITIVITY STUDIES

Some of the ICAP assessment reports included sensitivity or nodalization studies. Sensitivity studies were performed in many cases where the authors discovered a weakness in the code that they perceived to be caused by a particular algorithm or empirical correlation used in the code. The sensitivity of the results to changes in those algorithms or correlations was often determined by performing a series of simulations in which the algorithm was altered or alternate correlations were used.

Nodalization studies were performed in several assessments, particularly for heat structures during reflood conditions and for reactor vessels when bypass of ECC injection was possible. The sensitivity and nodalization studies reported in the ICAP assessments are discussed in the remainder of this chapter.

5.1. Sensitivity Studies

K. H. Ardron and A. J. Clare, GD/PE-N/557. The accuracy of the interphase-drag correlations used in TRAC-PF1/MOD1 was determined by comparing void fractions calculated from those correlations to void fractions found from standard correlations and test data. TRAC uses a two-fluid model in which separate momentum equations are solved for the gas and liquid phases. Calculations were performed for both upflow and downflow in the bubbly- and slug-flow regimes ($\alpha_g < 0.75$). Calculations were performed for various values of pipe diameter and pressure. Results of calculations using the TRAC algorithms were compared to results calculated using the Wilson (Ref. 5) and Rooney (Ref. 6) correlations for upflow and to the data of Petrick (Ref. 7) for downflow.

The authors conclude that the drag models used in TRAC-PF1/MOD1 are reasonably accurate for vertical flows. Errors in the two-phase mixture density increase with decreasing liquid flow, increasing vapor flow, increasing pipe size, and decreasing pressure. For upflow, at the pressures of interest in modeling SBLOCAs, the errors in two-phase mixture density are not grossly different from errors normally expected in applying standard correlations for void fraction. For downflow, the code models perform very well in comparison with the limited void fraction data available.

F. Pelayo, ICSP-LP-SB-2-T. A base-case calculation was performed using the unmodified version of TRAC. A second calculation was performed to determine the effect of controlling the quality in the break line as a function of the quality in the hot leg. The pump-head multipliers were also modified in an effort to reproduce better the asymmetric pump behavior. The pump-head multipliers were modified to force a sharp degradation at an inlet void fraction of 0.35, and the multipliers for Pump No. 1 were further modified to try to reproduce the asymmetrical pump behavior after degradation.

These changes did greatly improve the accuracy of the break-flow-rate calculation. The density in the break line matched the experimental data much more closely for the entire transient. There were also significant improvements in the predictions of primary pressures and temperatures, primary mass inventory, and vessel inventory and rod temperatures.

R. O'Mahoney, AEEW-M 2305. In this assessment the TRAC code was used to simulate reflood tests performed in the THETIS rig at Winfrith. Sensitivity studies were conducted to determine the effects of various modifications in the ISM. That model attempts to compensate for the fact that the interfacial shear package is not necessarily representative of the physical processes occurring during reflood. The model operates by explicitly attempting to limit the upward flow of liquid at a liquid/vapor interface according to an entrainment correlation.

A series of modifications were made to TRAC in an effort to improve results. The first modification was a reduction of the lower bound on liquid velocity for which the ISM was used. The limit was changed from 3/4 to 1/20 of the vapor velocity. The second modification replaced the entrainment correlation with the COBRA-TF model, modified the interfacial shear model to allow upflow of droplets, and further decreased the lower bound on the liquid velocity to 0.001 m/s. The third modification changed the test for invoking the cubic-spline model (used to interpolate the liquid fraction value using a cubic equation) to one based on height above the interface rather than the void fraction. The first modification had a limited effect. The second modification had a rather significant effect in smoothing out the predictions of the integrated-core-outlet liquid flow. The third modification had little effect.

J. Blanco, V. Lopez Montero, and J. Rivero, ICSP-LP-02-06. This assessment was a simulation of LOFT Experiment LP-02-06. As part of this work a study was performed to determine the sensitivity of rod temperatures to the minimum film-boiling temperature. The authors concluded that the minimum-film-boiling-temperature correlation in TRAC gives too high a value for high-pressure low-quality situations.

B. Spindler and M. Pellissier, SETh/LEML/89-165. The EPIS-2 tests simulate the ECC injection system in the cold leg of a PWR. A study of the sensitivity of the pressure distribution to the volume of the upstream plenum indicated that the period of the oscillations increases and the amplitude decreases as the upstream volume size is increased.

The PATRICIA experiments simulate the U-tube of a steam generator. Most calculations were performed using NFF = 1. Calculations using NFF = 2 were found to largely overpredict the pressure drops. The use of that option was not recommended.

W. M. Dempster, A. M. Bradford, T. M. S. Callender, and H. C. Simpson, Strathclyde-SB291. Simulations were performed to assess the capability of TRAC-PF1/MOD1 to simulate conditions existing in a vessel downcomer during the refill phase following a large-break LOCA. The effect of changing the discretization of the momentum equations to a more conservative form was investigated by simulating two cases using the modified code and comparing results to the results of base-case calculations. Noticeable improvements were seen in the overall distribution of liquid fractions and velocities. There was also significant improvement in predicting bypass for one of these cases.

D. M. Turner, RD/L/3455/R89. The purpose of this work was to determine the discretization effects for the momentum equation in TRAC-PF1/MOD1 on the prediction of low-subcooling countercurrent flow in a PWR downcomer. Studies were performed to determine the effect of a discretization of the momentum equation in conservative form, the effect of including cross-derivatives in the discretization, and the effect of an improved numerical treatment at the junction between a PIPE and a 3D VESSEL.

A comparison of results of the calculations performed with modified versions of the code to base-case results showed that the conservative scheme significantly reduced flow oscillations. Inclusion of the cross-derivative terms had very little effect on the results. The treatment at the junction between a PIPE and VESSEL was improved by the addition of a momentum source term. This modification is discussed in detail but its effect on calculated results was not quantified by the author.

A. Sjoberg, STUDSVIK/NP-88/101. This assessment is a simulation of an inadvertent feedwater-line isolation transient in the Ringhals 4 power plant. Sensitivity studies were carried out to determine the effect of fuel-gap conductance on initial stored energy in the fuel and temperatures in the primary circuit. The fuel-gap conductance was reduced from the base-case value of 10 kW/m^{2}K to a minimum value of 5.0 kW/m^{2}K in two steps. This increased the stored energy in the fuel and increased the primary- and secondary-side pressures. The lowest value of gap conductance gave the best agreement with data.

The sensitivity of the results to the moderator temperature reactivity coefficient was also investigated. These changes did not result in any noticeable improvement in the core power when the core coolant temperature was increased.

5.2. Nodalization Studies

D. M. Turner, RD/L/3455/R89. In this study, the effect of azimuthal nodalization in the vessel was studied in conjunction with sensitivity to the discretization scheme (see Sect. 5.1). The two cases for which calculations were performed used 4 and 8 sectors in the vessel. With the four-node downcomer model there was very little difference between the flooding curve predictions of the original and conservative formulations of the momentum equations. With the eight-node downcomer model the conservative scheme did not exhibit the oscillating flow patterns (believed to be nonphysical) that occurred with the four-node model.

R. O'Mahoney, AEEW-M 2552. The purpose of this assessment was to determine the effects of the choice of TRAC reflood-mesh parameters on calculations of fuel-rod quenching and to study axial effects in the heat-conduction calculations. The model consists of a single rod of typical PWR construction, a FILL to provide reflood water, and a BREAK to provide back pressure at the outlet. Series of simulations were performed for the two extremes likely to be encountered. These were (1) high temperatures ahead of the quench front combined with a low reflood rate, and (2) low temperatures ahead of the quench front combined with a high reflood rate.

A series of simulations were performed to determine the effect of the parameter DZNHT (minimum axial interval between node rows for the fine mesh calculation) on the temperature distribution in the rod. DZNHT was varied from 5.0 to 0.1 mm. There was a significant difference in results for the high-temperature low-flow case. Reducing the value of DZNHT leads to an earlier quench time at each elevation and a higher apparent quench temperature. These results strongly suggest that a choice of 5 mm will produce a rather poor representation of the quench front. The author suggests a value in the range of 0.2 to 0.5 mm.

A. Sjoberg, STUDSVIK/NP-88/101. The nodalization of the steam generator downcomer was increased in this study in an effort to eliminate oscillations in the liquid level. The number of cells in the downcomer was increased from 8 in the base-case model to 17 in the modified version. With the dense nodalization, the pressure distribution experienced a smoother behavior.

R. O'Mahoney, AEEW-M 2590. The purpose of this work was to explain the time-step- and axial-mesh-size dependencies of thermal calculations for fuel rods in TRAC-PF1/MOD1. A series of simulations were performed in which time-step size and axial-mesh size were varied. Results showed that there is a significant time-step-size dependency that arises from the explicit evaluation of the fluid-to-surface HTC and the smoothing technique applied to this coefficient. This time-step-size dependency disappears if the axial conduction term in the heat-conduction equation is removed. This study also identifies a small axial-mesh-size dependency.

W. M. Dempster, A. M. Bradford, T. M. S. Callender, and H. C. Simpson, Strathclyde-SB291. Calculations were performed with both 4- and eight-sector nodalization of the vessel. The authors concluded that a four-sector nodalization did not provide a converged solution for the dependent variables.

6. USER GUIDELINES

User guidelines are suggestions made by authors of the ICAP assessments that they believe will help other users to apply the TRAC code more accurately and efficiently. We divide these into guidelines for nodalization of components and guidelines related to various flow phenomena. Each guideline is referenced to the report from which it was taken. Some of these guidelines have been explicitly stated by the authors. Others have been inferred by the reviewer based on the assessment author's discussion. Some of the guidelines may be questionable or no longer applicable because of recent changes in the code. These are noted with footnotes.

Nodalization Guidelines.

(1) The cell at the bottom of an accumulator tank should be made as small as possible to minimize nitrogen diffusion into the adjacent accumulator line before the bottom cell empties. (ICSP-LP-02-06)

(2) A sufficient number of azimuthal sectors must be used in the core to accurately predict asymmetrical effects. (ICSP-LP-FP-1)

(3) The use of a relatively coarse mesh, consistent with acceptable accuracy, is preferable in situations where water packing may occur because it reduces the pressure peaks. (SETh/LEML/89-165)

(4) A thorough nodalization of the steam-generator downcomer is essential for accurate simulations during transients. (STUDSVIK/NP-88/101)

Flow-Phenomena Guidelines

(1) Care must be exercised in selecting pump parameters for two-phase flow conditions. (ICSP-LP-SB-2-T)

(2) The core interphase-friction model underpredicts interphase friction when INVAN = 0 is used. A value of 1 will likely give a better result.[1] (AEEW-M 2416)

(3) A careful representation of the rods and heat structures in the vessel is necessary for accurate calculation of vessel hydraulics. (AEEW-R 2288)

(4) The interface-sharpener logic should not be used.[2] (AEEW-M 2305)

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[1] For TRAC-PF1/MOD2, INVAN=1 is no longer an option. INVAN = 0 is generally recommended.

[2] Applies to MOD1 only.

(5) The use of slabs as heat structures during reflood can lead to inaccuracies because the axial spacing of nodes can be no less than the length of the corresponding hydrocell.[2] (AEEW-M 2305)

(6) A relatively fine mesh may be needed in the downcomer of the vessel to accurately calculate flow conditions during the refill phase. (Strathclyde-SB291)

(7) A quadrant type of vessel nodalization may not be sufficient to simulate two- and three-dimensional effects. (Strathclyde-SB291,1)

(8) At least eight azimuthal nodes should be used in a 3D VESSEL if ECC bypass is likely to occur to a significant extent. (RD/L/3455/R89)

(9) A value between 0.5 mm and 0.2 mm should be specified for the parameter DZNHT for quenching or blowdown conditions. (AEEW-M 2552)

(10) Proper modeling of steam-generator internals and pressurizer walls is important for accurate prediction of condensation phenomena. (ICSP-R2MSIV-T)

(11) Time-step size may have to be limited to values below that allowed by the code when the model contains controls with relatively small time constants to avoid severe oscillations. (ICSP-R2MSIV-T)

(12) Accurate calculation of bypass conditions requires accurate modeling of the broken cold-leg vessel connections. (Strathclyde-SB291, 2)

7. IDENTIFIED CODE DEFICIENCIES AND SUGGESTED CODE IMPROVEMENTS

In the course of performing the assessments discussed in this report, the ICAP authors have identified several code deficiencies. In some cases they recommended specific code improvements. These deficiencies and suggested improvements are given in this chapter.

Some of the deficiencies listed here are no longer present in later versions of the code. In some cases the suggested improvements of the ICAP authors have been incorporated in a new version of the code. In others, an algorithm has been changed in such a way that the one or more code deficiencies have been eliminated. Cases where code improvements may eliminate the code deficiency noted by ICAP authors are noted at the end of each section.

Heat Structures

- TRAC does not have a two-sided heat structure. (ICSP-LP-SB-2-T), (AEEW-M 2416)
- The limitation in axial node spacing for slabs as heat structures may cause discontinuities in the fluid flow. (AEEW-M 2305)
- A fully implicit two-dimensional conduction calculation for the rod would be preferable to the axial-implicit method used in MOD1. (AEEW-M 2552)
- The surface heat-transfer smoothing should be done on a per-second basis rather than a per-time-step basis. (AEEW-M 2552)
- A time-step dependency in thermal calculations for fuel rods is caused by the explicit evaluation of film coefficients and the application of under-relaxation to these coefficients. (AEEW-M 2590)

TRAC-PF1/MOD2 contains a new generalized heat-structure component. It may have two surfaces connected to different hydrocells. A fully implicit solution is available so that axial node spacing may be made much smaller without requiring excessive CPU time. The method of determining the wall-to-fluid HTC has been changed to improve numerical stability.

Reflood

- The reflood model is not sufficiently accurate. (AEEW-R 2288)
- The minimum-film-boiling-temperature correlation gives values that are too low, particularly for high-pressure, low-quality situations. (ICSP-LP-02-06)

The reflood model has been significantly upgraded in TRAC-PF1/MOD2. The interfacial-drag and wall-drag models are upgraded. Linear interpolation is used to determine local void fractions for use in wall heat transfer so that a boiling surface approach can be maintained. New post-CHF correlations are used.

Break Flows

- The code does not include an accurate offtake model for a break in a horizontal pipe. (ICSP-LP-SB-2-T), (AEEW-M 2416)
- The code should have a model relating quality in the break line to the void fraction of the fluid in the branch. (ICSP-LP-SB-2-T)

An improved offtake model for horizontal pipes developed at Winfrith has been added to the MOD2 version of TRAC. It allows the user to specify the location of the break at the top, bottom, or side of the pipe and includes an algorithm that determines whether the break flow is single-liquid, vapor, or two-phase.

Countercurrent Flow Limitation (CCFL)

- The modeling of interphase friction associated with the countercurrent flow limitation may need improving. (AEEW-M 2416)

A new CCFL model has been incorporated in TRAC-PF1/MOD2.

Condensation

- Condensation rates may be overpredicted. (AEEW-M 2416), (ICSP-LP-02-06), (SETh/LEML/89-165), (Strathclyde-SB291, 2)

The flow-regime maps have been improved for both vertical and horizontal flows. There are algorithms to predict when stratified flow will occur. This will greatly reduce the interphase area and significantly lower the calculated condensation rates for situations where the flow is stratified.

Momentum Equations

- The momentum equation was not in conservative form in TRAC-PF1/MOD2. (Strathclyde-SB291, 1), (RD/L/3455/R89), (Strathclyde-SB291, 2)
- TRAC does not contain a momentum convection term associated with a radial VESSEL-PIPE connection. (Strathclyde-SB291, 2)

The addition of the area-ratio algorithms to the MOD2 version produces a momentum calculation that is more nearly conservative. A rigorous, fully conservative discretization of the momentum equations does not appear to be practical because of the additional nonlinearities that would be introduced requiring additional iterations in the solution procedure.

Miscellaneous

- The interface-sharpener logic is inaccurate. (AEEW-M 2305)
- TRAC does not have an automatic method to limit the time step as a function of the performance of control systems. This is necessary to avoid severe oscillations for cases where a control with a time step smaller than the time step allowed by TRAC is operating. (ICSP-R2MSIV-T)

The interface-sharpener logic has been removed. The problem with time-step size must be handled by the user by reducing the time step when a control with a short time constant is operating. We recommend the use of trip-controlled time-step data.

Coding Errors

- An error (a missing factor in an equation) was found in the calculation of the critical gas velocity in stratified flow. (ICSP-LP-SB-2-T)
- An error was found in the calculation of a film coefficient. (AEEW-M 2305)

These errors have been corrected.

8. CONCLUSIONS

The USNRC has organized the International Code Assessment and Applications Program (ICAP) to assist in the evaluation of thermal-hydraulic reactor safety analysis codes such as TRAC. As part of this program, international users have applied TRAC to the prediction of test conditions obtained in safety-related integral and separate-effects tests. They have prepared assessment reports that indicate how well TRAC is able to simulate a wide variety of transient conditions.

Seventeen ICAP assessment reports were reviewed during FY 1990 and their results are summarized in this report. Those assessments revealed areas of strength and some areas of weakness in the code. They included several suggested user guidelines (Chap. 6) which will be valuable for future users of the code. These guidelines include several recommendations for noding various components, particularly accumulators, steam generators, and reactor vessels. In several of the assessment reports, code deficiencies were identified (Chap. 7). Many of these were related to the behavior of heat structures during blowdown and reflood. There were also deficiencies noted in algorithms used in calculations of countercurrent flow, break flow, and condensation. Several suggestions were made for improvements in TRAC. Many of these have led to corrections and improvements in later versions of the code. In some cases new methods developed by ICAP participants have been added to the code. These include a fully implicit conduction calculation developed at the Japanese Atomic Energy Research Institute and external thermocouple and offtake models developed at Winfrith. The latest official version of the code, TRAC-PF1/MOD2, includes all of the updates discussed in Chap. 7. That version of the code was released in June 1990.

Although many of the thermal-hydraulic phenomena have been covered in the ICAP assessments (Chap. 2), some areas have received little or no attention. Two-phase natural circulation, boron mixing and transport, and separator hydraulics are areas in which little has been done. Other areas, such as countercurrent flow in downcomers and fuel-rod heat transfer during blowdown and reflood have received a great deal of attention. Nevertheless, additional simulations are needed in these areas because the phenomena are of great importance in reactor safety and because there is an insufficient amount of detailed data to do comprehensive assessments. The release of a new version of the code increases the need for further assessment. Developmental assessments performed at Los Alamos indicate significant improvement in many areas of the code. The extent to which code deficiencies found by ICAP authors have been corrected can only be determined by rerunning simulations with the MOD2 version of the code.

ACKNOWLEDGMENTS

The author wishes to express his gratitude to all the members of ICAP who have provided the assessment reports discussed in this report. Jay W. Spore, Robert G. Steinke, Ju-Chuan Lin, Susan B. Woodruff, and Ralph A. Nelson of the Los Alamos National Laboratory provided valuable consultation and support. The encouragement and support of Dr. Gene Rhee of the United States Nuclear Regulatory Commission was also greatly appreciated.

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5. J. F. Wilson, R. J. Grenda, and J. F. Patterson, "Steam Volume Fraction in a Bubbling Two Phase Mixture," *Trans. ANS* , Vol. 4 (November 1961).

6. H. H. Rooney, "Void Fraction Prediction Under Saturated Conditions," INEL report no. 386 (1968).

7. M. Petrick, "A Study of Vapour Carryunder and Associated Problems," Argonne National Laboratory report ANL-6581 (July 1982).

APPENDIX

REVIEWS OF TRAC-RELATED ICAP REPORTS

This appendix includes the complete reviews of the seventeen ICAP TRAC user reports that were reviewed in FY 1990. Each review followed the guidelines presented in NUREG-1271, "Guidelines and Procedures for the International Code Assessment and Applications Program." Following are the reviews included in this appendix:

- K. H. Ardron and A. J. Clare, "Assessment of Interface Drag Correlations in the RELAP5/MOD2 and TRAC-PF1/MOD1 Codes," GD/PE-N/557 (March 1987).
- F. Pelayo, "TRAC-PF1/MOD1 Post-Test Calculations of the OECD-LOFT Experiment LP-SB-2," ICSP-LP-SB-2-T, AEEW-R 2002 (April 1987).
- C. G. Richards, "Pre-Test Calculation of LOBI Test BL-02 Using TRAC-PF1/MOD1," AEEW-M 2416 (February 1987).
- J. C. Birchley, P. Coddington, and C. R. Gill, "Analysis of LOFT Experiment LP-02-6 Using the TRAC-PF1/MOD1 Computer Code," AEEW-R 2288 (November 1987).
- R. O"Mahoney, "A Study of the Reflood Characteristics of TRAC-PF1/MOD1," AEEW-M 230 (April 1986).
- J. Blanco, V. Lopez Montero, and J. Rivero, "Analysis of LOFT Experiment LP-02-6 Using TRAC-PF1/MOD1," ICSP-LP-02-06 (January 1988).
- F. J. Barbero, "TRAC-PF1 Code Assessment Using OECD-LOFT LP-FP-1 Experiment," ICSP-LP-FP-1 (July 1988).
- B. Spindler and M. Pellissier, "Assessment of TRAC-PF1/MOD1 Version 14.3 Using Components Separate Effects Experiments," SETh/LEML/89-165 (March 1989).

- W. M. Dempster, A. M. Bradford, T. M. S. Callender, and H. C. Simpson, "An Assessment of TRAC-PF1/MOD1 Using Strathclyde 1/10 Scale Model Refill Tests," Strathclyde-SB291, Phase 1.
- D. M. Turner, "Discretization Effects in TRAC-PF1/MOD1 on the Prediction of Low Subcooling Counter Current Flow in a PWR Downcomer," CEGB report no. RD/L/3455/R89 (February 1989).
- P. Coddington, "OECD-LOFT LP-LB-1 Comparison Report," AEEW-R 2478 (February 1989).
- P. Coddington, "Analysis of the Blowdown of the Accumulator B Line in the OECD-LOFT Fission Product Experiment LP-FP-1," AEEW-R 2328 (February 1988).
- R. O'Mahoney, "A Study of Axial Effects in the TRAC-PF1/MOD1 Heat Conduction Solution During Quenching," AEEW-M 2552 (June 1989).
- A. Sjoberg, "Assessment of TRAC-PF1/MOD1 Against an Inadvertent Feedwater Line Isolation Transient in the Ringhals 4 Power Plant," STUDSVIK/NP-88/101 (S) (November 1988).
- F. Pelayo and A. Sjoberg, "Assessment of TRAC-PF1/MOD1 Against an Inadvertent Steam Line Isolation Valve Closure in the Ringhals 2 Power Plant," ICSP-R2MSIV-T (February 1988).
- R. O'Mahoney, "Time Step and Mesh Size Dependencies in the Heat Conduction Solution of a Semi-Implicit, Finite Difference Scheme for Transient Two-Phase Flow," AEEW-M 2590 (July 1989).
- W. M. Dempster, "An Assessment of TRAC-PF1/MOD1 Using Strathclyde 1/10 Scale Model Refill Tests, 2nd Report," submitted to CERL, Phase 2 of Contract RK: 1642 Job No. SB291, Strathclyde-SB291, Phase 2, (July 1989).

REVIEW OF ICAP REPORT NO. GD/PE-N/557

A. BASIC DATA

A1. ***Report Information:***

Author: K. H. Ardron and A. J. Clare

Report Title: Assessment of Interphase Drag Correlations in the RELAP5/MOD2 and TRAC-PF1/MOD1 Codes

Report Number: GD/PE-N/557, NUREG/IA-0015

Author's Nationality and Affiliation: United Kingdom, Central Electricity Generating Board

Report Date: March 1987

A2. ***Reviewer's Name:*** Norman M. Schnurr

Date of Review: January 1990

A3. ***Which code version was used for the baseline calculation: (Include cycle number or version number and any updates. Section 5.2.2)***

The TRAC code was not used directly. A separate code was written that used the interphase drag correlation from TRAC-PF1/MOD1, Version 13.2, and computed void fractions for comparison to standard correlations and test data.

A4. ***Report Classification (Proprietary, or non-proprietary, any restrictions. Section 4.1)****

Non-proprietary

A5. ***Is this an integral or separate-effects assessment?***

Separate-effects assessment

A6. ***Summarize why this assessment is being done. (Section 5.2.5 and Table 3)****

The purpose of this assessment is to check the accuracy of the interphase-drag correlations used in TRAC-PF1/MOD1 and RELAP5/MOD2.

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* Refers to section or table in NUREG-1271, "Guidelines and Procedures for the International Code Assessment and Applications Program," April 1987

A7. Provide a list of keywords descriptive of this analysis.

Interphase drag, hydraulic diameter, upflow, downflow, bubbly and slug flow.

B. BRIEF QUESTIONS RELATED TO THE COMPLETENESS OF THE REPORT (include report page number where information was found.)

B1. Did the author describe each test facility and each test used in the analysis? Elaborate. (Section 5.4.5 and 5.5.4)*

No. The data on which the correlations used in this assessment are based are referenced. Details of the test facilities can be obtained from those references.

B2. The author must identify the experimental data used for the assessment in the report. The data channels used for comparison with code results should be easy to identify. It is desirable, but not required, for the author to supply the very data used in the assessment on hardcopy, floppy, or tape as specified in NUREG-1271. Has the author done these things? (Section 5.5.3 and 5.3)*

The numerical calculations were compared to empirical correlations of data taken from a variety of experiments. The sources of these data may be obtained from the papers in which the correlations were published.

B3. The author must provide an evaluation of the experimental data uncertainty or clearly reference where it may be found. Has this been done? (Section 5.2.1)*

Ranges of accuracies for the experimental data are estimated by the authors.

B4. Was a base-case calculation performed using the unmodified, frozen code? Did the author include a clear, explicit figure of the Model? (Section 5.2.2).*

No. Calculations were performed using a standalone code that used correlations taken from frozen versions of RELAP5/MOD2 and TRAC-PF1/MOD1.

B5. The author must supply a copy of the input deck for one of his transient calculations on hardcopy, or floppy, or both. Has he done this? (Section 5.4.6 and 5.5.1)*

No. This assessment does not use the TRAC code directly.

B6. *Were sensitivity studies performed? Were the sensitivity studies adequately described? Were all identified code deficiencies explicitly described? (Section 5.2.3, 5.2.5, and 5.4.7)**

Calculations were performed for a wide range of conditions. Areas in which agreement between results of calculations using the TRAC algorithm and results of standard correlations and experimental data was not satisfactory were noted.

B7. *Were nodalization studies performed? Were the nodalization studies adequately described? Elaborate if necessary. (Section 5.2.4)**

Nodalization is not applicable for this assessment. The authors do point out that values of void fraction calculated by the TRAC code will be sensitive to cell size and that cell-size sensitivity should be investigated using TRAC.

B8. *The report should include run statistics for at least one transient calculation using the unmodified frozen code. Was this done? If a modified version of the code was produced, run statistics for the same transient calculation performed with the final version of the modified code should be included. Was this done? (Section 5.2.5 - para. 4, and Table 4 - p. 25, and Section 5.4.8)**

Not applicable for this assessment.

B9. *Were complete references included in the report? (Section 5.4.10)**

Yes.

B10. *Were the objectives satisfied?*

Yes.

C. DETAILED QUESTIONS

C1. *Did the author describe the model nodalization, assumptions, etc.? Were they appropriate? Did the nodalization follow the input deck preparation guidelines found in the TRAC User Guides? Elaborate if necessary. (Section 5.4.6)**

Not applicable.

C2. *Briefly describe the thermal-hydraulic phenomena and the reported code predictions addressed in the report. If appropriate, describe the*

phenomena in the context of thermal-hydraulic behavior in the vessel primary loop, secondary loop, and other phenomena of interest.

This report addressed the interphase-drag correlations used in the RELAP and TRAC codes. The range of conditions covered in this assessment applies to the vertical-loop components during small-break LOCAs and pressurized transients. The calculations of void fraction for cocurrent upflows and downflows are investigated.

C3. ***If the author has identified new user guidelines has he described them thoroughly? What are they?***

No new user guidelines have been identified.

C4. ***What user guidelines can you infer from the results described in the report?***

Care should be exercised in applying the codes for flow conditions where the interphase-drag correlations do not produce void fraction calculations that are in good agreement with standard correlations.

C5. ***What deficiencies were identified in the unmodified frozen version of the code? (Section 5.2.5 and 5.4.7)****

The TRAC interphase-drag correlations were found to agree well with standard correlations for all conditions except for upflow in large pipes at void fractions exceeding 0.5 and small pipes at pressures less than 4 MPa.

C6. ***Describe the impact of each identified code deficiency.***

The differences between predictions of void fraction using the TRAC algorithms and results of standard correlations are within the quoted experimental accuracy for most cases and are not excessively large for any case. The interphase-drag correlations used in later versions of the code have been upgraded. An assessment of the type performed by the authors should be repeated for the latest version of the code.

C7. ***What code modifications were made? What effect did they have? (Section 5.2.3)****

None.

C8. ***Run statistics must be provided for the calculation of one transient with the unmodified frozen code and the fully modified code. Compare and evaluate.***

The run statistics should include a description of the computer and operating system used to perform each calculation, and

a. A plot of CPU vs RT

b. A plot of DT vs RT

c. The value of the "grind time" = $[(CPU \times 10^3)/(C \times DT)]$

Where CPU = Total execution time
RT = Transient time
DT = Total number of time steps
C = Total number of volumes in the model

Not applicable.

*d. Evaluate the actual time step used. Did the transient run at the Courant time step or did the user specify a smaller maximum time step? Compare the actual time step vs transient time and the user specified maximum time step vs transient time. (Section 5.2.5-para.4, Table 4-p. 25, and Section 5.4.8)**

Not applicable.

C9. Does the work documented in this report appear to be good and generally valid or are there fundamental problems with it? (Solicit input of code developers to answer this question.)

This work is well conceived and executed and meets the authors' stated objective.

*C10. What conclusions were drawn in the report? Are they well supported by the results of the analysis? Elaborate. (Section 5.4.7 and 5.4.9)**

The authors conclude that the interphase-drag correlations used in TRAC-PF1/MOD1 give void fractions in good agreement with standard correlations and experimental data except for two regions that were noted. These conclusions are supported by a series of graphs comparing the calculated results to the standard correlations and to experimental data.

C11. Report summary. (This summary will be included in the year-end NUREG report. It should be about 2 to 5 pages long and could include several figures. A short paragraph description of each facility should be included. Also include a paragraph summarizing the baseline results.)

In some small-break LOCAs and pressurized transients in PWRs, system behavior depends strongly on the void fraction in vertical-loop components. For example, when the reactor core is partially uncovered, the boildown rate is influenced by the void fraction, which determines the continuous liquid level. Similarly, the void fraction in the core and other vertical-flow paths strongly influences the duration of core dryout when core uncovering is caused by a balance of hydrostatic forces. To provide an accurate numerical simulation of these situations it is necessary to properly model the interphase relative motion (slip) in the vertical-loop components.

An assessment was carried out to compare the interphase-drag correlations used in the RELAP5/MOD2 and TRAC-PF1/MOD1 codes. Both codes use a two-fluid model in which separate momentum equations are solved for the gas and liquid phases. Flow-regime-dependent constitutive equations are used to model interphase momentum transfer. The assessment was performed by using models from these codes to calculate void fractions in steam/water flows, and comparing those results with predictions of standard correlations and with test data. The assessment is confined to bubbly- and slug-flow conditions ($\alpha_g < 0.75$).

There are extensive data available for cocurrent upflow of steam/water and air/water mixtures, and a number of void fraction correlations have been proposed in the literature. The "best-estimate" model used in this assessment was developed by combining the correlations of Wilson et al.[1] and Rooney.[2] The Wilson correlation is based on steam/water data for pressures in the range 2.0 - 13.8 MPa and pipe diameters between 100 and 914 mm. For flow rates high enough to fall outside the range of validity of the Wilson correlation, the Rooney correlation was used. The best-estimate correlation of void fraction for upward flow combines these two correlations according to

$$\alpha_g = \min(\text{Wilson, Rooney}) .$$

These correlations are expected to give results with RMS errors in the two-phase mixture density in the range of 17-30 %.

For cocurrent downflow very little void fraction data are available and there are no well-established correlations. Therefore, the performance of the code models was assessed against the data of Petrick.[3]

To assess the interphase-drag models in the codes, the drag equations were first used to develop relationships between the void fractions and the phase flow rates for the

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[1] Wilson, J. F., Grenda, R. J., and Patterson, J. F., "Steam Volume Fraction in a Bubbling Two Phase Mixture." *Trans. ANS* (Nov. 1961).

[2] Rooney, H. H., "Void Fraction Prediction Under Saturated Conditions," NEL report no. 386 (1968).

[3] Petrick, M., "A Study of Vapour Carryunder and Associated Problems," ANL report ANL-6581 (July 1982).

case of steady, fully developed steam/water flow in a uniform-area vertical pipe. The void fractions obtained from these relationships were then compared with predictions of the best-estimate empirical correlation for upflow and with the available data for downflow.

Results of the calculations for vertical upflow are shown in Figs. A-1 and A-2. Results are given for two diameters and three pressures. These results show reasonably good agreement between both RELAP5 and TRAC results and the Wilson-Rooney correlation for moderate and high liquid flow-rates and small hydraulic diameters. Discrepancies are largest for low pressures, large pipe diameters, small liquid flows, and large vapor flows. Discrepancies between the code predictions and the correlations, measured in terms of density, are comparable for the two codes and are within the quoted experimental accuracy for most of the range of parameters covered in this assessment.

Results for upflow for a pressure of 7.0 MPa and a hydraulic diameter of 49 mm are compared to the test data of Petrick in Fig. A-3. Agreement is very good for both RELAP5 and TRAC. Comparisons were also made with data at pressures of 4.1 and 10.3 MPa and similar conclusions were reached.

This assessment led to the following conclusions:

1. The interphase-drag models in RELAP5/MOD2 and TRAC-PF1/MOD1 perform comparably well in modeling vertical flows.
2. Errors in the two-phase mixture density increase with decreasing liquid flow, increasing vapor flow, increasing pipe size, and decreasing pressure.
3. For upflow, at the pressures of interest in modeling small-break LOCAs, the errors in two-phase mixture density are not grossly different from errors normally expected in applying standard correlations for void fraction.
4. For downflow, the code models perform very well in comparison with the limited void fraction data available.

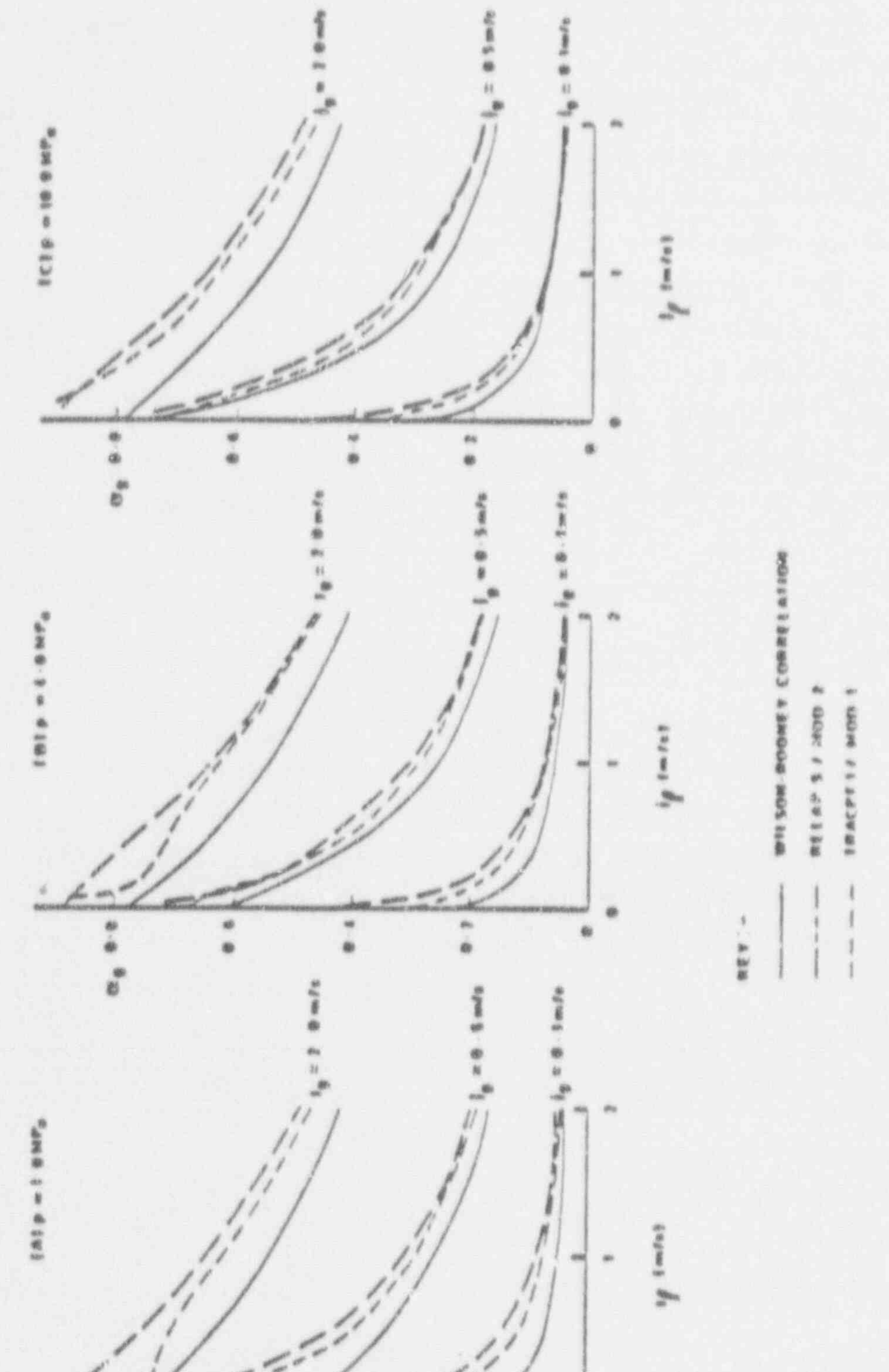

Fig. A-1. Comparison of void fraction calculations for Dh = 0.01 m.

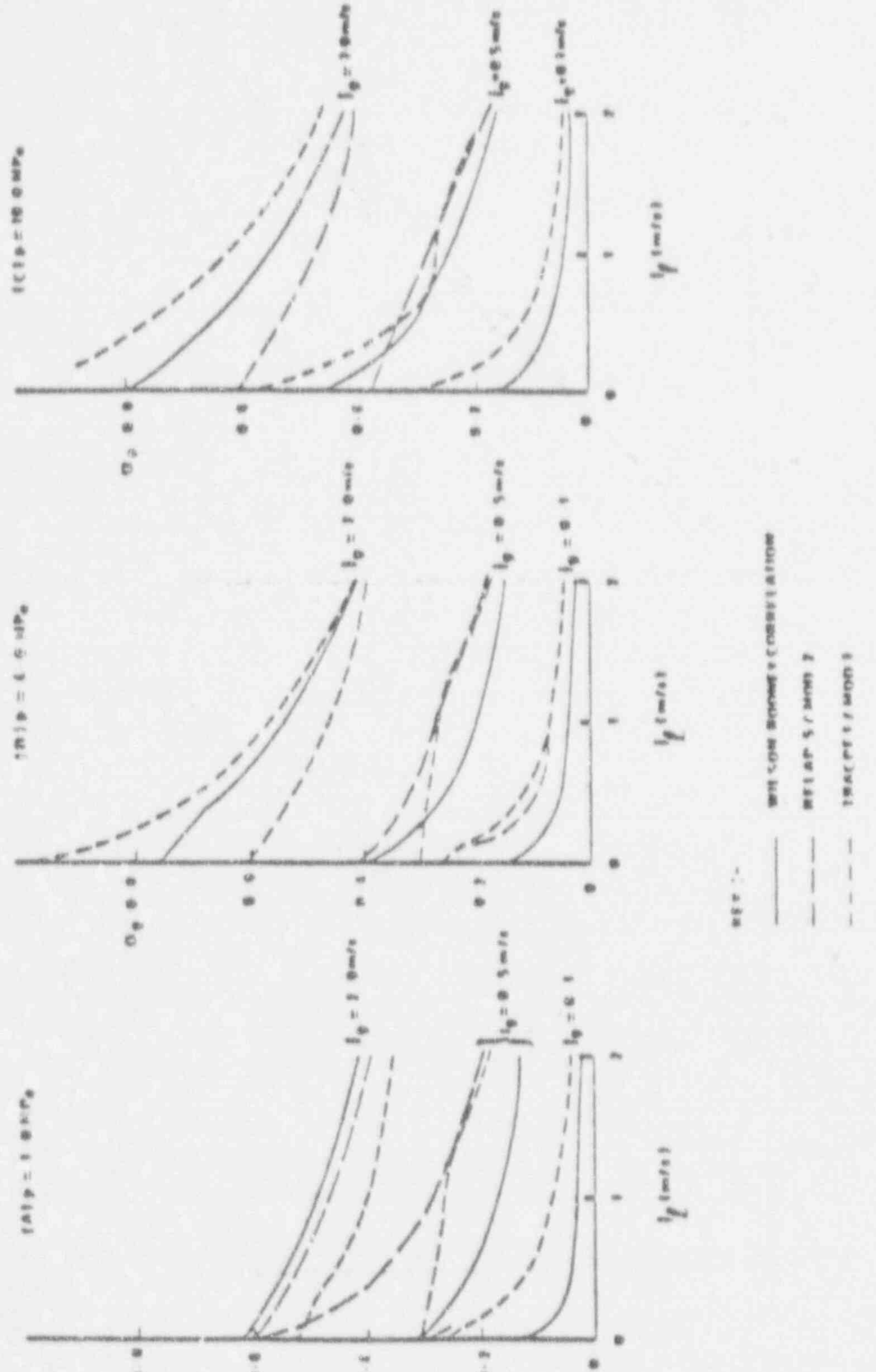

Fig. A-2. Comparison of void fraction calculations for Dh = 1.0 m.

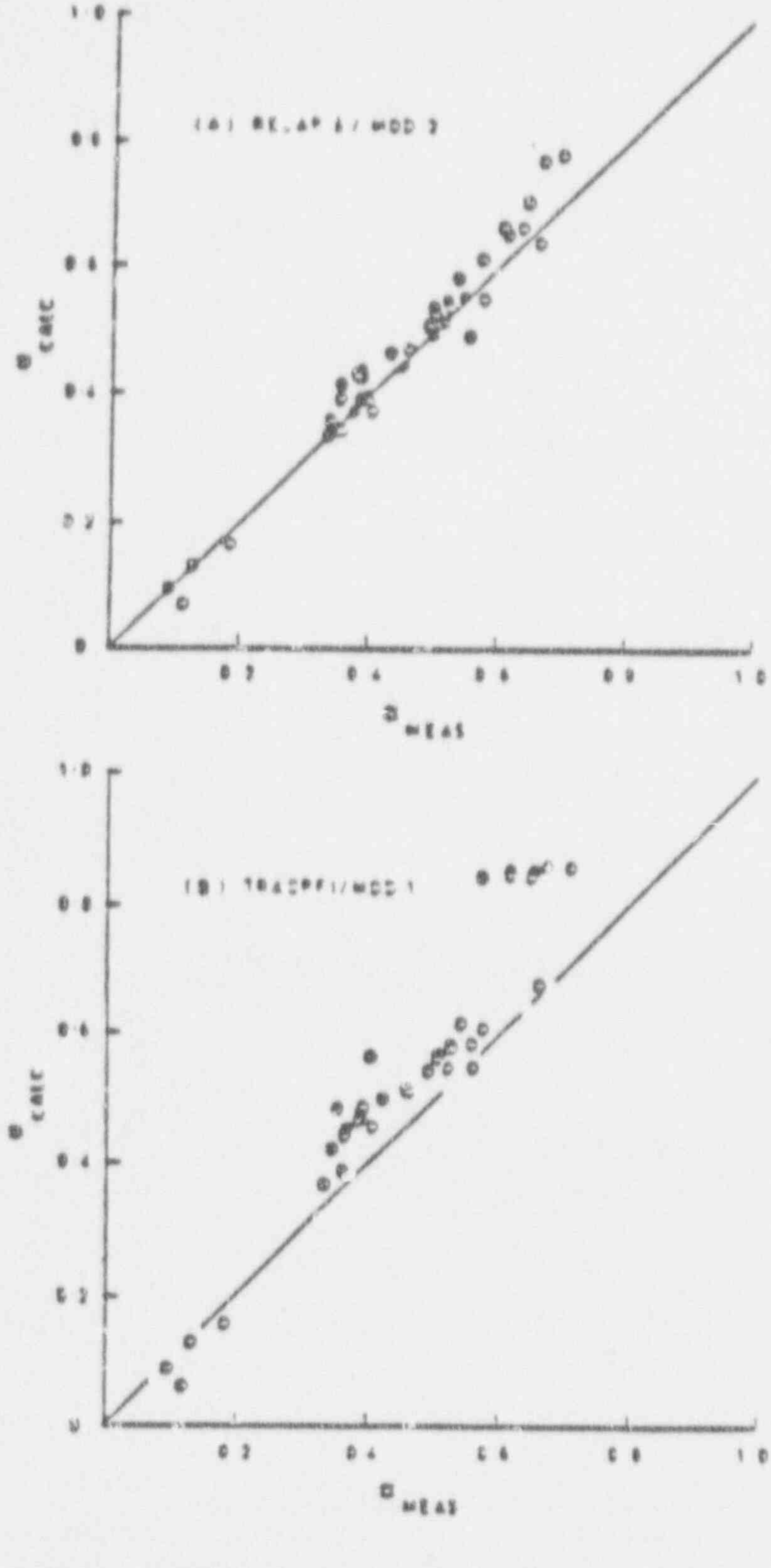

Fig. A-3. Comparison of measured and predicted void fractions, Petrick downflow data (P = 7.0 MPa, D_h = 49 mm).

REVIEW OF ICAP REPORT NO. ICSP-LP-SB-2-T

A. BASIC DATA

A1. Report Information:

Author: F. Pelayo

Report Title: TRAC-PF1/MOD1 Post-Test Calculations of the OECD-LOFT Experiment LP-SB-2.

Report Number: ICSP-LB-SB-2-T (AEEW-R 2202)

Author's Nationality and Affiliation: Spain, Consejo de Seguridad Nuclear.

Report Date: April 1987.

A2. Reviewer's Name: Norman M. Schnurr

Date of Review: February 1990

A3. Which code version was used for the baseline calculation: (include cycle number or version number and any updates. Section 5.2.2)*

A base-case run was made using TRAC-PF1/MOD1, Version 12.7. An additional run was made using Winfrith version BO2C. The Winfrith version is a revision of TRAC-PF1/MOD1 Version 12.7. Differences between the Winfrith and Los Alamos versions are listed Appendix B of the report.

A4. Report Classification (Proprietary, or non-proprietary, any restrictions. Section 4.1)*

Commercial in confidence.

A5. Is this an integral or separate-effects assessment?

An integral assessment.

A6. Summarize why this assessment is being done. (Section 5.2.5 and Table 3)*

This assessment tests the accuracy of the code in analyzing the effect of a delayed pump trip in a small-break LOCA scenario. In particular it tests the ability of the code to predict vapor pull-through and liquid entrainment in the break line and to correctly predict pump

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* Refers to section or table in NUREG-1271, "Guidelines and Procedures for the International Code Assessment and Applications Program," April 1987.

behavior. The PWR phenomena included for this assessment are (Table 3 of NUREG-1271) break flow, phase separation in T-junction and effect on break flow, stratification in horizontal pipes, and one- and two-phase pump behavior.

A7. Provide a list of keywords descriptive of this analysis.

Small-break LOCA, LOFT, vapor pull-through, liquid entrainment, pump behavior.

B. BRIEF QUESTIONS RELATED TO THE COMPLETENESS OF THE REPORT (Include report page number where information was found.)

B1. Did the author describe each test facility and each test used in the analysis? Elaborate. (Section 5.4.5 and 5.5.4)*

The LOFT test facility was discussed in some detail (pp. 1,2). An axonometric projection of the LOFT system (Fig. 1) and a piping schematic with instrumentation (Fig. 2) are included in the report. The specific experiment covered by this assessment was described briefly and a reference was given where a complete description of the experiment can be found (pp. 4,5). The chronology of events for the experiment was described in detail (pp. 6,7).

B2. The author must identify the experimental data used for the assessment in the report. The data channels used for comparison with code results should be easy to identify. It is desirable, but not required, for the author to supply the very data used in the assessment on hardcopy, floppy, or tape as specified in NUREG-1271. Has the author done these things? (Section 5.5.3 and 5.3)*

Experimental data are supplied in graphical form (Figs. 9-18, 21-33, and 35-64). The signal-variable number is given for each plot. The data include

- density in the break line and the hot and cold legs of the intact loop;
- liquid and vapor velocities in the cold leg, hot leg, downcomer, core inlet, core outlet, break line, and downcomer;
- pressure in the primary and secondary sides and pressure difference across the pump;
- liquid temperature in the hot and cold legs of the intact loop;
- cladding temperature near the top of the core;
- mass-flow rate at the hot-leg venturi location and at the break; and
- mass inventory of the primary system.

B3. ***The author must provide an evaluation of the experimental data uncertainty or clearly reference where it may be found. Has this been done? (Section 5.2.1)****

The uncertainty of the data is not discussed in this assessment but a reference is given where a complete description of the experiment can be found.

B4. ***Was a base-case calculation performed using the unmodified, frozen code? Did the author include a clear, explicit figure of the Model? (Section 5.2.2).***

A base-case calculation was performed using TRAC-PF1/MOD1, Version 12.7, a frozen version of the code. A facility noding diagram (Fig. 3) and noding diagrams of the steam generator and vessel (Figs. 5 and 6) are also given.

B5. ***The author must supply a copy of the input deck for one of his transient calculations on hardcopy, or floppy, or both. Has he done this? (Section 5.4.6 and 5.5.1)****

No copy of the input deck was provided.

B6. ***Were sensitivity studies performed? Were the sensitivity studies adequately described? Were all identified code deficiencies explicitly described? (Section 5.2.3, 5.2.5, and 5.4.7)****

Two complete simulations of LOFT LP-SB-2 were performed. The second calculation showed the effect of controlling the quality in the break line as a function of the quality in the hot leg. The pump-head multipliers were also modified in an effort to reproduce better the asymmetrical pump behavior. An error in the code was corrected. A deficiency of the code in the description of break flows was discussed in detail. The inability of the code to model two-sided heat structures was identified as a code deficiency that could have had some effect in these calculations.

B7. ***Were nodalization studies performed? Were the nodalization studies adequately described? Elaborate if necessary. (Section 5.2.4)****

No distinct nodalization studies were performed. Some discussion of nodalization was included in this report (pp. 3,4). The input deck was a modification of the input deck previously used in the analysis of LOFT experiment LP-SB-1. The major changes were the replacement of a the 3D vessel with a 1D model and some changes in nodalization in the broken loop and in the hot-leg break component. Noding in the steam generator was discussed in some detail.

B8. *The report should include run statistics for at least one transient calculation using the unmodified frozen code. Was this done? If a modified version of the code was produced, run statistics for the same transient calculation performed with the final version of the modified code should be included. Was this done? (Section 5.2.5 - para. 4, and Table 4 - p. 25, and Section 5.4.8)**

Graphs of CPU and time-step size as functions of problem time were given for the base case (Figs. 7,8). The ratio of CPU to problem time was given for three regions and for the entire simulation.

B9. *Were complete references included in the report? (Section 5.4.10)**

Yes.

B10. *Were the objectives satisfied?*

Yes. The results of the TRAC calculations were compared to the experimental data from LOFT experiment LP-SB-2. The calculated results were in fairly good agreement with the experimental data. The upgraded version of the code gave somewhat better agreement with the measured mass-flow rates at the break. The effects of code changes on the accuracy of the calculations was determined.

C. DETAILED QUESTIONS

C1. *Did the author describe the model nodalization, assumptions, etc.? Were they appropriate? Did the nodalization follow the input deck preparation guidelines found in the TRAC User Guides? Elaborate if necessary. (Section 5.4.6)**

The input deck used here is a modification of a deck used for the simulation of an earlier LOFT experiment. The nodalization is not described in detail. Complete dimensions are not given for all components so it is not possible to determine whether the nodalization follows guidelines found in the TRAC User's Guide. The number of cells is consistent with common practice for a system of the type considered in this study.

C2. *Briefly describe the thermal-hydraulic phenomena and the reported code predictions addressed in the report. If appropriate, describe the phenomena in the context of thermal-hydraulic behavior in the vessel primary loop, secondary loop, and other phenomena of interest.*

Thermal-hydraulic phenomena of importance in this assessment include critical flow at a break, flow patterns in the broken loop, vapor pull-through and liquid entrainment in the break line, and pump behavior. Many features of the TRAC code were exercised during these simulations. These include the flow-regime-dependent constitutive-equation package, the choked-flow model, the pump model under two-phase conditions, and fluid transport and associated two-phase pressure losses in the loop.

The experiment studies the effect of a delayed pump trip in a small-break LOCA scenario with a 3-in.-equivalent-diameter break in the hot leg of a commercial PWR operating at full power. The pumps were kept spinning at their steady-state velocity throughout the transient until their trip set point was reached. The secondary-side steam control valve assumed the function of the steam bypass valve.

Of primary interest in the experiment were pressures, temperatures, densities, and flow rates throughout the system, mass inventory in the vessel and the primary, pressure drop across the pump, and cladding temperatures. All of these parameters were calculated and compared with experimental data (Figs. 8-18 and 20-64).

C3. If the author has identified new user guidelines has he described them thoroughly? What are they?

No new user guidelines were explicitly stated.

C4. What user guidelines can you infer from the results described in the report?

If asymmetry in the vessel is expected to be unimportant, a 1D vessel should be used so that the multistep numerics can be used. This allows larger timesteps to be used with a resulting saving in computational cost. Care must be exercised in selecting pump parameters for two-phase flow conditions.

C5. What deficiencies were identified in the unmodified frozen version of the code? (Section 5.2.5 and 5.4.7)*

The version of the TRAC code used in this study did not have a two-sided heat structure. An error (a missing factor in an equation) was found in the calculation of the critical gas velocity in stratified flow. The code did not include an accurate offtake model for a break in a horizontal pipe. The code should also have a model relating quality in the break line to the void fraction of the fluid in the branch.

C6. Describe the impact of each identified code deficiency.

The effect of using a single-sided heat structure could not be determined. The heat structures were modeled in a manner that retained the correct surface areas and volumes, however, and it is unlikely that the limitation of a single-sided heat structure had a significant effect on the hydraulics. The lack of an adequate offtake model had a significant effect on the break-flow-rate calculations.

C7. ***What code modifications were made? What effect did they have? (Section 5.2.3)****

A factor of $\pi^{0.5}$ was added to the equation used to calculate the critical gas velocity in the stratified model. A stratified offtake-model option was added for TEE components. The pump-head multipliers were modified to force a sharp degradation at an inlet void fraction of 0.35. The pump-head multipliers for Pump No. 1 were further modified in an attempt to reproduce the asymmetric pump behavior after degradation. The effect of these changes was a much better calculation of break mass-flow rate. This also caused a significant improvement in the prediction of primary pressure.

C8. ***Run statistics must be provided for the calculation of one transient with the unmodified frozen code and the fully modified code. Compare and evaluate. The run statistics should include a description of the computer and operating system used to perform each calculation, and***

a. A plot of CPU vs RT

b. A plot of DT vs RT

c. The value of the "grind time" = [(CPU x 10^3)/(C x DT)]

Where CPU = Total execution time

RT = Transient time

DT = Total number of time steps

C = Total number of volumes in the model

Plots of CPU vs RT and DT vs RT are included in this report. Run statistics are given in the form of the ratio of CPU to RT. The value of this ratio was 1.95 ms for the base case and 2.3 ms for the second run. The grind time for the base case was 1.57 n.

d. Evaluate the actual time step used. Did the transient run at the Courant time step or did the user specify a smaller maximum time step? Compare the actual time step vs transient time and the user

specified maximum time step vs transient time. (Section 5.2.5-para.4, Table 4 p. 25, and Section 5.4.8)*

Multistep numerics were used so the time step could exceed the Courant limit. The actual time steps were less than the user-specified maximum time step during a significant portion of the calculation. Use of too large a maximum time step was found to cause the calculation to fail as the time step was being reduced.

C9. Does the work documented in this report appear to be good and generally valid or are there fundamental problems with it? (Solicit input of code developers to answer this question.)

This work is well conceived and executed and meets the author's stated objective. The important phenomena in the experiment were discussed, discrepancies between the data and the calculated results were discussed, and some changes were made in the code to improve the calculations or explain any lack of agreement with experimental data.

*C10. What conclusions were drawn in the report? Are they well supported by the results of the analysis? Elaborate. (Section 5.4.7 and 5.4.9)**

The author's conclusions were as follows:

- It would be desirable to perform the calculations using a 3D representation of the vessel in order to assess the effect of asymmetry of the flow distribution in the downcomer.
- Limitations in TRAC's description of the heat structures may significantly affect the calculated results.
- The use of large time steps was a possible source of running problems as the code sometimes failed when trying to reduce the time step from large values.
- The chronology of events predicted by the analysis matched the experiment fairly well.
- Vapor pull-through and liquid entrainment were observed at the offtake of the break line. TRAC did not have an algorithm that could adequately model those phenomena.
- The TRAC built-in flow-regime map performed well.
- The reproduction of pump behavior constituted an important problem for which no satisfactory solution was found. There were too many uncertainties involved in the asymmetrical degradation of the pumps in parallel. More sophisticated models of the pumps may be necessary.
- The choked-flow model predicted results with reasonable accuracy.

These conclusions were, in general, well supported by the analysis. The major question is the effect that a 3D vessel would have on the calculations. This should be determined before other details, such as the modeling of the pumps, are considered.

C11. *Report summary.* ***(This summary will be included in the year-end NUREG report. It should be about 2 to 5 pages long and could include several figures. A short paragraph description of each facility should be included. Also include a paragraph summarizing the baseline results.)***

The LOFT test facility simulates a four-loop PWR 1000-MWe commercial plant. It has a thermal power of 50 MW produced by nuclear fission sustained in the reactor core. The system was designed to simulate the major components and system response during LOCAs or operational-transient accidents. The facility components are instrumented to record the main-system variables during experiments. The facility consists of a reactor vessel volumetrically scaled to 1/47; an intact loop with an active steam generator, a pressurizer, and two primary coolant pumps connected in parallel; a broken loop connected by recirculation lines to the intact loop to keep the fluid temperature at about the core-inlet temperature prior to the experiment, a reflood-assist bypass valve connecting both legs of the broken loop as a safety device, and two quick-opening valves connecting both legs of the broken loop to the suppression-tank header. The LOFT ECCS simulates that of a commercial PWR. It consists of two accumulators, a high-pressure injection system (HPIS), and a low-pressure injection system (LPIS). Each system is arranged to inject scaled flow of emergency core coolant directly into the primary-coolant system.

Experiment LP-SB-2 studies the effect of a delayed pump trip in a small-break LOCA scenario with a 3-in.-equivalent-diameter break in the hot leg of a commercial PWR operating at full power. During this experiment the accumulators and LPIS were not used and scaled-HPIS flow was directed into the intact cold leg. The experiment started with the opening of the break valve in the hot leg of the intact loop. After 1.8 s the pressurizer fell below the reactor-scram set-point value. Simultaneously, the main-feedwater valve started to close and, with a 1-s delay, the main steam-control valve began to close. At 4.3 s, the main-feedwater valve was isolated, and the main steam-control valve was fully closed at 4.8 s. As a consequence of the subsequent pressure increase, the steam-bypass valve was actuated. Meanwhile, at 42 s the HPIS was initiated and at 50.3 s the subcooled blowdown ended. At 63.8 s the steam-generator auxiliary feedwater was manually initiated. At 582.2 s the pump degradation was observed and at around 600 s the onset of partial phase separation in the hot leg was detected. At around 1200 s the break started to uncover, increasing the pressurization rate, and after 1290 s the secondary pressure exceeded the primary pressure. After 1864 s the auxiliary feedwater was shut off and at about 2853 s the primary-coolant pumps were tripped after reaching their pressure set point.

The input deck used for the numerical simulations was an adaptation of a deck previously used at the Atomic Energy Establishment of Winfrith (AEEW) to simulate LOFT experiment LP-SB-1. The major changes included replacing the 3D vessel with a 1D model, removing an accumulator and line, and adding nodalization of the broken loop, pump injection, and nodalization of the hot-leg break. The model included 36 components with 142 cells and 42 junctions.

The results of two different simulations are discussed. The base case, called Run A, used the frozen version of TRAC-PF1/MOD1, Version 12.7. A second run, Run B, was made with a Winfrith version of TRAC with additional modifications. It included a setup using the TRAC control logic and two offtakes producing an option which could control the quality in the break line as a function of the void fraction in the hot leg. The pump-head multipliers were altered to force a sharp degradation at an inlet void fraction of about 0.35, and a further modification was added to the Pump No. 1 head multiplier to try to reproduce the asymmetrical pump behavior after degradation. A correction was made in an equation for calculating the critical gas velocity in the stratified model.

Run A was a 3000-s simulation of the SB-2 test that required about 1.63 h of CPU time on a Cray X-MP computer. The SETS numerics were used so the Courant time limit could be exceeded and time steps as large as 0.5 s could be used for a large part of the calculation. The TRAC-PF1/MOD1 (Version 12.7) code was able to predict reasonably well the evolution of the SB-2 transient. The flow-regime map performed well in identifying fully stratified conditions. The main discrepancy between the experiment and the calculation was the overprediction of mass loss from the primary system (Fig. A-4). The author concluded that for transients where phase separation upstream of the break affects the break density, the predictive capability of the code could be improved by incorporating a model relating quality in a branch to the thermal-hydraulic conditions in the main pipe. An offtake model should be used that considers the geometric relationship between the break junction and the main line.

Run B was made in an attempt to improve the accuracy of the break-flow calculation and to determine whether a better prediction of that parameter would improve the predictions of primary pressure, hot- and cold-leg densities, and vessel inventory and subsequent heatup. The most important modifications for Run B was the use of a method which could control the quality in the break line as a function of the void fraction in the hot leg. The pump-head multipliers were modified to force a sharp degradation at an inlet void fraction of 0.35, and the multipliers for Pump No. 1 were further modified to try to reproduce the asymmetrical pump behavior after degradation. The equation for calculating the critical gas velocity in the stratified model was corrected by including a missing factor.

These changes did indeed greatly improve the accuracy of the break flow rate calculation (Fig. A-5). The density in the break line also matched the experimental data much more closely for the entire transient. There were also significant improvements in the predictions of primary pressures and temperatures, primary mass inventory, and vessel inventory and rod temperatures.

One difficult aspect of the simulation was the accurate prediction of pump behavior. The velocities predicted by the code after pump degradation were not entirely satisfactory and the steady fall in the velocity observed in the experiment was not reproduced. One area of uncertainty was the performance of the pumps under two-phase conditions. The intact loop of the facility contains two similar pumps working in parallel. The strong coupling between these pumps constitutes a potential source of instability when asymmetric perturbations in flow conditions are felt at the pump inlets. The use of a 1D vessel did not allow reproduction of the asymmetrical flow distribution in the downcomer and its influence on the flow distribution in the bypasses. It was not possible, therefore, to determine whether the poor predictions of flow rates in some instances were caused by the pump-characteristic curves and multipliers or by the lack of accurate predictions of pump-inlet conditions.

No new user guidelines were explicitly stated in this assessment. Some code deficiencies were identified. The lack of a good offtake model for stratified flow in horizontal pipes was noted. The performance curves for pumps may be somewhat inaccurate in some two-phase flow regimes.

The assessment included the following information on run statistics.

1. The base-case calculation required 5850 s of CPU time on a Cray X-MP. The average time-step size was 0.23 s. The ratio of CPU to real time was 1.94 for run A and 2.3 for run B. The model contained 36 components and 142 cells. The grind time for the base case was 1.57 s.
2. The use of the SETS numerics allowed time steps as large as 0.5 s. The specification of a large maximum time step caused difficulties in some cases because the code failed when trying to reduce the time step.

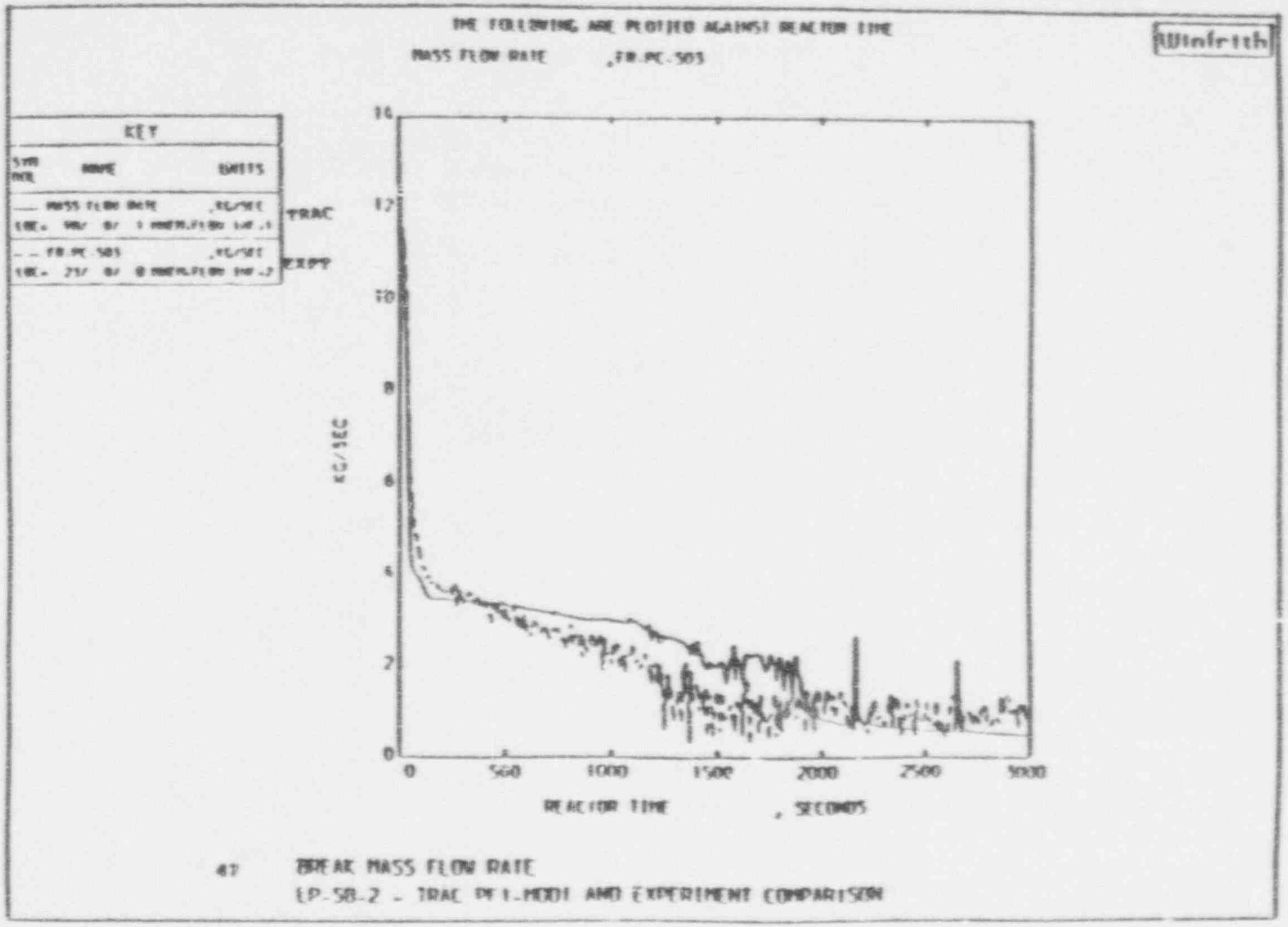

Fig. A-4. Break mass-flow rate, Run A.

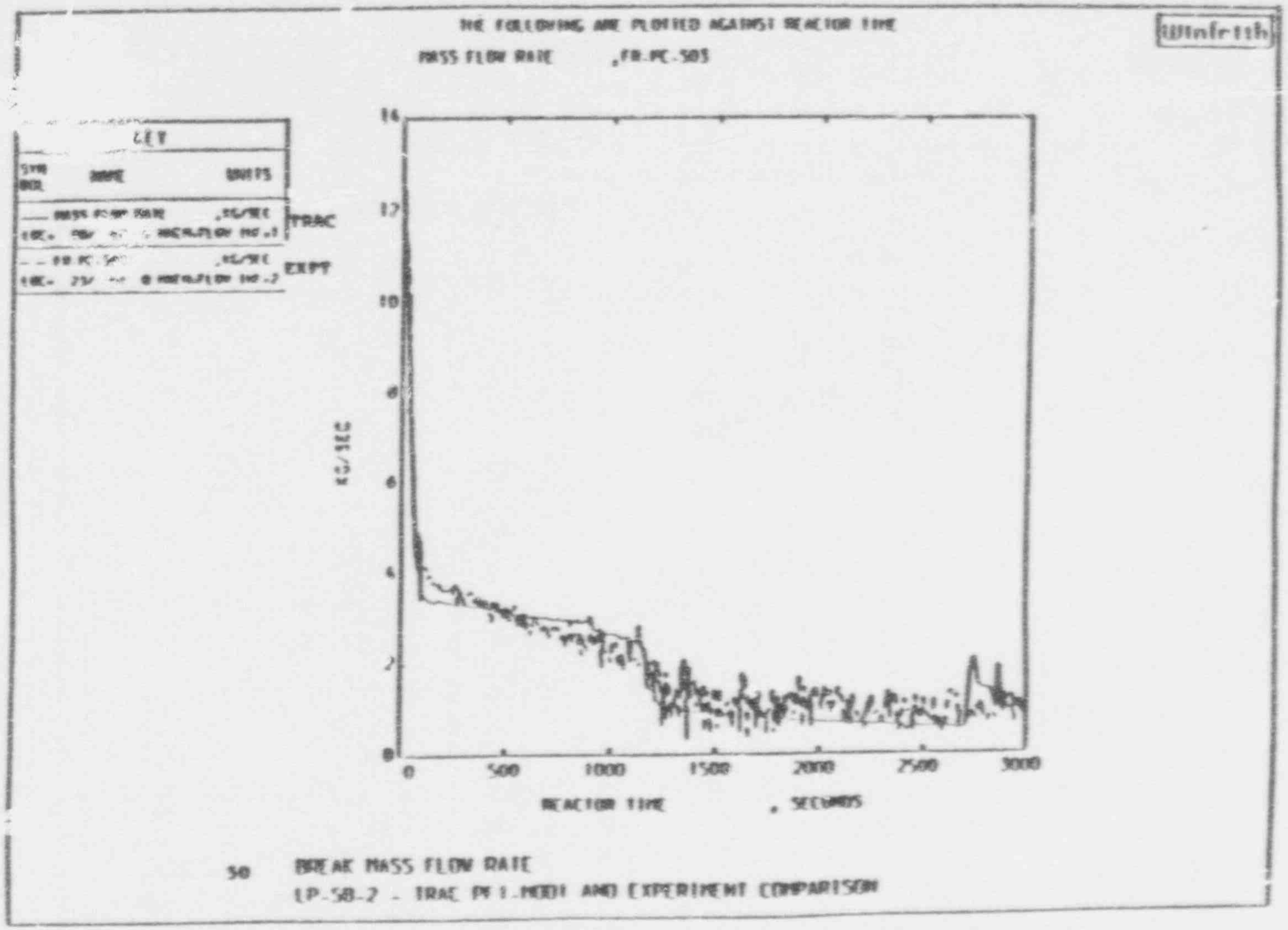

Fig. A-5. Break mass-flow rate, Run B.

REVIEW OF ICAP REPORT NO. AEEW-M 2416

A. BASIC DATA

A1. ***Report Information:***

Author: C. G. Richards

Report Title: Pre-Test Calculation of LOBI Test BL-02 Using TRAC-PF1/MOD1

Report Number: AEEW-M 2416

Author's Nationality and Affiliation: United Kingdom, Atomic Energy Establishment at Winfrith

Report Date: February 1987

A2. ***Reviewer's Name:*** Norman M. Schnurr

Date of Review: March 1990

A3. ***Which code version was used for the baseline calculation: (Include cycle number or version number and any updates. Section 5.2.2)***[*]

The version of TRAC used for the calculations was Winfrith version C26. This is based on LANL Version 12.2 with Winfrith corrections and additions.

A4. ***Report Classification (Proprietary, or non-proprietary, any restrictions. Section 4.1)***[*]

Not for publication.

A5. ***Is this an integral or separate-effects assessment?***

An integral assessment.

A6. ***Summarize why this assessment is being done. (Section 5.2.5 and Table 3)***[*]

This assessment tests the accuracy of the code in analyzing the effect of a 3% cold-leg-break LOCA in a Sizewell-type PWR. In particular, it tests the ability of the code to predict loop-seal clearance. The PWR phenomena included for this assessment are (Table 3 of NUREG-1271) break flow, liquid-inventory distribution, and loop-seal clearance.

A7. ***Provide a list of keywords descriptive of this analysis.***

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[*] Refers to section or table in NUREG-1271, "Guidelines and Procedures for the International Code Assessment and Applications Program," April 1987.

Small-break LOCA, LOBI, loop-seal clearance, PWR simulation, TRAC.

B. BRIEF QUESTIONS RELATED TO THE COMPLETENESS OF THE REPORT (Include report page number where information was found.)

B1. Did the author describe each test facility and each test used in the analysis? Elaborate. (Section 5.4.5 and 5.5.4)*

The LOBI test facility was discussed in some detail (p. 1) and a reference to a more complete description is given. A schematic diagram of the test facility is given in Fig. 2/1. This is a pretest calculation so draft test specifications were used. Experiment BL-02 is described (p. 2) and the most important trips and events for the experiment are listed in Table 1 of the report.

B2. The author must identify the experimental data used for the assessment in the report. The data channels used for comparison with code results should be easy to identify. It is desirable, but not required, for the author to supply the very date used in the assessment on hardcopy, floppy, or tape as specified in NUREG-1271. Has the author done these things? (Section 5.5.3 and 5.3)*

Diagrams showing locations and data channels for the instrumentation are given in Figs. 4/3, 4/4, and 4/5. No experimental-data report had been received by the author before this assessment was completed. All experimental results were taken directly from a preliminary data tape supplied by JRC Ispra. Experimental data are supplied in graphical form. The data include

- primary and secondary pressures,
- density in the broken-leg pump inlet and outlet,
- cold-leg density in the broken and intact loops,
- hot-leg density in the broken and intact loops,
- mass loss from the primary circuit,
- primary-mass inventory,
- differential pressure across the vessel,
- differential pressures across steam generators in broken and intact loops,
- total bypass steam flow and hot-leg flow,
- differential pressure in the broken-loop pump inlet,
- differential pressure in the intact-loop pump suction,
- various pressure differences in the intact and broken loops, and
- fluid temperatures at various points.

B3. ***The author must provide an evaluation of the experimental data uncertainty or clearly reference where it may be found. Has this been done? (Section 5.2.1)****

The uncertainty of the data is not discussed in this assessment. There was a statement that indicated some uncertainty in the experimental primary-mass determination.

B4. ***Was a base-case calculation performed using the unmodified, frozen code? Did the author include a clear, explicit figure of the Model? (Section 5.2.2).****

The calculation discussed in this report was performed using Winfrith version C26. This version is based on LANL Version 12.2 of TRAC-PF1/MOD1 with Winfrith corrections and additions.

B5. ***The author must supply a copy of the input deck for one of his transient calculations on hardcopy, or floppy, or both. Has he done this? (Section 5.4.6 and 5.5.1)****

A microfiche copy of the input deck was provided.

B6. ***Were sensitivity studies performed? Were the sensitivity studies adequately described? Were all identified code deficiencies explicitly described? (Section 5.2.3, 5.2.5, and 5.4.7)****

No sensitivity studies were performed. Some code deficiencies were listed (p. 15). It was not possible to determine the specific effect of some of these deficiencies from the single simulation performed in this assessment.

B7. ***Were nodalization studies performed? Were the nodalization studies adequately described? Elaborate if necessary. (Section 5.2.4)****

No nodalization studies were performed. The input deck is an adaptation of a model developed at AEEW for participation in the ISP18 exercise.

B8. ***The report should include run statistics for at least one transient calculation using the unmodified frozen code. Was this done? If a modified version of the code was produced, run statistics for the same transient calculation performed with the final version of the modified code should be included. Was this done? (Section 5.2.5 - para. 4, and Table 4 - p. 25, and Section 5.4.8)****

Run statistics are included for the simulation discussed in this assessment.

B9. ***Were complete references included in the report? (Section 5.4.10)****

Yes. A total of 10 references are included in this assessment.

B10. ***Were the objectives satisfied?***

Yes. This was a pretest calculation for LOBI Test BL-02. Results of the simulation were later compared to preliminary data from the experiment.

C. DETAILED QUESTIONS

C1. ***Did the author describe the model nodalization, assumptions, etc.? Were they appropriate? Did the nodalization follow the input deck preparation guidelines found in the TRAC User Guides? Elaborate if necessary. (Section 5.4.6)****

The nodalization used in this assessment is identical to that used in an input deck developed for the ISP18 exercise. Diagrams are included that show the noding of the vessel, steam generator, and the intact and broken loops. Complete dimensions are not given for all components so it is not possible to determine whether the nodalization follows guidelines found in the TRAC User's Guide in all cases. The number and geometry of cells appear to be consistent with common practice.

C2. ***Briefly describe the thermal-hydraulic phenomena and the reported code predictions addressed in the report. If appropriate, describe the phenomena in the context of thermal-hydraulic behavior in the vessel primary loop, secondary loop, and other phenomena of interest.***

Experiment BL-02 was a 3% cold-leg break at full reactor power. When the valve in the break assembly is opened the pressure throughout the system drops. When the set point of 131 bar is reached, the steam-line valve is closed, the main coolant pumps begin coastdown, the reactor power is scrammed, and valves in the feedwater line are closed. Auxiliary feedwater is turned on after a delay of 60 s. The main coolant pumps reach zero speed 201 s after the 131-bar set point is reached. When the pressure drops to 117 bar, the high-pressure injection starts after a 35-s delay. The cooldown control for the secondary side is activated 600 s after the 117-bar set point is reached. The accumulators begin injection when the pressure reaches 41 bar.

Of primary interest in the experiment were pressures, temperatures, densities, and flow rates throughout the system, mass inventory in the vessel, and fuel-rod temperatures. The primary-side pressure initially drops rapidly but levels out somewhat when high-pressure injection begins. The pressure drop becomes steeper again after loop-seal clearance in the broken loop. The pressure in the secondary rises at the beginning of the transient because of the closing of the steam valves and shutoff of the feedwater supplied to the steam generators. When it reaches the secondary set point, steam is again discharged from the steam generator and the secondary pressure slowly drops for the rest of the transient. Uncovery of the fuel rods depends on the break mass-flow rate, which is significantly affected by loop-seal clearing in the primary.

C3. If the author has identified new user guidelines has he described them thoroughly? What are they?

No new user guidelines were explicitly stated.

C4. What user guidelines can you infer from the results described in the report?

The author suggests that the core interphase-friction model underpredicts interphase friction when INVAN = 0 is used and that a value of 1 would likely give a better result.

C5. What deficiencies were identified in the unmodified frozen version of the code? (Section 5.2.5 and 5.4.7)*

Code deficiencies identified by the author are

- the lack of an accurate offtake model,
- inadequate modeling of heat-structures,
- possibly inadequate modeling of interphase friction associated with C[illegible].
- possibly overpredicted condensation rates.

C6. Describe the impact of each identified code deficiency.

The author states that it is not possible to draw definite conclusions regarding the adequacy of TRAC models of individual phenomena on the basis of a single calculation. A major difference between the experiment and calculations in this assessment was loop-seal clearance in the intact leg. That phenomena is a complex function of several of the deficiencies listed here and the effects of individual deficiencies cannot be easily determined.

C7. What code modifications were made? What effect did they have? (Section 5.2.3)*

A second run was made with some variations needed to obtain the best fit to ISP18. The results of that calculation were not discussed in this report.

C8. ***Run statistics must be provided for the calculation of one transient with the unmodified frozen code and the fully modified code. Compare and evaluate. The run statistics should include a description of the computer and operating system used to perform each calculation, and***

a. ***A plot of CPU vs RT***

b. ***A plot of DT vs RT***

c. ***The value of the "grind time" = [(CPU x 10^3)/(C x DT)]***

Where CPU = Total execution time
RT = Transient time
DT = Total number of time steps
C = Total number of volumes in the model

Plots of CPU vs RT and time step size vs RT are included in this report. The ratio of CPU to transient time for the entire simulation was 3.0. Time steps averaged about 0.3 s, which implies a DT value of about 3000. There are 175 volumes in the model. This gives a grind time of 5.1 s.

d. ***Evaluate the actual time step used. Did the transient run at the Courant time step or did the user specify a smaller maximum time step? Compare the actual time step vs transient time and the user specified maximum time step vs transient time. (Section 5.2.5-para.4, Table 4-p. 25, and Section 5.4.8)****

The simulation was severely limited by the maximum allowable time step. The calculation was discontinued after 900 s because of slow running. Average CPU time/problem time was about 3.0. Toward the end of the transient, following accumulator injection, this ratio was as high as 18:1 as a result of selection of short time steps. The author speculates that this difficulty may arise because of the use of a control system to model the accumulator and indicates that this problem may be overcome by using a proper accumulator model.

C9. ***Does the work documented in this report appear to be good and generally valid or are there fundamental problems with it? (Solicit input of code developers to answer this question.)***

This work is well done and some useful information is obtained. Because it was a pretest calculation, it was not possible to run additional sensitivity tests to try to improve the agreement between the simulations and experimental data. Nevertheless, the simulations showed satisfactory agreement with data that were obtained after the calculations had been completed. The author provides some insight into the calculation of loop-seal clearing and the effect it has on various system parameters.

C10. What conclusions were drawn in the report? Are they well supported by the results of the analysis? Elaborate. (Section 5.4.7 and 5.4.9)*

The author's conclusions were as follows:

- TRAC ran efficiently for the first 900 s of the transient. After accumulator injection began the code ran much slower but this may have been caused by the use of a control system to model the accumulator.
- As a pretest prediction, the general level of accuracy was considered reasonable. The timing of the main events in the transient was reasonably well reproduced, and no significant temperature excursion was calculated within the simulated core region. The only qualitative discrepancies were related to the loop-seal clearance. Only the broken loop was predicted to clear, no preloop clearance mixture-level depression was predicted, and the mixture-level depression after loop-seal clearance was overpredicted.
- The following comments can be made about quantitative agreement with the experimental data. The secondary-side cooldown was more rapid in the test than had been specified. Taking this into account, primary pressure is reasonably well predicted prior to loop-seal clearance. Break flow is initially well predicted. TRAC predicts no CCFL although the experiment indicates that CCFL occurred. After loop-seal clearance, the primary system continued to lose mass in the calculation to a larger extent than in the experiment.
- It is not possible to draw definite conclusions regarding the adequacy of the TRAC models of individual phenomena on the basis of a single calculation. Nevertheless the following potential deficiencies in the code are noted. Interphase friction in the core may be underpredicted. There are serious inadequacies in modeling heat structures. The interphase friction associated with CCFL may need improving. Condensation rates may be overpredicted.

These conclusions are supported by the results. The author makes no definite statements about deficiencies in the code. A complete posttest analysis including sensitivity studies will be required to further test the specific effect of each of the code deficiencies listed in this report.

C11. Report summary. (This summary will be included in the year-end NUREG report. It should be about 2 to 5 pages long and could include several

figures. A short paragraph description of each facility should be included. Also include a paragraph summarizing the baseline results.)

The LOBI two-loop test facility (Fig. A-6) simulates the cooling system of a four-loop, 1300-MWe PWR. One test loop, having 3 times the capacity in water volume and mass flow of the other, represents the three intact primary loops. The other represents the broken primary loop. Both loops contain an active steam generator and coolant pump. An active secondary loop system contains two condensers, a cooler, and a feedwater pump. The power input, the primary-circuit coolant mass flow, and the volume are scaled from reactor values by a factor of 712, leading to a heating power of 5.3 MW in the 8 x 8 heater rod bundle and to 28 kg/s of core mass flow. The absolute heights and relative elevations of the individual system components have been kept at reactor values to preserve the gravitational heads. The broken-loop steam generator has 8 full-size active U-tubes while the intact-loop steam generator has 24. Both the primary and secondary side of the LOBI rig are extensively instrumented. Emergency core cooling is provided by high-pressure injection and accumulator flow to the intact loop.

Experiment BL-O2 is a 3% cold-leg break at full power. The break nozzle is at the center of the cold leg. The secondary side undergoes a controlled cooldown at the rate of 56 K/h. At the beginning of the test, the break valve is opened and the pressurizer heaters are turned off. When the primary side pressure reaches a set point of 131 bar the steam-line valve is closed and the main coolant pumps begin coastdown. The auxiliary feedwater is turned on 60 s after the 131-bar set point is reached and the main coolant pumps reach zero speed 141 s later. The high-pressure injection system begins to operate 35 s after a 117-bar set point is reached. The accumulators begin injection when the primary-loop pressure drops to 41 bar.

The input deck is a revision of a deck developed at the Atomic Energy Establishment of Winfrith (AEEW) for participation in the ISP18 exercise. Changes were made in the control system and boundary conditions to reflect the specification of BL-02. A control system was used to model the accumulator.

The calculation was run to 900 s before being terminated because of slow running. Only a short portion of the refill phase of the transient was modeled. Figure A-7 shows a comparison of numerical predictions and experimental data for pressures in the primary and secondary loops. In general the agreement is reasonable. The primary-side pressure initially drops rapidly but levels out somewhat when high-pressure injection begins. The pressure drop becomes steeper again after loop-seal clearance in the broken loop. The pressure in the secondary rises at the beginning of the transient because of the closing of the steam valves and shutoff of the feedwater supplied to the steam generators. When it reaches the secondary set point, steam is again discharged from the steam generator and then slowly drops for the rest of the transient. The measured secondary-side pressure drops somewhat more rapidly than the calculated value but this is partly caused by the fact that the secondary-side cooldown was larger than was specified in the test. Given the slight differences between the effective boundary conditions in the experiment and those assumed in the calculation, the TRAC pretest calculation gave a reasonable prediction of the pressure behavior experienced in the test.

Figure A-8 shows the calculated and measured primary mass derived from the break and injection flow rates. The early break flow is evidently reasonably well predicted by TRAC, but after about 200 s, TRAC incorrectly predicts that the break flow increases. This increase is probably caused by the upstream void fraction decreasing at 200 s. This takes the critical-flow model into the interpolation region between void fractions of 0 and 0.1. The result of the overprediction of the break flow is premature loop-seal clearance. The reason for the overprediction of the broken-loop cold-leg density that gives rise to this error in break flow has not yet been determined. It should be noted that there is some uncertainty attached to the experimental primary-mass measurement. A significant qualitative difference between the experimental and calculated behavior is the failure of the intact-loop seal to clear in the calculation. The author gives a rather detailed discussion of the phenomena that contribute to differences between numerical predictions and experimental data. He does not, however, draw definite conclusions regarding the adequacy of TRAC models of individual phenomena. He does suggest several areas in the code that may contribute to the differences. These include underprediction of interphase friction, inadequacies of heat-structure modeling, possible overprediction of condensation rates, and inaccuracies in modeling the interphase friction associated with CCFL in the hot legs of steam generators. No new user guidelines were explicitly stated in this assessment.

The assessment included the following information on run statistics.

1. The ratio of CPU to transient time for the entire simulation was 3.0. Time steps averaged about 0.3 s, which implies a DT value of about 3000. There are 175 volumes in the model. This gives a grind time of about 5.1 s.
2. The simulations were severely limited by the maximum allowable time step. The calculation was discontinued after 900 s because of slow running. Average CPU time/problem time was about 3.0. Toward the end of the transient, following accumulator injection, this ratio was as high as 18:1 as a result of selection of short time steps. The author speculates that this difficulty may arise because of the use of the control system to model the accumulator and indicates that this problem may be overcome by using a proper accumulator model.

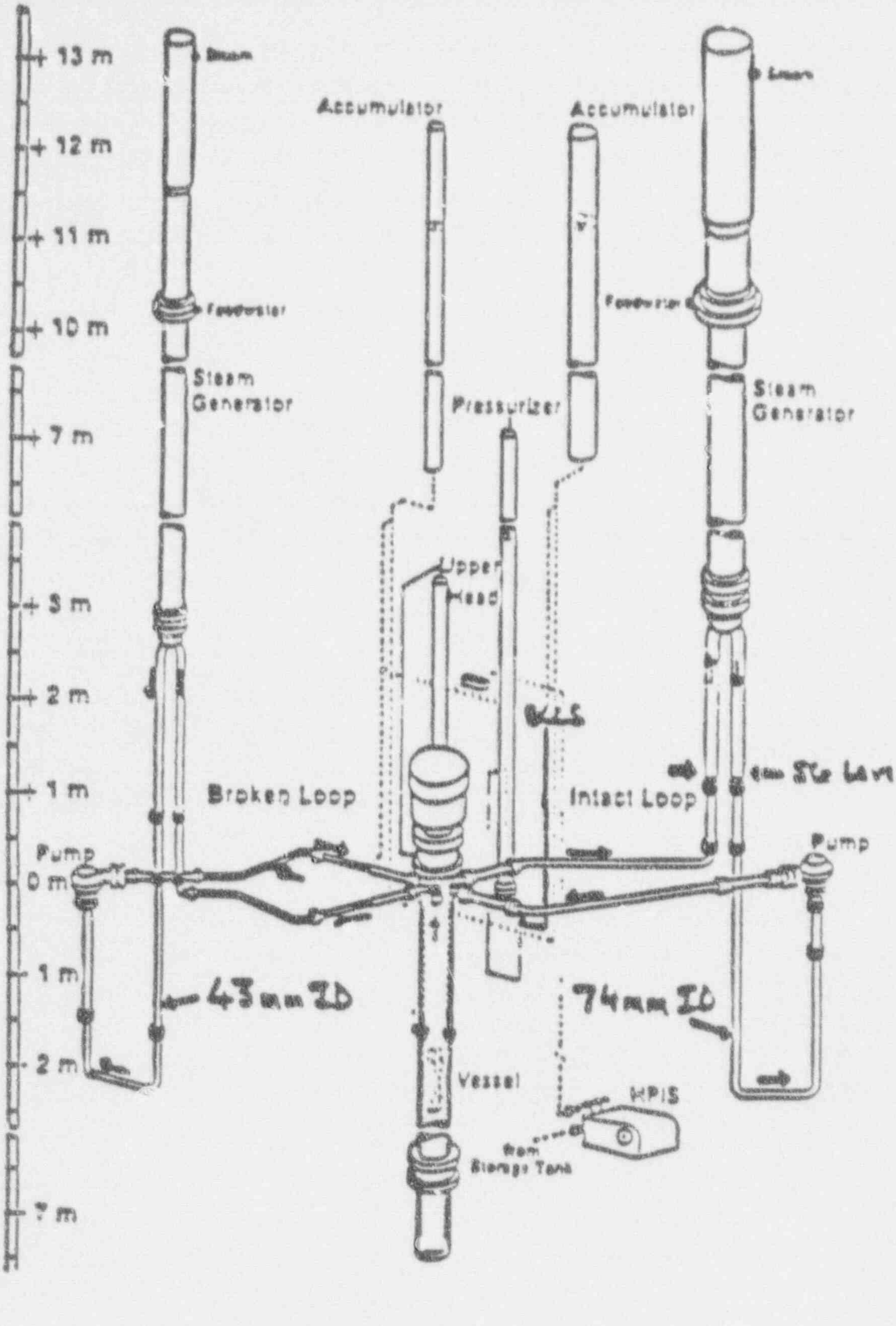

Fig. A-6. LOBI-MOD2 test facility, primary circuit.

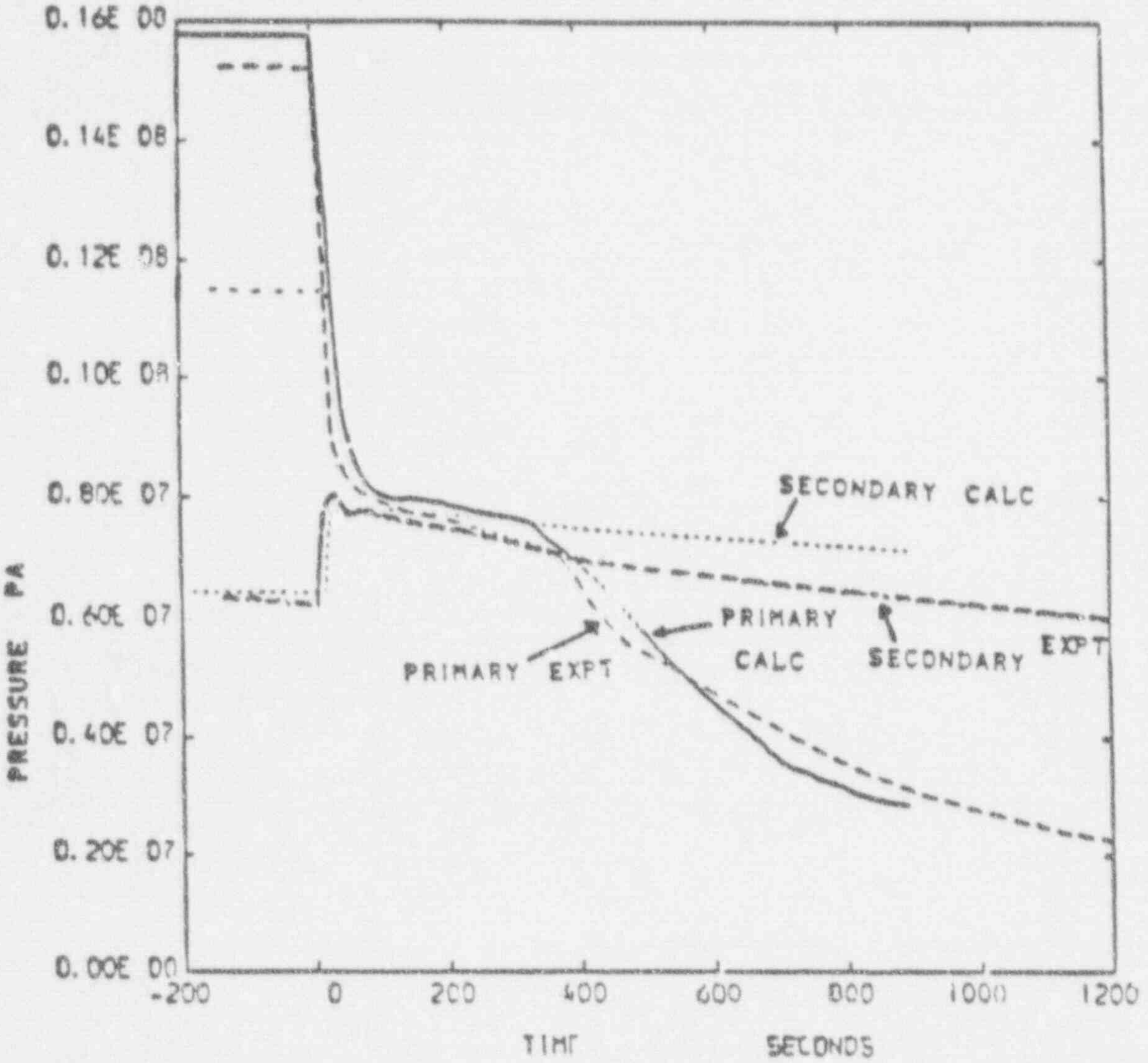

Fig. A-7. Primary and secondary pressures.

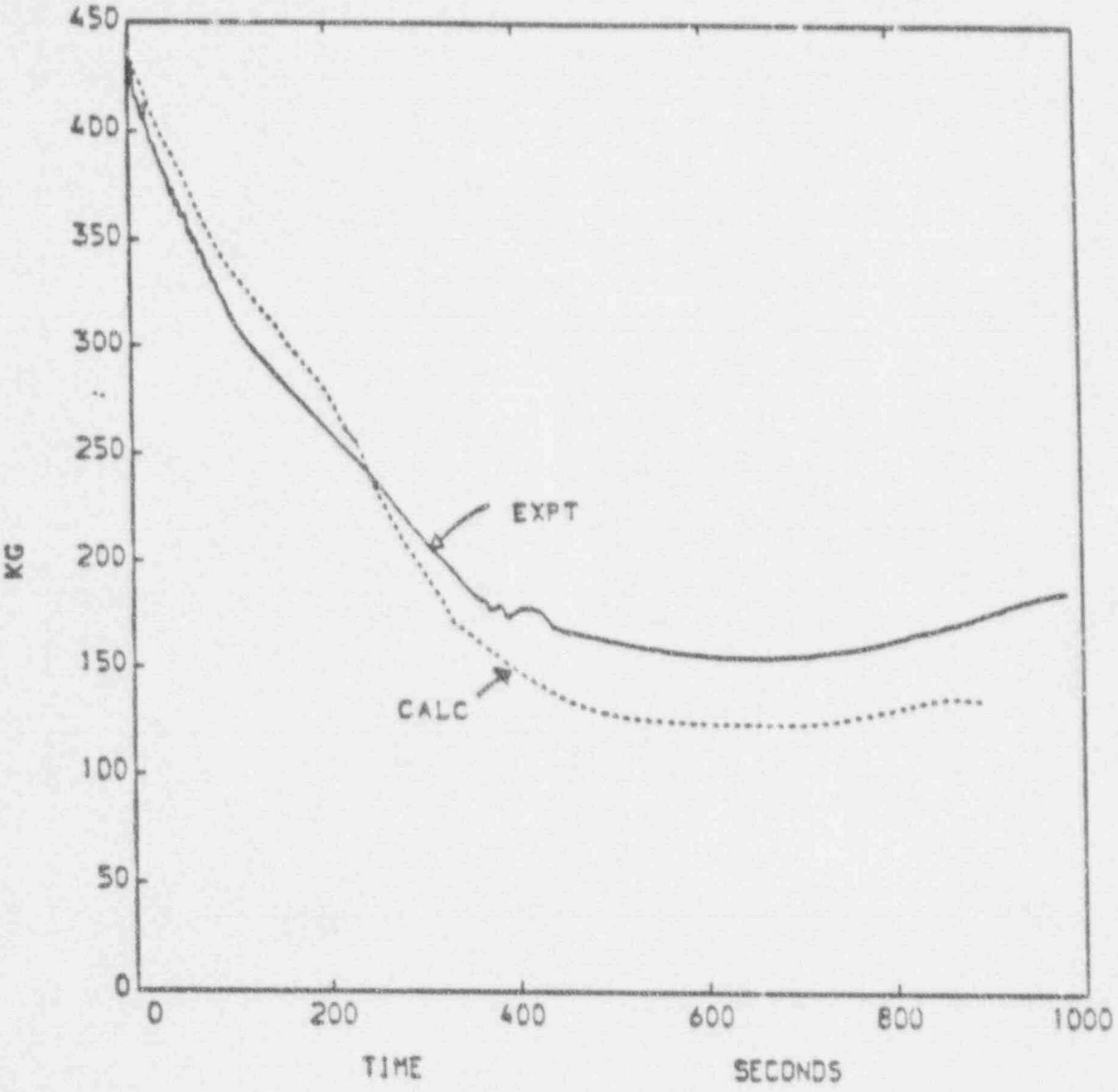

Fig. A-8. Primary mass inventory.

REVIEW OF ICAP REPORT NO. AEEW-R 2288

A. BASIC DATA

A1. ***Report Information:***

Author: J. C. Birchley, P. Coddington, and C. R. Gill

Report Title: Analysis of LOFT Experiment LP-02-6 Using the TRAC-PF1/MOD1 Computer Code

Report Number: AEEW-R 2288

Author's Nationality and Affiliation: United Kingdom, Atomic Energy Establishment at Winfrith

Report Date: November 1987

A2. ***Reviewer's Name:*** Norman M. Schnurr

Date of Review: March 1990

A3. ***Which code version was used for the baseline calculation: (Include cycle number or version number and any updates. Section 5.2.2)****

TRAC-PF1/MOD1, Version 12.2.

A4. ***Report Classification (Proprietary, or non-proprietary, any restrictions. Section 4.1)****

Commercial in confidence.

A5. ***Is this an integral or separate-effects assessment?***

An integral assessment.

A6. ***Summarize why this assessment is being done. (Section 5.2.5 and Table 3)****

Experiment LP-02-6 was the first large-break LOCA carried out in the LOFT facility under the auspices of the Organization for Economic Cooperation and Development (OECD). The programmatic objectives were directed toward an assessment of a large commercial PWR with respect to a design-basis LOCA as defined by the United States federal regulations. The purpose of the work discussed in this report was to assess the ability of TRAC to model this type of accident. The PWR phenomena included for this assessment are (Table 3 of NUREG-

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* Refers to section or table in NUREG-1271, "Guidelines and Procedures for the International Code Assessment and Applications Program," April 1987.

1271) break flow, liquid-inventory distribution, phase separation, ECC bypass and penetration, core-wide void and flow distribution, mixture level in core, mixture level in downcomer, core heat transfer, quench-front propagation, and asymmetric loop behavior.

A7. Provide a list of keywords descriptive of this analysis.

Large-break LOCA, LOFT, PWR simulation, TRAC, reflood.

B. BRIEF QUESTIONS RELATED TO THE COMPLETENESS OF THE REPORT (include report page number where information was found.)

*B1. Did the author describe each test facility and each test used in the analysis? Elaborate. (Section 5.4.5 and 5.5.4)**

The LOFT experimental facility is described briefly (p. 2). A reference to a more complete description of the facility is given. A drawing showing the major components (Fig. 2.1) and a piping and instrumentation schematic (Fig. 2.2) are included. The LOFT reactor vessel is shown in Figs. 2.6 - 2.8. Volumes and flow areas of all major components are given in Table 1. Test LP-02-6 is described in detail (pp. 6-7). Initial conditions are given in Table 3. An events sequence for the experiment is given in Table 5.

*B2. The author must identify the experimental data used for the assessment in the report. The data channels used for comparison with code results should be easy to identify. It is desirable, but not required, for the author to supply the very data used in the assessment on hardcopy, floppy, or tape as specified in NUREG-1271. Has the author done these things? (Section 5.5.3 and 5.3)**

Figure 2.2 shows the locations and data channels for the instrumentation. Experimental data are supplied in graphical form only. The data include primary and secondary pressures; flow rates, temperatures and densities of both the hot and cold legs of the broken and intact loops; accumulator liquid levels and flow rates; HPIS and LPIS flow rates; downcomer velocity, momentum flux, void fraction, and fluid temperatures; and a large amount of cladding temperature data.

*B3. The author must provide an evaluation of the experimental data uncertainty or clearly reference where it may be found. Has this been done? (Section 5.2.1)**

The uncertainty of the data is briefly discussed in this assessment. The uncertainty of the mass-flow rate through the bypass paths is estimated at 50%. Table 5 gives uncertainties for the time of events in the experiment. The accuracy of other experimental data is only discussed qualitatively.

B4. *Was a base-case calculation performed using the unmodified, frozen code? Did the author include a clear, explicit figure of the Model? (Section 5.2.2).**

The simulation of the experiment was performed using Version 12.2 with a modification to allow the specification of negative friction factors. The model is clearly described.

B5. *The author must supply a copy of the input deck for one of his transient calculations on hardcopy, or floppy, or both. Has he done this? (Section 5.4.6 and 5.5.1)**

A microfiche copy of the input deck was provided.

B6. *Were sensitivity studies performed? Were the sensitivity studies adequately described? Were all identified code deficiencies explicitly described? (Section 5.2.3, 5.2.5, and 5.4.7)**

No sensitivity studies were performed. The authors refer to "inherent weaknesses in the code's finite difference representation of the three-dimensional vessel" but do not elaborate. They also imply that the lack of an external-thermocouple model for fuel rods may cause significant differences between predictions and data.

B7. *Were nodalization studies performed? Were the nodalization studies adequately described? Elaborate if necessary. (Section 5.2.4)**

No nodalization studies were performed. The input deck is an adaptation of a model developed at AEEW for TRAC PD-2 calculations of LOFT large-break experiments L2-3 and LP-02-6. It is also very similar to an input deck that has been used at Los Alamos.

B8. *The report should include run statistics for at least one transient calculation using the unmodified frozen code. Was this done? If a modified version of the code was produced, run statistics for the same transient calculation performed with the final version of the modified code should be included. Was this done? (Section 5.2.5 - para. 4, and Table 4 - p. 25, and Section 5.4.8)**

Run statistics are included.

B9. *Were complete references included in the report? (Section 5.4.10)**

Yes. A total of 14 references are included covering all important aspects of this assessment.

B10. *Were the objectives satisfied?*

Yes. Results of the simulation were compared to experimental data and showed generally good agreement.

C. DETAILED QUESTIONS

C1. *Did the author describe the model nodalization, assumptions, etc.? Were they appropriate? Did the nodalization follow the input deck preparation guidelines found in the TRAC User Guides? Elaborate if necessary. (Section 5.4.6)**

The nodalization used in this assessment is similar to that used in previous simulations of the LOFT facility. Diagrams are included that show the noding of the vessel, steam generator, and the intact and broken loops. The number and geometry of cells appear to be consistent with guidelines found in the TRAC User's Guide.

C2. *Briefly describe the thermal-hydraulic phenomena and the reported code predictions addressed in the report. If appropriate, describe the phenomena in the context of thermal-hydraulic behavior in the vessel primary loop, secondary loop, and other phenomena of interest.*

Experiment LP-02-6 was a 200% double-ended cold-leg LOCA test carried out at full power (47 MW). The transient was initiated by opening the quick-opening blowdown valves. The reactor was scrammed on indication of loss of pressure in the intact-loop hot leg and the coolant pumps were tripped within 0.1 s and allowed to coast down. The system pressure fell rapidly to the saturation pressure corresponding to the temperature of fluid in the hot leg. The rapid discharge of liquid in the broken loop caused voiding of the core, a large reduction of heat transfer from the fuel rods, and a rapid rise in cladding temperatures. Saturated conditions in the broken-loop cold leg were reached at about 4 s, accompanied by a reduction in cold-leg break flow. This reduced flow, accompanied by a partial sustaining influence from the pumps, produced a partial bottom-up flow through the core and quenching of rods in the bottom 60% of the core. The intact-loop cold leg also began to void from about 5 s onward so that the break flow again exceeded the flow into the vessel and the core reemptied and the fuel rods heated up again. At about 15 s a top-down flow of liquid through the core began. This quenched the top 25 in. of the central fuel assembly. Flow from the accumulator began at 17.5 s and the HPIS and LPIS were activated at 21.8 and 34.8 s, respectively. Quenching of the fuel rods, which began at about 30 s, was completed very rapidly by the filling of the core, with all the fuel quenched at about 56 s. Of primary interest in the experiment were mass inventory in the vessel and fuel-rod temperatures.

C3. If the author has identified new user guidelines has he described them thoroughly? What are they?

No new user guidelines were explicitly stated.

C4. What user guidelines can you infer from the results described in the report?

The authors indicate that careful representation of the rods and heat structures in the vessel is necessary for accurate calculation of vessel hydraulics.

C5. What deficiencies were identified in the unmodified frozen version of the code? (Section 5.2.5 and 5.4.7)*

The authors believe there are inherent weaknesses in the code's finite-difference representation of the 3D vessel but did not elaborate. There is also some question about the adequacy of the reflood model but no definite conclusions could be made based on this work because of uncertainties concerning the initial stored energy and the effect of thermocouples on the quenching process.

C6. Describe the impact of each identified code deficiency.

The impact of these code deficiencies could not be clearly determined.

C7. What code modifications were made? What effect did they have? (Section 5.2.3)*

Only one simulation was made for this experiment.

C8. Run statistics must be provided for the calculation of one transient with the unmodified frozen code and the fully modified code. Compare and evaluate. The run statistics should include a description of the computer and operating system used to perform each calculation, and

- ***a. A plot of CPU vs RT***
- ***b. A plot of DT vs RT***
- ***c. The value of the "grind time" = $[(CPU \times 10^3)/(C \times DT)]$***

Where CPU = Total execution time

RT = Transient time
DT = Total number of time steps
C = Total number of volumes in the model

Timing statistics are given in Appendix A1. The entire simulation was divided into 9 runs. The transient time, execution time, and number of time steps are given for each run. The average time step for each run can be computed. The average time step for the entire simulation is 3.25 ms. The value of the grind time is 3.78 s.

d. Evaluate the actual time step used. Did the transient run at the Courant time step or did the user specify a smaller maximum time step? Compare the actual time step vs transient time and the user specified maximum time step vs transient time. (Section 5.2.5-para.4, Table 4-p. 25, and Section 5.4.8)*

The user-specified maximum time step is not given. The ratio of CPU to RT was 398.8. The CPU per RT per cell was 1.163.

C9. Does the work documented in this report appear to be good and generally valid or are there fundamental problems with it? (Solicit input of code developers to answer this question.)

This work is judged to be a good simulation of an important experiment. There are two problems that affected the results to some extent. The first was an overestimation of the initial stored energy in the rods and vessel structure. This was largely the result of a lack or sufficient experimental data. The second problem was an inadvertent overspecification of HPIS flow causing the combined ECC flow to be 5-10% too high. The effect of the overestimate of stored energy is discussed qualitatively. It caused increased differences between predicted and measured values for some parameters. The overestimated flow rate had no effect until relatively late in the simulation.

C10. What conclusions were drawn in the report? Are they well supported by the results of the analysis? Elaborate. (Section 5.4.7 and 5.4.9)*

The authors' conclusions were as follows:

- Most of the characteristics of the primary system and vessel-hydraulic response to a large-break LOCA can be accurately calculated by TRAC.
- The main weaknesses in the hydraulic representation are (1) flow distribution in the upper plenum following the draining of the liquid from the pressurizer and steam-generator hot side and (2) condensation phenomenon during accumulator injection. The failure to

calculate the top-down quench had a lasting effect on the calculation during subsequent stages of the transient.

- It is important to represent the energy stored in the fuel rods and in the vessel metalwork correctly if the subsequent vessel hydraulics are to be calculated correctly.
- The input model used in the calculation sought to represent the metalwork heat as accurately as possible, within the limitations of the code. Although the depressurization rate during blowdown was well calculated, discrepancies between calculation and data for the vessel fluid temperatures during reflood suggests that inadequacies remain in this representation.
- The adequacy of the post-CHF heat transfer package for calculation of quenching cannot be evaluated with confidence for this analysis, partly because of the excessive initial fuel-stored energy in the calculation, and partly because of the probable effect of the thermocouples themselves on the quenching process.
- The hydraulic behavior in the vessel downcomer during accumulator injection appears to have been well calculated.
- The effect of the discharge of accumulator nitrogen into the primary-coolant system has an important influence in promoting reflood. Despite some differences in the flow rate from the accumulator tank, the code simulated this aspect of the system behavior well.

These conclusions are supported by the results.

C11. *Report summary. (This summary will be included in the year-end NUREG report. It should be about 2 to 5 pages long and could include several figures. A short paragraph description of each facility should be included. Also include a paragraph summarizing the baseline results.)*

The LOFT facility (Fig. A-9) simulates the major components and system response of a commercial PWR during a LOCA. It has a single active intact loop which simulates the three intact loops of a commercial four-loop PWR during a large-break LOCA. The intact loop contains a steam generator, pressurizer, two primary-coolant pumps in parallel, and connecting pipe work. It also has two major measurement stations, one in the hot leg located just downstream of the vessel connection, and one in the cold leg located a few inches upstream of the ECCS cold-leg injection junction.

Experiment LP-02-6 was the first large-break (200%) double-ended cold-leg LOCA experiment carried out at the LOFT facility under the auspices of the Organization for Economic Cooperation and Development (OECD). The programmatic objectives were directed toward an assessment of a large commercial PWR with respect to a design-basis LOCA as defined by the United States federal regulations. The experiment was carried out at full power (47 MW) with the primary-coolant pumps tripped at the start of the transient and allowed to coast down naturally.

The experiment was initiated at time zero by opening the blowdown valves. The reactor was scrammed on indication of low pressure and the primary-coolant pumps were tripped within 1 s. The system pressure fell rapidly to the hot-leg saturation pressure, whereupon the core and upper plenum began to flash as liquid flowed out of the broken-loop hot and cold legs. The tripping of the primary-coolant pumps resulted in a coastdown of the fluid circulating in the intact loop, but the flywheel's inertia caused the pumps to continue to deliver mechanical energy to the fluid for several seconds so that sufficient liquid flowed into the downcomer to produce a bottom-up flow through the core after about 5 s. The core flow temporarily arrested the cladding temperature excursion and resulted in a quench for the lower half of the core. The bottom-up flow through the core terminated at about 8 s. The flow in the intact-loop hot leg reversed at about 10 s as fluid from the pressurizer and steam-generator hot side flowed back to the vessel, producing an accumulation of liquid in the upper plenum. This was followed by a quench of the upper part of the central fuel assembly. This top-down quench began at about 15 s. The cooling associated with the top-down flow was only temporary, and the core began to heat up again after about 20 s.

Flow from the accumulator was initiated at 17.5 s at a trip point of 4.11 MPa. The HPIS and LPIS were activated at 21.8 and 34.8 s, respectively. The ECCS injection was dominated by the accumulator until the accumulator flow terminated at about 55 s. During the accumulator-flow period, the injection of subcooled liquid caused a reduction in local pressure as vapor condensed into the liquid, leading to a global reduction in pressure as more vapor flowed toward the injection location. After the injection line was cleared, nitrogen flowed into the intact-loop cold leg and the condensation terminated. The accumulator nitrogen caused an increase in the cold-leg pressure of about 0.2 MPa. This forced the bulk of the liquid in the intact-loop cold leg and at the top of the downcomer down through the downcomer and lower plenum and into the core. The surge of liquid into the core occurred between about 53 and 60 s and resulted in most of the core being filled with liquid. The fuel rods were completely quenched at about 56 s. The reflood and quenching of the core was accompanied by a series of flow oscillations in the vessel. Each time liquid flowed into the core, a fraction of the fuel was quenched, generating vapor which pressurized the core and drove liquid back into the downcomer, thus perpetuating the oscillations until all the fuel was quenched.

The input deck used for the simulation of experiment LP-02-6 is similar to that used in previous simulations performed at Winfrith for LOFT experiments. There are a total of 343 cells (192 in the vessel). The simulation accurately reproduced most of the characteristics of the primary system and vessel-hydraulic response. Calculated and measured pressures for the intact hot leg are shown in Fig. A-10. Agreement is very good. The calculations of flows and fluid conditions are in quite good agreement with data for most of the transient. Agreement is best in the early part of the blowdown when the flow is more strongly influenced by the subcooled break-flow model rather than conditions in the vessel. Calculations of accumulator flow are also in good agreement with the data.

Calculations of reactor-vessel flows and rod temperatures do not agree with the experimental data as well as the pressures, temperatures, and flow rates computed for the hot and cold legs of the intact and broken loops. Nevertheless, the agreement is qualitative and moderately good considering the uncertainties in initial conditions (energy content of the heat structures, pump characteristics, etc) and uncertainties in some of the experimental data. Core entry velocity and momentum flux are shown in Fig. A-11. The similarity is quite good when one takes into account that the velocity measurement is unidirectional and that there is a time-dependent zero offset on the momentum flux.

Calculated and measured fuel-rod cladding temperatures are shown in Fig. A-12 at the 11-in. elevation for one of the highest-power rods. During the first few seconds there was a rapid heatup following departure from nucleate boiling. The first temperature peak occurs at about 5 s for both the data and the calculations. The size of the peak is overpredicted. The major cause of the discrepancy appears to be a significant overprediction of the initial stored energy of the fuel. There is also some question concerning the size of the fuel-cladding gap. The fuel rods had experienced numerous power escalations, scrams, temperature transients, and quenches prior to the conduct of this test. It is possible that the gap has been substantially reduced. More recent calculations using zero gap gave much closer agreement with the data for the initial temperature peak. The bottom-up flow of liquid caused a rapid decrease in temperature at about 7 s,but as the water level in the core decreased, the rod heated up again. After the onset of the reflood quench at 34 s, cooling and quenching gradually moved upward in the core, reaching the 11-in. elevation at slightly above 40 s. The calculation did not show the second quench until nearly 80 s because the temperatures were too high.

The authors conclude that most of the primary and vessel hydraulic response were accurately simulated. The hydraulic behavior in the vessel downcomer and the effect of the discharge of accumulator nitrogen in promoting reflood were also accurately simulated. The major discrepancies were in the rod temperature calculations. The adequacy of TRAC's post-CHF heat-transfer package could not be evaluated with confidence from this analysis, partly because of the excessive initial fuel-stored energy and partly because of the probable effect of the thermocouples on the quenching process.

No new user guidelines were explicitly stated in this assessment. Some code deficiencies were identified. The authors believe there are inherent weaknesses in the code's finite-difference representation of the 3D vessel. There is also some question about the adequacy of the reflood model but no definite conclusions could be made based on this work because of uncertainties concerning the initial stored energy and the effect of thermocouples on the quenching process.

The assessment included the following information on run statistics. The total CPU time on the Winfrith Cray for a 106-s simulation was 11.74 h. The average time step was 3.25 x 10^{-3} s. The CPU time per transient time per cell was 1.163 and the CPU time per time step per cell was 3.778 x 10^{-3} s.

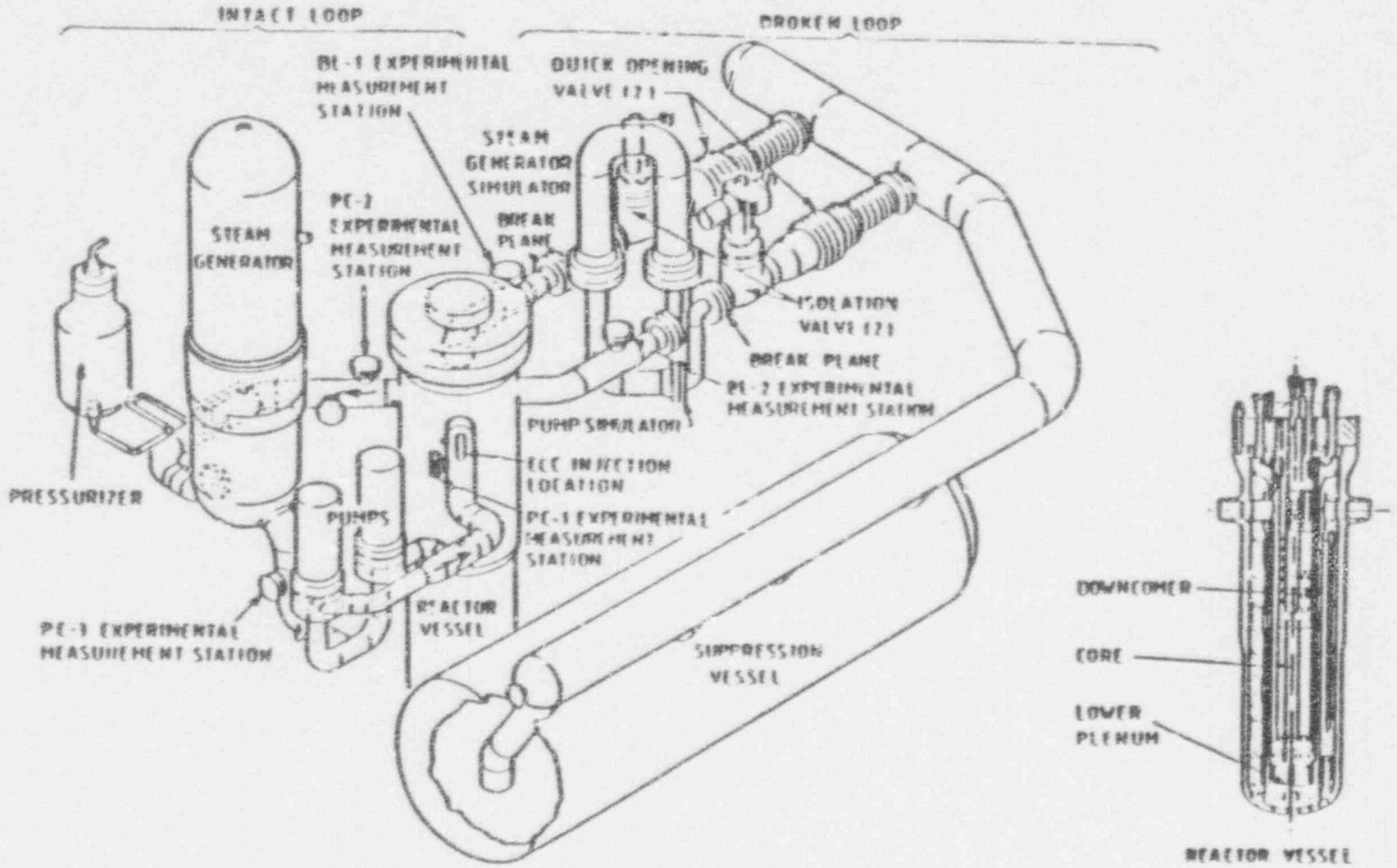

Fig. A-9. Major components of the LOFT system.

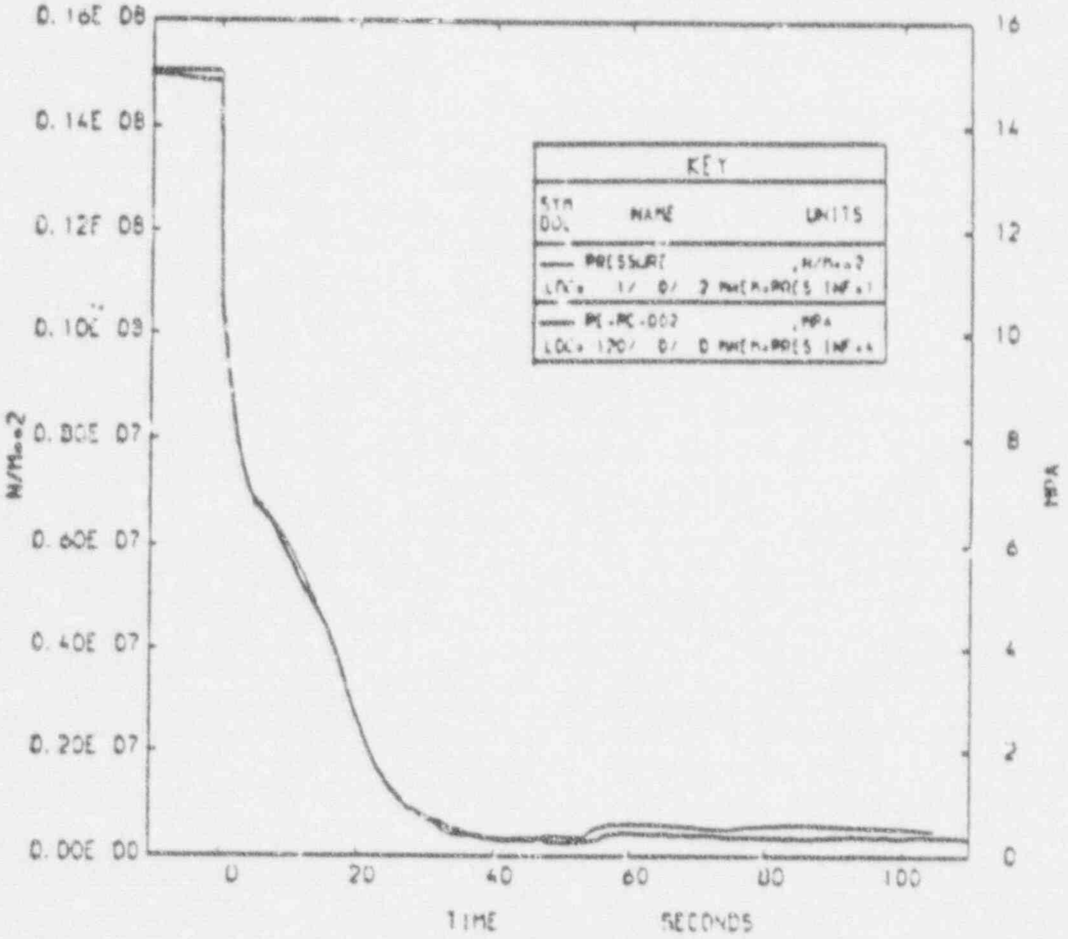

Fig. A-10. Hot-leg pressures.

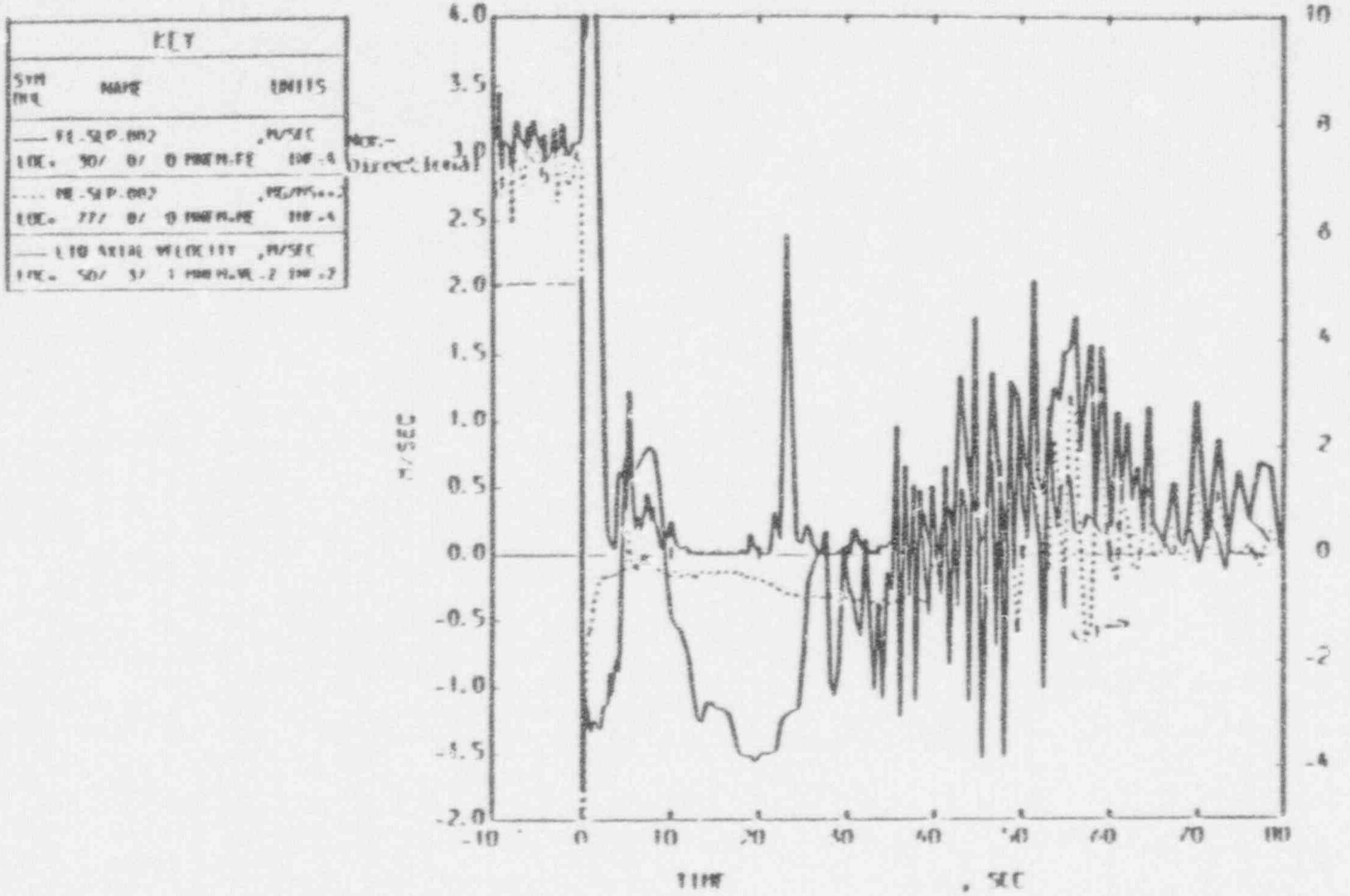

Fig. A-11. Core entry velocity and momentum flux.

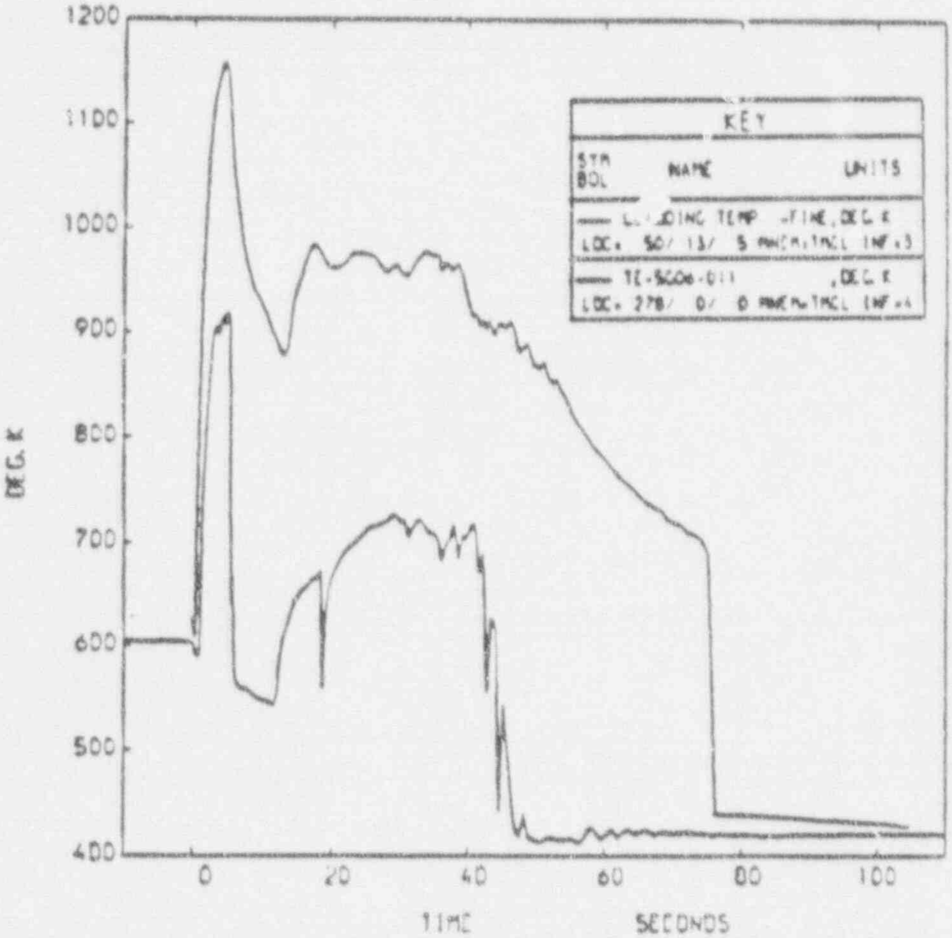

Fig. A-12. Cladding temperature at 11-in. elevation.

REVIEW OF ICAP REPORT NO. AEEW-M 2305

A. BASIC DATA

A1. ***Report Information:***

Author: R. O'Mahoney

Report Title: A Study of the Reflood Characteristics of TRAC-PF1/MOD1

Report Number: AEEW-M 2305

Author's Nationality and Affiliation: United Kingdom, Atomic Energy Establishment at Winfrith

Report Date: April 1986

A2. ***Reviewer's Name:*** Norman M. Schnurr

Date of Review: April 1990

A3. ***Which code version was used for the baseline calculation: (include cycle number or version number and any updates. Section 5.2.2)****

TRAC-PF1/MOD1, Version 11.9.

A4. ***Report Classification (Proprietary or non-proprietary, any restrictions. Section 4.1)****

Not for publication.

A5. ***Is this an integral or separate-effects assessment?***

A separate-effects assessment.

A6. ***Summarize why this assessment is being done. (Section 5.2.5 and Table 3)****

The purpose of this assessment is to study the reflood characteristics of TRAC-PF1/MOD1. Particular attention is focused on the ability of the TRAC reflood-hydraulics models to predict the correct distribution and entrainment of liquid during reflood. Calculations were made for comparison with data from the THETIS experimental rig at Winfrith. The PWR phenomena included for this assessment are (Table 3 of NUREG-1271) entrainment and deentrainment in the core, mixture level in core, core heat transfer including partially covered core, and quench-front propagation.

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* Refers to section or table in NUREG-1271, "Guidelines and Procedures for the International Code Assessment and Applications Program," April 1987.

A7. *Provide a list of keywords descriptive of this analysis.*

TRAC, THETIS, reflood, entrainment.

B. BRIEF QUESTIONS RELATED TO THE COMPLETENESS OF THE REPORT (Include report page number where information was found.)

B1. *Did the author describe each test facility and each test used in the analysis? Elaborate. (Section 5.4.5 and 5.5.4)**

The THETIS facility and the two tests covered in this assessment are briefly described (pp. 14, 15) and a reference to a more detailed description of the experimental facility is given.

B2. *The author must identify the experimental data used for the assessment in the report. The data channels used for comparison with code results should be easy to identify. It is desirable, but not required, for the author to supply the very data used in the assessment on hardcopy, floppy, or tape as specified in NUREG-1271. Has the author done these things? (Section 5.5.3 and 5.3)**

The experimental data include flow rates and rod temperatures. Void fractions are inferred from a collapsed-liquid level determined from differential pressure transducers. Figure 3 shows thermocouple locations on a fuel-rod simulator. The experimental data are given only in graphical form (Figs. 5-8, 11, 15-22, 24-37, 39-44).

B3. *The author must provide an evaluation of the experimental data uncertainty or clearly reference where it may be found. Has this been done? (Section 5.2.1)**

The uncertainty of the thermocouple data is 6 K (p. 16). Scatter in the void fraction data is also discussed qualitatively (p. 16).

B4. *Was a base-case calculation performed using the unmodified, frozen code? Did the author include a clear, explicit figure of the Model? (Section 5.2.2).**

The simulation of the experiment was performed using Version 11.9. The model is clearly described (p. 15). The noding is shown in Fig. 4.

B5. *The author must supply a copy of the input deck for one of his transient calculations on hardcopy, or floppy, or both. Has he done this? (Section 5.4.6 and 5.5.1)**

No input deck was provided.

*B6. Were sensitivity studies performed? Were the sensitivity studies adequately described? Were all identified code deficiencies explicitly described? (Section 5.2.3, 5.2.5, and 5.4.7)**

A total of 11 simulations were performed. They showed the effect of various aspects of the interface-sharpener logic on reflood hydraulics. These sensitivity studies were discussed in detail (pp. 16-29) and deficiencies in the code were discussed.

*B7. Were nodalization studies performed? Were the nodalization studies adequately described? Elaborate if necessary. (Section 5.2.4)**

No nodalization studies were performed. The noding used for this separate-effects assessment was finer than would be practical for an integral assessment. The effect of replacing heat-transfer slabs with rods, which has the effect of using much finer noding for the heat structure, was investigated in the sensitivity studies (pp. 25, 26).

*B8. The report should include run statistics for at least one transient calculation using the unmodified frozen code. Was this done? If a modified version of the code was produced, run statistics for the same transient calculation performed with the final version of the modified code should be included. Was this done? (Section 5.2.5 - para. 4, and Table 4 - p. 25, and Section 5.4.8)**

Run statistics are not included in this assessment.

*B9. Were complete references included in the report? (Section 5.4.10)**

Yes. A total of 7 references are included covering all important aspects of this assessment (p. 35).

B10. Were the objectives satisfied?

Yes. The ability of TRAC to simulate reflood was analyzed in detail. The effect of the interface-sharpener logic was assessed and the entrainment algorithm was compared to other empirical models. Recommendations were made for improvement in the TRAC model.

C. DETAILED QUESTIONS

C1. Did the author describe the model nodalization, assumptions, etc.? Were they appropriate? Did the nodalization follow the input deck preparation *guidelines found in the TRAC User Guides? Elaborate if necessary. (Section 5.4.6)**

The nodalization used in this assessment is described. The nodalization in the vessel is somewhat finer for this separate-effects assessment than might be used for an integral assessment.

C2. ***Briefly describe the thermal-hydraulic phenomena and the reported code predictions addressed in the report. If appropriate, describe the phenomena in the context of thermal-hydraulic behavior in the vessel primary loop, secondary loop, and other phenomena of interest.***

The experimental facility consists of a single cluster of heated rods in a shroud tube housed in a pressure vessel. Reflood is simulated by introducing water into the bottom of the cluster through a penetration in the pressure-vessel wall. The top of the shroud tube is open to the pressure vessel via a steam separator. The vessel is then vented to the atmosphere through a pressure-control valve. The cluster consists of a 7 x 7 square array of electrically heated, Inconel-clad, fuel-rod simulators.

Before an experiment is begun, the rods are slowly heated to a given temperature. Then the power is set at a high level and water is introduced at the bottom of the vessel to simulate reflood. Rapid generation of steam causes an upflow of vapor that can entrain liquid.

Of particular interest is the upward flow of liquid. Since the interfacial-shear package used in TRAC is not necessarily representative of the physical processes occurring during reflood, a special model is to used limit the upward flow of liquid to a value consistent with an entrainment correlation. The study of these thermal/hydraulic phenomena during reflood is the primary goal of this assessment.

C3. ***If the author has identified new user guidelines has he described them thoroughly? What are they?***

The author recommends that the interface-sharpener logic not be used.

C4. ***What user guidelines can you infer from the results described in the report?***

The use of slabs as heat structures during reflood can lead to inaccuracies because the axial spacing of nodes can be no less than the length of the corresponding hydrodynamic cell. This means that all of a particular heat slab quenches at one time. This tends to cause spikes in the liquid and vapor mass flow above the slab. Replacement of the slabs by rods that can have fine node spacing greatly decreases the axial discontinuities.

C5. What deficiencies were identified in the unmodified frozen version of the code? (Section 5.2.5 and 5.4.7)*

- The interface-sharpener logic was found to be inaccurate.
- The limitation on axial node spacing for slabs as heat structures caused discontinuities in the fluid flow.
- An error in the calculation of a film coefficient was found.

C6. Describe the impact of each identified code deficiency.

The interface-sharpener logic caused a very sharp liquid/vapor interface. A significant amount of liquid is present ahead of the general interface if the interface-sharpener logic is not used. This is in better agreement with the experimental data.

Slabs, as heat structures, quench as a single unit during reflood. This causes a severe discontinuity in the axial-fluid-flow distribution.

Correcting the error in the film-coefficient calculation caused differences in the film coefficient by a factor of 10 in some cases. This had a significant impact on the local rod temperatures.

C7. What code modifications were made? What effect did they have? (Section 5.2.3)*

Several code modification were made. These included the following.

- The lower bound on liquid velocity for which the interface-sharpener logic is used was changed from 3/4 of the gas velocity to 1/20 of the gas velocity. The effect of this modification was a small reduction of the oscillation predicted during the refilling period.
- The entrainment correlation used in TRAC was replaced by the COBRA-TF correlation. This significantly increased the entrainment of liquid at vapor velocities less than 8 m/s. The droplet-size calculation was also modified. The lower bound on the liquid velocity was lowered to 0.001 m/s. These three changes resulted in a significant improvement in the results. There was a generally smoother behavior and longer filling time for individual cells. The discontinuities in the axial-flow distribution were much less pronounced.
- The range of operation of a cubic spline was modified. A more physically based approach was used based on a measure of the height of a cell above the liquid/vapor interface. This modification did not show a significant additional improvement.
- A correction was made in the calculation of a liquid film coefficient. The input file was also changed to use rods rather than slabs to model the shroud. These changes produced some additional improvement in the results. The spikes were further reduced and overall agreement of the calculated results with the experimental data was improved.

C8. Run statistics must be provided for the calculation of one transient with the unmodified frozen code and the fully modified code. Compare and evaluate. The run statistics should include a description of the computer and operating system used to perform each calculation, and

a. A plot of CPU vs RT

b. A plot of DT vs RT

c. The value of the "grind time" = [(CPU x 10^3)/(C x DT)]

Where CPU = Total execution time
RT = Transient time
DT = Total number of time steps
C = Total number of volumes in the model

No timing statistics were provided.

d. Evaluate the actual time step used. Did the transient run at the Courant time step or did the user specify a smaller maximum time step? Compare the actual time step vs transient time and the user specified maximum time step vs transient time. (Section 5.2.5-para.4, Table 4-p. 25, and Section 5.4.8)*

The time step was not discussed in this assessment.

C9. Does the work documented in this report appear to be good and generally valid or are there fundamental problems with it? (Solicit input of code developers to answer this question.)

This work represents a rather comprehensive assessment of the capability of the TRAC code in hydraulic calculations during reflood. A series of simulations was performed to determine the effects of various aspects of the TRAC model on accuracy. The results of this work lead to some recommendations for improvements in the code. The work appears to have been well conceived and executed.

C10. What conclusions were drawn in the report? Are they well supported by the results of the analysis? Elaborate. (Section 5.4.7 and 5.4.9)*

The author's conclusions were as follows:

- TRAC-PF1/MOD1 with the interface-sharpener model included is not adequate to predict the detailed hydraulic behavior observed during the THETIS reflood tests. The predictions display an oscillatory and discontinuous behavior dominated by the movement of a sharp liquid interface. These phenomena are not observed in the experiments.

- Modifications of the interface-sharpener model and the relevant interfacial-shear model, in line with published entrainment correlations, remove much of the unphysical behavior.
- Significant amounts of stored metalwork heat cannot be adequately represented by heat slabs in TRAC during reflood.
- The TRAC code contained an error in implementation of the rod-to-liquid heat-transfer correlation used in the film-boiling regime.
- Excluding the interface-sharpener model significantly improves the overall hydraulic predictions of the THETIS tests although some oscillation is still predicted.

These conclusions are supported by the results.

C11. ***Report summary. (This summary will be included in the year-end NUREG report. It should be about 2 to 5 pages long and could include several figures. A short paragraph description of each facility should be included. Also include a paragraph summarizing the baseline results.)***

The purpose of this assessment was to determine the accuracy of the hydraulics model in TRAC-PF1/MOD1 for reflood conditions. The accuracy of the TRAC simulations was determined by comparison of calculated results with experimental data from forced-reflooding tests in the THETIS experimental rig at Winfrith. The THETIS facility consists of a single cluster of rods in a shroud tube housed in a pressure vessel. Water may be introduced into the bottom of the cluster through a penetration of the pressure vessel wall. The top of the shroud tube is open to the pressure vessel via a steam separator. The vessel is then vented to the atmosphere through a pressure control valve.

The cluster consists of a 7 x 7 square array of electrically heated, Inconel-clad fuel-rod simulators. Before an experiment is begun, a low power level is applied to the test section to heat the rods to a selected temperature. The experiment is then initiated by increasing the power input to a specified level and, a few seconds later, closing a fast-acting drain valve to force the reflood water to rise in the test section. Simulations were performed for two THETIS experiments, Run 65 with a reflood rate of 2.0 cm/s and power of 99 kW, and Run 75 with a reflood rate of 5.7 cm/s and a power of 200 kW.

The base case was run with TRAC-PF1/MOD1 Version 11.9. This version of the code contains an interface-sharpener model (ISM) which attempts to compensate for the fact that the interfacial-shear package is not necessarily representative of the physical processes occurring during reflood. The model operates by explicitly attempting to limit the upward flow of liquid at a liquid/vapor interface according to an entrainment correlation. Comparisons of the results of the base-case simulation with the data from Run 65 are shown in Figs. A-13 and A-14. The integrated liquid carryover calculated by TRAC is in fair overall agreement with the experimental data (Fig. A-13) but the calculated curve is a series of steps instead of the smooth curve one would expect. This effect is also clearly evident in the liquid volume fraction predictions shown in Fig. A-14. TRAC predicts alternating periods of filling and emptying producing a sawtooth effect.

A series of modifications were made to TRAC in an effort to improve the results. The first modification was a reduction of the lower bound on liquid velocity for which the ISM was used. The limit was changed from 3/4 to 1/20 of the vapor velocity. The second modification replaced the entrainment correlation with the COBRA-TF model, modified the interfacial-shear model to allow upflow of droplets, and further decreased the lower bound on the liquid velocity to 0.001 m/s. The third modification changed the test for invoking the cubic-spline model (used to interpolate the liquid fraction value using a cubic equation) to one based on height above the interface rather than void fraction. The first modification had a limited effect. The second modification had a rather significant effect in smoothing out the predictions of the integrated core-outlet liquid flow (Fig. A-15). The third modification had little additional effect.

A detailed examination of the calculations indicated that the timing of the discontinuities was largely coincident with the quenching of the heat slabs used to represent the shroud. A heat slab is used in each fluid cell but the heat-slab model does not allow any axial subdivisions within a slab. This means that a particular heat slab will quench all at once rather than in a smooth axial progression. This has the effect of causing spikes in the liquid and vapor flow rates above the slab. A simulation was therefore performed with the slabs replaced by rods. An error found in the equation for calculating the liquid film coefficient during film boiling was also corrected. The results of a simulation of Run 65 with a code containing these modifications (as well as those discussed in the previous paragraph) are shown in Fig. A-16. The core-outlet liquid mass flow for this case is compared to the results of a simulation performed with a code that did not include the error correction and substitution of rods for slabs. Note that the amplitude of oscillations is greatly reduced.

Finally, a sensitivity study was performed to determine the effect of the ISM. Simulations were performed, with and without the ISM, for the case with slabs replaced with rods and the error correction included. These calculations were performed with a later version of TRAC, Version 12.2. The results are somewhat better for the calculation with no ISM. The prediction of vapor fractions is significantly improved although some oscillation is still predicted as the cells fill. There is also significant improvement in the overall cladding temperature history, particularly in the time to quench.

Two sets of simulations were also performed for Run 75, an experiment with a much higher reflood rate. The first set compares the base version of TRAC (Version 11.9) with a version containing the basic modifications but slabs representing the shroud. Both versions give good agreement with experimental data up to 100 s but become increasingly poor after that time. The modified version shows no improvement over the base case other than being slightly smoother. The second set compares the TRAC base case (Version 12.2) and TRAC with no ISM. These results show a significant change in both the hydraulic and thermal predictions when the ISM is excluded. The change in hydraulic predictions is toward the experimental trends although an early spike in the flows causes too much liquid to be carried out. The change in heat-transfer predictions is also toward the experimental trend up until the time of quenching in the experiment. The lower quench temperature in the calculations causes rather late quenching in the no-ISM calculation.

The author concludes that TRAC-PF1/MOD1 with the ISM included is not adequate to predict the detailed hydraulic behavior observed during the THETIS reflood tests. The predictions display an oscillatory and discontinuous behavior dominated by the movement of a sharp liquid interface. Modifications of the ISM and the interfacial-shear model, in line with published entrainment correlations, removes much of the unphysical behavior. A significant amount of stored metalwork heat cannot be adequately represented by heat slabs in TRAC. Replacing the slabs by heated rods improves the accuracy of the calculation. The lack of any axial subdivisions leads to unphysical discontinuities in the heat transfer and related fluid behavior. Excluding the ISM significantly improves the overall hydraulic predictions although some oscillation is still predicted.

The author recommends that the interface-sharpener model not be used. Some code deficiencies were identified. Using rods rather than slabs to represent stored heat in the core for a reflood situation will largely eliminate oscillations in fluid flow. An error in the calculation of a film coefficient for liquids in film boiling was uncovered. No run statistics were included for this separate-effects assessment.

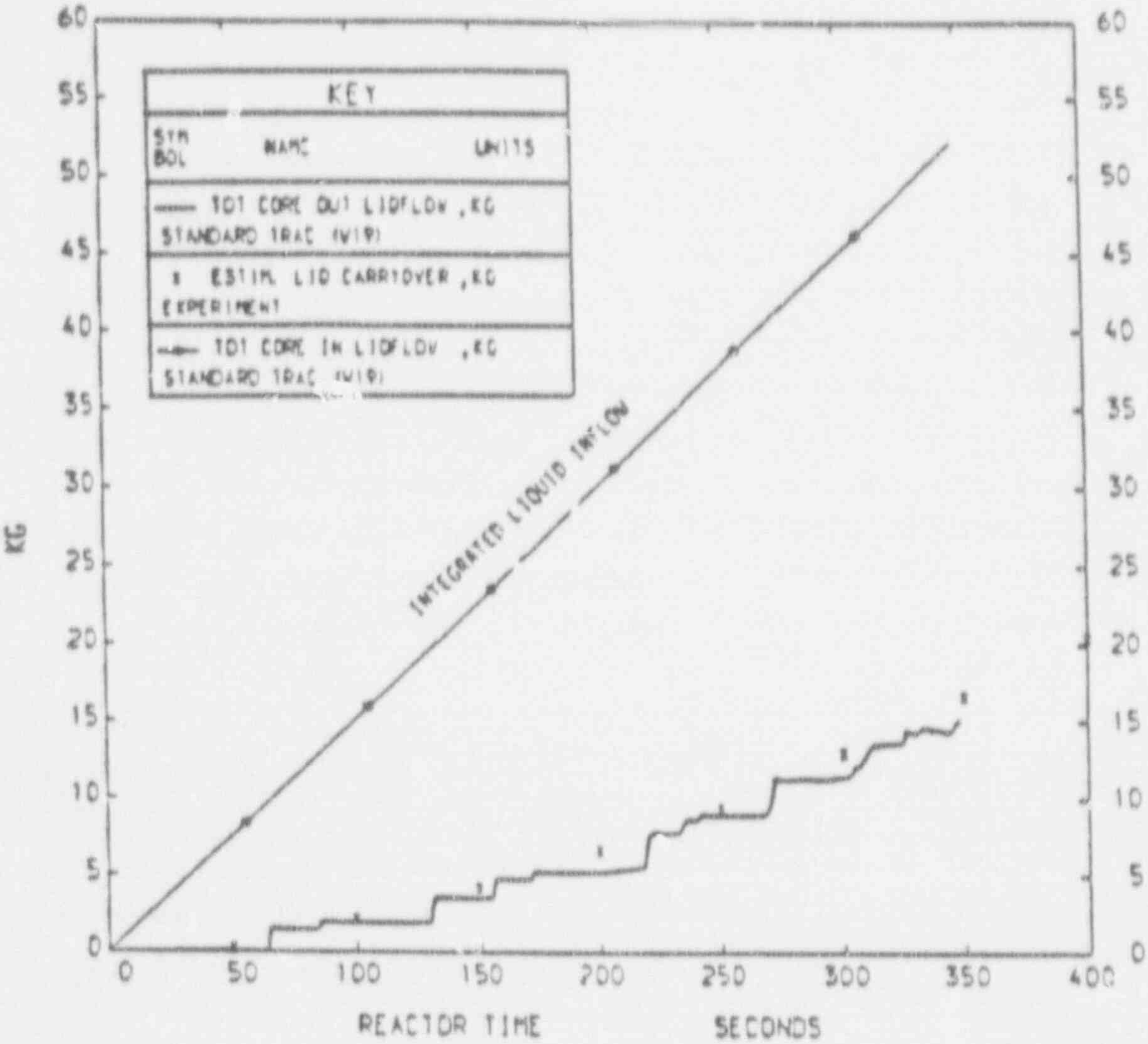

Fig. A-13. Integrated liquid carryover, standard TRAC and experiment.

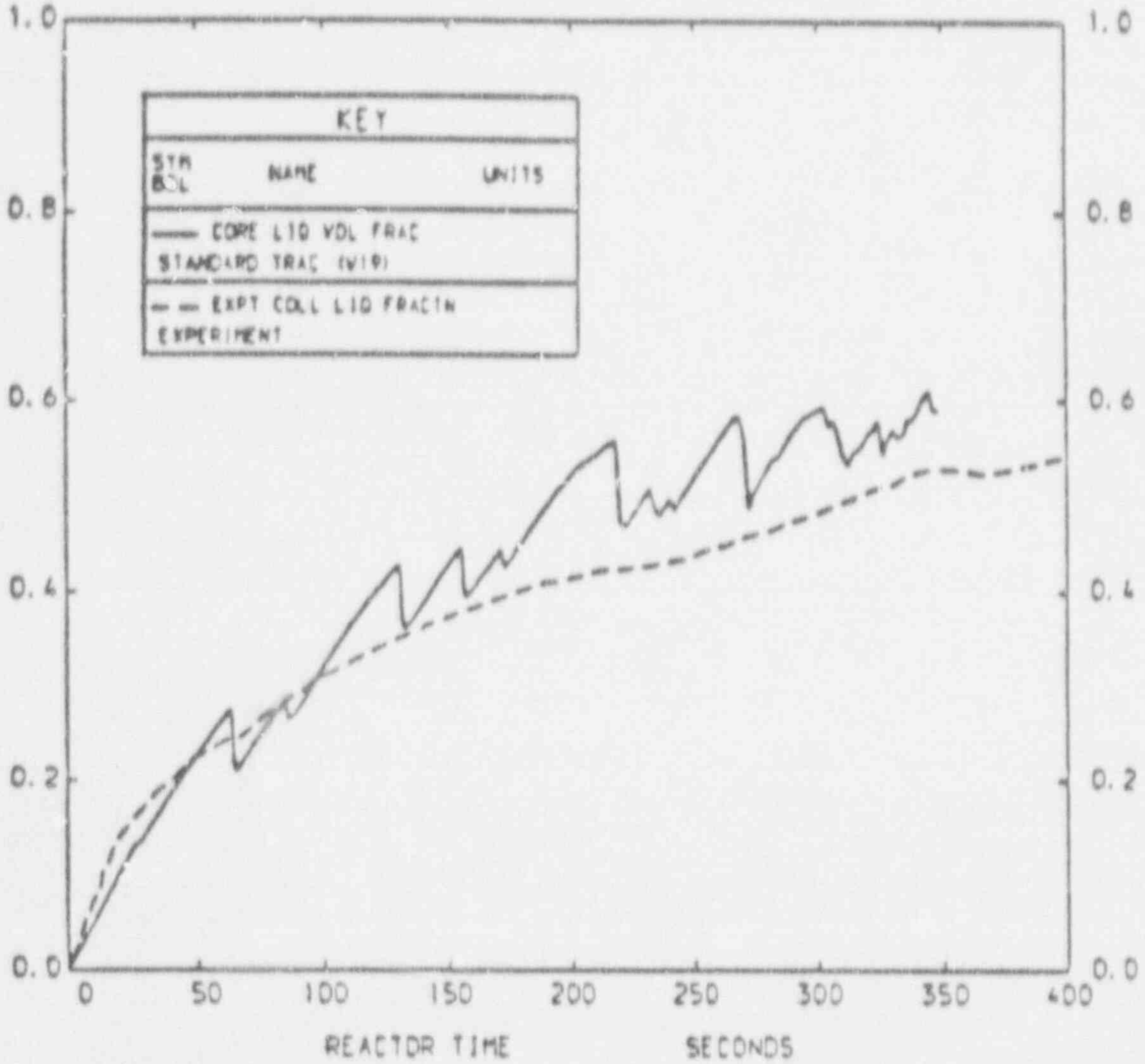

Fig. A-14. Core liquid volume fraction, standard TRAC and experiment.

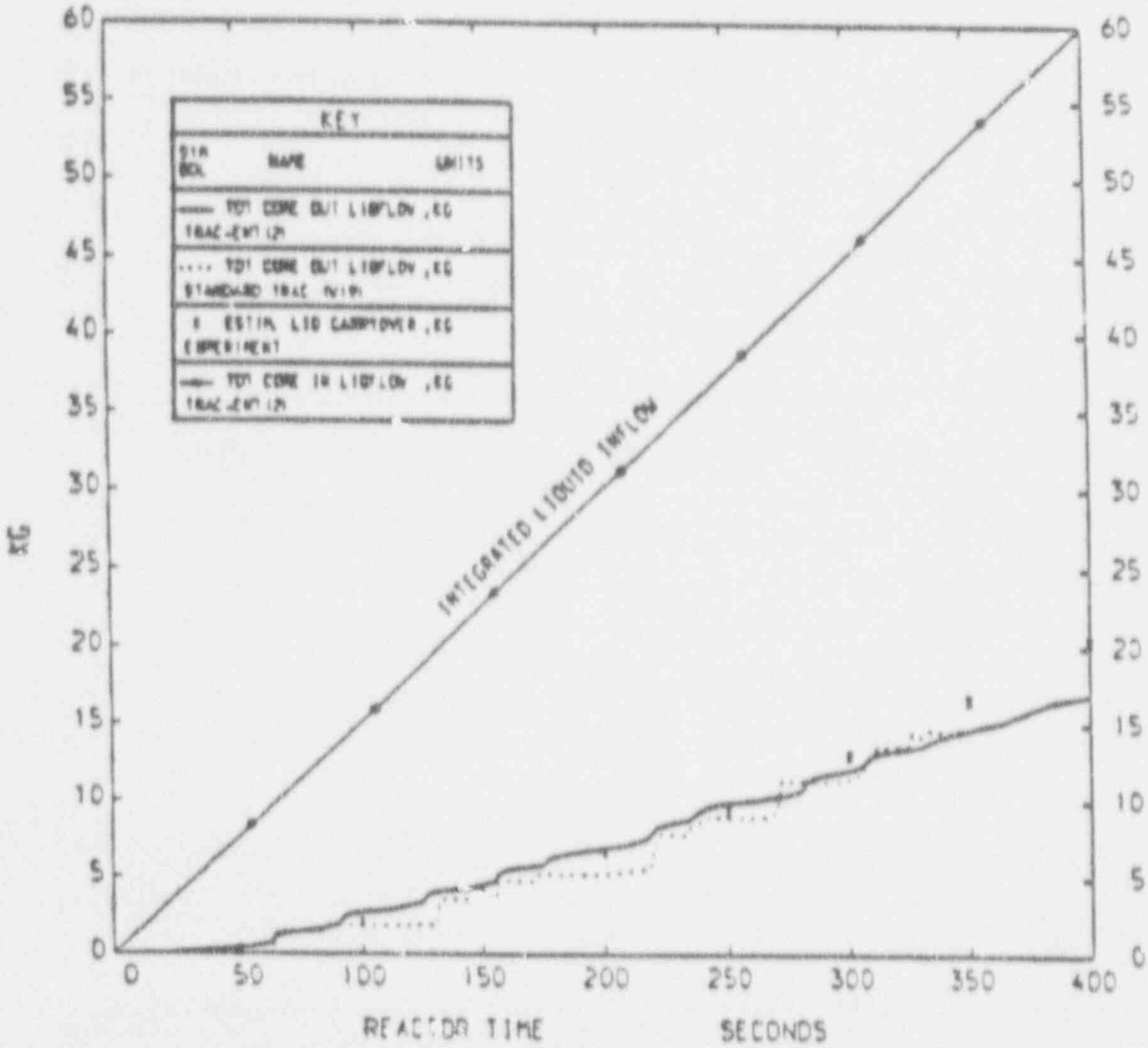

Fig. A-15. Integrated liquid carryover, standard TRAC, modified TRAC, and experiment.

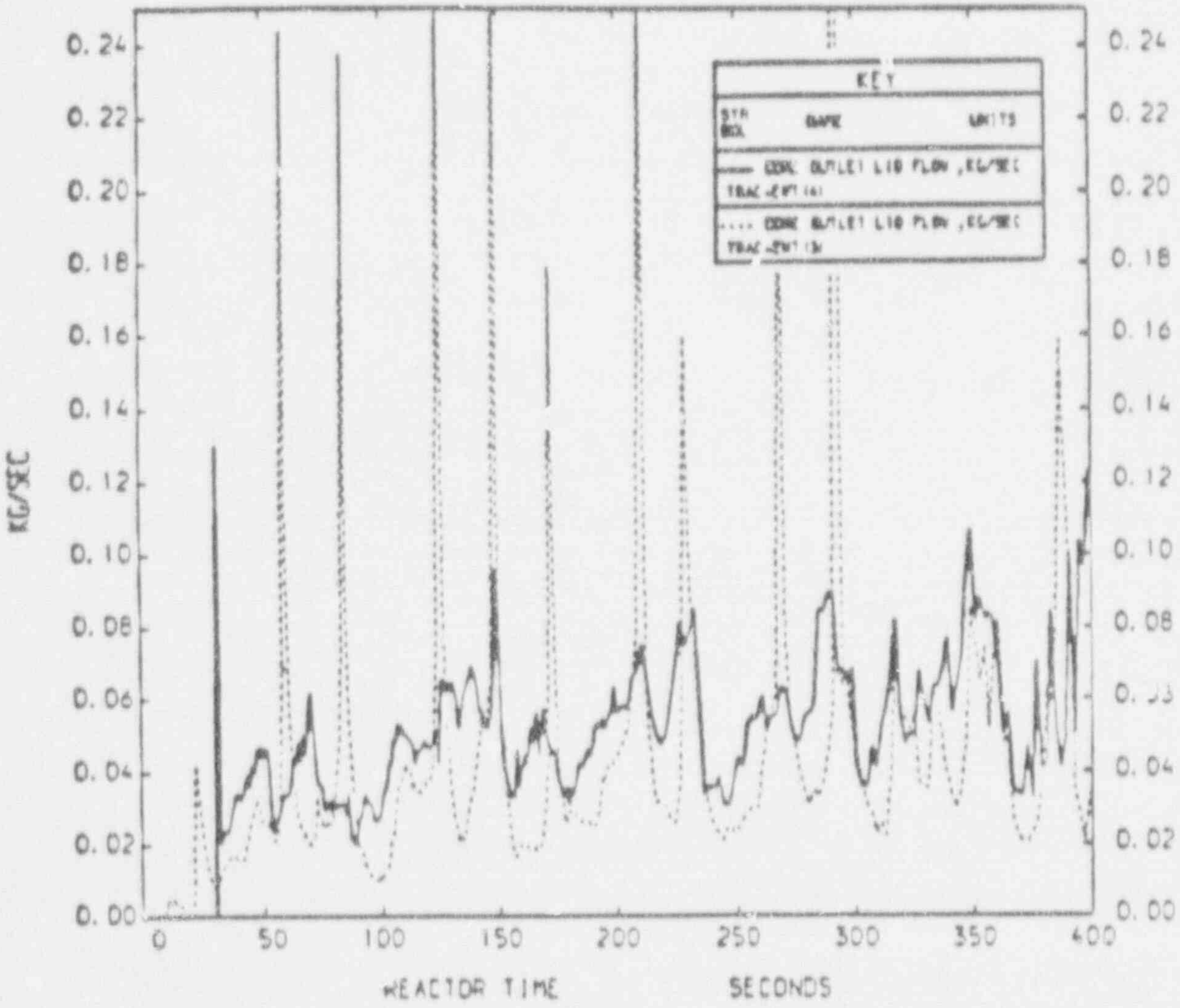

Fig. A-16. Core outlet liquid mass flow, the effect of replacing slabs with rods.

REVIEW OF ICAP REPORT NO. ICSP-LP-02-06

A. BASIC DATA

A1. ***Report Information:***

Author: J. Blanco, V. Lopez Montero, and J. Rivero

Report Title: Analysis of Loft Experiment LP-02-06 Using TRAC-PF1/MOD1

Report Number: ICSP-LP-02-06

Author's Nationality and Affiliation: Spain, Consejo de Seguridad Nuclear

Report Date: January 1988.

A2. ***Reviewer's Name:*** Norman M. Schnurr

Date of Review: April 1990

A3. ***Which code version was used for the assessment calculation: (Include cycle number or version number and any updates (Section 5.2.2)****

TRAC-PF1/MOD1, version not stated

A4. ***Report Classification (Proprietary, or non-proprietary, any restrictions. Section 4.1)****

LOFT members only.

A5. ***Is this an integral or separate-effects assessment?***

An integral assessment.

A6. ***Summarize why this assessment is being done. (Section 5.2.5 and Table 3)****

Experiment LP-02-6 was the first large-break LOCA carried out in the LOFT facility under the auspices of the Organization for Economic Cooperation and Development (OECD). This experiment simulated a double-ended offset shear of a commercial PWR main-coolant pipe, initiated from design-basis boundary conditions. The purpose of the work discussed in this report was to assess the ability of TRAC to model this type of accident. The PWR phenomena included for this assessment are (Table 3 of NUREG-1271) break flow, liquid-inventory distribution, phase separation, ECC bypass and penetration, core-wide void and flow distribution, mixture level in core, mixture level in downcomer, core heat transfer, quench-front propagation, and asymmetric loop behavior.

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* Refers to section or table in NUREG-1271, "Guidelines and Procedures for the International Code Assessment and Applications Program," April 1987.

A7. ***Provide a list of keywords descriptive of this analysis.***

Large-break LOCA, LOFT, PWR simulation, TRAC, reflood.

B. BRIEF QUESTIONS RELATED TO THE COMPLETENESS OF THE REPORT (Include report page number where information was found.)

B1. ***Did the author describe each test facility and each test used in the analysis? Elaborate. (Section 5.4.5 and 5.5.4)****

The LOFT facility and experiment LP-02-06 are described in some detail (pp. 3-5). Diagrams of the LOFT system and the vessel are given in Figs. 1 and 2. A chronology of events for the experiment, operational set points, and initial conditions are given in Tables I-III. A reference to a more complete description of the LOFT facility is included.

B2. ***The author must identify the experimental data used for the assessment in the report. The data channels used for comparison with code results should be easy to identify. It is desirable, but not required, for the author to supply the very data used in the assessment on hardcopy, floppy, or tape as specified in NUREG-1271. Has the author done these things? (Section 5.5.3 and 5.3)****

The experimental data (including flow rates, pressures, densities, fluid temperatures, pump speed, and rod temperatures) are given in the report in graphical form (Figs. 3-5, 7-10, 13-18, and 24-27). A tape containing the input data was also provided and a complete description of the tape is included as Appendix 3.

B3. ***The author must provide an evaluation of the experimental data uncertainty or clearly reference where it may be found. Has this been done? (Section 5.2.1)****

The uncertainty of the experimental data is not discussed.

B4. ***Was a base-case calculation performed using the unmodified, frozen code? Did the author include a clear, explicit figure of the Model? (Section 5.2.2).****

The simulation of the experiment was performed using TRAC-PF1/MOD1. The version number is not given. The model is discussed in detail (pp. 6-9) and the noding is illustrated in Appendix I, Figs. 1-4.

B5. ***The author must supply a copy of the input deck for one of his transient calculations on hardcopy, or floppy, or both. Has he done this? (Section 5.4.6 and 5.5.1)[*]***

A hardcopy of the input deck is given as Appendix I.

B6. ***Were sensitivity studies performed? Were the sensitivity studies adequately described? Were all identified code deficiencies explicitly described? (Section 5.2.3, 5.2.5, and 5.4.7)[*]***

A study to determine the sensitivity of rod temperatures to the minimum film-boiling temperature was discussed in this report. That study was performed using TRAC-PD2/MOD1. The author indicates that those results are also applicable to TRAC-PF1/MOD1.

B7. ***Were nodalization studies performed? Were the nodalization studies adequately described? Elaborate if necessary. (Section 5.2.4)[*]***

No nodalization studies were performed. The noding was similar to that used in an input deck developed at INEL for an earlier analysis of the same experiment using TRAC-PD2/MOD1. Some changes in the noding were made to reflect recent changes in the code.

B8. ***The report should include run statistics for at least one transient calculation using the unmodified frozen code. Was this done? If a modified version of the code was produced, run statistics for the same transient calculation performed with the final version of the modified code should be included. Was this done? (Section 5.2.5 - para. 4, and Table 4 - p. 25, and Section 5.4.8)[*]***

Run statistics are included for the steady-state and transient simulations.

B9. ***Were complete references included in the report? (Section 5.4.10)[*]***

Yes. A total of 11 references are included covering all important aspects of this assessment (p. 20 and Appendix II, p. 7).

B10. ***Were the objectives satisfied?***

Yes. The ability of TRAC to simulate reflood was assessed. Some potential weaknesses in the code were noted.

C. DETAILED QUESTIONS

C1. ***Did the author describe the model nodalization, assumptions, etc.? Were they appropriate? Did the nodalization follow the input deck preparation guidelines found in the TRAC User Guides? Elaborate if necessary. (Section 5.4.6)****

The nodalization used in this assessment is described in detail. It is similar to nodalization used in a deck developed at INEL for a simulation of the same experiment using TRAC-PD2/MOD1. Noding modifications made to the original deck are listed in the report. The nodalization generally follows guidelines in the TRAC User's Guide. Only four azimuthal sections were used in the vessel but this appeared to be necessary to reduce the CPU time to a reasonable level.

C2. ***Briefly describe the thermal-hydraulic phenomena and the reported code predictions addressed in the report. If appropriate, describe the phenomena in the context of thermal-hydraulic behavior in the vessel primary loop, secondary loop, and other phenomena of interest.***

Experiment LP-02-6 was a 200% double-ended cold-leg LOCA test carried out at full power (47 MW). The transient was initiated by opening the quick-opening blowdown valves. The reactor was scrammed on indication of loss of pressure in the intact-loop hot leg and the coolant pumps were tripped at 0.8 s and allowed to coast down until 16.5 s, when they were disconnected from their flywheels. The system pressure fell rapidly to the saturation pressure corresponding to the temperature of fluid in the hot leg. The rapid discharge of liquid in the broken loop caused voiding of the core, a large reduction of heat transfer from the fuel rods, and a rapid rise in cladding temperatures. Saturated conditions in the broken-loop cold leg were reached at about 4 s, accompanied by a reduction in cold-leg break flow. This reduced flow accompanied by a partial sustaining influence from the pumps, produced a partial bottom-up flow through the core and quenching of rods in the bottom 60% of the core. The intact-loop cold leg also began to void from about 5 s onward so that the break flow again exceeded the flow into the vessel and the core reemptied and the fuel rods heated up again. At about 15 s a top-down flow of liquid through the core began. This quenched the top 25 in. of the central fuel assembly. Flow from the accumulator began at 17.5 s and the HPIS and LPIS were activated at 21.8 and 34.8 s, respectively. Quenching of the fuel rods, which began at about 30 s, was completed very rapidly by the filling of the core, with all the fuel quenched at about 56 s. Of primary interest in the experiment were mass inventory in the vessel and fuel rod temperatures.

C3. If the author has identified new user guidelines has he described them thoroughly? What are they?

The authors suggest that the cell at the bottom of an accumulator tank should be made as small as possible because when nitrogen appears in the bottom cell of the accumulator, TRAC-PF1/MOD1 allows it to diffuse into the adjacent accumulator line before the bottom cell empties.

C4. What user guidelines can you infer from the results described in the report?

The addition of a choked-flow model in TRAC allows a reduction in the number of fluid cells near a break.

C5. What deficiencies were identified in the unmodified frozen version of the code? (Section 5.2.5 and 5.4.7)*

- The minimum-film-boiling-temperature correlation gives values that are too low, particularly for high-pressure, low-quality situations.
- The condensation model implemented in TRAC-PF1/MOD1 gives too high a condensation rate.

C6. Describe the impact of each identified code deficiency.

The minimum film-boiling temperature being too low causes the code to underestimate the film coefficients in some cases. This causes calculated rod temperatures to be too high. The condensation model calculates excessively high condensation rates during accumulator discharge. This has a significant effect on other system variables.

C7. What code modifications were made? What effect did they have? (Section 5.2.3)*

The sensitivity studies reported in this assessment were performed using TRAC-PD2/MOD2 but are also applicable to TRAC-PF1/MOD1. Three different minimum-film-boiling-temperature correlations were tested. The algorithm that gave the best results used Siegel's correlation for pressures below 5 MPa. Above that value, the higher of the minimum film-boiling temperatures calculated from Siegel's and Sakurai's correlations was used. This modification in the code produced rod temperatures in better agreement with experimental data than the unmodified version of the code.

C8. Run statistics must be provided for the calculation of one transient with the unmodified frozen code and the fully modified code. Compare and evaluate.

The run statistics should include a description of the computer and operating system used to perform each calculation, and

a. ***A plot of CPU vs RT***

b. ***A plot of DT vs RT***

c. ***The value of the "grind time" = [(CPU x 10^3)/(C x DT)]***

Where ***CPU = Total execution time***
RT = Transient time
DT = Total number of time steps
C = Total number of volumes in the model

The calculations were performed on a CDC 170 Cyber 835. The values of the above parameters were CPU = 230699 s, RT = 110 s, DT =18563, and C = 336. The grind time was 37.0 s.

d. ***Evaluate the actual time step used. Did the transient run at the Courant time step or did the user specify a smaller maximum time step? Compare the actual time step vs transient time and the user specified maximum time step vs transient time. (Section 5.2.5-para.4, Table 4-p. 25, and Section 5.4.8)****

The time step was limited by the Courant condition during part of the calculation.

C9. ***Does the work documented in this report appear to be good and generally valid or are there fundamental problem with it? (Solicit input of code developers to answer this question.)***

This work represents a valid simulation of an important experiment. The authors were somewhat limited by the relatively slow speed of the computer used to perform these simulations.

C10. ***What conclusions were drawn in the report? Are they well supported by the results of the analysis? Elaborate. (Section 5.4.7 and 5.4.9)****

The authors' conclusions were as follows:

- The general thermal-hydraulic behavior was correctly predicted. Densities and mass-flow rates throughout the hot and cold legs for both the broken and intact loops were in very good agreement with experimental data.

- Some effort is needed in improving the reflood calculations. The minimum-film-boiling-temperature correlation should be changed to one that gives a higher value for high-pressure, low-quality situations.
- The condensation model used in TRAC-PF1/MOD1 gives condensation rates that are too large during accumulator discharge.

These conclusions are consistent with the results of the simulations. I do not believe, however, that the authors made a strong case for the second conclusion. Other factors can have a significant impact on rod temperatures during reflood. A more comprehensive study would be necessary to isolate the main weaknesses in the reflood model.

C11. Report summary. (This summary will be included in the year-end NUREG report. It should be about 2 to 5 pages long and could include several figures. A short paragraph description of each facility should be included. Also include a paragraph summarizing the baseline results.)

The LOFT facility simulates the major components and system response of a commercial PWR during a LOCA. It has a single active intact loop which simulates the three intact loops of a commercial four-loop PWR during a large-break LOCA. The intact loop contains a steam generator, pressurizer, two primary-coolant pumps in parallel, and connecting pipe work. It also has two major measurement stations, one in the hot leg located just downstream of the vessel connection, and one in the cold leg located a few inches upstream of the ECCS cold-leg injection junction.

LP-02-6 was a large-break (200%) double-ended cold-leg LOCA experiment. It was carried out at full power (47 MW) with the primary-coolant pumps tripped at the start of the transient and allowed to coast down naturally. The experiment was initiated by opening the blowdown valves. The reactor was scrammed on indication of low pressure and the primary-coolant pumps were tripped within 1 s. The system pressure fell rapidly to the hot-leg saturation pressure, whereupon the core and upper plenum began to flash as liquid flowed out of the broken-loop hot and cold legs. The tripping of the primary-coolant pumps resulted in a coastdown of the fluid circulating in the intact loop, but the flywheel's inertia caused the pumps to continue to deliver mechanical energy to the fluid for several seconds so that sufficient liquid flowed into the downcomer to produce a bottom-up flow through the core after about 5 s. The core flow temporarily arrested the cladding temperature excursion and resulted in a quench for the lower half of the core. The bottom-up flow through the core terminated at about 8 s. The flow in the intact-loop hot leg reversed at about 10 s as fluid from the pressurizer and steam-generator hot side flowed back to the vessel, producing an accumulation of liquid in the upper plenum. This was followed by a quench of the upper part of the central fuel assembly. This top-down quench began at about 15 s. The cooling associated with the top-down flow was only temporary, and the core began to heat up again after about 20 s.

Flow from the accumulator was initiated at 17.5 s at a trip point of 4.11 MPa. The HPIS and LPIS were activated at 21.8 and 34.8 s, respectively. The ECCS injection was dominated by the accumulator until the accumulator flow terminated at about 55 s. During the accumulator-flow period, the injection of subcooled liquid caused a reduction in local pressure as vapor condensed into the liquid, leading to a global reduction in pressure as more vapor flowed toward the injection location. After the injection line was cleared, nitrogen flowed into the intact-loop cold leg and the condensation terminated. The accumulator nitrogen caused an increase in the cold-leg pressure of about 0.2 MPa. This forced the bulk of the liquid in the intact-loop cold leg and at the top of the downcomer down through the downcomer and lower plenum and into the core. The surge of liquid into the core occurred between about 53 and 60 s and resulted in most of the core being filled with liquid. The fuel rods were completely quenched at about 56 s. The input deck used for the simulation of experiment LP-02-6 is similar to an input deck produced at INEL and used for a TRAC-PD2/MOD1 calculation. The simulation accurately reproduced most of the general thermal-hydraulic behavior. Predictions of rod temperatures are not as accurate, however. Centerline and cladding temperatures at a height of 0.647 m are shown in Figs. A-17 and A-18. The centerline temperature predictions (Fig. A-17) are in fair agreement with the data, although there are differences in excess of 300 K at t = 70 s. The cladding temperature predictions (Fig. A-18) fail to simulate either the initial or secondary quench accurately. This may be caused partly by the effect of the external thermocouples on the quenching process. TRAC did not include an external-thermocouple model to simulate this effect. The authors also believe that the minimum-film-boiling temperature correlation in the code gives too high a value for high-pressure, low-quality situations.

One user guideline was proposed. The authors suggest that the cell at the bottom of an accumulator tank should be made as small as possible because when nitrogen appears in the bottom cell of the accumulator, TRAC-PF1/MOD1 allows it to diffuse into the adjacent accumulator line before the bottom cell empties. Two code deficiencies were identified: (1) the minimum-film-boiling-temperature correlation gives values that are too low, particularly for high-pressure, low-quality situations, and (2) the condensation model implemented in TRAC-PF1/MOD1 gives a condensation rate that is too high.

The assessment included the following information on run statistics. The total CPU time on a CDC 170 Cyber 835 for a 110-s simulation was 64.1 h. The average time step was 5.93×10^{-3} s. The grind time was 37 s.

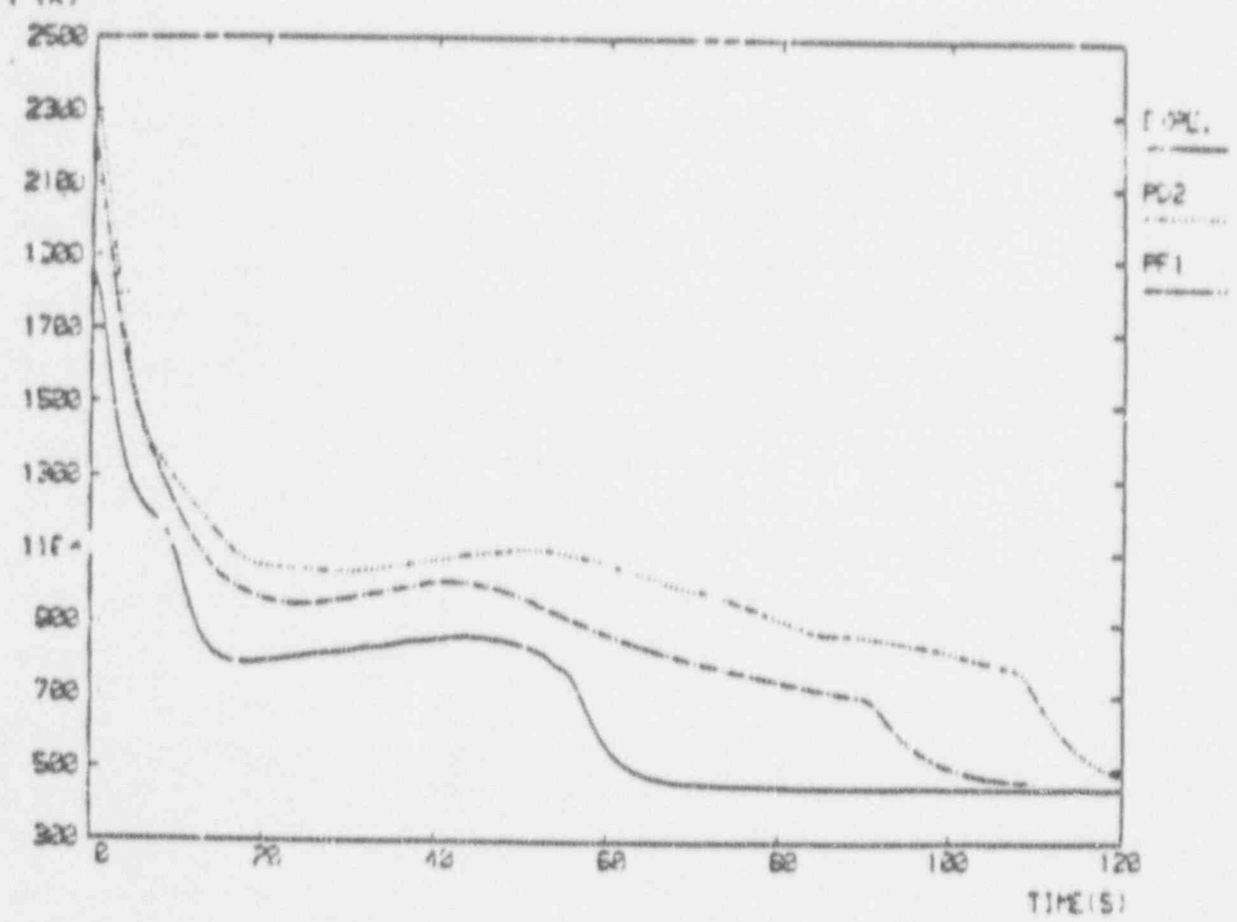

Fig. A-17. Centerline rod temperature at 0.647 m.

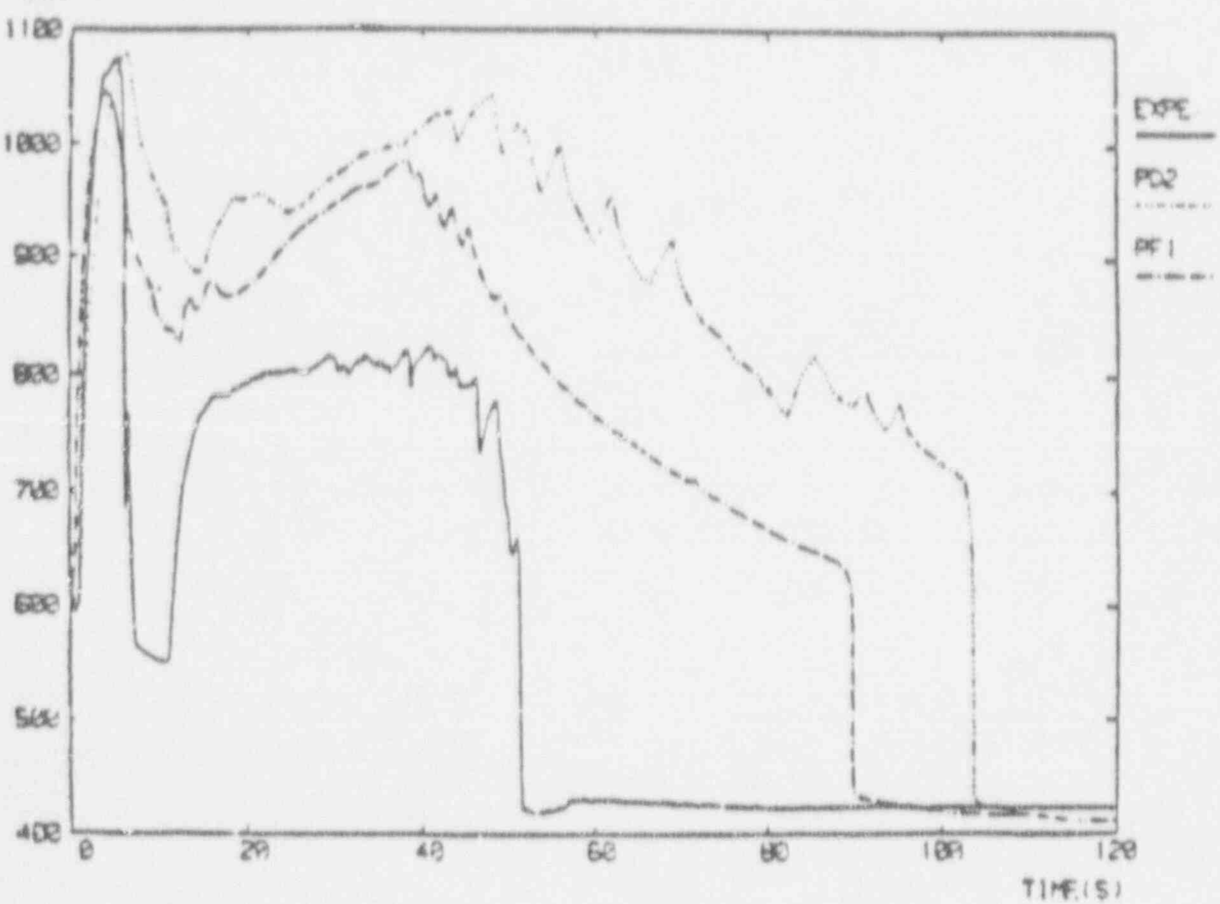

Fig. A-18. Cladding temperature at 0.647 m.

REVIEW OF ICAP REPORT NO. ICSP-LP-FP-1

A. BASIC DATA

A1. *Report Information:*

Author: F. J. Barbero

Report Title: TRAC-PF1 Code Assessment Using OECD-LOFT LP-FP-1 Experiment

Report Number: ICSP-LP-FP-1

Author's Nationality and Affiliation: Spain, Consejo de Seguridad Nuclear

Report Date: July 1988.

A2. *Reviewer's Name:* Norman M. Schnurr

Date of Review: April 1990

A3. *Which code version was used for the baseline calculation: (Include cycle number or version number and any updates. Section 5.2.2)**

TRAC-PF1/MOD1 Version 11.0 running on a CDC Cyber 830.

A4. *Report Classification (Proprietary, or non-proprietary, any restrictions. Section 4.1)**

LOFT members only.

A5. *Is this an integral or separate-effects assessment?*

An integral assessment.

A6. *Summarize why this assessment is being done. (Section 5.2.5 and Table 3)**

LOFT experiment LP-FP-1 was a fission-products-release test. It simulated a large-break LOCA in the cold leg with delayed ECC injection to allow pin rupture and fission-product release. The objectives of this assessment were to determine the ability of TRAC-PF1/MOD1 to predict the thermal hydraulics and core response and to determine the fission-product-retention effectiveness of the ECCS operating in the mode of a German ECCS. The PWR phenomena included for this assessment are (Table 3 of NUREG-1271) break flow, liquid-inventory distribution, phase separation, ECC bypass and penetration, core-wide void and

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* Refers to section or table in NUREG-1271, "Guidelines and Procedures for the International Code Assessment and Applications Program," April 1987.

flow distribution, mixture level in core, mixture level in downcomer, core heat transfer, quench-front propagation, and asymmetric loop behavior.

A7. ***Provide a list of keywords descriptive of this analysis.***

Large-break LOCA, LOFT, PWR simulation, TRAC, fission-product release.

B. BRIEF QUESTIONS RELATED TO THE COMPLETENESS OF THE REPORT (Include report page number where information was found.)

B1. ***Did the author describe each test facility and each test used in the analysis? Elaborate. (Section 5.4.5 and 5.5.4)****

The LOFT facility and experiment LP-FP-1 are described in some detail (Section 2). Diagrams of the LOFT system are given in Figs. 2.1 and 2.2. Details of the reactor vessel are illustrated in Figs. 2.3-2.6. Details of the accumulator system are shown in Figs. 2.7 and 2.8. Locations of all instrumentation are shown in Figs. A-1 to A-5. Initial conditions for the experiment are given in Table 2.1. Operational set points are given in Table 2.2. A reference to a more complete description of the LOFT facility is also included.

B2. ***The author must identify the experimental data used for the assessment in the report. The data channels used for comparison with code results should be easy to identify. It is desirable, but not required, for the author to supply the very data used in the assessment on hardcopy, floppy, or tape as specified in NUREG-1271. Has the author done these things? (Section 5.5.3 and 5.3)****

The experimental data (including flow rates in hot and cold legs of the broken and intact loops, upper plenum pressure, densities, and rod temperatures) are given in the report in graphical form (Figs. 4.1, 4.2, 4.4-4.9, 4.19, and 4.20). The sources of the data are referenced.

B3. ***The author must provide an evaluation of the experimental data uncertainty or clearly reference where it may be found. Has this been done? (Section 5.2.1)****

The uncertainty of the experimental data is not discussed. Initial conditions listed in Table 2.1 are given with tolerances from which data accuracy may be inferred.

B4. ***Was a base-case calculation performed using the unmodified, frozen code? Did the author include a clear, explicit figure of the Model? (Section 5.2.2).****

The simulation of the experiment was performed using TRAC-PF1/MOD1, Version 11.0. The model is discussed in detail in Section 3 and the noding is illustrated in Figs. 3.4-3.6.

*B5. The author must supply a copy of the input deck for one of his transient calculations on hardcopy, or floppy, or both. Has he done this? (Section 5.4.6 and 5.5.1)**

Hard copies of the input decks for the steady-state and transient calculations are given in Tables 3.2 and 3.5.

*B6. Were sensitivity studies performed? Were the sensitivity studies adequately described? Were all identified code deficiencies explicitly described? (Section 5.2.3, 5.2.5, and 5.4.7)**

No sensitivity studies were performed.

*B7. Were nodalization studies performed? Were the nodalization studies adequately described? Elaborate if necessary. (Section 5.2.4)**

No nodalization studies were performed.

*B8. The report should include run statistics for at least one transient calculation using the unmodified frozen code. Was this done? If a modified version of the code was produced, run statistics for the same transient calculation performed with the final version of the modified code should be included. Was this done? (Section 5.2.5 - para. 4, and Table 4 - p. 25, and Section 5.4.8)**

Run statistics are given in Section 5.

*B9. Were complete references included in the report? (Section 5.4.10)**

Yes. A total of 9 references are included covering all important aspects of this assessment.

B10. Were the objectives satisfied?

The stated objectives were to predict thermal-hydraulic and core thermal response for experiment LP-FP-1 and to determine the fission-product-retention effectiveness of the ECCS. The first objective was satisfied. The second could not be completely satisfied because the code does not track fission products. Some qualitative results were obtained in the form of velocity vectors in the region of fission-product release.

C. DETAILED QUESTIONS

C1. ***Did the author describe the model nodalization, assumptions, etc.? Were they appropriate? Did the nodalization follow the input deck preparation guidelines found in the TRAC User Guides? Elaborate if necessary. (Section 5.4.6)****

The nodalization used in this assessment is described in detail. It is nearly identical to the noding used in AEEW-R 2288. The nodalization generally follows the TRAC User's Guide guidelines. Only four azimuthal sections were used in the vessel but this appeared to be necessary to reduce the CPU time to a reasonable level for the computer used.

C2. ***Briefly describe the thermal-hydraulic phenomena and the reported code predictions addressed in the report. If appropriate, describe the phenomena in the context of thermal-hydraulic behavior in the vessel primary loop, secondary loop, and other phenomena of interest.***

Experiment LP-FP-1 was a fission-products-release test. It simulated a large-break LOCA in the cold leg with ECC injection delayed long enough to allow pin rupture and fission-product release from 24 fuel rods that were enriched to 6% U^{235} and prepressurized at cold conditions. The transient phase of the experiment started with reactor scram followed by the opening of the QOBVs. The primary-coolant system quickly depressurized to saturation pressure. A bottom-up partial core quench occurred between 6 and 7 s followed at 12 to 18 s by a total top-down quench of the central fuel assembly. The cold-leg QOBV was closed at 68 s, forcing all break flow out the cold leg and core flow from bottom to top. A sustained heatup of most of the core started at 90 s, resulting in the rupture of some of the enriched fuel rods beginning at 325 s. The ECCS was initiated at 344 s and the entire core was quenched by 365 s. Of primary interest in the experiment were the system thermal hydraulics, core thermal response, and the fission-product-retention effectiveness of the ECCS.

C3. ***If the author has identified new user guidelines has he described them thoroughly? What are they?***

No new user guidelines were identified.

C4. What user guidelines can you infer from the results described in the report?

A sufficient number of azimuthal sectors must be used in the core to accurately predict asymmetrical effects.

C5 What deficiencies were identified in the unmodified frozen version of the code? (Section 5.2.5 and 5.4.7)*

No code deficiencies were identified. Inaccuracies in rod temperature calculations may, however, be caused by lack of a sufficiently detailed reflood model.

C6. Describe the impact of each identified code deficiency.

MOD1 did not contain a reflood model. The fine-mesh option used at that time may not have given sufficiently close spacing to accurately predict cladding temperatures.

C7. What code modifications were made? What effect did they have? (Section 5.2.3)*

No code modifications were made in this assessment.

C8. Run statistics must be provided for the calculation of one transient with the unmodified frozen code and the fully modified code. Compare and evaluate. The run statistics should include a description of the computer and operating system used to perform each calculation, and

a. A plot of CPU vs RT

b. A plot of DT vs RT

c. The value of the "grind time" = $[(CPU \times 10^3)/(C \times DT)]$

Where CPU = Total execution time
RT = Transient time
DT = Total number of time steps
C = Total number of volumes in the model

The calculations were performed on a CDC Cyber 830. The values of the above parameters were CPU = 1200000 s, RT = 400 s, DT = 37500, and C = 302. The grind time was 106.0 s.

d. Evaluate the actual time step used. Did the transient run at the Courant time step or did the user specify a smaller maximum time step? Compare the actual time step vs transient time and the user specified maximum time step vs

transient time. (Section 5.2.5-para.4, Table 4-p. 25, and Section 5.4.8)*

The time step was limited by the Courant condition for the entire calculation. The time-step profile shows values mostly in the range of 10 to 25 ms.

C9. ***Does the work documented in this report appear to be good and generally valid or are there fundamental problems with it? (Solicit input of code developers to answer this question.)***

This work represents a valid simulation of an important experiment. The work was severely handicapped, however, by the relatively slow computer used to perform the calculations. The entire transient simulation required 333 hours of CPU. It was therefore impossible to do any meaningful sensitivity or nodalization studies. The lack of a fission-product-tracking capability in TRAC made it impossible to determine the retention effectiveness of the ECCS. The expansion of the fuel rods and resulting blockage of the flow tubes cannot be simulated by TRAC. The flow pattern calculated in the portion of the core where fission-product release occurs are therefore questionable.

C10. ***What conclusions were drawn in the report? Are they well supported by the results of the analysis? Elaborate. (Section 5.4.7 and 5.4.9)****

The authors' conclusions were as follows:

- The pressures, mass-flow rates, and densities were accurately predicted during blowdown.
- TRAC cannot simulate observed initial quenches and final quench time.
- Good agreement is found between calculated and measured cladding temperatures for the 4%-enriched rods in the central fuel assembly.
- Flow patterns during the rod-rupture period show two possible paths for fission products in the liquid phase.

These conclusions are generally consistent with the results of the simulations. I do not believe that the flow patterns can be accurately calculated during rod rupture, however, because the code does not simulate the blockage of the flow tubes caused by the expanding cladding.

C11. ***Report summary. (This summary will be included in the year-end NUREG report. It should be about 2 to 5 pages long and could include several figures. A short paragraph description of each facility should be included. Also include a paragraph summarizing the baseline results.)***

The LOFT facility simulates the major components and system response of a commercial PWR during a LOCA. It has a single active intact loop which simulates the three intact loops of a commercial four-loop PWR during a large-break LOCA. The intact loop contains a steam generator, pressurizer, two primary-coolant pumps in parallel, and connecting pipe work. It also has two major measurement stations, one in the hot leg located just downstream of the vessel connection, and one in the cold leg located a few inches upstream of the ECCS cold-leg injection junction.

Experiment LP-FP-1 is a fission-products-release test. The experiment simulates a large-break LOCA in the cold leg with delayed ECC injection to allow pin rupture and fission-product release. The core consists of 1300 enriched (4% U^{235}) uranium fuel rods. For this experiment, 24 of the rods were enriched to 6% and were prepressurized at cold conditions to 2.41 MPa. The transient phase of the experiment started with reactor scram followed by the opening of the QOBVs. The primary-coolant system quickly depressurized to saturation pressure. A bottom-up partial core quench occurred between 6 and 7 s followed at 12 to 18 s by a total top-down quench of the central fuel assembly. The cold-leg QOBV was closed at 68 s, forcing all break flow out the cold leg and core flow from bottom to top. A sustained heatup of most of the core started at 90 s, resulting in the rupture of some of the enriched fuel rods beginning at 325 s. The ECCS was initiated at 344 s and the entire core was quenched by 365 s.

The simulation of this experiment accurately reproduced the thermal-hydraulic behavior during the blowdown phase. There is also good agreement between calculated and measured cladding temperatures for the 4%-enriched rods in the central fuel assembly. The predicted temperatures of the 6%-enriched rods which undergo quench during the blowdown phase are in fair agreement with experimental data. For the remaining 6%-enriched rods, the predicted temperatures are too high. The author suggests that quenching may be prevented by the minimum stable film boiling temperature (MSFBT) used in the code.

An attempt is made to predict paths the fission products might follow based on flow directions in the vessel during the rod-rupture period. There is some question about the accuracy of the flow calculations in this region, however, because the code does not account for the severe changes in flow-channel dimensions caused by swelling of the rods. The code does not have the capability to track fission products.

No user guidelines were proposed and no code deficiencies were explicitly stated. The assessment included the following information on run statistics. The total CPU time on a CDC Cyber 830 for a 400-s simulation was 333 h. The average time step was 10.6×10^{-3} s. The grind time was 106 s.

REVIEW OF ICAP REPORT NO. SETh/LEML/89-165

A. BASIC DATA

A1. *Report Information:*

Author: B. Spindler and M. Pellissier

Report Title: Assessment of TRAC-PF1/MOD1 Version 14.3 Using Components Separate Effects Experiments

Report Number: SETh/LEML/89-165

Author's Nationality and Affiliation: France, Centre D'Etudes Nucleaires de Grenoble, Service d'Etudes Thermohydrauliques.

Report Date: March 1989

A2. *Reviewer's Name:* Norman M. Schnurr

Date of Review: May 1990

A3. *Which code version was used for the baseline calculation: (Include cycle number or version number and any updates. Section 5.2.2)***

TRAC-PF1/MOD1 Version 14.3

A4. *Report Classification (Proprietary, or non-proprietary, any restrictions. Section 4.1)***

Restricted to the organizations or the persons to whom the report is addressed.

A5. *Is this an integral or separate-effects assessment?*

Separate-effects assessment.

A6. *Summarize why this assessment is being done. (Section 5.2.5 and Table 3)***

Separate-effects assessments are performed using data from EPIS-2 simulating the behavior of an emergency core cooling (ECC) system and from PATRICIA-SG1 simulating the behavior of a U-tube of a steam generator in accident conditions. These calculations assess the ability of TRAC to simulate some of the important phenomena that take place in specific components in a nuclear power plant under emergency conditions.

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* Refers to section or table in NUREG-1271, "Guidelines and Procedures for the International Code Assessment and Applications Program," April 1987.

A7. ***Provide a list of keywords descriptive of this analysis.***

TRAC, ECC injection, vapor generation.

B. BRIEF QUESTIONS RELATED TO THE COMPLETENESS OF THE REPORT (Include report page number where information was found.)

B1. ***Did the author describe each test facility and each test used in the analysis? Elaborate. (Section 5.4.5 and 5.5.4)****

The EPIS-2 test facility is described on p. 15. A schematic diagram of the system is given in Fig. 2.1. The PATRICIA loop is described on p. 30 and a diagram of the test section is given in Fig. 3.1.

B2. ***The author must identify the experimental data used for the assessment in the report. The data channels used for comparison with code results should be easy to identify. It is desirable, but not required, for the author to supply the very data used in the assessment on hardcopy, floppy, or tape as specified in NUREG-1271. Has the author done these things? (Section 5.5.3 and 5.3)****

The experimental data (including pressures, temperatures, and void fractions) are given in the report in graphical form (Figs. 2.4-2.8 for EPIS-2 and Figs. 3.4-3.10 for PATRICIA-SG1). The sources of the data are referenced.

B3. ***The author must provide an evaluation of the experimental data uncertainty or clearly reference where it may be found. Has this been done? (Section 5.2.1)****

The uncertainties of the pressure, temperature, void fraction, and flow rate measurements for the EPIS tests are discussed on pp. 16 and 17. The accuracy of pressure-drop measurements for the PATRICIA loop is given on p. 31.

B4. ***Was a base-case calculation performed using the unmodified, frozen code? Did the author include a clear, explicit figure of the Model? (Section 5.2.2).****

The base-case simulations were performed using TRAC-PF1/MOD1, Version 14.3. The models are discussed on pp. 17-18 and 32-33 and noding diagrams are given in Figs. 2.2 and 3.2.

B5. *The author must supply a copy of the input deck for one of his transient calculations on hardcopy, or floppy, or both. Has he done this? (Section 5.4.6 and 5.5.1)**

Hard copies of the input decks for the two test rigs are given on pp. 26-28 and 45-49.

B6. *Were sensitivity studies performed? Were the sensitivity studies adequately described? Were all identified code deficiencies explicitly described? (Section 5.2.3, 5.2.5, and 5.4.7)**

The sensitivity of the existence of oscillations to upstream volume size was studied for the EPIS-2 tests (p. 23). The sensitivity of pressure drop to the friction-factor model (NFF=1 or 2) was studied for the PATRICIA-SG1 tests (p. 39).

B7. *Were nodalization studies performed? Were the nodalization studies adequately described? Elaborate if necessary. (Section 5.2.4)**

Nodalization studies were carried out for both cases. The results of these studies are discussed on pp. 22-23 and 38.

B8. *The report should include run statistics for at least one transient calculation using the unmodified frozen code. Was this done? If a modified version of the code was produced, run statistics for the same transient calculation performed with the final version of the modified code should be included. Was this done? (Section 5.2.5 - para. 4, and Table 4 - p. 25, and Section 5.4.8)**

Run statistics are given on pp. 22 and 38.

B9. *Were complete references included in the report? (Section 5.4.10)**

A total of four references are given including sources for test descriptions and experimental data.

B10. *Were the objectives satisfied?*

The stated objectives were to present results of the code simulations and comparisons with experimental data for tests selected from the EPIS-2 and PATRICIA-SG1 experiments. This was done and some code deficiencies were identified.

C. DETAILED QUESTIONS

C1. Did the author describe the model nodalization, assumptions, etc.? Were they appropriate? Did the nodalization follow the input deck preparation guidelines found in the TRAC User Guides? Elaborate if necessary. (Section 5.4.6)[*]

The nodalization used in this assessment is described in detail. The nodalization for both the EPIS and PATRICIA experimental rigs conforms to the TRAC manual guidelines.

C2. Briefly describe the thermal-hydraulic phenomena and the reported code predictions addressed in the report. If appropriate, describe the phenomena in the context of thermal-hydraulic behavior in the vessel primary loop, secondary loop, and other phenomena of interest.

EPIS-2 simulates the ECC injection system in the cold leg of a PWR. The cold leg is simulated by a horizontal pipe 9.13 m long with an inside diameter of 28 mm. Two pipes connected to the cold leg are used to simulate accumulator injection and pump injection. During a test, vapor flows through the cold leg at a given rate and water is injected at a specified rate which may vary with time. Pressures, temperatures, and void fractions are measured at various locations along the test section and steam and water flow rates are measured as functions of time. Hydraulic effects such as mixing, condensation, slug formation, and pressure oscillations are of primary interest.

The PATRICIA experiments simulate the U-tube of a steam generator. Water flowing in the tube simulates the primary circuit. The secondary circuit is simulated by the flow of an organic fluid in the annulus around the tube. In some of the tests a noncondensable gas (nitrogen) was injected in the primary circuit upstream of the test section. The pressure drops and heat transfer in the primary circuit for accident conditions are important phenomena.

C3. If the author has identified new user guidelines has he described them thoroughly? What are they?

No new user guidelines were identified.

C4. What user guidelines can you infer from the results described in the report?

The use of a relatively coarse mesh, consistent with acceptable accuracy, is preferable in situations where water packing may occur because it reduces the pressure peaks.

C5. ***What deficiencies were identified in the unmodified frozen version of the code? (Section 5.2.5 and 5.4.7)****

The condensation model used in Version 14.3 of TRAC-PF1/MOD1 was judged to be unsatisfactory for the EPIS-2 calculations. This model does not give accurate results in situations where the injected liquid is in the form of a jet because the code assumes a bubble flow regime and greatly overestimates the interfacial area. The use of the annular model friction factor (NFF = 2) gives significant errors over a wide range of conditions.

C6. ***Describe the impact of each identified code deficiency.***

The condensation model overestimates the interfacial area for cases where liquid water is injected as a jet. The result was an overprediction of condensation rates for the EPIS-2 simulations. The use of NFF = 2 caused an overprediction of pressure drops in the primary circuit for the PATRICIA-SG1 tests.

C7. ***What code modifications were made? What effect did they have? (Section 5.2.3)****

No code modifications were made in this assessment.

C8. ***Run statistics must be provided for the calculation of one transient with the unmodified frozen code and the fully modified code. Compare and evaluate. The run statistics should include a description of the computer and operating system used to perform each calculation, and***

a. ***A plot of CPU vs RT***

b. ***A plot of DT vs RT***

c. ***The value of the "grind time" = [(CPU x 10^3)/(C x DT)]***

Where CPU = Total execution time
RT = Transient time
DT = Total number of time steps
C = Total number of volumes in the model

The calculations were performed on a Cray XMP-2800 computer. The CPU times per cell per time step were 1.3-1.8 ms for EPIS-2 and 0.9-1.0 ms for PATRICIA-SG1. Grind times were in the range of 1.35-1.76 s for EPIS-2 and 0.87-1.09 s for PATRICIA-SG1.

d. ***Evaluate the actual time step used. Did the transient run at the Courant time step or did the user specify a smaller maximum time*** _**step? Compare the actual time step vs transient time and the user specified maximum time step vs transient time. (Section 5.2.5-para.4, Table 4-p. 25, and Section 5.4.8)**_*

The time step was limited by the Courant condition for the first 20% of the simulation for the EPIS-2 simulations and by a user-specified maximum value for the rest of the calculation. The PATRICIA-SG1 simulations were also limited by a user-specified maximum time step for some portion of the calculation.

**C9. Does the work documented in this report appear to be good and generally valid or are there fundamental problems with it? (Solicit input of code developers to answer this question.)**

The simulations performed in this assessment give some insight into the ability of TRAC in analyzing ECC injection and the performance of steam generators. The work was well conceived and executed. Nodalization studies and a limited number of sensitivity studies were performed. The only serious limitation was an inability to model the secondary heat transfer in the PATRICIA-SG1 tests because an organic fluid was used in the experiments and TRAC does not include thermodynamic and transport property data for that fluid. The power extracted from the primary circuit was used as a boundary condition.

_**C10. What conclusions were drawn in the report? Are they well supported by the results of the analysis? Elaborate. (Section 5.4.7 and 5.4.9)**_*

The authors' conclusions were as follows:

EPIS-2 simulations

- The condensation model in TRAC was not satisfactory for simulating these tests. This is probably caused by an overprediction of interfacial area for liquid injection in the form of a jet.
- Pressure profiles are not well predicted.
- The temperature at the outlet is overpredicted for tests with oscillations.

PATRICIA-SG1 simulations

- Steady state is reached for tests with high mass-flow rates but not for tests with low mass-flow rates.
- The pressure drops for [illegible] of the test section are generally well predicted.
- The results of the calculations are rather insensitive to nodalization.
- Pressure drops were largely overpredicted with the use of the friction factor option NFF=2. This option is not recommended.

These conclusions are consistent with the results of the simulations.

C11. *Report summary. (This summary will be included in the year-end NUREG report. It should be about 2 to 5 pages long and could include several figures. A short paragraph description of each facility should be included. Also include a paragraph summarizing the baseline results.)*

The EPIS-2 experiments simulate the ECC injection system in the cold leg of a PWR. The cold leg is simulated by a horizontal pipe 9.13 m long with an inside diameter of 28 mm. Two pipes connected to the cold leg are used to simulate accumulator injection and pump injection. During a test, vapor flows through the cold leg at a given rate and water is injected at a specified rate which may vary with time. Local pressures, temperatures, and void fractions, and steam and water mass-flow rates were measured as functions of time.

Tests were performed within four series covering a wide range of parameters. The tests selected for the TRAC simulations were chosen from the last series of tests, which is the most reliable. Test 81.23 corresponds to a stable regime. Test 80.19 corresponds to a large-oscillation regime with a liquid plug passing alternately upstream and downstream of the injection point. Test 85.14 is in a small-oscillation regime with the liquid front not passing upstream of the injection point.

The cold leg was modeled with the primary side of a TEE component with the secondary side modeling the injection pipe. The upstream end of the primary side was connected to a PLENUM simulating the volume preceding the cold leg. The downstream end of the TEE was connected to a BREAK simulating the outlet of the test section where the back pressure is imposed. A FILL component, connected to the secondary side of the TEE, was used to provide the liquid-injection rate.

A comparison of the experimental pressure distribution at steady state to that predicted by TRAC for Test 81.23 is shown in Fig. A-19. The measured pressure exhibits a pressure increase near the injection point caused by condensation and vapor deceleration followed by an increase attributed to liquid acceleration downstream of the injection point. The predicted pressure shows only the sharp decrease. The code does, however, accurately predict the liquid and vapor temperatures.

In Test 80.19 a plug immediately formed and oscillated with a period of about 0.6 s. The code predicted an oscillating plug with a period of 0.7-1.0 s but the simulation eventually failed because the minimum-time-step limitation was reached caused by a water-packing effect.

Test 85.14 had a liquid-injection flow rate about 3 times that of test 80.19. The results of the simulations for this case showed oscillations with a period much larger than the data. The amplitude of the oscillations was approximately twice that of the data.

The authors conclude that the condensation model in TRAC was not satisfactory for these tests. This is probably caused by an overprediction of interfacial area for a case where liquid injection is in the form of a jet. They also note that the use of the water-packing option sometimes causes a sharp reduction in the time step. Nodalization studies show little difference in results for the range of cell lengths from 0.1 to 3.0 m. They recommended a relatively coarse mesh. A study of the sensitivity of the pressure distribution to the volume of the upstream plenum indicated that the period of the oscillations increases and the amplitude decreases as the upstream volume size is increased. This is in qualitative agreement with the experiments. Grind times for these calculations were in the range of 1.35-1.76 s.

The PATRICIA experiments simulate the U-tube of a steam generator. Water flowing in the tube simulates the primary circuit. The secondary circuit is simulated by the flow of an organic fluid in the annulus around the tube. The test section is divided into four sections, each having an independent secondary circuit. Pressure drops across the test section are measured with a manometer. Temperatures in the primary circuit are measured with thermocouples located in the connection pieces between segments.

About 600 tests were performed. Six series of tests (a total of 85 tests) were selected for TRAC simulations. Twenty-nine of these tests included the injection of a noncondensable gas. Each part of the test section is modeled with a PIPE component. Four nodes are used in the walls and experimentally measured power is extracted at the external node to simulate the secondary side of the steam generator. The first PIPE component is connected to a FILL where the inlet conditions are imposed and the last PIPE is connected to a BREAK component where the back pressure is specified. An entire series of tests was simulated in one run using a 10 s ramp in the boundary conditions. These conditions were then maintained for 250 to 1000 s to reach an equilibrium state. Steady state was reached for most of the runs, although oscillations with small pressure-drop variations occurred in some cases. For the series of tests with a noncondensable gas, steady state was not reached and this series was abandoned.

The TRAC predictions are reasonably good for most calculations. Exceptions are for a series of runs at high void fractions. This is attributed to the fact that TRAC uses a homogeneous wall shear stress model whereas the flow is rather annular at large void fractions. In cases with countercurrent flow, the pressure drops are too low in the first and second segments, but good in the third and fourth parts of the test section, where there is little liquid. Thermal resistances calculated by TRAC are in poor agreement with measured values. These discrepancies are attributed to the poor accuracy of the temperature measurements.

A nodalization study for this apparatus indicates little effect for the range of cell sizes studied. The sensitivity of pressure drops to the friction factor option was also performed. Most calculations were performed using NFF=1. Calculations using NFF=2 were found to largely overpredict the pressure drops. The use of that option was not recommended. Grind times for these calculations were in the range of 0.87 to 1.09 s.

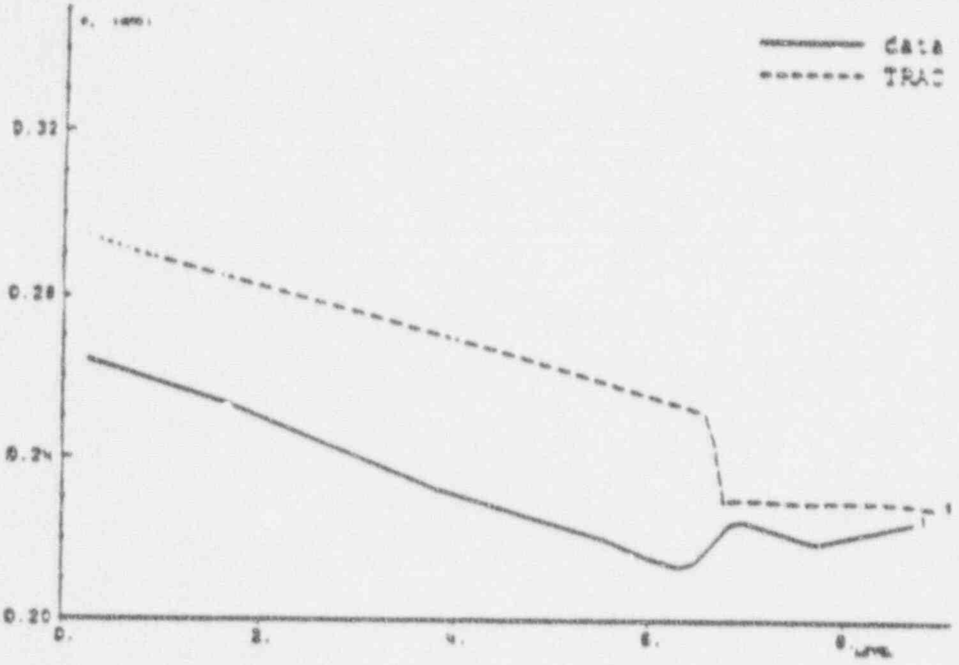

Fig. A-19. Steady-state pressure distributions for EPIS-2, Test 81.23.

REVIEW OF ICAP REPORT NO. Strathclyde-SB291, Phase 1

A. BASIC DATA

A1. ***Report Information:***

Author: W. M. Dempster, A. M. Bradford, T. M. S. Callender, H. C. Simpson

Report Title: An Assessment of TRAC PF1/MOD1 Using Strathclyde 1/10 Scale Model Refill Tests

Report Number: Contract RK:1642 Job No. SB291, Phase 1.

Author's Nationality and Affiliation: United Kingdom, University of Strathclyde, Department of Mechanical and Process Engineering.

Report Date: None

A2. ***Reviewer's Name:*** Norman M. Schnurr

Date of Review: June 1990

A3. ***Which code version was used for the baseline calculation: (Include cycle number or version number and any updates. Section 5.2.2)******

Winfrith modified code B05 and version B03 modified by D. M. Turner.

A4. ***Report Classification (Proprietary, or non-proprietary, any restrictions. Section 4.1)******

Restricted to the organizations or the persons to whom the report is addressed.

A5. ***Is this an integral or separate-effects assessment?***

Separate-effects assessment.

A6. ***Summarize why this assessment is being done. (Section 5.2.5 and Table 3)******

The purpose of this work is to assess the capabilities of TRAC PF1/MOD1 to simulate the conditions existing in the vessel downcomer during the refill phase following a large-break LOCA.

A7. ***Provide a list of keywords descriptive of this analysis.***

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* Refers to section or table in NUREG-1271, "Guidelines and Procedures for the International Code Assessment and Applications Program," April 1987.

TRAC, ECC injection, LOCA, refill, downcomer penetration, bypass.

B. BRIEF QUESTIONS RELATED TO THE COMPLETENESS OF THE REPORT (Include report page number where information was found.)

B1. Did the author describe each test facility and each test used in the analysis? Elaborate. (Section 5.4.5 and 5.5.4)*

The Strathclyde 1/10-scale facility is described on pp. 2-3 and is illustrated in Figs. 2.1-2.4. The test procedure is discussed on pp. 3-5. Conditions for the four tests covered by this report are summarized in Table 4.1

B2. The author must identify the experimental data used for the assessment in the report. The data channels used for comparison with code results should be easy to identify. It is desirable, but not required, for the author to supply the very data used in the assessment on hardcopy, floppy, or tape as specified in NUREG-1271. Has the author done these things? (Section 5.5.3 and 5.3)*

The experimental data include inlet steam (or air) flow rate, injected water flow rate, water inventory in the lower plenum, and various temperatures, pressures, and pressure differences in the lower plenum. Mass-flow rates are given in graphical form in Figs 5.1, 5.2, 5.4, 5.5, 5.8, 5.9, 5.11, 5.12, 5.15, and 5.17. All data are taken from the Strathclyde test data bank.

B3. The author must provide an evaluation of the experimental data uncertainty or clearly reference where it may be found. Has this been done? (Section 5.2.1)*

The uncertainty of the experimental data was not discussed.

B4. Was a base-case calculation performed using the unmodified, frozen code? Did the author include a clear, explicit figure of the Model? (Section 5.2.2).*

The base-case simulations were performed using the Winfrith modified code B05. The models are discussed on pp. 5-6 and noding diagrams are given in Figs. 3.1-3.3.

B5. The author must supply a copy of the input deck for one of his transient calculations on hardcopy, or floppy, or both. Has he done this? (Section 5.4.6 and 5.5.1)*

The input deck is not included in this assessment.

B6. ***Were sensitivity studies performed? Were the sensitivity studies adequately described? Were all identified code deficiencies explicitly described? (Section 5.2.3, 5.2.5, and 5.4.7)****

A sensitivity analysis of the interfacial drag model is included (pp. 14-16). The identified code deficiencies were clearly described.

B7. ***Were nodalization studies performed? Were the nodalization studies adequately described? Elaborate if necessary. (Section 5.2.4)****

Nodalization studies are not performed in this assessment but were performed in Phase 2 of this project. The Phase 2 report is among the assessments to be reviewed during FY 1990.

B8. ***The report should include run statistics for at least one transient calculation using the unmodified frozen code. Was this done? If a modified version of the code was produced, run statistics for the same transient calculation performed with the final version of the modified code should be included. Was this done? (Section 5.2.5 - para. 4, and Table 4 - p. 25, and Section 5.4.8)****

Run statistics are not included for this separate-effects assessment.

B9. ***Were complete references included in the report? (Section 5.4.10)****

A total of 11 references are given covering all important aspects of the work.

B10. ***Were the objectives satisfied?***

The stated objective was to assess the ability of TRAC to simulate conditions existing in a vessel downcomer during the refill phase of a large-break LOCA. This was done and some code deficiencies were identified.

C. DETAILED QUESTIONS

C1. ***Did the author describe the model nodalization, assumptions, etc.? Were they appropriate? Did the nodalization follow the input deck preparation guidelines found in the TRAC User Guides? Elaborate if necessary. (Section 5.4.6)****

The nodalization used in this assessment is described in detail. The number of cells and their distribution are similar to the nodalization used in TRAC large-plant calculations that have been recently carried out in the UK and conform to guidelines given in the TRAC-

PF1/MOD1 User's Guide. The suitability of this noding for refill conditions is determined in Phase 2 of this project.

C2. Briefly describe the thermal-hydraulic phenomena and the reported code predictions addressed in the report. If appropriate, describe the phenomena in the context of thermal-hydraulic behavior in the vessel primary loop, secondary loop, and other phenomena of interest.

The Strathclyde experiments simulate the refill stage of a double-ended cold-leg-break LOCA in a PWR. The reactor vessel includes four hot legs and four cold legs. Two of the hot legs are used to supply steam (or air) to the core. Three of the cold legs are used as ECC-injection points and the fourth represents the broken leg. A particularly critical phase of the transient may occur when ECC water is prevented from entering the vessel due to an opposing flow of steam originating from the core intact loops. This phase of the transient, known as the refill phase, includes highly complex interactions of steam and water involving multidimensional, nonequilibrium countercurrent two-phase flow. Some or all of the injected water may fail to penetrate the downcomer and may be carried out the broken cold leg, bypassing the core.

C3. If the author has identified new user guidelines has he described them thoroughly? What are they?

No new user guidelines were identified.

C4. What user guidelines can you infer from the results described in the report?

A relatively fine mesh may be needed in the downcomer of the reactor vessel to accurately calculate flow conditions during the refill phase. The authors indicate that the quadrant type of vessel nodalization may not be sufficient to simulate the two-dimensional effects of the process.

C5. What deficiencies were identified in the unmodified frozen version of the code? (Section 5.2.5 and 5.4.7)*

The film and droplet drag coefficients and the entrainment correlations are deemed unlikely to be appropriate for the conditions that exist in the downcomer. The momentum equation was not in conservative form for the version of the code used in this study. The conservative form was found to produce better results.

C6. Describe the impact of each identified code deficiency.

The drag correlations gave interphase-shear values that were too small, resulting in underpredictions of the amount of water penetrating the downcomer.

C7. *What code modifications were made? What effect did they have? (Section 5.2.3)**

The code was altered to use a conservative form of the momentum equation. This change produced little effect on the overall mass balance for the tests with little or no bypass but did cause marked improvement in the overall distribution of liquid fractions and velocities for those cases. For the test in which total bypass occurred, changing the momentum calculation to the conservative form caused marked improvement in the calculations.

C8. *Run statistics must be provided for the calculation of one transient with the unmodified frozen code and the fully modified code. Compare and evaluate. The run statistics should include a description of the computer and operating system used to perform each calculation, and*

a. A plot of CPU vs RT

b. A plot of DT vs RT

c. The value of the "grind time" = [(CPU x 10^3*)/(C x DT)]*

Where CPU = Total execution time

RT = Transient time

DT = Total number of time steps

C = Total number of volumes in the model

No run-time statistics were provided for this separate-effects assessment.

*d. Evaluate the actual time step used. Did the transient run at the Courant time step or did the user specify a smaller maximum time step? Compare the actual time step vs transient time and the user specified maximum time step vs transient time. (Section 5.2.5-para.4, Table 4-p. 25, and Section 5.4.8)**

No information concerning time steps was given.

C9. *Does the work documented in this report appear to be good and generally valid or are there fundamental problems with it? (Solicit input of code developers to answer this question.)*

The work documented in this report was well executed and gives some useful information concerning the ability of TRAC to model the complex flow conditions in the downcomer of a reactor vessel during the refill phase of a large-break LOCA. It represents the first phase in a project sponsored by the Central Electricity Generating Board . Some of the elements that are lacking, such as nodalization sensitivity studies, are included in the Phase 2 report.

The report does lack some of the elements that should normally be included in ICAP assessments such as timing studies, a discussion of the accuracy of the experimental data, and a copy of the input deck. Nevertheless, the conclusions are of significant value in assessing TRAC capabilities.

C10. *What conclusions were drawn in the report? Are they well supported by the results of the analysis? Elaborate. (Section 5.4.7 and 5.4.9)**

The authors' conclusions were as follows:

- The refill process is highly complex, involving various flow regimes distributed around the downcomer.
- The spatial distribution of flow regimes is such that quadrant-type vessel nodalization is believed to be insufficient to capture the two-dimensional effects of the process.
- TRAC was found to underpredict the amount of bypass as measured in Strathclyde 1/10-scale PWR model refill experiments studied.
- An analysis of the current interfacial-drag modeling in TRAC has shown that the film and droplet drag coefficients and the entrainment correlations are unlikely to be appropriate for the conditions that exist in the vessel downcomer.
- The use of the conservative form of the momentum equations in the code can, for the cases studied, produce better results than the standard code and therefore, any future calculations should be carried out using the momentum equations set in the conservative form.

These conclusions are consistent with the results of the simulations. The flow situations is so complex, however, that more detailed examination of the interphase-drag calculations will be necessary before final conclusions can be drawn. More experimental data covering a wider range of conditions will be necessary for a more complete study. The effect of finer nodalization, particularly in the azimuthal direction, should also be determined.

C11. *Report summary. (This summary will be included in the year-end NUREG report. It should be about 2 to 5 pages long and could include several*

figures. A short paragraph description of each facility should be included. Also include a paragraph summarizing the baseline results.)

The Strathclyde test facility was designed for operation with steam/water and steam/air as the working fluids and incorporates a closed-loop recirculation system. The reactor vessel test section was a 1/10-scale model of a Westinghouse PWR, with particular emphasis on the downcomer annulus. Two test sections were available, one with a transparent exterior, restricting operation to pressures less than 1.7 bar and allowing visual observation; the other of stainless steel permitted pressures up to 5 bar. The reactor vessel simulation included the provision of four hot legs, connected through the annulus to the core, and four cold legs connected to the annulus. Two of the hot legs were used to supply steam/air to the core; three of the cold legs were used as ECC-injection points, while the fourth represented the broken leg.

The main measurements taken during the tests included inlet steam/air flow rate, injected water flow rate, water penetrating to the lower plenum, and various temperatures, pressures, and pressure differences. Two types of tests were performed. In the "water first" tests a particular water flow rate was set and then the steam flow rate was increased in steps until complete bypass occurred. In "steam first" tests the steam flow rate was set and the water flow rate was increased until bypass ceased.

The nodalization scheme used was similar to that used in TRAC large plant calculations that had been previously carried out in the UK. The vessel nodalization included 13 axial levels, 4 sectors, and 1 radial ring to represent the downcomer. The core also had 13, 4, 1 noding and simply acted as a flow path for the flow of steam or air. The ECC-injection flow rates were modelled using FILL components injecting into PIPE components. A BREAK component was used to specify the experimental break pressure in the nozzle of the broken cold leg.

It was not possible to directly model the heat transfer between hydrodynamic cells separated by solid structures using TRAC-PF1/MOD1. Therefore the 1D conduction slab model was adapted in an attempt to include wall-heat-transfer effects. The first node of the heat structure modeled the core steam temperature, which remained at an approximately constant value throughout the test. To maintain a constant temperature boundary condition at the first node, an artificial material with very high thermal capacity was used. The thermal conductivity associated with this material corresponded to a value determined using the Dittus-Boelter convective-heat-transfer correlation.

Four tests were chosen from the Strathclyde data bank that covered the entire range of available conditions varying from total penetration to total bypass at moderately high subcooling. Test A was a steam/water total-penetration test, tests B and C were partial-penetration tests with steam/water and air/water respectively, and test D was a high-subcooling steam/water bypass test. All four tests were simulated using TRAC and calculations for tests B and D were repeated using an upgraded code that used a conservative form of the momentum equations.

Test A was a high-subcooling total-penetration test in which a high degree of thermal equilibrium was reached. The TRAC predictions of the test are shown in Figs. A-20 and A-21. They indicate that TRAC calculated the correct situation with all the injected liquid flowing to the lower plenum. The amount of steam condensed in the vessel was slightly underpredicted, however. Overall, TRAC predictions agreed well with experimental results for this case.

Test B was a partial-penetration test with approximately 45% of the inlet water flow bypassing the lower plenum. The TRAC comparisons with the experimental results (Figs. A-22 and A-23) show a far greater amount of liquid predicted to penetrate the downcomer than in the test. There is poor agreement between TRAC predictions and the experimental measurements and (visually) observed flow patterns in the downcomer.

Test C was an air/water penetration test where 75% of the inlet liquid flow rate was bypassed across the downcomer and out of the break. Again, the results are in very poor agreement with the experimental values with the majority of the inlet liquid flow being calculated by TRAC to penetrate the lower plenum.

Test D consisted of a total bypass condition at a relatively high subcooling. TRAC calculated that approximately 55% of the steam flow condensed in the downcomer which compared well with the measured value of nearly 57% of the steam flow condensed in the vessel. TRAC correctly predicted that the majority of liquid flowing into the downcomer was held up and bypassed the downcomer.

Simulations of tests B and D were repeated using a modified version of TRAC in which the momentum equations were set in conservative form. Calculations for case B show very little improvement in the overall predictions. However, noticeable differences are seen when comparing the overall distribution of liquid fractions and velocities. The most dramatic difference occurred when recalculating test D. It was now found that TRAC correctly predicted total bypass.

A computer program was written at Strathclyde to carry out sensitivity calculations on the annular-mist model used in TRAC. Conditions typical of the test simulated in this assessment were used. The results of the calculations showed that the mist drag coefficient was many magnitudes larger than the annular-film-drag coefficient across the whole void fraction range. The consequence of this is that the entrainment fraction plays an important role in determining if the annular-film coefficient has any significance in the total drag coefficient. It is found that the entrainment is negligible and the interfacial-drag coefficient is dominated by the annular-film-drag coefficient for velocities up to 10 m/s. For higher velocities, the increasing entrainment causes the total drag to be quickly dominated by the droplet drag. Velocities in the Strathclyde tests are generally larger than 10 m/s. Deficiencies in the modeling were attributed to the Wallis correlation. A correlation by Bharathan which is more appropriate to countercurrent flow than the Wallis correlation was found to produce better results. This was attributed to the fact that this correlation produces interfacial-film drag coefficients approximately 5 times higher than those predicted by the Wallis correlation.

The authors conclude that TRAC consistently underpredicted the amount of bypass. This, in addition to the underprediction of the amount of steam being condensed, suggests that deficiencies in the interfacial-drag modeling exist. The use a conservative form of the momentum equations produces better results and is a more correct formulation. This form of the momentum equation should be used together with suitable experimental data to determine the validity of the interfacial closure relations.

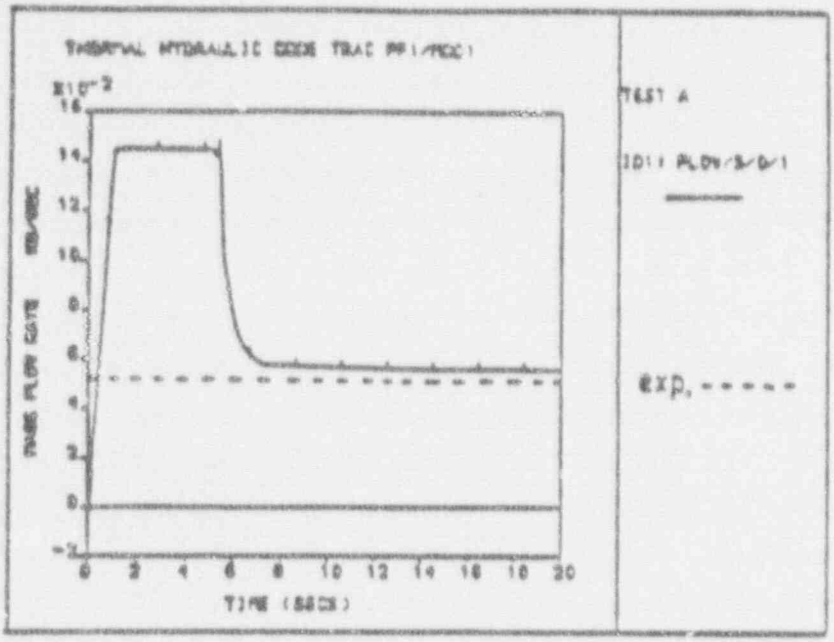

Fig. A-20. Experimental and predicted break mass-flow rates for Test A.

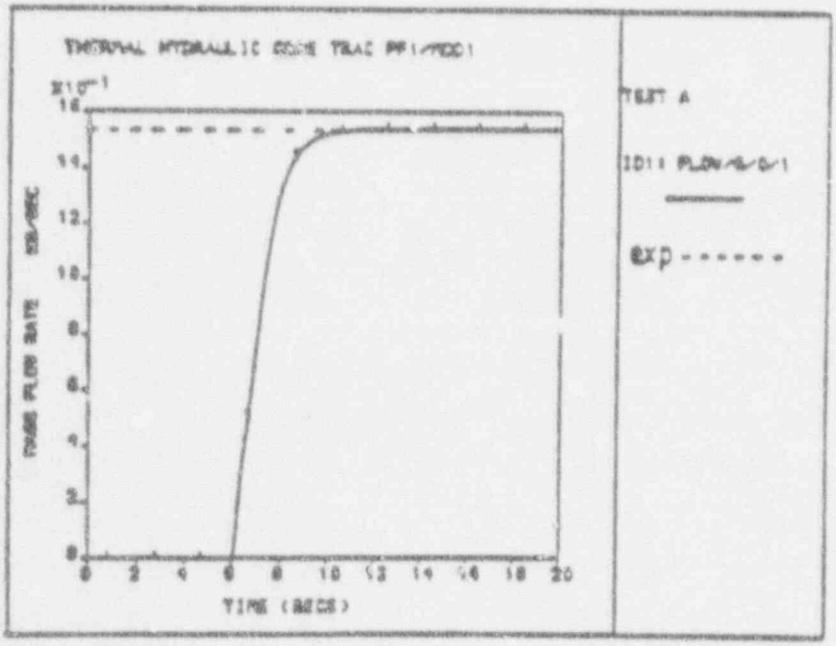

Fig. A-21. Experimental and predicted mass-flow rates from the lower plenum for Test A.

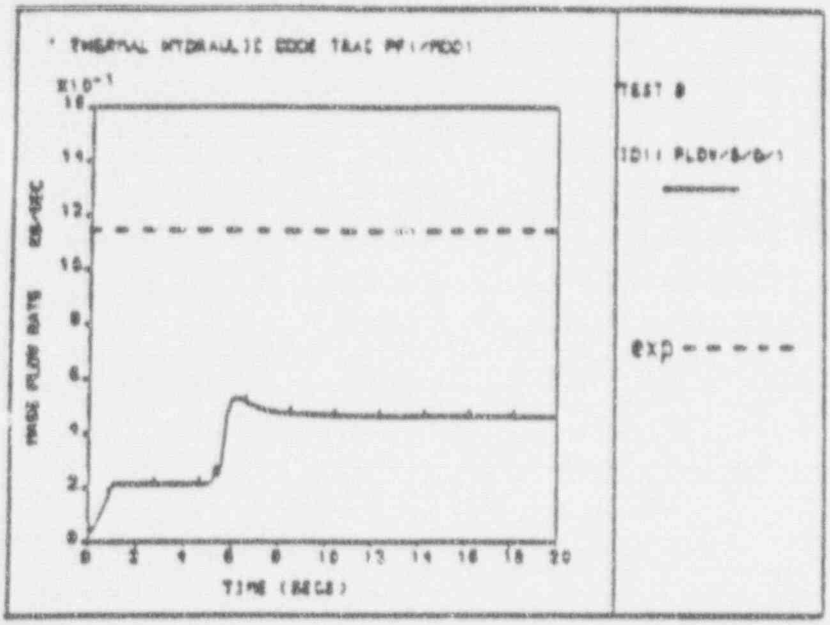

Fig. A-22. Experimental and predicted break mass-flow rates for Test B.

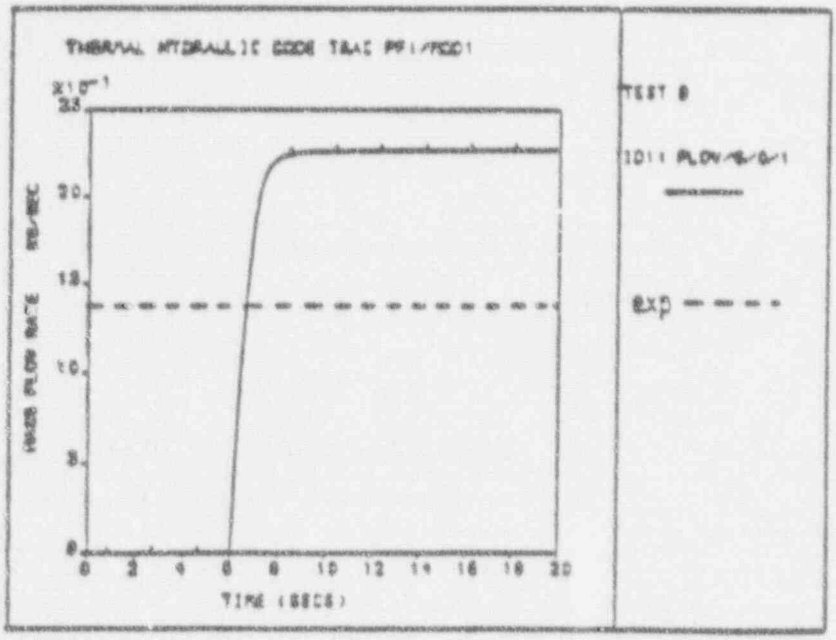

Fig. A-23. Experimental and predicted mass-flow rates from the lower plenum for Test B.

REVIEW OF ICAP REPORT NO. RD/L/3455/R89

A. BASIC DATA

A1. *Report Information:*

Author: D. M. Turner

Report Title: Discretization Effects in TRAC-PF1/MOD1 on the Prediction of Low Subcooling Countercurrent Flow in a PWR Downcomer

Report Number: RD/L/3455/R89

Author's Nationality and Affiliation: United Kingdom, Central Electricity Generating Board

Report Date: February 1989

A2. *Reviewer's Name:* Norman M. Schnurr

Date of Review: July 1990

A3. *Which code version was used for the baseline calculation: (Include cycle number or version number and any updates. Section 5.2.2)**

Winfrith-modified code B03B.

A4. *Report Classification (Proprietary, or non-proprietary, any restrictions. Section 4.1)**

CEGB Research in Confidence (not to be declassified).

A5. *Is this an integral or separate-effects assessment?*

Separate-effects assessment.

A6. *Summarize why this assessment is being done. (Section 5.2.5 and Table 3)**

The purpose of this work was to determine the discretization effects for the momentum equation in TRAC-PF1/MOD1 on the prediction of low-subcooling countercurrent flow in a PWR downcomer.

A7. *Provide a list of keywords descriptive of this analysis.*

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* Refers to section or table in NUREG-1271, "Guidelines and Procedures for the International Code Assessment and Applications Program," April 1987.

TRAC, ECC injection, countercurrent flow, refill, downcomer penetration, bypass, discretization, momentum equation.

B. BRIEF QUESTIONS RELATED TO THE COMPLETENESS OF THE REPORT (include report page number where information was found.)

B1. Did the author describe each test facility and each test used in the analysis? Elaborate. (Section 5.4.5 and 5.5.4)*

The CREARE countercurrent flow experiments are discussed briefly (p. 6). A schematic diagram of the experimental rig is shown in Fig. 1 of the assessment.

B2. The author must identify the experimental data used for the assessment in the report. The data channels used for comparison with code results should be easy to identify. It is desirable, but not required, for the author to supply the very data used in the assessment on hardcopy, floppy, or tape as specified in NUREG-1271. Has the author done these things? (Section 5.5.3 and 5.3)*

The experimental data include only a limited amount of nondimensional liquid-flow-rate vs dimensionless-steam-flux data (Table 1 and Fig. 2). A reference to a complete collection of data from the CREARE experiments is given.

B3. The author must provide an evaluation of the experimental data uncertainty or clearly reference where it may be found. Has this been done? (Section 5.2.1)*

The uncertainty of the experimental data was not discussed. The large range given for the experimental results in Table 1 indicates a rather large amount of scatter in the experimental data. A reference to a report that gives details of the experiments is given.

B4. Was a base-case calculation performed using the unmodified, frozen code? Did the author include a clear, explicit figure of the Model? (Section 5.2.2).*

The base-case simulations were performed using the Winfrith-modified code B03B. The model is discussed on pp. 6-7 and noding diagrams are given in Figs. 1 and 53.

B5. The author must supply a copy of the input deck for one of his transient calculations on hardcopy, or floppy, or both. Has he done this? (Section 5.4.6 and 5.5.1)*

The input deck is not included in this assessment.

B6. Were sensitivity studies performed? Were the sensitivity studies adequately described? Were all identified code deficiencies explicitly described? (Section 5.2.3, 5.2.5, and 5.4.7)*

A series of sensitivity studies were performed to determine the effect of a discretization of the momentum equation in conservative form, the effect of including cross-derivatives in the discretization, and the effect of an improved numerical treatment at the junction between pipes and a 3D vessel. These studies were described in detail and constitute the main thrust of the assessment. The only code deficiencies mentioned in this report are those related to these sensitivity studies.

B7. Were nodalization studies performed? Were the nodalization studies adequately described? Elaborate if necessary. (Section 5.2.4)*

Initial calculations were performed for a vessel having four azimuthal nodes. Additional computations were performed for the case of eight azimuthal nodes. A comparison of results for these cases is discussed in Section 3.2 of the assessment.

B8. The report should include run statistics for at least one transient calculation using the unmodified frozen code. Was this done? If a modified version of the code was produced, run statistics for the same transient calculation performed with the final version of the modified code should be included. Was this done? (Section 5.2.5 - para. 4, and Table 4 - p. 25, and Section 5.4.8)*

Run statistics are given for a standard TRAC run and for calculations using the conservative discretization, cross-derivative discretization, and a combination of the two (Table 2).

B9. Were complete references included in the report? (Section 5.4.10)*

A total of 6 references are given covering all important aspects of the work.

B10. Were the objectives satisfied?

Although the objectives were not stated explicitly, the main thrust of the work was to determine the effects of various discretization options on the prediction of low-subcooling countercurrent flow in a PWR downcomer. The effects of these options are determined in a relative sense. There is insufficient experimental data to clearly determine their effects in an absolute sense.

C. DETAILED QUESTIONS

C1. ***Did the author describe the model nodalization, assumptions, etc.? Were they appropriate? Did the nodalization follow the input deck preparation guidelines found in the TRAC User Guides? Elaborate if necessary. (Section 5.4.6)****

The nodalization used in this assessment is described in detail. The use of only four azimuthal cells (for the original calculations) in the 3D vessel may not be sufficient for refill calculations. However, additional calculations were performed with eight azimuthal cells in the vessel.

C2. ***Briefly describe the thermal-hydraulic phenomena and the reported code predictions addressed in the report. If appropriate, describe the phenomena in the context of thermal-hydraulic behavior in the vessel primary loop, secondary loop, and other phenomena of interest.***

The CREARE tests are 1/5-scale countercurrent flow experiments in a reactor vessel. Superheated steam is injected at a constant rate at the top of the vessel. It flows downward through the "core" and upward through the downcomer and out the broken cold leg. ECC water enters the top of the downcomer through the three intact cold legs. The phenomena of interest are the flow of the ECC water countercurrent to the steam in the downcomer and the fraction of water that penetrates into the lower plenum. Condensation during refill is an important aspect of the refill process.

C3. ***If the author has identified new user guidelines has he described them thoroughly? What are they?***

No new user guidelines were identified.

C4. ***What user guidelines can you infer from the results described in the report?***

At least eight azimuthal nodes should be used in a 3D vessel if ECC bypass is likely to occur to a significant extent.

C5. ***What deficiencies were identified in the unmodified frozen version of the code? (Section 5.2.5 and 5.4.7)****

The nonconservative discretization of the momentum equation is judged to be inferior to the conservative form.

C6. ***Describe the impact of each identified code deficiency.***

The effect of the nonconservative discretization of the momentum equation is discussed in the next section.

C7. ***What code modifications were made? What effect did they have? (Section 5.2.3)****

Two major modifications were made in the TRAC numerical scheme. These were called the "conservative" scheme and the "cross-derivative" scheme. The conservative scheme resulted in slightly lower filling rates. It also led to enhanced countercurrent flow within a cell, lower pressure gradients, more uniform variations between adjacent cells, and less oscillatory solutions. With the eight-azimuthal-node model, the original scheme showed alternating flow patterns within the downcomer that were strongly linked to nodalization and geometry and were believed to be nonphysical. The conservative scheme did not exhibit these patterns. With the four-node downcomer model there was little difference in the flooding-curve predictions between the original and conservative schemes. The conservative scheme did have a slight tendency to underpredict the downcomer penetration. The original TRAC scheme had been tuned to predict the CREARE data so any change in the code would be expected to give worse agreement with the data. The effect of the cross-derivative scheme was not judged to be significant.

C8. ***Run statistics must be provided for the calculation of one transient with the unmodified frozen code and the fully modified code. Compare and evaluate. The run statistics should include a description of the computer and operating system used to perform each calculation, and***

a. ***A plot of CPU vs RT***

b. ***A plot of DT vs RT***

c. ***The value of the "grind time" = [(CPU x 10^3)/(C x DT)]***

Where *CPU = Total execution time*

RT = Transient time

DT = Total number of time steps

C = Total number of volumes in the model

CPU-vs-RT and DT-vs-RT data are not included. Run statistics are given for a standard TRAC calculation, a cross-derivative calculation, a conservative calculation, and a run with both the conservative and cross-derivative discretizations used. The grind times for these four cases were 2.90, 3.04, 2.23, and 2.93 s, respectively.

d. Evaluate the actual time step used. Did the transient run at the Courant time step or did the user specify a smaller maximum time step? Compare the actual time step vs transient time and the user specified maximum time step vs transient time. (Section 5.2.5-para.4, Table 4-p. 25, and Section 5.4.8)*

No information concerning time steps was given.

C9. Does the work documented in this report appear to be good and generally valid or are there fundamental problems with it? (Solicit input of code developers to answer this question.)

The work documented in this report constitutes a very careful and detailed study of the discretization of the momentum equations in TRAC. It determines the effects of a conservative approach and of including cross-derivative terms in the discretization. The magnitudes of the various terms in the momentum equation are investigated to determine how close TRAC calculations are to predicting a classical 1D countercurrent flow in the downcomer. Unfortunately, the experimental data used for comparison is somewhat limited and contains sufficient scatter so that it is impossible to draw firm conclusions concerning the relative merits of the discretization schemes. The authors do make a case that the conservative scheme is more physically realistic.

C10. What conclusions were drawn in the report? Are they well supported by the results of the analysis? Elaborate. (Section 5.4.7 and 5.4.9)*

The authors' conclusions were as follows:

- The results obtained from the cross-derivative scheme are no better than those obtained from the original scheme.
- The results obtained from the conservative scheme appear to be much more physically realistic than those obtained from the original scheme.
- Results from the conservative scheme lead to enhanced countercurrent flow within a cell, lower pressure gradients, more uniform variations between adjacent cells, and a less oscillatory solution.
- For the conservative scheme, when the time derivative is small the flow in the downcomer is very similar to a classical vertical countercurrent flow except that the convective derivative in the vapor equation remains significant.
- With the eight-node downcomer model, the original scheme showed unrealistic alternating patterns in the downcomer while the conservative scheme did not.

- With the four-node downcomer model there was very little difference between the flooding-curve predictions of the original and conservative schemes.

These conclusions are generally consistent with the results of the simulations.

C11. ***Report summary.* (This summary will be included in the year-end NUREG report. It should be about 2 to 5 pages long and could include several figures. A short paragraph description of each facility should be included. Also include a paragraph summarizing the baseline results.)**

The CREARE experimental rig consists of a 1/5-scale vessel with superheated steam injected at a constant rate at the top. When equilibrium conditions prevail, subcooled water is injected into the top of the downcomer from three pipes simulating cold legs. There is no structure equivalent to hot legs in this vessel. An outlet pipe, simulating a broken cold leg, has a larger diameter than the other cold legs to prevent a significant buildup of pressure within the rig. Unless complete bypass occurs, the lower plenum gradually fills up with water during the experiment as a steam/water mixture issues from the outlet pipe. The results from the CREARE experiments are presented as a flooding curve with a dimensionless countercurrent steam flux on one axis and a dimensionless liquid flux delivered to the lower plenum on the other axis.

The nodalization scheme used for the TRAC calculations used three, four, and seven nodes in the radial, azimuthal, and axial directions, respectively. Only one radial node was used in the downcomer. Later calculations were performed with eight azimuthal nodes. Calculations were performed for a given liquid flow rate and five different steam flow rates for four different versions of TRAC. These were the standard version, the modified cross-derivative version, a conservative scheme, and a version including both modifications. An asymptotic filling rate for the liquid flow into the lower plenum was calculated for each run. This filling rate was converted to a nondimensional flow rate for comparison to experimental data. In general, the lower plenum filling rates were underpredicted. The conservative scheme gave slightly worse agreement but the original TRAC scheme had been tuned to predict the CREARE data and any changes made to the code would be expected to produce worse agreement. It should be noted that the scatter in the experimental data was quite large so that the comparisons of calculated and experimental results was inconclusive.

The major thrust of this assessment was a comparison of results produced by the standard version to those predicted by the modified versions. Calculated void fractions and liquid and vapor velocities are shown for several cells using all four versions of the code. These results show that the conservative scheme significantly reduces the flow variability, both locally node-to-node and during the transient. Examples of vapor velocities calculated with the standard and conservative versions are shown in Figs. A-24 and A-25. The solutions produced by the conservative scheme are much less oscillatory than those produced by the original scheme.

A series of simulations were performed using eight azimuthal nodes for comparison to the four-node results. With the eight-node downcomer model, the original scheme produced flows with an alternating pattern in the downcomer. This pattern was strongly linked to nodalization and the geometry of the ECC-water input and was thought to be nonphysical. The conservative scheme with the eight-node downcomer model did not exhibit the alternating flow pattern. Predictions for the conservative scheme for the eight-node downcomer were similar to the four-node downcomer results with water flow up around the break-flow side of the vessel and down elsewhere.

A series or curves are presented showing the magnitude of the various terms in the momentum equation. These terms include the [illegible]rivative, interfacial friction, convective derivative, pressure gradient, and velocity head. These data suggest that in general the pressure gradients will be lower with the conservative scheme. This is believed to be the reason for the lower liquid velocities observed with the conservative scheme. For the conservative scheme, when the time derivative is small, the flow in the downcomer is very similar to a classical vertical countercurrent flow except that the convective derivative in the vapor equation remains significant.

Run-time information for each scheme is presented for the same conditions. The conservative scheme is able to perform more time steps per unit time than the original scheme.

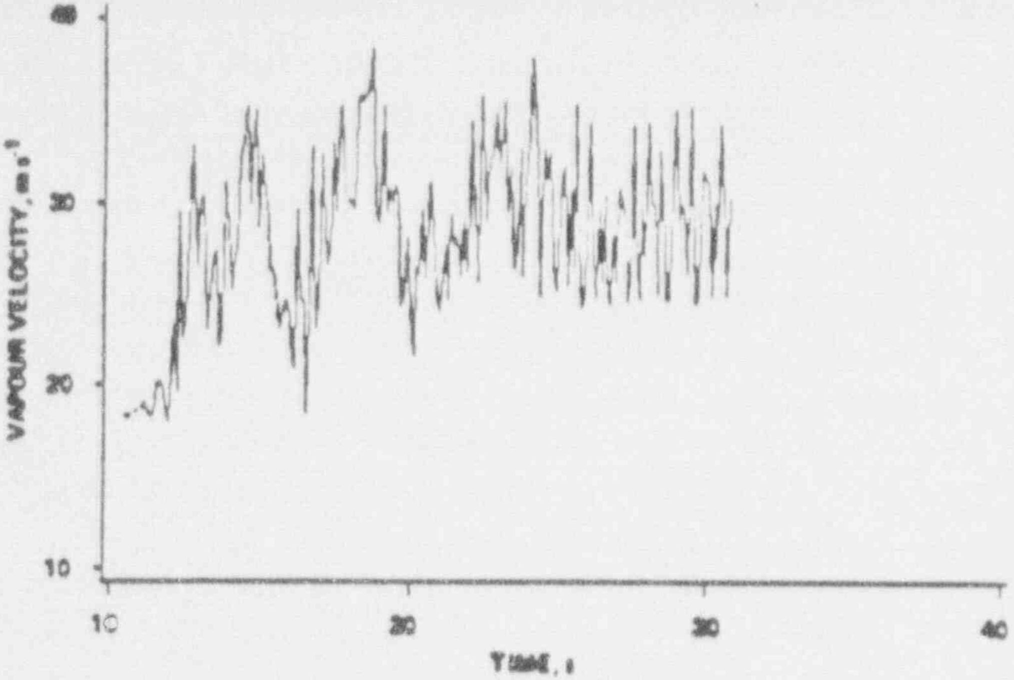

Fig. A-24. Vapor velocity predictions using the original scheme, Cell 45.

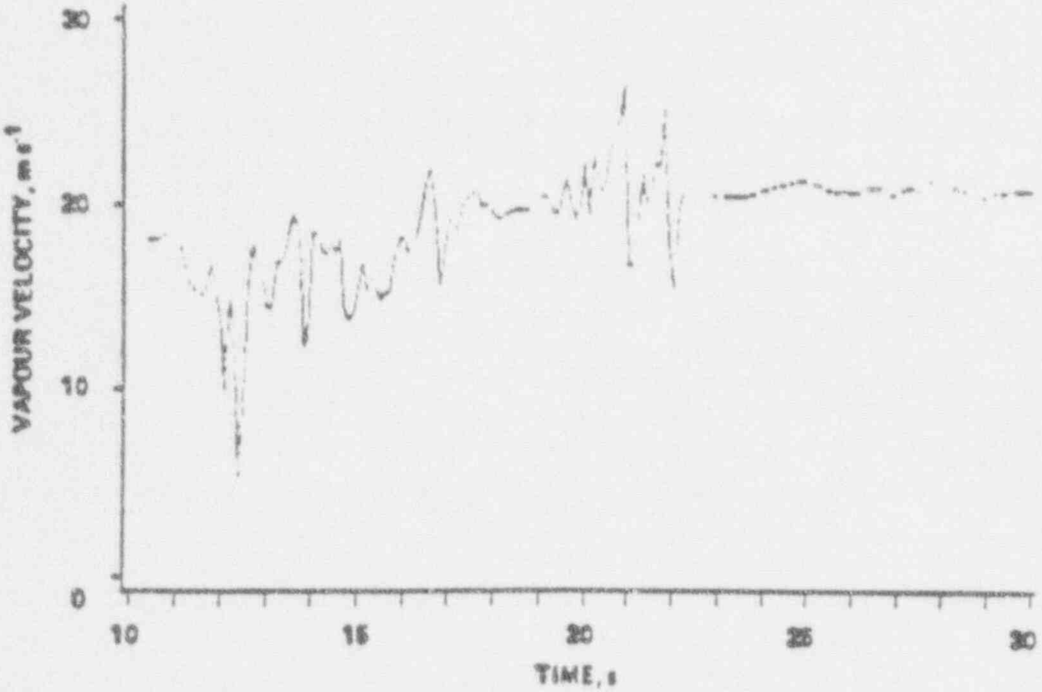

Fig. A-25. Vapor velocity predictions using the conservative scheme, Cell 45.

REVIEW OF ICAP REPORT NO. AEEW-R 2478

A. BASIC DATA

A1. *Report Information.*

Author: P. Coddington

Report Title: OECD-LOFT LP-LB-1 Comparison Report

Report Number: AEEW-R 2478

Author's Nationality and Affiliation: United Kingdom, Reactor Systems Analysis Division, Winfrith AEE.

Report Date: February 1989.

A2. ***Reviewer's Name:*** Norman M. Schnurr

Date of Review: September 1990

A3. ***Which code version was used for the baseline calculation: (Include cycle number or version number and any updates. Section 5.2.2)****

TRAC-PF1/MOD1 Version 11.0.

A4. ***Report Classification (Proprietary, or non-proprietary, any restrictions. Section 4.1)****

Not for publication.

A5. ***Is this an integral or separate-effects assessment?***

Integral assessment.

A6. ***Summarize why this assessment is being done. (Section 5.2.5 and Table 3)****

This study is primarily a comparison of six posttest calculations of the LP-LB-1 transient submitted by five separate organizations from five different countries. TRAC-PF1/MOD1 was used by the UKAEA. Other codes used include DRUFAN/FLUT, RELAP5/MOD2, and RELAP5/MOD1. Results of each calculation are compared to experimental data in an effort to assess the strengths and weaknesses of the various codes.

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* Refers to section or table in NUREG-1271, "Guidelines and Procedures for the International Code Assessment and Applications Program," April 1987.

17. ***Provide a list of keywords descriptive of this analysis.***

TRAC, LOFT, LBLOCA, code comparison study.

B. BRIEF QUESTIONS RELATED TO THE COMPLETENESS OF THE REPORT (Include report page number where information was found.)

B1. ***Did the author describe each test facility and each test used in the analysis? Elaborate. (Section 5.4.5 and 5.5.4)****

The LOFT facility is described in detail on pp. 2-4 and is illustrated in Figs. 1-5. The LP-LB-1 transient is described on pp. 19-21. The sequence of events is given in Table 4.

B2. ***The author must identify the experimental data used for the assessment in the report. The data channels used for comparison with code results should be easy to identify. It is desirable, but not required, for the author to supply the very data used in the assessment on hardcopy, floppy, or tape as specified in NUREG-1271. Has the author done these things? (Section 5.5.3 and 5.3)****

The data-measuring stations are shown in Figs. 2, 4, and 5. A large amount of data is presented for comparison to the calculated results. These include pressure, momentum flux, fluid density, and fluid temperature in the intact-loop hot and cold legs and the broken-loop hot and cold legs, intact-loop differential pressure, pressurizer pressure, accumulator flow rate, downcomer mass inventory, and fuel-rod temperatures for both central and peripheral fuel assemblies.

B3. ***The author must provide an evaluation of the experimental data uncertainty or clearly reference where it may be found. Has this been done? (Section 5.2.1)****

The accuracy of the data is discussed for several measured parameters (pp. 34, 42, 59, and 61). Error bands are given for mass inventory and vessel flow rates.

B4. ***Was a base-case calculation performed using the unmodified, frozen code? Did the author include a clear, explicit figure of the Model? (Section 5.2.2).****

Only one calculation was performed using TRAC. Noding diagrams are given in Figs. 6-10. Initial conditions are given in Table 2.

B5. *The author must supply a copy of the input deck for one of his transient calculations on hardcopy, or floppy, or both. Has he done this? (Section 5.4.6 and 5.5.1)**

The input deck is not included.

B6. *Were sensitivity studies performed? Were the sensitivity studies adequately described? Were all identified code deficiencies explicitly described? (Section 5.2.3, 5.2.5, and 5.4.7)**

No sensitivity studies were performed.

B7. *Were nodalization studies performed? Were the nodalization studies adequately described? Elaborate if necessary. (Section 5.2.4)**

No nodalization studies were performed.

B8. *The report should include run statistics for at least one transient calculation using the unmodified frozen code. Was this done? If a modified version of the code was produced, run statistics for the same transient calculation performed with the final version of the modified code should be included. Was this done? (Section 5.2.5 - para. 4, and Table 4 - p. 25, and Section 5.4.8)**

The ratio of CPU time to real time is given in Table 1

B9. *Were complete references included in the report? (Section 5.4.10)**

Twenty-four references are included (pp. 92-94) covering all important aspects of the study.

B10. *Were the objectives satisfied?*

The objectives were satisfied. The relative strengths and weaknesses of the various codes in analyzing a LBLOCA were clearly demonstrated.

C. DETAILED QUESTIONS

C1. *Did the author describe the model nodalization, assumptions, etc.? Were they appropriate? Did the nodalization follow the input deck preparation guidelines found in the TRAC User Guides? Elaborate if necessary. (Section 5.4.6)**

The nodalization used in this assessment is described in detail and conforms to recommendations in the TRAC User's Guide.

C2. ***Briefly describe the thermal-hydraulic phenomena and the reported code predictions addressed in the report. If appropriate, describe the phenomena in the context of thermal-hydraulic behavior in the vessel primary loop, secondary loop, and other phenomena of interest.***

OECD-LOFT experiment LP-LB-1 simulates a large-break (200% double-ended cold-leg) LOCA. The transient was initiated by opening the blowdown valves in the broken loop. The reactor was scrammed on indication of low pressure in the intact-loop hot leg and the primary pumps were tripped and decoupled from their flywheels, all within 1 s. The upper-plenum and hot-leg fluid began to flash as liquid flowed rapidly out of the broken-loop hot and cold legs. The voiding in the core resulted in the initial departure from nucleate boiling of the core fuel rods at a time just less than 1 s. After this, the fuel-rod cladding temperatures rose rapidly. As a result of the decoupling of the primary coolant pumps from their flywheel systems, the flow in the intact-loop cold leg fell rapidly. After 3.5 s, saturated conditions were reached in the broken-loop cold leg and the break flow fell. Initially the fuel-rod cladding temperatures rose rapidly as the stored heat in the center of the fuel was distributed across the entire fuel pin. Once this was complete, the rate of the temperature rise fell, as the source of heat became the core decay heat.

At about 13 s, a top-down flow of liquid through the core began. This caused a quenching of the top 18 in. of the fuel rods. The ECCS injection was initiated at 17.5 and 32 s from the accumulator and the LPIS, respectively. The liquid from the accumulator flowed into the vessel downcomer and down into the lower plenum with a minimal amount bypassing the vessel and flowing across the top of the downcomer and out the broken-loop cold leg. The lower plenum filled rapidly and fluid entered the core at about 33 s. A complete core reflood was accomplished at about 48-50 s.

C3. ***If the author has identified new user guidelines has he described them thoroughly? What are they?***

No user guidelines were identified.

C4. ***What user guidelines can you infer from the results described in the report?***

No user guidelines were inferred by the reviewer.

C5. *What deficiencies were identified in the unmodified frozen version of the code? (Section 5.2.5 and 5.4.7)**

No code deficiencies were specifically stated.

C6. *Describe the impact of each identified code deficiency.*

Not applicable.

C7. *What code modifications were made? What effect did they have? (Section 5.2.3)**

No code modifications were made.

C8. *Run statistics must be provided for the calculation of one transient with the unmodified frozen code and the fully modified code. Compare and evaluate. The run statistics should include a description of the computer and operating system used to perform each calculation, and*

a. *A plot of CPU vs RT*

b. *A plot of DT vs RT*

c. *The value of the "grind time"* = $[(CPU \times 10^{3})/(C \times DT)]$

Where
CPU = *Total execution time*
RT = *Transient time*
DT = *Total number of time steps*
C = *Total number of volumes in the model*

The ratio of CPU time to real time for the TRAC simulation was 240:1.

d. *Evaluate the actual time step used. Did the transient run at the Courant time step or did the user specify a smaller maximum time step? Compare the actual time step vs transient time and the user specified maximum time step vs transient time. (Section 5.2.5-para.4, Table 4-p. 25, and Section 5.4.8)**

The time-step size was not discussed.

C9. *Does the work documented in this report appear to be good and generally valid or are there fundamental problems with it? (Solicit input of code developers to answer this question.)*

This work is very useful and satisfied its intended purpose. It shows the relative strengths and weaknesses of four different codes in the transient analysis of a LBLOCA. The assessments of the various codes are objective, detailed, and thorough.

C10. *What conclusions were drawn in the report? Are they well supported by the results of the analysis? Elaborate. (Section 5.4.7 and 5.4.9)*

No specific conclusions are presented concerning the relative merits of the codes. This is apparently because, for much of the experimental data, the error bands are so large that firm conclusions regarding the accuracy of the various codes is not possible. The author draws some general conclusions concerning the simulation of LBLOCAs. They include the following:

- Whether or not liquid flows up into the core following the initial voiding after a LBLOCA is very difficult to predict since this will depend on both the net flow into the downcomer and the distribution of the hot and cold liquid and the steam within the vessel.
- The ability to accurately predict blowdown behavior in the loops does not necessarily imply that the behavior in the vessel, and particularly in the core, will be accurately predicted.
- The behavior in the peripheral assemblies of the core is particularly difficult to model with TRAC and impossible to model with one-dimensional codes.

C11. *Report summary. (This summary will be included in the year-end NUREG report. It should be about 2 to 5 pages long and could include several figures. A short paragraph description of each facility should be included. Also include a paragraph summarizing the baseline results.)*

This report presents a comparative analysis of six posttest calculations performed by five different organizations in five different countries for the LOFT experiment LP-LB-1. The organizations and computer codes used were

(1) UKAEA/UK using TRAC-PF1/MOD1,
(2) GRS/Germany using DRUFAN/FLUT,
(3) VTT/Finland using RELAP5/MOD2,
(4) EIR/Switzerland using RELAP5/MOD2 (2 calculations), and
(5) University of Bologna/Italy using RELAP5/MOD1.

Only the TRAC-PF1/MOD1 results will be discussed in this report summary.

OECD-LOFT experiment LP-LB-1 simulates a large-break (200% double-ended cold-leg) LOCA. The transient was initiated by opening the blowdown valves in the broken loop. The reactor was scrammed on indication of low pressure in the intact-loop hot leg and the primary pumps were tripped and decoupled from their flywheels, all within 1 s. The upper plenum and hot-leg fluid began to flash as liquid flowed rapidly out of the broken-loop hot and cold legs. The voiding in the core resulted in the initial departure from nucleate boiling of the core fuel rods at a time just less than 1 s. After this, the fuel-rod cladding temperatures rose rapidly. As a result of the decoupling of the primary-coolant pumps from their flywheel systems, the flow in the intact-loop cold leg fell rapidly. After 3.5 s, saturated conditions were reached in the broken cold leg and the break flow fell. Initially the fuel-rod cladding temperatures rose rapidly as the stored heat in the center of the fuel was distributed across the entire fuel pin. Once this was complete the rate of the temperature rise fell, as the source of heat became the core decay heat.

At about 13 s, a top-down flow of liquid through the core began. This caused a quenching of the top 18 in. of the fuel rods. The ECCS injection was initiated at 17.5 and 32 s from the accumulator and the LPIS, respectively. The liquid from the accumulator flowed into the vessel downcomer and down into the lower plenum with a minimal amount bypassing the vessel and flowing across the top of the downcomer and out the broken-loop cold leg. The lower plenum filled rapidly and fluid entered the core at about 33 s. A complete core reflood was accomplished at about 48-50 s.

The input description used for the TRAC calculations is similar to earlier TRAC-PD2 descriptions of LOFT used in the analysis of experiments L2-3 and L2-5 as well as LP-LB-1 at various laboratories. It is also similar to the input deck used at Los Alamos in the analysis of experiments L2-3 and LP-02-6. The input deck contains a total of 112 loop and 192 vessel cells.

The TRAC simulation gave satisfactory agreement with test data for thermal-hydraulic phenomena in both the intact and broken loops. The calculated parameters that were compared to experimental data included pressure, momentum flux, fluid density, and fluid temperatures in the intact- and broken-loop hot and cold legs. The broken-loop cold leg pressure, for example, is shown in Fig. A-26. The calculations show a reasonably good agreement up to about 12.5 s. After 24 s the absolute pressure is lower in the TRAC calculation because of the more rapid fall in pressure between about 10 and 15 s, so that the TRAC and experimental pressures do not begin to fall into line until after about 30 s. The agreement between the calculated and experimental pressures after 40 s is very good. The density, momentum flux, and fluid temperatures are also in fairly good agreement with experimental data. It should be noted that the data errors quoted on all of these measurements are relatively large. In the broken-loop hot leg, for example, TRAC predicts a maximum flow rate of 140 kg/s compared to a measured value of 180 kg/s but is still within the experimental error band. The intact-loop cold leg mass-flow rate calculated by TRAC is in good agreement with the test data and is well within the large experimental error range.

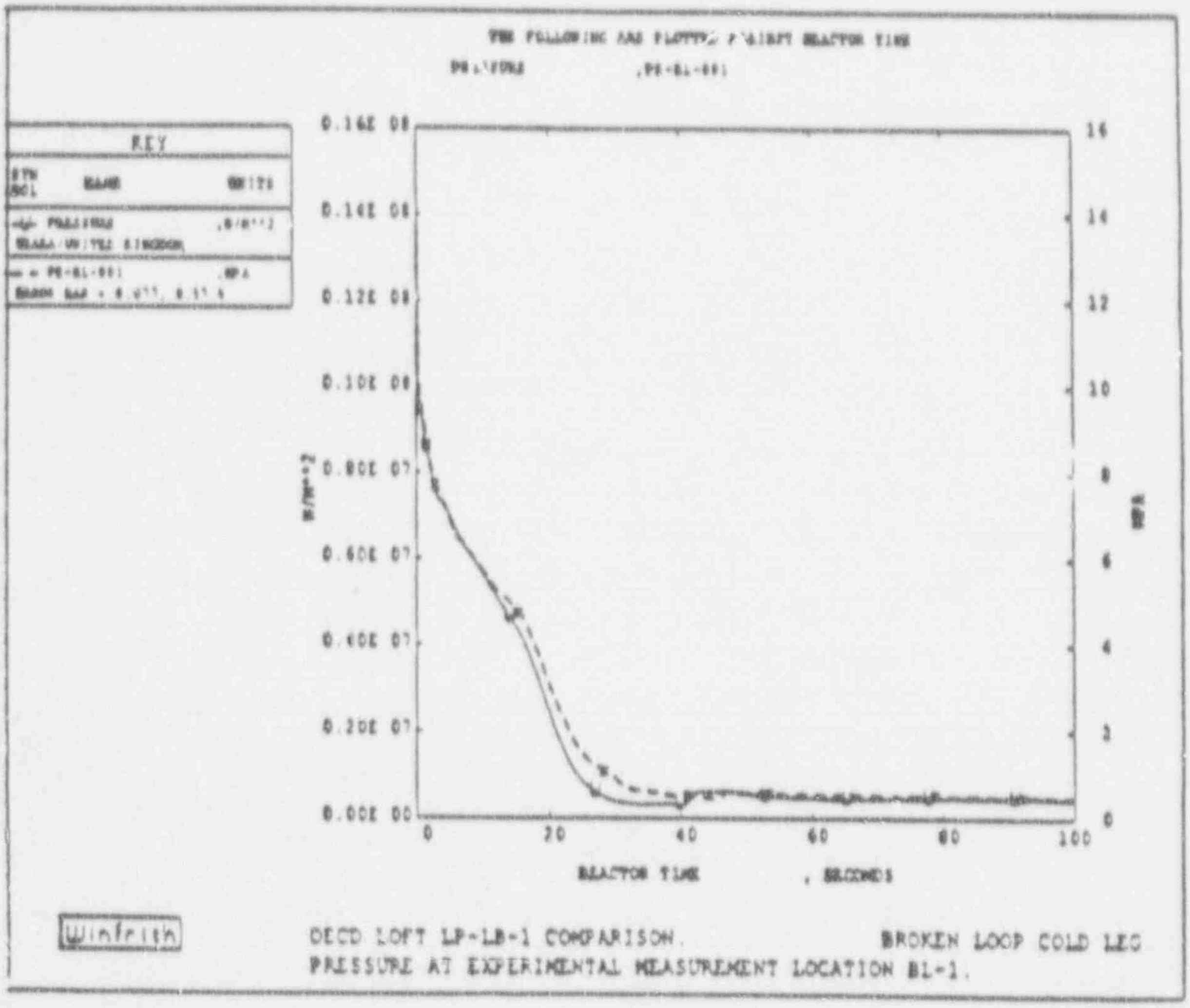
One area where TRAC did not give accurate predictions was the calculation of steady-state pump speed. The calculated pressure drop through the 3D vessel was greater than the experimental value so that a larger-than-measured pump speed was needed to obtain the required steady-state mass-flow rate. During the rapid coastdown of the pump following trip and decoupling [illegible] the flywheels, however, the TRAC predictions accurately followed the experimental data.

The most difficult phenomena to accurately predict in this type of simulation are the hydraulic effects in the vessel and the core heat transfer during blowdown and refill. The 1D codes exhibited a core upflow after blowdown while the 3D TRAC calculation showed a downflow that was in general agreement with the experimental data. The accuracy of the calculations during the subsequent refill and reflood stages is difficult to determine. The error in the measurement of flow out of the vessel along the broken-loop cold leg was large and the momentum flux instruments on which the mass-flow data is based were, after about 25 s, operating at a level below the minimum of their range. The time for initiation of reflood in the TRAC calculation was in very good agreement with experimental data. However, an underestimation of the broken-loop cold-leg flow during the refill period helped to compensate for an equivalent overestimation during blowdown.

The central fuel assembly fuel-rod cladding temperatures predicted by TRAC are in very good agreement with the experimental data up to the time of reflooding of the core at 40 to 45 s (See Fig. A-27). After 45 s the calculations overpredict liquid fractions in the core fluid cells which produces an overestimate of the clad-to-coolant heat transfer. The fuel-rod center-line temperatures predicted by TRAC are in good agreement with the experimental data (Fig. A-28). Agreement is not as good for the peripheral fuel assemblies. An examination of the experimental data from the peripheral fuel assemblies shows that there is a significant azimuthal variation in the thermocouple transients across the core during the blowdown period. The TRAC predictions for each of the instrumented assemblies shows a much smaller azimuthal variation of the cladding temperature.

In general, one may conclude that TRAC does an adequate job of predicting thermal-hydraulic behavior in both the intact and broken loops. Hydraulic behavior in the vessel is not as well predicted, although the large error bands on the experimental data makes assessment of code performance difficult. Maximum core temperatures are fairly well predicted but the quench times for cladding do not agree well with data. The large azimuthal temperature variations measured in the peripheral fuel assemblies are not predicted by the calculations.

This report is a rather comprehensive study of the predictive capability of four different codes for analyzing a very difficult transient. It gives a clear description of the complex phenomena that occur in the core during blowdown and refill and points to areas in the codes where future work should be concentrated.



OECD LOFT LP-LB-1 COMPARISON. BROKEN LOOP COLD LEG PRESSURE AT EXPERIMENTAL MEASUREMENT LOCATION BL-1.

Fig. A-26. Comparison of calculated and measured pressures in the broken-loop cold leg.

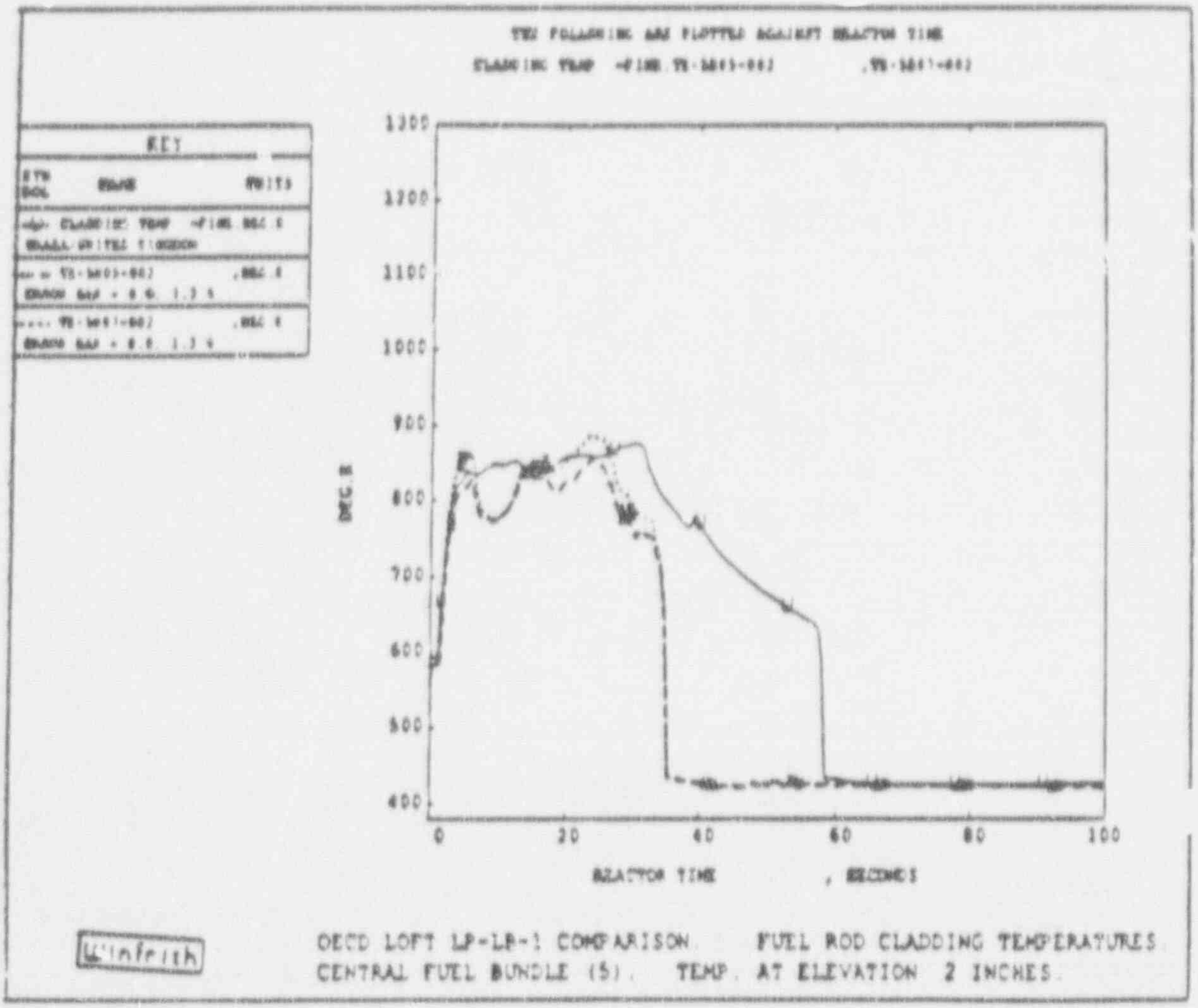


Fig. A-27. Comparison of calculated and measured fuel-rod cladding temperatures in the central fuel bundle at 2.0-in. elevation.

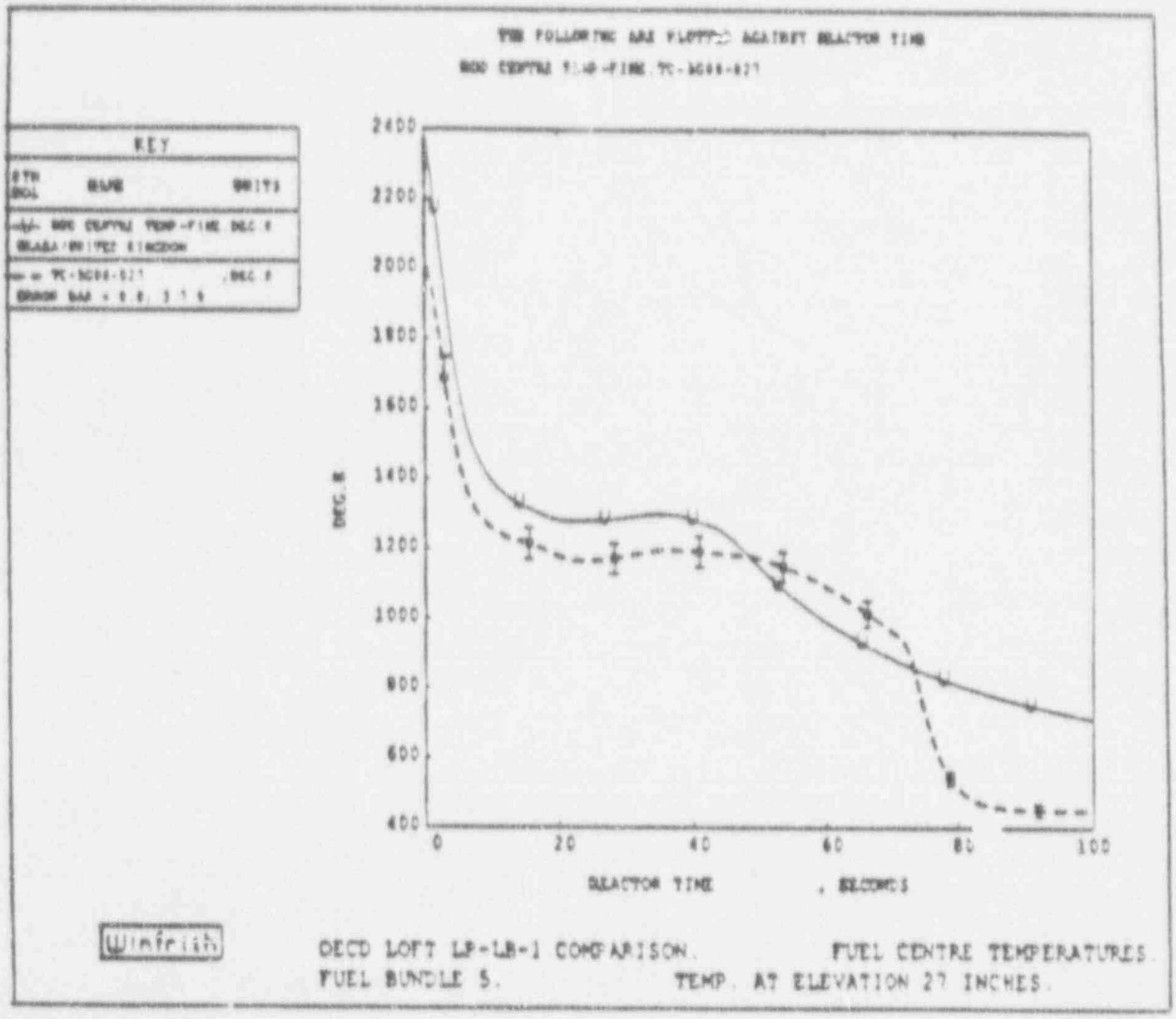


Fig. A-28. Comparison of calculated and measured fuel-rod centerline temperatures for fuel bundle 5 at 27-in. elevation.

REVIEW OF ICAP REPORT NO. AEEW-R 2328

A. BASIC DATA

A1. *Report Information:*

Author: P. Coddington

Report Title: Analysis of the Blowdown of the Accumulator B Line in the OECD-LOFT Fission Product Experiment LP-FP-1.

Report Number: AEEW-R 2328

Author's Nationality and Affiliation: United Kingdom, Reactor Systems Analysis Division, Winfrith AEE.

Report Date: February 1988.

A2. *Reviewer's Name:* Norman M. Schnurr

Date of Review: September 1990

A3. *Which code version was used for the baseline calculation: (Include cycle number or version number and any updates. Section 5.2.2)** [*]

Winfrith Version B03.

A4. *Report Classification (Proprietary, or non-proprietary, any restrictions. Section 4.1)** [*]

Commercial in confidence.

A5. *Is this an integral or separate-effects assessment?*

An integral assessment.

A6. *Summarize why this assessment is being done. (Section 5.2.5 and Table 3)** [*]

This study is not a true assessment although it gives some insight into the ability of the TRAC code to analyze certain types of phenomena. The purpose of the analysis was to examine the mechanism for the unintentional upper-plenum injection during the LOFT LP-FP-1 experiment by modeling the process using the TRAC-PF1/MOD1 code.

A7. *Provide a list of keywords descriptive of this analysis.*

---

[*] Refers to section or table in NUREG-1271, "Guidelines and Procedures for the International Code Assessment and Applications Program," April 1987.

TRAC, LOFT, accumulator.

B. BRIEF QUESTIONS RELATED TO THE COMPLETENESS OF THE REPORT (Include report page number where information was found.)

*B1. Did the author describe each test facility and each test used in the analysis? Elaborate. (Section 5.4.5 and 5.5.4)**

The portion of the LOFT facility being analyzed is described in detail in Tables 1 and 2 and Figs. 1 and 2.

*B2. The author must identify the experimental data used for the assessment in the report. The data channels used for comparison with code results should be easy to identify. It is desirable, but not required, for the author to supply the very data used in the assessment on hardcopy, floppy, or tape as specified in NUREG-1271. Has the author done these things? (Section 5.5.3 and 5.3)**

The data channels are shown in Figs. 1 and 2. The experimental data are shown graphically.

*B3. The author must provide an evaluation of the experimental data uncertainty or clearly reference where it may be found. Has this been done? (Section 5.2.1)**

The data uncertainty is not quantified. Some general comments concerning the uncertainty of the data are given on p.10.

*B4. Was a base-case calculation performed using the unmodified, frozen code? Did the author include a clear, explicit figure of the Model? (Section 5.2.2).**

All calculations used Winfrith version B03. This corresponds to TRAC-PF1/MOD1 Version 13.0.

*B5. The author must supply a copy of the input deck for one of his transient calculations on hardcopy, or floppy, or both. Has he done this? (Section 5.4.6 and 5.5.1)**

The input deck is included on microfiche.

B6. ***Were sensitivity studies performed? Were the sensitivity studies adequately described? Were all identified code deficiencies explicitly described? (Section 5.2.3, 5.2.5, and 5.4.7)****

A series of studies were performed using various masses of a nitrogen bubble to determine its effect on mass-flow rate to the upper plenum.

B7. ***Were nodalization studies performed? Were the nodalization studies adequately described? Elaborate if necessary. (Section 5.2.4)****

No nodalization studies were performed.

B8. ***The report should include run statistics for at least one transient calculation using the unmodified frozen code. Was this done? If a modified version of the code was produced, run statistics for the same transient calculation performed with the final version of the modified code should be included. Was this done? (Section 5.2.5 - para. 4, and Table 4 - p. 25, and Section 5.4.8)****

No run statistics are included.

B9. ***Were complete references included in the report? (Section 5.4.10)****

Nine references are included (p. 21) covering all important aspects of the analysis.

B10. ***Were the objectives satisfied?***

The objectives were satisfied. The results of the calculations largely confirmed the postulated explanation of the inadvertent water injection into the upper plenum.

C. DETAILED QUESTIONS

C1. ***Did the author describe the model nodalization, assumptions, etc.? Were they appropriate? Did the nodalization follow the input deck preparation guidelines found in the TRAC User Guides? Elaborate if necessary. (Section 5.4.6)****

The nodalization used in this assessment is described in detail and conforms to recommendations in the TRAC User's Guide.

C2. ***Briefly describe the thermal-hydraulic phenomena and the reported code predictions addressed in the report. If appropriate, describe the***

phenomena in the context of thermal-hydraulic behavior in the vessel primary loop, secondary loop, and other phenomena of interest.

This study is confined to the behavior of the accumulator B line in the LOFT facility during experiment LP-FP-1, a fission-product experiment. During the experiment, most of the water in the accumulator B line was unintentionally injected into the upper plenum during blowdown. The cause of this injection is attributed to a noncondensable gas (N_2) trapped in the injection line prior to the experiment from an earlier test that had been prematurely aborted. During the time period between the two tests, the injection lines of the accumulators were not vented or flushed with water so that gas left from the first experiment remained until the beginning of the second experiment. This noncondensable gas was then pressurized in the injection line to the system pressure during the pretransient phase of the experiment. As a result, the system blowdown triggered a second blowdown in the injection line through the expansion of the noncondensable gas.

C3. If the author has identified new user guidelines has he described them thoroughly? What are they?

No user guidelines were identified.

C4. What user guidelines can you infer from the results described in the report?

No user guidelines were inferred by the reviewer.

C5. What deficiencies were identified in the unmodified frozen version of the code? (Section 5.2.5 and 5.4.7)*

No code deficiencies were identified.

C6. Describe the impact of each identified code deficiency.

Not applicable.

C7. What code modifications were made? What effect did they have? (Section 5.2.3)*

No code modifications were made.

C8. Run statistics must be provided for the calculation of one transient with the unmodified frozen code and the fully modified code. Compare and evaluate. The run statistics should include a description of the computer and operating system used to perform each calculation, and

a. A plot of CPU vs RT

b. A plot of DT vs RT

c. The value of the "grind time" = [(CPU x 10^3)/(C x DT)]

Where CPU = Total execution time
RT = Transient time
DT = Total number of time steps
C = Total number of volumes in the model

No run statistics were given.

*d. Evaluate the actual time step used. Did the transient run at the Courant time step or did the user specify a smaller maximum time step? Compare the actual time step vs transient time and the user specified maximum time step vs transient time. (Section 5.2.5-para.4, Table 4-p. 25, and Section 5.4.8)**

The time-step size was not discussed.

C9. Does the work documented in this report appear to be good and generally valid or are there fundamental problems with it? (Solicit input of code developers to answer this question.)

This work is very useful and satisfied its intended purpose. It showed that the TRAC code could simulate the flow in an accumulator line with satisfactory accuracy and that TRAC could be used as a diagnostic tool to help explain unusual (and unintended) phenomena during a large-scale experiment.

*C10. What conclusions were drawn in the report? Are they well supported by the results of the analysis? Elaborate. (Section 5.4.7 and 5.4.9)**

The author concluded that a comparison of the results of the calculations with experimental flow measurements show a surprising level of agreement. This almost certainly confirms the assumption that the expansion of a bubble (or bubbles) of trapped nitrogen was the mechanism that produced the unintentional upper-plenum injection in the LP-FP-1 experiment. This conclusion was consistent with the results of the simulations.

C11. Report summary. (This summary will be included in the year-end NUREG report. It should be about 2 to 5 pages long and could include several figures. A short paragraph description of each facility should be included. Also include a paragraph summarizing the baseline results.)

The purpose of this study was to use TRAC to help in determining the cause of an unintended injection of ECC water into the upper plenum during LOFT experiment LP-FP-1. It was not primarily intended to be an assessment of TRAC. Nevertheless, it is of some value to the ICAP program in that it demonstrates another way in which the code may be used.

This study is confined to the behavior of the accumulator B line in the LOFT facility during experiment LP-FP-1, a fission-product experiment. During that experiment, most of the water in the accumulator B line was unintentionally injected into the upper plenum during blowdown. The cause of this injection was attributed to a noncondensable gas (N_2) trapped in the injection line prior to the experiment from an earlier test that had been prematurely aborted. During the time period between the two tests, the injection lines of the accumulators were not vented or flushed with water so that gas left from the first experiment remained until the beginning of the second experiment. This noncondensable gas was then pressurized in the injection line to the system pressure during the pretransient phase of the experiment. As a result, the system blowdown triggered a second blowdown in the injection line through the expansion of the noncondensable gas.

Two series of TRAC simulations were carried out in an effort to better understand the phenomenon and to verify the proposed explanation. The first series of runs used the model of a direct line connecting the accumulator to the upper plenum. Initially a single nitrogen bubble was trapped in this line at the system pressure. A total of 10 simulations were performed for this configuration using 5 different initial bubble sizes and 2 different expressions for the upper-plenum system pressure. The general profile of the initial flow from the accumulator line into the upper plenum was in good agreement with the flow measurements. The range of nitrogen masses used for these calculations was believed to be consistent with the actual mass. One of the runs in this series gave flow rates that approximately coincided with the flow measurements.

A second series of simulations were performed using an accumulator line configuration that included an additional length of pipe that allowed two possible locations for the compressed nitrogen to be trapped. Six runs were made, four using the plenum pressure history thought to be more probable and the other two runs using the other distribution. The calculated flow was found to be similar to results from the first set of calculations. The multiple-bubble calculations confirmed but did not particularly enhance the information obtained from the single-bubble calculations.

In general, it was concluded that the observed and calculated flows exhibited the same general behavior. There was a reasonable comparison of the general shape of the volumetric flow and the peak flow rate between the experiment and calculations. This almost certainly confirms the assumption that the expansion of one or more bubbles of trapped nitrogen was the mechanism that produced the unintentional upper-plenum injection in LOFT experiment LP-FP-1.

A detailed flow-behavior study was also carried out as part of this analysis. A series of graphics were produced (using the SMART program) at various times during the transient that clearly show the void fraction distribution within the pipe by using colored shading. This appears to be a very useful tool visualizing the distribution of fluid and gas within a pipe and clearly shows the location of bubbles and stratification effects.

REVIEW OF ICAP REPORT NO. AEEW-M 2552

A. BASIC DATA

A1. *Report Information:*

Author: R. O'Mahoney

Report Title: A Study of Axial Effects in the TRAC-PF1/MOD1 Heat Conduction Solution During Quenching

Report Number: AEEW-M 2552

Author's Nationality and Affiliation: United Kingdom, Safety and Engineering Science Division, Winfrith Technology Centre

Report Date: June 1989

A2. *Reviewer's Name:* Norman M. Schnurr

Date of Review: July 1990

A3. *Which code version was used for the baseline calculation: (Include cycle number or version number and any updates. Section 5.2.2)** [*]

Winfrith version B03E (LANL Version 13.0).

A4. *Report Classification (Proprietary, or non-proprietary, any restrictions. Section 4.1)** [*]

Not for publication.

A5. *Is this an integral or separate-effects assessment?*

Separate-effects assessment.

A6. *Summarize why this assessment is being done. (Section 5.2.5 and Table 3)** [*]

The purpose of this work was to determine the effects of the choice of TRAC reflood mesh parameters on calculations of quenching. A secondary purpose was to provide some understanding of the observed sensitivity to the DZNHT parameter.

A7. *Provide a list of keywords descriptive of this analysis.*

---

[*] Refers to section or table in NUREG-1271, "Guidelines and Procedures for the International Code Assessment and Applications Program," April 1987.

TRAC, quenching, reflood, blowdown, axial conduction.

B. BRIEF QUESTIONS RELATED TO THE COMPLETENESS OF THE REPORT (include report page number where information was found.)

B1. ***Did the author describe each test facility and each test used in the analysis? Elaborate. (Section 5.4.5 and 5.5.4)****

No experimental data is used in this assessment.

B2. ***The author must identify the experimental data used for the assessment in the report. The data channels used for comparison with code results should be easy to identify. It is desirable, but not required, for the author to supply the very data used in the assessment on hardcopy, floppy, or tape as specified in NUREG-1271. Has the author done these things? (Section 5.5.3 and 5.3)****

No experimental data is used.

B3. ***The author must provide an evaluation of the experimental data uncertainty or clearly reference where it may be found. Has this been done? (Section 5.2.1)****

No experimental data is used.

B4. ***Was a base-case calculation performed using the unmodified, frozen code? Did the author include a clear, explicit figure of the Model? (Section 5.2.2).****

A base-case calculation was performed using a Winfrith version of the code. The model is discussed on p. 2.

B5. ***The author must supply a copy of the input deck for one of his transient calculations on hardcopy, or floppy, or both. Has he done this? (Section 5.4.6 and 5.5.1)****

The input deck is included as Appendix A.

B6. ***Were sensitivity studies performed? Were the sensitivity studies adequately described? Were all identified code deficiencies explicitly described? (Section 5.2.3, 5.2.5, and 5.4.7)****

A series of sensitivity studies were performed to determine the effects of user-specified input parameters such as DTXHT1, DTXHT2, and DZNHT on heat conduction during quenching. The effects of time-step size and elimination of the axial-conduction term from the conduction equation were also studied.

B7. ***Were nodalization studies performed? Were the nodalization studies adequately described? Elaborate if necessary. (Section 5.2.4)****

Mesh-size studies were an important part of this assessment. They are discussed in detail.

B8. ***The report should include run statistics for at least one transient calculation using the unmodified frozen code. Was this done? If a modified version of the code was produced, run statistics for the same transient calculation performed with the final version of the modified code should be included. Was this done? (Section 5.2.5 - para. 4, and Table 4 - p. 25, and Section 5.4.8)****

Total CPU time, typical minimum time-step size, and problem times were given for several runs on pp. 3-4.

B9. ***Were complete references included in the report? (Section 5.4.10)****

Only the TRAC code and documentation are referenced. No other references were necessary for the work discussed in this report.

B10. ***Were the objectives satisfied?***

The objectives were satisfied. The effects of various parameters on heat conduction in fuel rods during reflood were determined and new guidelines for user input were developed.

C. DETAILED QUESTIONS

C1 ***Did the author describe the model nodalization, assumptions, etc.? Were they appropriate? Did the nodalization follow the input deck preparation guidelines found in the TRAC User Guides? Elaborate if necessary. (Section 5.4.6)****

The nodalization used in this assessment is described in detail. It is consistent with the input-deck-preparation guidelines in the TRAC User's guide.

C2. ***Briefly describe the thermal-hydraulic phenomena and the reported code predictions addressed in the report. If appropriate, describe the***

phenomena in the context of thermal-hydraulic behavior in the vessel primary loop, secondary loop, and other phenomena of interest.

The phenomenon studied in this assessment is conduction heat transfer and the temperature distributions in a fuel rod during quenching. A core component containing a single fuel rod of typical PWR construction is used along with a FILL and BREAK component to simulate both blowdown and refill conditions. TRAC simulations are performed for conditions ranging from high temperatures ahead of the quench front combined with a low reflood rate to low temperatures ahead of the quench front combined with a high reflood rate. The effects of user-input parameters on the temperature profile is determined.

C3. ***If the author has identified new user guidelines has he described them thoroughly? What are they?***

The author recommends a value between 0.5 mm and 0.2 mm for the user-input parameter DZNHT. For quenching under blowdown conditions, a value at the lower end of the range is needed in order to reasonably represent the axial effects. A value of 0.5 mm is conservative in terms of quench front progression.

C4. ***What user guidelines can you infer from the results described in the report?***

The user guidelines are explicitly stated by the author.

C5. ***What deficiencies were identified in the unmodified frozen version of the code? (Section 5.2.5 and 5.4.7)****

A fully implicit two-dimensional conduction calculation for the rod would be preferable to the axial-explicit one used in TRAC-PF1/MOD1. The surface heat-transfer smoothing should be done on a per-second basis rather than a per-time-step basis.

C6. ***Describe the impact of each identified code deficiency.***

The effect of the axial-implicit conduction solution is to require unrealistically small time steps if the axial distance between nodes is reduced to very small values. This may make it impossible to accurately simulate reflood heat transfer for many practical cases. The lack of sufficient smoothing can cause instabilities in the radial conduction term.

C7. ***What code modifications were made? What effect did they have? (Section 5.2.3)****

The smoothing technique applied to the surface HTC was disabled. Removing the smoothing produced approximately one-third of the effect of reducing the maximum time step size. This suggests that at least a part of the effect seen in going to a small time step is attributable to heat-transfer smoothing.

Some simulations were also performed with a version of the code in which the axial term in the conduction equation was removed. This caused a 35-45% reduction in quench-front speed for high-temperature/low-flow calculations.

C8. ***Run statistics must be provided for the calculation of one transient with the unmodified frozen code and the fully modified code. Compare and evaluate. The run statistics should include a description of the computer and operating system used to perform each calculation, and***

a. ***A plot of CPU vs RT***

b. ***A plot of DT vs RT***

c. ***The value of the "grind time" = $[(CPU \times 10^3)/(C \times DT)]$***

Where

CPU = Total execution time

RT = Transient time

DT = Total number of time steps

C = Total number of volumes in the model

Total CPU time, typical minimum time-step size, and problem time were given for eight different simulations. Grind times are in the range of 2.18 - 2.82 s.

d. ***Evaluate the actual time step used. Did the transient run at the Courant time step or did the user specify a smaller maximum time step? Compare the actual time step vs transient time and the user specified maximum time step vs transient time. (Section 5.2.5-para.4, Table 4-p. 25, and Section 5.4.8)****

The time-step size was limited by both the Courant condition and the stability criterion for the explicit axial conduction solution. For very small values of DZNHT, the conduction stability condition was the limiting condition.

C9. ***Does the work documented in this report appear to be good and generally valid or are there fundamental problems with it? (Solicit input of code developers to answer this question.)***

This work represents a rather comprehensive analysis of the conduction in rods during reflood. In particular, the effect of the user-input variable DZNHT is investigated and a new user guideline is suggested.

C10. What conclusions were drawn in the report? Are they well supported by the results of the analysis? Elaborate. (Section 5.4.7 and 5.4.9)*

The authors' conclusions were as follows:

- The commonly used value of 5 mm for DZNHT reflood mesh parameter is too large. A value of between 0.5 and 0.2 mm is needed in order to reasonably represent the axial defects present during quenching. For high-pressure blowdown quenching a value at the lower end of the range is needed. However, a high value of DZNHT is conservative so a value of 0.5 mm is probably sufficient for general calculations.
- A significant part of the effect of using a smaller value for DZNHT is due to the reduction in time-step size that occurs, rather than the reduction in axial mesh size.
- Removal of the axial term from the rod conduction equation reduces the quench-front speed. It also removes the apparent mesh-size and time-step-size dependencies.
- Removal of the surface heat-transfer-smoothing algorithm increases the quench-front speed slightly. It also leads to apparent instability in the rod conduction solution.
- Further progress could be assisted by making two modifications in the code: replacing the explicit axial differencing in the conduction equation by an implicit scheme, and changing the surface heat-transfer smoothing to be on a per-second basis instead of a per-time-step basis.

These conclusions are consistent with the results of the simulations.

C11. Report summary. (This summary will be included in the year-end NUREG report. It should be about 2 to 5 pages long and could include several figures. A short paragraph description of each facility should be included. Also include a paragraph summarizing the baseline results.)

The model for which all simulations were performed consisted of a CORE component containing a single rod of typical PWR construction, a FILL component to provide reflood water, and a BREAK component providing a back pressure at the outlet. The CORE component was subdivided into 20 equal hydraulic cells. The calculations are initiated with all but the bottom cell in dryout. The bottom cell is initially quenched. The quench front then advances as the reflood water flows in.

A series of simulations was performed for each of the two extremes likely to be encountered. These were (1) high temperature ahead of the quench front combined with a low reflood rate, and (2) low temperatures ahead of the quench front combined with a high reflood rate. For each series of simulations the parameter DZNHT was varied from 5.0 to 0.1. The results for the low-temperature/high-flow case are shown in Fig. A-29 in the form of cladding temperature histories at successive elevations for four separate values of DZNHT.

There are small differences in the quench time at elevations up to 50 cm. There are also small differences in the apparent quench temperatures. Overall, the changes are not very significant. The results of a similar series of calculations for the high-temperature/low-flow case (Fig. A-30) show a much larger effect of DZNHT. Reducing the value of DZNHT leads to an earlier quench time at each elevation and a higher apparent quench temperature. These results strongly suggest that a choice of 5 mm for DZNHT will produce a rather poor representation of the quench front. The author suggests a value in the range of 0.2 to 0.5 mm.

Additional simulations were performed for the high-temperature/low-flow case to determine the effect of the axial conduction term on the quench-front speed. This was done with a version of the code having the axial term removed from the conduction equation. The quench-front speed was reduced 35-45% when the axial term was removed. The dependence of the solution on time-step size and mesh size disappears almost completely for this case. The absence of the axial conduction term also has a significant effect on the distance over which the temperature rise occurs at the quench front. That distance was about 1.5 mm with no axial conduction term and closer to 2.5 mm with that term included.

Additional calculations are performed using a version of the code that does not use the smoothing/limiting techniques applied to the calculation of the surface-to-coolant HTC. The author concludes that at least a part of the effect seen in going to a small time step is attributable to heat-transfer smoothing. He suggests that the heat-transfer smoothing be done on a per-second rather than a per-time-step basis. It is also recommended that the conduction solution in TRAC be changed to a fully-implicit formulation.

Run-time data is presented for eight simulations. Grind times are in the range of 2.18 - 2.82 s based on the typical minimum time step.

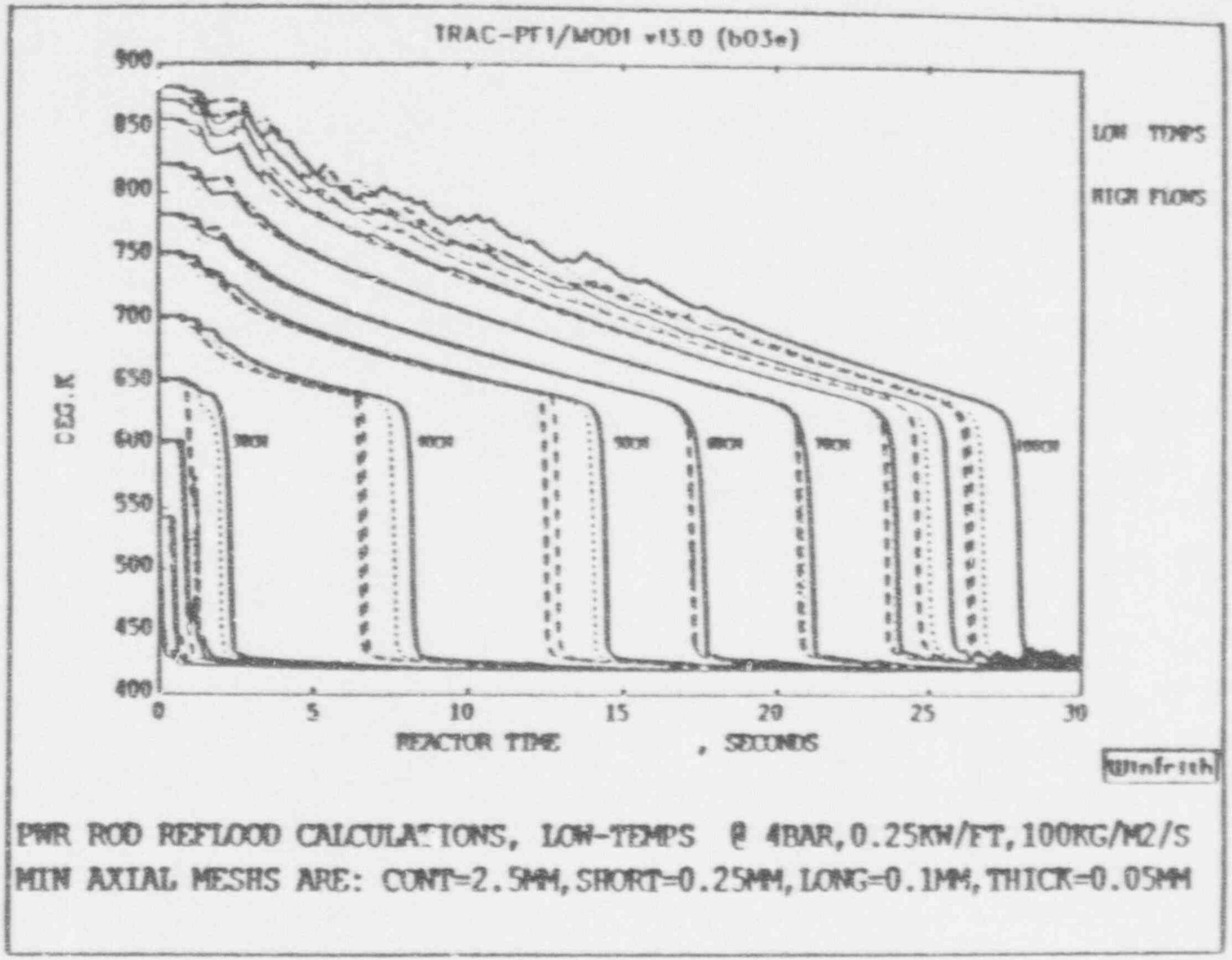


Fig. A-29. Temperature profiles for the low-temperature/ high-flow case.

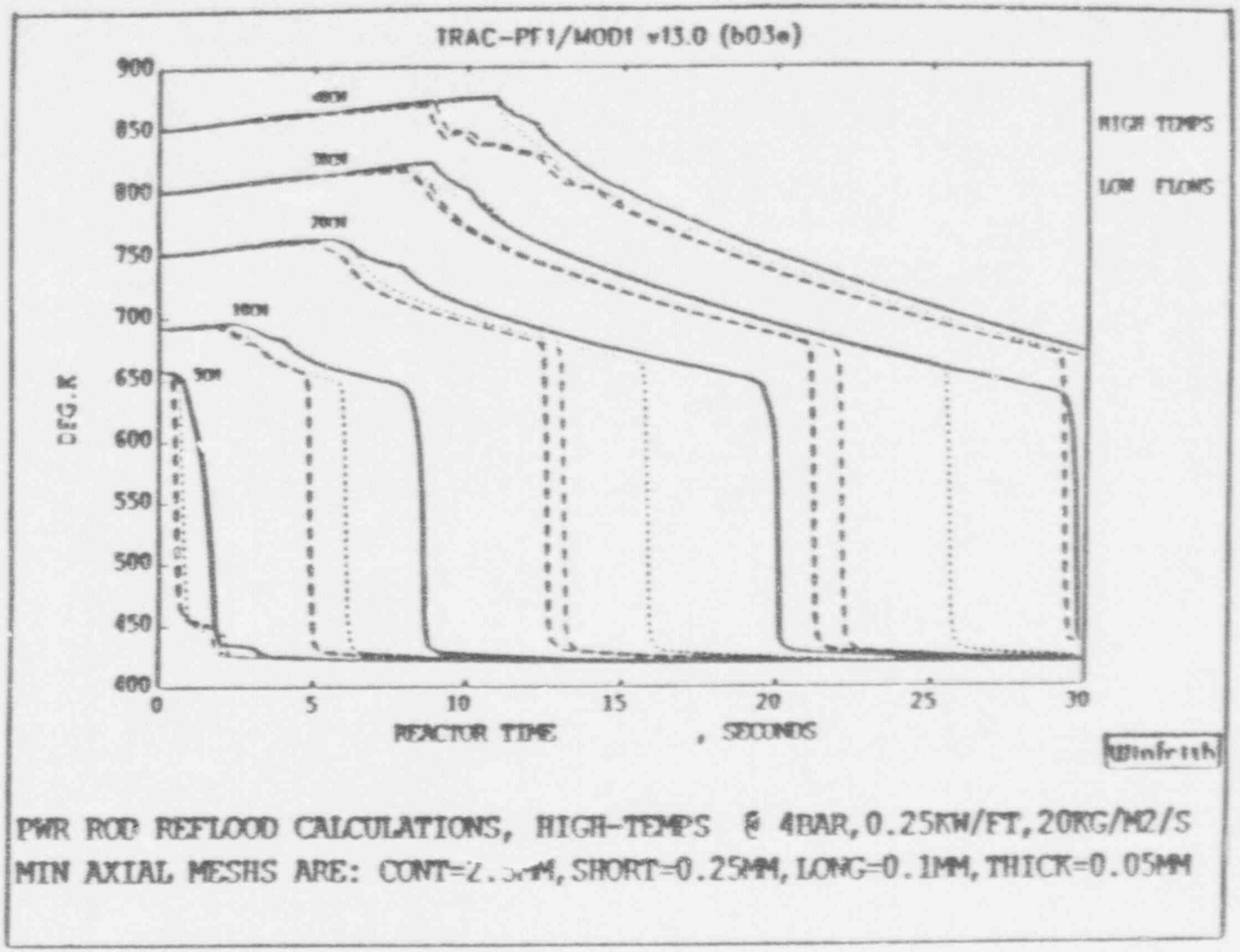


Fig. A-30. Temperature profiles for the high-temperature/ low-flow case.

REVIEW OF ICAP REPORT NO. STUDSVIK/NP-88/101 (S)

A. BASIC DATA

A1. ***Report Information:***

Author: Anders Sjoberg

Report Title: Assessment of TRAC-PF1/MOD1 Against an Inadvertent Feedwater Line Isolation Transient in the Ringhals 4 Power Plant

Report Number: STUDSVIK/NP-88/101 (S)

Author's Nationality and Affiliation: Sweden, Studsvik Nuclear

Report Date: November 1988

A2. *Reviewer's Name:* Norman M. Schnurr

Date of Review: August 1990

A3. ***Which code version was used for the baseline calculation: (Include cycle number or version number and any updates. Section 5.2.2)****

TRAC-PF1/MOD1, Version 14.0.

A4. ***Report Classification (Proprietary, or non-proprietary, any restrictions. Section 4.1)****

No restrictions.

A5. ***Is this an integral or separate-effects assessment?***

Integral assessment.

A6. ***Summarize why this assessment is being done. (Section 5.2.5 and Table 3)****

The purpose of this work was to assess the capability of TRAC to predict conditions in a full-scale PWR during a transient caused by a steam-generator-feedwater-line isolation.

A7. ***Provide a list of keywords descriptive of this analysis.***

TRAC, reactor transient, feedwater-line isolation, Ringhals 4 Power Plant.

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* Refers to section or table in NUREG-1271, "Guidelines and Procedures for the International Code Assessment and Applications Program," April 1987.

B. BRIEF QUESTIONS RELATED TO THE COMPLETENESS OF THE REPORT (Include report page number where information was found.)

B1. *Did the author describe each test facility and each test used in the analysis? Elaborate. (Section 5.4.5 and 5.5.4)**

The Ringhals 4 power plant was described in some detail on pp. 5 and 6.

B2. *The author must identify the experimental data used for the assessment in the report. The data channels used for comparison with code results should be easy to identify. It is desirable, but not required, for the author to supply the very data used in the assessment on hardcopy, floppy, or tape as specified in NUREG-1271. Has the author done these things? (Section 5.5.3 and 5.3)**

The data collected by the Ringhals 4 data acquisition system during the transient included steam flow, main-feedwater flow, narrow-range steam-generator level, wide-range steam-generator level, auxiliary-feedwater flow, local pressures and temperatures, and a time sequence of trips, control signals, and pertinent time plots. These data are given in the report in graphical form. They are also stored on the plant computer.

B3. *The author must provide an evaluation of the experimental data uncertainty or clearly reference where it may be found. Has this been done? (Section 5.2.1)**

The uncertainty of the experimental data is not discussed..

B4. *Was a base-case calculation performed using the unmodified, frozen code? Did the author include a clear, explicit figure of the Model? (Section 5.2.2).**

A base-case calculation was performed using the unmodified, frozen code. The model is discussed in detail (pp. 8-12, Figs. 1, 2, 3, 22).

B5. *The author must supply a copy of the input deck for one of his transient calculations on hardcopy, or floppy, or both. Has he done this? (Section 5.4.6 and 5.5.1)**

The input deck was not included in the report.

B6. *Were sensitivity studies performed? Were the sensitivity studies adequately described? Were all identified code deficiencies explicitly described? (Section 5.2.3, 5.2.5, and 5.4.7)**

Sensitivity studies were carried out to determine the effect of fuel-gap conductance on initial stored energy in the fuel and temperatures in the primary circuit. The effect of the moderator temperature reactivity coefficient on core power was also investigated. Finally an investigation was made of the importance of including pressure compensation to the steam flow when calculated as a function of dome outlet pressure drop. These studies are adequately described on pp. 21-23. No specific code deficiencies were identified.

B7. Were nodalization studies performed? Were the nodalization studies adequately described? Elaborate if necessary. (Section 5.2.4)*

Two nodalization studies were performed. The two areas of the model in which the effects of nodalization were studied were the steam-line downstream generator and the steam-generator downcomer. These studies were described on pp. 21-23.

B8. The report should include run statistics for at least one transient calculation using the unmodified frozen code. Was this done? If a modified version of the code was produced, run statistics for the same transient calculation performed with the final version of the modified code should be included. Was this done? (Section 5.2.5 - para. 4, and Table 4 - p. 25, and Section 5.4.8)*

Complete run statistics are given for the base-case simulation (p. 2) and for a steady-state simulation. The code modifications made in this study would not be expected to have a significant effect on run times.

B9. Were complete references included in the report? (Section 5.4.10)*

A total of 5 references (p. 27) are included. These are sufficient for this assessment.

B10. Were the objectives satisfied?

The objectives were satisfied. The code was found to simulate the steam-line-isolation transient with acceptable accuracy. The effects of various input parameters and noding changes were determined.

C. DETAILED QUESTIONS

C1. Did the author describe the model nodalization, assumptions, etc.? Were they appropriate? Did the nodalization follow the input deck preparation guidelines found in the TRAC User Guides? Elaborate if necessary. (Section 5.4.6)*

The nodalization used in this assessment is described in detail. It is consistent with the input-deck preparation guidelines in the TRAC User's guide. The boundary conditions used for the simulations are also discussed in detail.

C2. ***Briefly describe the thermal-hydraulic phenomena and the reported code predictions addressed in the report. If appropriate, describe the phenomena in the context of thermal-hydraulic behavior in the vessel primary loop, secondary loop, and other phenomena of interest.***

The phenomenon studied in this assessment was an isolation of the steam-generator feedwater line. Following the closure of the feedwater valves, the steam flow through the feedwater-preheater train ceased, with a corresponding increase of flow through the turbine. This was automatically compensated for by the throttling of the turbine valves. The impulse-chamber pressure of the turbine was, as a consequence, decreased by about 10%. This was felt by the control logic of the turbines as a corresponding load rejection, resulting in deblocking of 25% steam-dumping capacity.

Because of the loss of main-feedwater flow the average temperature of the primary coolant increased while the reference temperature was decreased due to reduced impulse-chamber pressure. This deviation resulted in a dump demand signal, and about 14 s after the feedwater isolation, steam dumping from the turbines was initiated. The continued steam flow resulted in depletion of steam-generator-liquid inventory, and reactor scram was obtained on low downcomer-level signal. Isolation of the turbines was activated and auxiliary-feedwater supply was initiated. The level then slowly increased and finally reached the normal value.

C3. ***If the author has identified new user guidelines has he described them thoroughly? What are they?***

No new user guidelines were explicitly stated.

C4. ***What user guidelines can you infer from the results described in the report?***

A thorough nodalization of the steam-generator downcomer is essential because of the sensitivity of system response to downcomer conditions. Decreasing the maximum time-step size may be necessary to maintain stability for some transients.

C5. ***What deficiencies were identified in the unmodified frozen version of the code? (Section 5.2.5 and 5.4.7)***

The author suggests that the failure of TRAC to properly account for elevation head and density differences when calculating pressure drop at the steam-generator-dome outlet may cause significant error at very low flow rates.

C6. Describe the impact of each identified code deficiency.

The effect of omitting the terms discussed in C5 is an error in the pressure drop at the steam-generator secondary-side outlet and a resulting error in the steam flow rate.

C7. What code modifications were made? What effect did they have? (Section 5.2.3)*

The code was modified to include elevation head and the absolute pressure influence through the density in the calculation of pressure drop at the steam-generator-dome outlet. This modification produced steam flow rates in better agreement with experimental data. The only other code modifications were an update to provide proper functioning of the restart capability of the core component and the creation of additional output for plotting with a separate program. These changes had no effect on the results of the simulations.

C8. Run statistics must be provided for the calculation of one transient with the unmodified frozen code and the fully modified code. Compare and evaluate. The run statistics should include a description of the computer and operating system used to perform each calculation, and

- ***a. A plot of CPU vs RT***
- ***b. A plot of DT vs RT***
- ***c. The value of the "grind time" = [(CPU x 10^3)/(C x DT)]***

Where CPU = Total execution time
RT = Transient time
DT = Total number of time steps
C = Total number of volumes in the model

The 310-s base-case simulation used 1066 time steps with a maximum allowable time-step size of 0.5 s. This computation required 4784 s of CPU time on a CDC Cyber 180-835 computer. The model contained 37 components and 144 nodes. The grind time for this calculation was 31.1 s. The steady-state calculation was run for 180 s and required 985 s of CPU time. The grind time for that calculation was 34 s. There were no code modifications that affected run time.

d. ***Evaluate the actual time step used. Did the transient run at the Courant time step or did the user specify a smaller maximum time step? Compare the actual time step vs transient time and the user specified maximum time step vs transient time. (Section 5.2.5-para.4, Table 4-p. 25, and Section 5.4.8)****

The maximum time-step size had to be limited to 0.5 s to ensure convergence during the entire transient.

C9. ***Does the work documented in this report appear to be good and generally valid or are there fundamental problems with it? (Solicit input of code developers to answer this question.)***

The work discussed in this report assesses the ability of TRAC to simulate a specific type of transient. The simulations were accurately and carefully performed. Several nodalization and sensitivity studies were performed to determine the effects of various input parameters and node spacing in key components.

C10. ***What conclusions were drawn in the report? Are they well supported by the results of the analysis? Elaborate. (Section 5.4.7 and 5.4.9)****

The authors' conclusions were as follows:

- The TRAC code was capable of a satisfactory simulation of a feedwater-line isolation transient in a full-scale PWR.
- The steam flow, taken as proportional to the square root of a pressure drop, revealed for the base case a discrepancy when compared to measurement. The basic reason for the discrepancy was found to be the omission of pressure compensation in the flow algorithm.
- Initial calculations showed an oscillation in the narrow-range level signal which did not occur in the measured data. A denser nodalization of the upper part of the downcomer in the steam generator helped to alleviate this problem.
- The primary temperature in the base-case model was lower than the measured data. This temperature could be raised by reducing the gap conductance of the fuel. A value of 5.0 kW/m^2K gave reasonable agreement with the experimental data.
- External restriction on the maximum allowable time step had to be imposed for convergence of the solution procedure.

These conclusions are generally consistent with the results of the simulations. The second conclusion is somewhat questionable, however. The graphical results comparing the effect of including the additional terms is, in the opinion of the reviewer, inconclusive when the accuracy of the data is taken into account. There is also the question of the effect other pressure differences, such as irreversible form losses, may have.

C11. Report summary. ***(This summary will be included in the year-end NUREG report. It should be about 2 to 5 pages long and could include several figures. A short paragraph description of each facility should be included. Also include a paragraph summarizing the baseline results.)***

A TRAC-PF1/MOD1 simulation has been conducted to assess the capability of the code to predict feedwater-line isolation. The measured data were obtained from an inadvertent feedwater-line isolation at full-power operation in the Ringhals 4 power plant. Ringhals 4 is a 915-MWe Westinghouse PWR with three loops and two turbines. It is [illegible] with three Westinghouse steam generators with a feedwater preheater section [illegible] cold-leg side of the U-tube bundle and a division is made of the feedwater flow [illegible] lower feedwater inlet and the top inlet at the upper part of the downcomer. [illegible] etransient stationary phase the total feedwater was apportioned so that about [illegible] low was delivered to the top inlet and the rest to the preheater. The circulation [illegible] condition was about 2.43.

The transient was initiated by a failure in an electronic logical circuit, causing the feedwater-line-isolation valves to close in all three loops. Following the closure of the feedwater valves, the steam flow through the feedwater-preheater train ceased, with a corresponding increase of flow through the turbine. This was automatically compensated for by the throttling of the turbine valves. The impulse-chamber pressure of the turbine was, as a consequence, decreased by about 10%. This was felt by the control logic of the turbines as a corresponding load rejection, resulting in deblocking of 25% steam-dumping capacity.

Because of the loss of main-feedwater flow the average temperature of the primary coolant increased while the reference temperature was decreased due to reduced impulse-chamber pressure. This deviation resulted in a dump demand signal, and about 14 s after the feedwater isolation, steam dumping from the turbines was initiated. The continued steam flow resulted in depletion of steam generator liquid inventory and reactor scram was obtained on low downcomer-level signal. Isolation of the turbines was activated and auxiliary-feedwater supply was initiated. The level then slowly increased and finally reached the normal value.

In the TRAC simulation, only a single-loop representation was used and the core was modeled by the TRAC neutron point kinetics specified with middle-of-cycle conditions. The complete model comprised 37 components made up of 144 nodes. The boundary conditions were either taken directly from the recordings of the plant computer or were inferred from those data.

Prior to the transient simulations, a steady-state analysis was run and conditions were adjusted to replicate the actual pretransient conditions. A heat balance calculation of the plant during the stationary phase provided information of recirculation pump power and primary-coolant mass flow which were not known from measurements. The model steady-state conditions were saved for later use as initial conditions for transient simulations.

The base-case transient was simulated for 300 s, including 10 s of pretransient steady-state condition. At 10 s the feedwater isolation started with feedwater flow being ramped down to 0 in 2.5 s. The measured and calculated steam flow at the outlet of the steam generator are shown in Fig. A-31. The curve "Direct" indicates the total flow as represented by a TRAC signal variable. This was in full agreement with the imposed boundary conditions downstream of the turbine valves. The flow taken as differential pressure between the steam-generator dome and the steam line did not agree well with the direct flow when the flow was reduced and the pressure increased. The reason for this discrepancy was the omission of pressure dependence in the flow algorithm. When this compensation was introduced a favorable comparison with measured steam flow was obtained.

As the steam generator level was decreasing there was an oscillation in the narrow-range level signal predicted by the calculations that was not measured during the actual transient. A denser nodalization of the upper part of the downcomer helped to alleviate this problem. The primary temperature in the base case model was too low compared to measurements. An increase of the initial stored energy of the fuel would have raised the coolant temperature. An increase of stored energy was obtained by decreasing the gap conductance of the fuel. A sensitivity analysis showed that a gap conductance of 5.0 kW/m^2·K (half the base case value) resulted in reasonable response of the reactor system when compared to measurements.

External restriction of the maximum allowable time step of 0.5 s had to be imposed on the solution procedure. For a 310 s transient 4748 CPU s was needed on a CDC Cyber 170-835 computer. The grind time was 31.1 s.

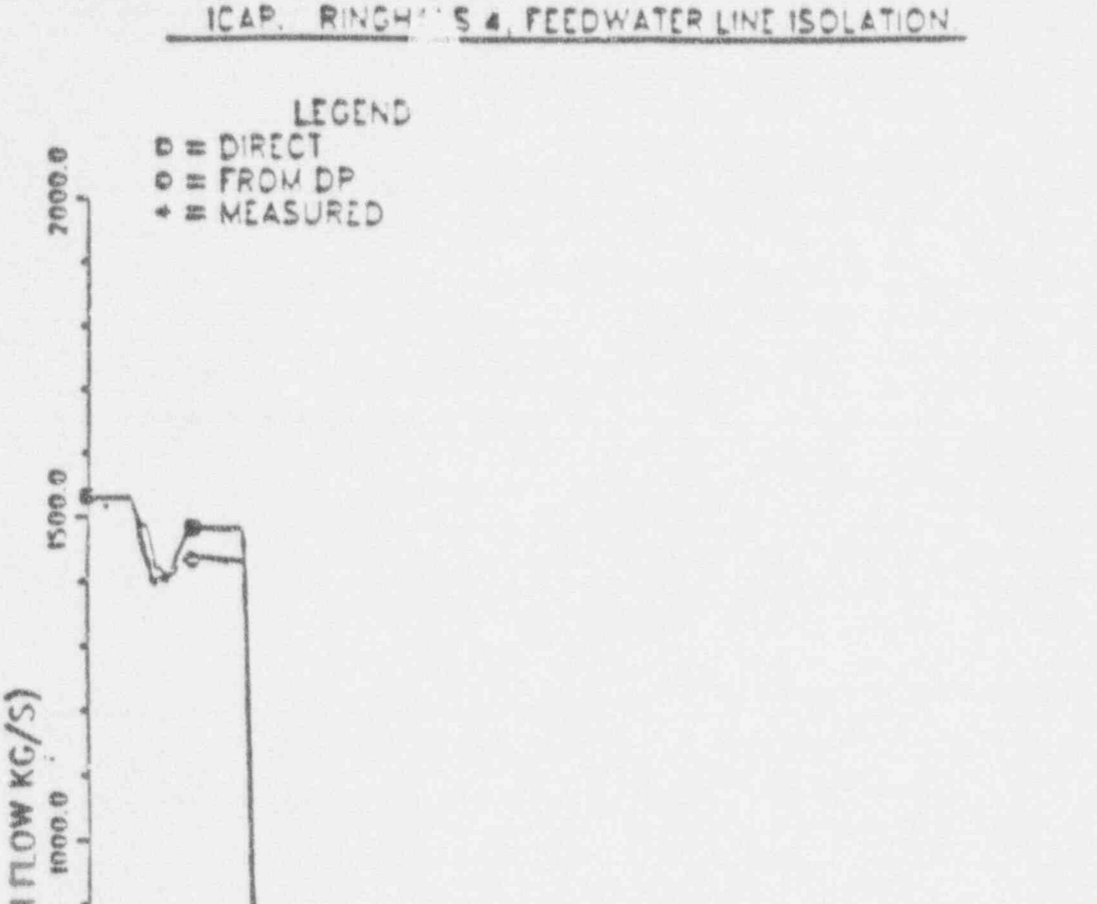

Fig. A-31. Steam flow at the steam-generator outlet nozzle.

REVIEW OF ICAP REPORT NO. ICSP-R2MSIV-T

A. BASIC DATA

A1. ***Report Information:***

Author: F. Pelayo and A. Sjoberg

Report Title: Assessment of TRAC-PF1/MOD1 Against an Inadvertent Steam Line Isolation Valve Closure in the Ringhals 2 Power Plant

Report Number: ICSP-R2MSIV-T

Author's Nationality and Affiliation: Spain, Consejo de Seguridad Nuclear and Sweden, Studsvik Energiteknik A. B.

Report Date: February 1988.

A2. ***Reviewer's Name:*** Norman M. Schnurr

Date of Review: September 1990

A3. ***Which code version was used for the baseline calculation: (Include cycle number or version number and any updates. Section 5.2.2)[*]***

TRAC-PF1/MOD1 Version 14.0 updated to provide proper restart capability of the CORE component.

A4. ***Report Classification (Proprietary, or non-proprietary, any restrictions. Section 4.1)[*]***

Unlimited.

A5. ***Is this an integral or separate-effects assessment?***

An integral assessment.

A6. ***Summarize why this assessment is being done. (Section 5.2.5 and Table 3)[*]***

This simulation was performed to assess the capability of TRAC-PF1/MOD1 to predict a steam-line isolation-valve-closure transient.

A7. ***Provide a list of keywords descriptive of this analysis.***

TRAC, PWR simulation, TRAC, steam-line isolation valve.

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[*] Refers to section or table in NUREG-1271, "Guidelines and Procedures for the International Code Assessment and Applications Program," April 1987.

B. BRIEF QUESTIONS RELATED TO THE COMPLETENESS OF THE REPORT (Include report page number where information was found.)

B1. ***Did the author describe each test facility and each test used in the analysis? Elaborate. (Section 5.4.5 and 5.5.4)****

The Ringhals 2 power plant is described in detail on pp. 5 and 6.

B2. ***The author must identify the experimental data used for the assessment in the report. The data channels used for comparison with code results should be easy to identify. It is desirable, but not required, for the author to supply the very data used in the assessment on hardcopy, floppy, or tape as specified in NUREG-1271. Has the author done these things? (Section 5.5.3 and 5.3)****

The experimental data are taken from plant signals that were monitored and stored on the plant computer. The data are presented only in graphical form in Figs. 4, 7-14, 18, 19, and 21. These data include main-feedwater flow rate, steam-line pressure and flow rate, steam-generator level, core power, pressurizer level and pressure, and safety-injection flow.

B3. ***The author must provide an evaluation of the experimental data uncertainty or clearly reference where it may be found. Has this been done? (Section 5.2.1)****

The uncertainty of the experimental data is not discussed quantitatively. Some qualitative statements are made concerning uncertainties in the deduced sequence of events (p. 6) and in measured flows (p.13).

B4. ***Was a base-case calculation performed using the unmodified, frozen code? Did the author include a clear, explicit figure of the Model? (Section 5.2.2).****

A base-case calculation was performed using TRAC-PF1/MOD2. The code was modified only to provide proper functioning of the restart capability of the core component and to add printout for graphics. These modifications had no effect on the results of the TRAC simulation.

B5. ***The author must supply a copy of the input deck for one of his transient calculations on hardcopy, or floppy, or both. Has he done this? (Section 5.4.6 and 5.5.1)****

A copy of the input deck has not been provided.

B6. ***Were sensitivity studies performed? Were the sensitivity studies adequately described? Were all identified code deficiencies explicitly described? (Section 5.2.3, 5.2.5, and 5.4.7)****

Both single- and double-loop representations of the system were simulated. An additional simulation was also performed to determine the effect of gap conductance.

B7. ***Were nodalization studies performed? Were the nodalization studies adequately described? Elaborate if necessary. (Section 5.2.4)****

No nodalization studies were performed.

B8. ***The report should include run statistics for at least one transient calculation using the unmodified frozen code. Was this done? If a modified version of the code was produced, run statistics for the same transient calculation performed with the final version of the modified code should be included. Was this done? (Section 5.2.5 - para. 4, and Table 4 - p. 25, and Section 5.4.8)****

Run statistics are given on p. 22.

B9. ***Were complete references included in the report? (Section 5.4.10)****

Yes. A total of 7 references are included.

B10. ***Were the objectives satisfied?***

The stated objective was to assess the capability of TRAC-PF1/MOD1 to predict a steam-line isolation-valve closure transient. This objective was satisfied. The accuracy of the calculation was assessed, some user guidelines were inferred, and some suggestions for code improvement were made.

C. DETAILED QUESTIONS

C1. ***Did the author describe the model nodalization, assumptions, etc.? Were they appropriate? Did the nodalization follow the input deck preparation guidelines found in the TRAC User Guides? Elaborate if necessary. (Section 5.4.6)****

The nodalization used in this assessment is described in detail. Figure 1 is a nodalization diagram of the entire system. The authors specifically state that the pressurizer and all pressurizer valves were modeled according to recommendations in the TRAC User's Guide. The VESSEL was modeled using 1D components, but that should be adequate for the relatively mild transient being considered here. The omission of most of the structural materials in the secondary side of the steam generator may have caused an overestimation of the transient pressure decrease in the steam line. In general, however, the nodalization follows guidelines presented in the TRAC User's Guide.

C2. ***Briefly describe the thermal-hydraulic phenomena and the reported code predictions addressed in the report. If appropriate, describe the phenomena in the context of thermal-hydraulic behavior in the vessel primary loop, secondary loop, and other phenomena of interest.***

Ringhals 2 is a three-loop, two-turbine PWR having nominal thermal power of 2400 MW and a net electrical output of 800 MW. An assessment was performed to determine the ability of TRAC-PF1/MOD1 to simulate a transient caused by an inadvertent steam-line isolation-valve closure in the Ringhals 2 power plant. The transient was initiated by an interruption of power to the electrical coil in the pilot valve in the steam-line isolation valve of loop 3. The isolation valve closed and and the steady flow decreased by 1/3 quite rapidly. This caused a rapid pressure decrease in the other two steam lines and a corresponding steam flow increase. The steam flow in loops 1 and 2 increased to the trip set point, resulting in a closure signal for the steam-line isolation valves in the two intact loops, activation of safety injection, isolation of main feedwater, scram-signal generation, and termination of letdown and charging flows. The auxiliary-feedwater flow was automatically activated. Because of the isolation of the steam generators, the circulation flow on the secondary side ceased and a stagnant condition occurred. The steam-generators downcomer level quickly decreased. The core decay heat and the stored energy in the structures on the primary side caused the secondary-side pressure to slowly increase.

The main phenomena of interest in the simulation were pressure levels, water levels, and flow rates in the reactor and steam generators. Heat transfer to structural components was found to be important for the correct calculation of pressures and flow rates.

C3. ***If the author has identified new user guidelines has he described them thoroughly? What are they?***

No new user guidelines were explicitly stated.

C4. ***What user guidelines can you infer from the results described in the report?***

Proper modeling of steam-generator internals and pressurizer walls are important for accurate prediction of condensation phenomena. Time steps may have to be limited to values below that allowed by the code when the model contains controls with relatively small time constants if severe oscillations are to be avoided.

C5. ***What deficiencies were identified in the unmodified frozen version of the code? (Section 5.2.5 and 5.4.7)****

It would be desirable to implement an internal limitation on the time step as a function of the performance of control systems. Another possible approach is to allow for some degree of implicitness by closing the thermal-hydraulic and control loops during the convergence calculations.

C6. ***Describe the impact of each identified code deficiency.***

The lack of time-step limitations related to control systems causes numerical oscillations unless a user-specified maximum time step is input. This user-input value would be applicable for the entire transient, and might greatly increase the cost of the calculation.

C7. ***What code modifications were made? What effect did they have? (Section 5.2.3)****

The code was modified to provide proper functioning of the restart capability of the core component and to print signal-variable and control-block output for plotting with a separate program. Neither of these modifications caused any change in the results computed by TRAC.

C8. ***Run statistics must be provided for the calculation of one transient with the unmodified frozen code and the fully modified code. Compare and evaluate. The run statistics should include a description of the computer and operating system used to perform each calculation, and***

a. A plot of CPU vs RT

b. A plot of DT vs RT

c. The value of the "grind time" = $[(CPU \times 10^3)/(C \times DT)]$

Where CPU = Total execution time

RT = Transient time

DT = Total number of time steps

C = Total number of volumes in the model

The calculations were performed on a CDC Cyber 170-835 computer. The 300-s simulation required 465 time steps and a total CPU time of 5379 s. The model had 96 components with 295 cells. The grind time was 39.2 s.

d. ***Evaluate the actual time step used. Did the transient run at the Courant time step or did the user specify a smaller maximum time step? Compare the actual time step vs transient time and the user specified maximum time step vs transient time. (Section 5.2.5-para.4, Table 4-p. 25, and Section 5.4.8)***[*]

During the 300-s transient no limitation of the time step was imposed from the input and TRAC was allowed to use as big a time step as the solution method permitted. The size of the time step ranged from 0.01 to 3.8 s. Some unstable behavior was observed with controls having short time constants.

C9. ***Does the work documented in this report appear to be good and generally valid or are there fundamental problems with it? (Solicit input of code developers to answer this question.)***

This work represents a valid simulation of a relatively slow transient caused by an inadvertent steam-line isolation-valve closure. The results give some indication of the accuracy of the TRAC code for this type of calculation and the authors were able to provide some useful guidelines related to model selection and time-step selection. There are some questions concerning the comparison of calculated results and plant data. There were inaccuracies in measured flow rates that caused the measured feedwater flows to be out of balance. The plant signal follower, which records the time sequence of trips and control signals, was not functioning properly during the transient and the sequence of events could not be definitely established.

C10. ***What conclusions were drawn in the report? Are they well supported by the results of the analysis? Elaborate. (Section 5.4.7 and 5.4.9)***[*]

The authors' conclusions were as follows:

- Discrepancies between calculated and measured results were found in pressurizer liquid levels and pressures, thermal stratification of pressurizer liquid during the insurge period, and the steam-generator liquid level calculated from a pressure difference algorithm. These discrepancies were explained in terms of overestimated primary-to-secondary heat transfer, the use of a slightly overestimated HPIS flow, TRAC's inability to reproduce thermal-mixing phenomena, the omission of major heat structures from the model, and an oversimplified Δp algorithm ignoring the vapor.
- The code's robustness was limited by the control system performance. The use of large time steps caused unstable operation of several control blocks, particularly those with short time constants.

- For this fairly mild transient, no problem with the thermal-hydraulic calculations was encountered. The control system performance was the main source of difficulty.

These conclusions are consistent with the results of the simulations.

C11. ***Report summary. (This summary will be included in the year-end NUREG report. It should be about 2 to 5 pages long and could include several figures. A short paragraph description of each facility should be included. Also include a paragraph summarizing the baseline results.)***

The Ringhals 2 power plant is a three-loop, two-turbine PWR of Westinghouse Stal-Laval design with ASEA electrical generators. The nominal thermal power is 2440 MW and the electrical net output is 800 MW. The plant is equipped with three Westinghouse steam generators of the vertical U-tube design. Because of problems with U-tubes in the steam generators, the core power has been reduced to about 80% of normal.

A transient in the system operation was initiated by an interruption of power to the electrical coil in the magnetic pilot valve of the steam-line isolation valve in loop 3. The isolation valve closed and the steam flow decreased by 1/3 quite rapidly. This caused a rapid pressure decrease in the other two steam lines and a corresponding steam flow increase. The steam flow in loops 1 and 2 increased to the trip set point resulting in a closure signal for the steam-line isolation valves in the two intact loops, activation of safety injection, isolation of main feedwater, scram-signal generation, and termination of letdown and charging flows. The auxiliary-feedwater flow was automatically activated. Because of the isolation of the steam generators, the circulation flow on the secondary side ceased and a stagnant condition occurred. The steam-generators downcomer level quickly decreased. The core decay heat and the stored energy in the structures on the primary side caused the secondary-side pressure to slowly increase. Throughout the transient, important plant signals were monitored and stored on the plant computer. Unfortunately, the plant signal follower, which records the time sequence of trips and control signals, was not functioning properly and thus no true sequence of events could be established. The sequence of events was inferred from the time plots of relevant signals.

The simulation of the transient was made with TRAC-PF1/MOD1, Version 14.0. A two-loop representation of the plant was used. A 1D representation of the vessel made up of of seven components was used. A lumped-parameter model and adiabatic walls represented the vessel and its externals. The axial-heat-flux shape and hot-rod peaking factors were derived from in-core measurements. The pressurizer was modeled by a TEE containing six cells, and the bottom of the pressurizer was a PIPE component divided into four cells. The pressurizer walls were simulated by heat structures with four radial nodes. All the pressurizer valves were sized to their rated capacities under choked-flow conditions. The steam generators were modeled in detail. Each steam generator comprised a number of components where the STGEN component included the primary side of the U-tube bundle and the secondary-side riser and separator parts. The downcomer was nodalized so as to permit adequate tracing of the water level as well as correct placement of level pressure taps. The steam flow was measured by means of a differential pressure between the steam-dome pressure tap in the relief and safety-valve header. Control-system and trip-logic modeling was extensive. Boundary conditions for the simulations were either taken directly from the recordings of the plant computer or were inferred from them.

Prior to the transient simulation the TRAC model was adjusted to replicate the plant stationary pretest conditions. The measured steam flows and corresponding feedwater flows were found not to balance during the pretransient phase, indicating that some of the flows were miscalibrated. A heat balance for the steam generator revealed that the steam flows were erroneously recorded. Therefore, the steam flows were assumed to match the feedwater flows.

The transient simulations were made using both a single- and double-loop representation. Measured thermal-hydraulic data were obtained for each loop and an averaging procedure was used to provide data for the double loop. The main heat source during the transient was the core power and decay heat. The default kinetic parameters were used. The speed of the reactor-coolant pumps was assumed constant throughout the transient. The feedwater flow was specified using a trip-controlled FILL component with tabulated data as a function of time taken from recorded data.

The single-loop steam-generator pressure, level, and flow behavior were well reproduced in the calculation (Fig. A-32). The calculated transient pressure decrease in the double-loop steam line prior to the reactor and turbine trip was slightly overestimated (Fig. A-33). This was believed to be caused by the omission of most of the structural materials in the secondary side of the steam-generator model. Following the reactor trip, the average temperature on the primary side decreased more rapidly than the measured data indicated. This may be due to overestimating primary-to-secondary heat transfer and underestimating the stored energy in the fuel. The calculations were rerun with a modified gap conductance which produced more stored energy in the fuel during steady state and better results were obtained.

For this fairly mild transient, no problems with the thermal-hydraulic calculations were encountered. Instead, the control system performance was a source of difficulty. No time-step control was imposed in the input deck, and TRAC was allowed to use as big a time step as the solution method permitted. This resulted in some unstable behavior for some of the controls having relatively small time constants. The authors suggest the implementation in TRAC of internal limitations on the time step as a function of the performance of the control systems.

The calculations were performed on a CDC Cyber 170-835 computer. The 300-s simulation required 465 time steps and a total CPU time of 5379 s. The model had 96 components with 295 cells. The grind time was 39.2 s.

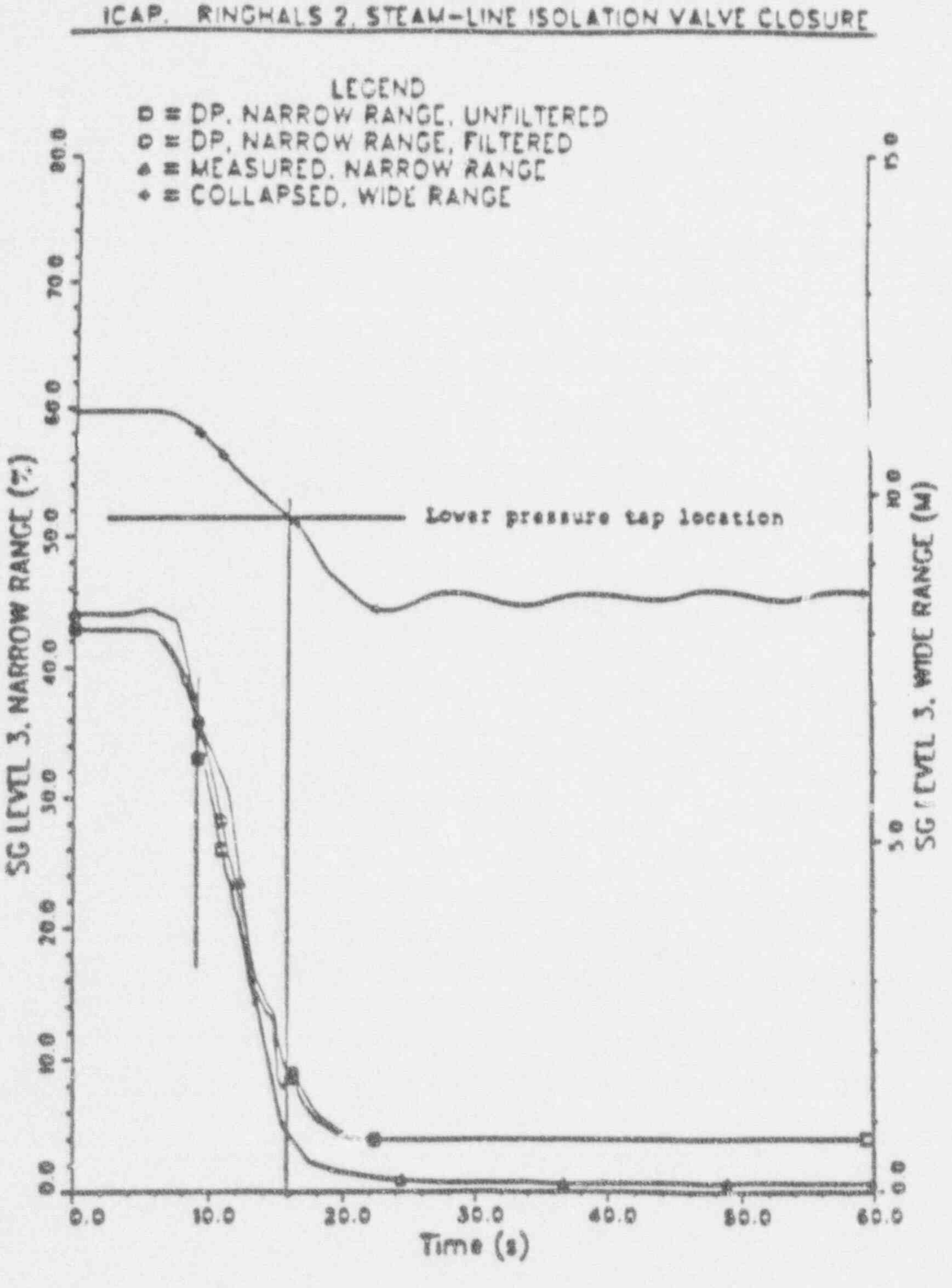

Fig. A-32. Single-loop steam-generator level.

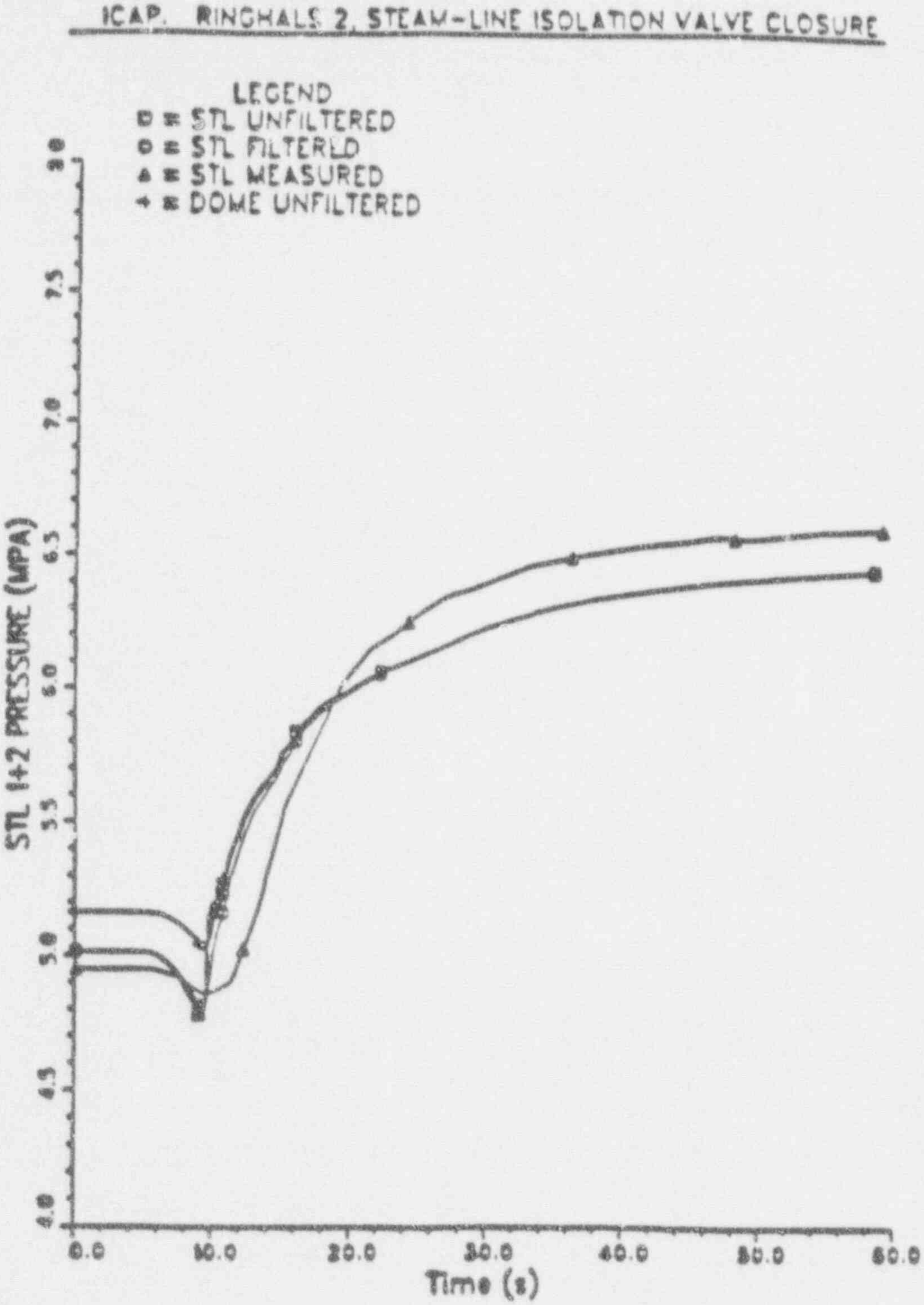

Fig. A-33. Double-loop steam-line pressure.

REVIEW OF ICAP REPORT NO. AEEW-M 2590

A. BASIC DATA

A1. *Report Information:*

Author: R. O'Mahoney

Report Title: Time Step and Mesh Size Dependencies in the Heat Conduction Solution of a Semi-Implicit, Finite Difference Scheme for Transient Two-Phase Flow

Report Number: AEEW-M 2590

Author's Nationality and Affiliation: United Kingdom, Safety and Engineering Science Division, Winfrith Technology Centre

Report Date: July 1989

A2. *Reviewer's Name:* Norman M. Schnurr

Date of Review: September 1990

A3. *Which code version was used for the baseline calculation: (include cycle number or version number and any updates. Section 5.2.2)**

Winfrith version B03E (LANL Version 13.0).

A4. *Report Classification (Proprietary, or non-proprietary, any restrictions. Section 4.1)**

Not for publication.

A5. *Is this an integral or separate-effects assessment?*

Separate-effects assessment.

A6. *Summarize why this assessment is being done. (Section 5.2.5 and Table 3)**

The purpose of this work was to examine and explain the time-step and axial-mesh-size dependencies of thermal calculation for fuel rods in the TRAC-PF1/MOD1 code.

A7. *Provide a list of keywords descriptive of this analysis.*

TRAC, fuel-rod heat transfer, reflood, axial conduction.

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* Refers to section or table in NUREG-1271, "Guidelines and Procedures for the International Code Assessment and Applications Program," April 1987.

B. BRIEF QUESTIONS RELATED TO THE COMPLETENESS OF THE REPORT (Include report page number where information was found.)

B1. *Did the author describe each test facility and each test used in the analysis? Elaborate. (Section 5.4.5 and 5.5.4)*"

No experimental data is used.

B2. *The author must identify the experimental data used for the assessment in the report. The data channels used for comparison with code results should be easy to identify. It is desirable, but not required, for the author to supply the very data used in the assessment on hardcopy, floppy, or tape as specified in NUREG-1271. Has the author done these things? (Section 5.5.3 and 5.3)**

No experimental data is used.

B3. *The author must provide an evaluation of the experimental data uncertainty or clearly reference where it may be found. Has this been done? (Section 5.2.1)**

No experimental data is used.

B4. *Was a base-case calculation performed using the unmodified, frozen code? Did the author include a clear, explicit figure of the Model? (Section 5.2.2).**

A base-case calculation was performed using Winfrith version B03E (LANL Version 13.0). The model is discussed on p. 2 of a related report, AEEW-M 2552.

B5. *The author must supply a copy of the input deck for one of his transient calculations on hardcopy, or floppy, or both. Has he done this? (Section 5.4.6 and 5.5.1)**

The input deck is included as Appendix A of AEEW-M 2552.

B6. *Were sensitivity studies performed? Were the sensitivity studies adequately described? Were all identified code deficiencies explicitly described? (Section 5.2.3, 5.2.5, and 5.4.7)**

A series of calculations were performed to determine the effects of time-step size, axial-mesh size, and axial conduction. The code deficiency was discussed in detail.

B7. Were nodalization studies performed? Were the nodalization studies adequately described? Elaborate if necessary. (Section 5.2.4)*

Mesh-size studies were an important part of this assessment. They are discussed in detail.

B8. The report should include run statistics for at least one transient calculation using the unmodified frozen code. Was this done? If a modified version of the code was produced, run statistics for the same transient calculation performed with the final version of the modified code should be included. Was this done? (Section 5.2.5 - para. 4, and Table 4 - p. 25, and Section 5.4.8)*

Total CPU time, typical minimum time-step size, and problem times were given for several runs on pp. 3-4 of AEEW-M 2552

B9. Were complete references included in the report? (Section 5.4.10)*

Only the TRAC code and the companion report are referenced. No other references were necessary for the work discussed in this report.

B10. Were the objectives satisfied?

The objectives were satisfied. The effects of time-step size, axial-mesh size, and axial conduction on heat transfer in fuel rods were determined.

C. DETAILED QUESTIONS

C1. Did the author describe the model nodalization, assumptions, etc.? Were they appropriate? Did the nodalization follow the input deck preparation guidelines found in the TRAC User Guides? Elaborate if necessary. (Section 5.4.6)*

The nodalization used in this assessment is described in detail in AEEW-M 2552. It is consistent with the input deck preparation guidelines in the TRAC User's guide.

C2. Briefly describe the thermal-hydraulic phenomena and the reported code predictions addressed in the report. If appropriate, describe the phenomena in the context of thermal-hydraulic behavior in the vessel primary loop, secondary loop, and other phenomena of interest.

The phenomenon studied in this assessment is conduction heat transfer and the temperature distributions in a fuel rod during quenching. A core component containing a single fuel rod of typical PWR construction is used along with a FILL and a BREAK component to simulate conduction in fuel rods during reflood. Of particular interest is the numerical calculation of the convective boundary condition at the rod surface.

C3. If the author has identified new user guidelines has he described them thoroughly? What are they?

No new user guidelines are identified in this report.

C4. What user guidelines can you infer from the results described in the report?

The user should perform sensitivity studies to determine the effect of time-step size on the calculated temperature distribution in fuel rods.

C5. What deficiencies were identified in the unmodified frozen version of the code? (Section 5.2.5 and 5.4.7)*

A time-step dependency in thermal calculations for fuel rods is caused by the explicit evaluation of film coefficients and the application of under-relaxation to these coefficients.

C6. Describe the impact of each identified code deficiency.

The effect of this numerical solution procedure is to cause significant errors in calculated rod temperatures unless very small time steps are used.

C7. What code modifications were made? What effect did they have? (Section 5.2.3)*

Some simulations were performed with a version of the code in which the axial term in the conduction equation was removed.

C8. Run statistics must be provided for the calculation of one transient with the unmodified frozen code and the fully modified code. Compare and evaluate. The run statistics should include a description of the computer and operating system used to perform each calculation, and

a. A plot of CPU vs RT

b. A plot of DT vs RT

c. The value of the "grind time" = $[(CPU \times 10^3)/(C \times DT)]$

Where CPU = Total execution time

RT = Transient time

DT = Total number of time steps

C = Total number of volumes in the model

Run statistics were provided in AEEW-M 2552.

d. *Evaluate the actual time step used. Did the transient run at the Courant time step or did the user specify a smaller maximum time step? Compare the actual time step vs transient time and the user specified maximum time step vs transient time. (Section 5.2.5-para.4, Table 4-p. 25, and Section 5.4.8)**

The time-step size was a parameter in the sensitivity studies performed in this work. In general, it was less than the Courant limit. Time-step sizes in the range of 5-10 ms were used for base-case calculations but values as low as 0.3 ms were used in the time-step sensitivity studies.

C9. *Does the work documented in this report appear to be good and generally valid or are there fundamental problems with it? (Solicit input of code developers to answer this question.)*

This work is a careful study of one specific aspect of the TRAC code. It satisfies the stated objective.

C10. *What conclusions were drawn in the report? Are they well supported by the results of the analysis? Elaborate. (Section 5.4.7 and 5.4.9)**

The author's conclusions were as follows:

- A significant time-step-size dependency has been identified in the solution of the coupled system of heat-transfer and two-phase flow partial differential equations. This dependency is caused by the explicit evaluation of the film coefficient at the rod surface and by the smoothing techniques applied to the coefficient.
- The time-step-size dependency disappears if the axial conduction term of the heat-conduction equation is removed.
- A small axial-mesh-size dependency was also identified.
- The time-step-size dependency represents a potential problem in the use of the TRAC-PF1/MOD1 code with regard to running time.

These conclusions are consistent with the results of the simulations.

C11. *Report summary. (This summary will be included in the year-end NUREG report. It should be about 2 to 5 pages long and could include several*

figures. A short paragraph description of each facility should be included. Also include a paragraph summarizing the baseline results.)

This report is not intended primarily as an assessment of the TRAC code. Its purpose is to establish the cause of time-step and mesh-size dependencies identified in a previous report (AEEW-M 2552) by the same author. These dependencies are related to the coupling between the hydrodynamic equations and the heat-conduction equations used to calculate the temperature distribution in fuel rods. The coupling takes place via the surface heat transfer between the rod and the surrounding fluid. The convective conductance (film coefficient) at the surface depends on the surface temperature and fluid properties. It provides a surface boundary condition for the heat-conduction equation and contributes to the energy and mass conservation equations for the fluid.

The finite-difference representation of the conduction equation is implicit in the radial direction but explicit in the axial direction. Of particular significance is the explicit treatment of the convective boundary condition. The film coefficient is calculated using surface temperature and fluid conditions from the previous time step. The author shows that this explicit evaluation, taken together with the smoothing that is applied to the HTC, is the major cause of the time-step-size dependency. Sensitivity studies show that reducing the time step causes the solution to asymptotically approach the numerically correct result. However, the time step required for good accuracy, particularly for reflood calculations, may be significantly smaller than that determined by the Courant limit and may severely increase CPU time.

Additional calculations showed there was also an axial-mesh-size dependency. This was found to be much smaller than the time-step-size dependency. The author suggests that some computation method should be found to improve or replace the explicit film coefficient evaluation and that the time-step-size dependency be removed from the heat-transfer-smoothing technique.

REVIEW OF ICAP REPORT NO. Strathclyde-SB291, Phase 2

A. BASIC DATA

A1. ***Report Information:***

Author: W. M. Dempster, A. M. Bradford, T. M. S. Callender, H. C. Simpson

Report Title: An Assessment of TRAC-PF1/MOD1 Using Strathclyde 1/10 Scale Model Refill Tests, 2nd Report

Report Number: Contract RK: 1642 Job No. SB291, Phase 2.

Author's Nationality and Affiliation: United Kingdom, University of Strathclyde, Department of Mechanical and Process Engineering.

Report Date: July 1989

A2. *Reviewer's Name:* Norman M. Schnurr

Date of Review: September 1990

A3. ***Which code version was used for the baseline calculation: (Include cycle number or version number and any updates. Section 5.2.2)****

Winfrith version B03 modified by D. M. Turner.

A4. ***Report Classification (Proprietary, or non-proprietary, any restrictions. Section 4.1)****

Restricted to the organizations or the persons to whom the report is addressed.

A5. ***Is this an integral or separate-effects assessment?***

Separate-effects assessment.

A6. ***Summarize why this assessment is being done. (Section 5.2.5 and Table 3)****

This report covers the second and final phase of a study whose goal was to assess the capabilities of TRAC-PF1/MOD1 to simulate the refill phase of a double-ended cold-leg

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* Refers to section or table in NUREG-1271, "Guidelines and Procedures for the International Code Assessment and Applications Program," April 1987.

break LOCA. The first phase report** has been summarized in a separate assessment review.

A7. ***Provide a list of keywords descriptive of this analysis.***

TRAC, ECC injection, LOCA, refill, downcomer penetration, bypass.

B. BRIEF QUESTIONS RELATED TO THE COMPLETENESS OF THE REPORT (include report page number where information was found.)

B1. ***Did the author describe each test facility and each test used in the analysis? Elaborate. (Section 5.4.5 and 5.5.4)****

The Strathclyde 1/10-scale facility is described on p. 1 and in Figs. 2.1 and 2.2. The test facility and procedure are also described in more detail in the Phase 1 report.

B2. ***The author must identify the experimental data used for the assessment in the report. The data channels used for comparison with code results should be easy to identify. It is desirable, but not required, for the author to supply the very data used in the assessment on hardcopy, floppy or tape as specified in NUREG-1271. Has the author done these things? (Section 5.5.3 and 5.3)****

The experimental data are taken from the Strathclyde data base. Mass-flow rates and condensation rates are given in graphical form.

B3. ***The author must provide an evaluation of the experimental data uncertainty or clearly reference where it may be found. Has this been done? (Section 5.2.1)****

The uncertainty of the experimental data was not discussed.

B4. ***Was a base-case calculation performed using the unmodified, frozen code? Did the author include a clear, explicit figure of the Model? (Section 5.2.2).****

The base-case simulations (Phase 1) were performed using the Winfrith modified code B05. The noding for the various cases is given in Figs. 1.3 and 4.1-4.5.

** W. M. Dempster, A. M. Bradford, T. M. S. Callender, and H. C. Simpson, "An Assessment of TRAC-PF1/MOD1 Using Strathclyde 1/10 Scale Model Refill Tests", submitted to CERL, [ICAP00112].

B5. The author must supply a copy of the input deck for one of his transient calculations on hardcopy, or floppy, or both. Has he done this? (Section 5.4.6 and 5.5.1)*

The input deck is not included in this assessment.

B6. Were sensitivity studies performed? Were the sensitivity studies adequately described? Were all identified code deficiencies explicitly described? (Section 5.2.3, 5.2.5, and 5.4.7)*

A sensitivity analysis (pp. 1-2) was performed for downcomer hydraulic diameter. The identified code deficiencies were clearly described.

B7. Were nodalization studies performed? Were the nodalization studies adequately described? Elaborate if necessary. (Section 5.2.4)*

Nodalization studies were performed to determine the effect of increasing the number of azimuthal sectors (pp. 6-12). The effect of altering the location of the cold-leg connections to the vessel was also determined

B8. The report should include run statistics for at least one transient calculation using the unmodified frozen code. Was this done? If a modified version of the code was produced, run statistics for the same transient calculation performed with the final version of the modified code should be included. Was this done? (Section 5.2.5 - para. 4, and Table 4 - p. 25, and Section 5.4.8)*

CPU time is shown as a function of reactor time for four typical calculations in Fig. 4.31. A range of values for the time step is also included (p. 12) and a graph of time-step size vs reactor time is given in Fig. 4.32.

B9. Were complete references included in the report? (Section 5.4.10)*

A total of 11 references are given covering all important aspects of the work.

B10. Were the objectives satisfied?

The purpose of this phase of the work was to perform some sensitivity analyses and nodalization studies. That goal was accomplished and some code deficiencies were identified. No specific guidelines were developed but some general conclusions were reached concerning nodalization for a reactor vessel.

C. DETAILED QUESTIONS

C1. ***Did the author describe the model nodalization, assumptions, etc.? Were they appropriate? Did the nodalization follow the input deck preparation guidelines found in the TRAC User Guides? Elaborate if necessary. (Section 5.4.6)****

The nodalization used in this assessment is described in detail. The number of cells and their distribution are similar to the nodalization used in TRAC large-plant calculations that have been recently carried out in the UK and conform to guidelines given in the TRAC-PF1/MOD2 User's Guide. A nodalization study was carried out as part of this work.

C2. ***Briefly describe the thermal-hydraulic phenomena and the reported code predictions addressed in the report. If appropriate, describe the phenomena in the context of thermal-hydraulic behavior in the vessel primary loop, secondary loop, and other phenomena of interest.***

The Strathclyde experiments simulate the refill stage of a double-ended cold-leg-break LOCA in a PWR. The reactor vessel includes four hot legs and four cold legs. Two of the hot legs are used to supply steam (or air) to the core. Three of the cold legs are used as ECC-injection points and the fourth represents the broken leg. A particularly critical phase of the transient may occur when ECC water is prevented from entering the vessel due to an opposing flow of steam originating from the core intact loops. This phase of the transient, known as the refill phase, includes highly complex interactions of steam and water, involving multidimensional, nonequilibrium countercurrent two-phase flow. Some or all of the injected water may fail to penetrate the downcomer and may be carried out the broken cold leg, bypassing the core. For cases with substantial liquid subcooling, the effects produced by interfacial heat transfer, interfacial friction, wall friction, and wall-to-fluid heat transfer are important.

C3. ***If the author has identified new user guidelines has he described them thoroughly? What are they?***

No user guidelines were specifically stated.

C4. ***What user guidelines can you infer from the results described in the report?***

A relatively fine mesh may be needed in the downcomer of the reactor vessel to accurately calculate flow conditions during the refill phase. The authors indicate that four azimuthal sectors are not sufficient to provide a converged solution. For bypass conditions it is important to accurately model the location of the broken-cold-leg vessel connection.

C5. *What deficiencies were identified in the unmodified frozen version of the code? (Section 5.2.5 and 5.4.7)**

(1) The TRAC condensation heat-transfer rates can be an order of magnitude higher than experimentally derived values. This may occur in cases where the liquid is in the form of a sheet adhering to a wall and the interfacial area is much lower than TRAC would predict if it does not assume a stratified flow regime.

(2) The authors state that a more conservative form of the conservation of momentum equation gives better results for downcomer-penetration calculations.

(3) The TRAC code does not contain a momentum convection term associated with a radial vessel/pipe connection.

C6. *Describe the impact of each identified code deficiency.*

(1) The condensation rates will be overpredicted.

(2) Downcomer penetration calculations will be in error.

(3) Flow distribution in the region where a pipe connects to the vessel will not be accurately predicted.

C7. *What code modifications were made? What effect did they have? (Section 5.2.3)**

The code was altered to use a conservative form of the momentum equation. This change produced little effect on the overall mass balance for the tests with little or no bypass but did cause marked improvement in the overall distribution of liquid fractions and velocities for those cases. For the test in which total bypass occurred, changing the momentum calculation to the conservative form caused marked improvement in the calculations.

C8. *Run statistics must be provided for the calculation of one transient with the unmodified frozen code and the fully modified code. Compare and evaluate. The run statistics should include a description of the computer and operating system used to perform each calculation, and*

a. A plot of CPU vs RT

b. A plot of DT vs RT

c. The value of the "grind time" = $[(CPU \times 10^3)/(C \times DT)]$

Where CPU = Total execution time

RT = Transient time

DT = Total number of time steps

C = Total number of volumes in the model

The total CPU time and time-step size are given as functions of reactor time for two different nodalizations. The total number of time steps is not given so the grind time cannot be readily calculated.

*d. Evaluate the actual time step used. Did the transient run at the Courant time step or did the user specify a smaller maximum time step? Compare the actual time step vs transient time and the user specified maximum time step vs transient time. (Section 5.2.5-para.4, Table 4-p. 25, and Section 5.4.8)**

The time step was apparently limited by the Courant condition.

C9. Does the work documented in this report appear to be good and generally valid or are there fundamental problems with it? (Solicit input of code developers to answer this question.)

The work documented in this report is the second phase of a project to assess the ability of TRAC to simulate the Strathclyde 1/10-scale-model refill tests. In this phase of the work, sensitivity studies have been carried out to determine the effect of hydraulic diameter and nodalization. There are some difficulties in analyzing the differences between test results and numerical calculations because of the complexity of the problem and because of geometrical complications associated with the downcomer thermal shield. Nevertheless some useful conclusions were reached concerning vessel nodalization and the condensation-heat-transfer calculations.

*C10. What conclusions were drawn in the report? Are they well supported by the results of the analysis? Elaborate. (Section 5.4.7 and 5.4.9)**

The authors' conclusions were as follows:

- The TRAC liquid-side HTC for the condensation process is an order of magnitude greater than experimentally derived values.
- A nodalization study showed that the four-sector nodalization does not provide a converged solution for the dependent variables.
- For bypass conditions it is important to model the geometry of the break positions relative to the intact cold legs.
- TRAC's inability to predict the circumferential redistribution of liquid injected into the downcomer due to the lack of appropriate terms in the momentum equations is a major deficiency.

- TRAC's excessive computer run times is an important limitation in the progress to a possible solution of the downcomer flows during the refill phase.

These conclusions are consistent with the results of the simulations.

C11. **Report summary.** ***(This summary will be included in the year-end NUREG report. It should be about 2 to 5 pages long and could include several figures. A short paragraph description of each facility should be included. Also include a paragraph summarizing the baseline results.)***

The Strathclyde test facility was designed for operation with steam/water and steam/air as the working fluids and incorporates a closed loop recirculation system. The reactor vessel test section was a 1/10-scale model of a Westinghouse PWR, with particular emphasis on the downcomer annulus. Two test sections were available, one with a transparent exterior, restricting operation to pressures less than 1.7 bar and allowing visual observation; the other of stainless steel, permitting pressures up to 5 bar. The reactor-vessel simulation included the provision of four hot legs, connected through the annulus to the core, and four cold legs, connected to the annulus. Two of the hot legs were used to supply steam/air to the core; three of the cold legs were used as ECC-injection points, while the fourth represented the broken leg.

The main measurements taken during the tests included inlet steam/air flow rate, injected-water flow rate, water penetrating to the lower plenum, and various temperatures, pressures, and pressure differences. Two types of tests were performed. In the "water first" tests a particular water flow rate was set and then the steam flow rate was increased in steps until complete bypass occurred. In "steam first" tests the steam flow rate was set and the water flow rate was increased until bypass ceased.

Comparisons of calculated results with experimental data for several tests were reported in the Phase 1 report. The Phase 2 report discusses the results of some nodalization and sensitivity studies. The effect of the hydraulic diameter selected for the downcomer was investigated. There is a thermal shield in the downcomer that divides it into two separate flow paths. The downcomer was, however, modeled with only one ring and the two channels were combined into a single flow path. There was some question concerning the hydraulic diameter that should be specified for the resulting cells. Two limiting values were used, producing slightly different results. Agreement with experimental data,however, was not markedly different for the two cases.

A study was also carried out to assess the accuracy of the condensation-rate heat-transfer calculations in TRAC. Comparison of TRAC predictions with values deduced from experimental data showed that the condensation-rate heat transfer can be an order of magnitude higher than the experimentally derived values. This is apparently caused by the use of interfacial areas based on a uniform flow distribution in cases where the flow is actually stratified.

Nodalization studies were performed for a case in which total bypass occurred. This study was primarily restricted to changing the number of azimuthal sectors in the vessel. The authors conclude that using only four azimuthal sectors is not sufficient for good accuracy. They also find that it is important to correctly model the position of the cold-leg vessel connections. TRAC's inability to predict the circumferential redistribution of liquid injected into the downcomer is attributed to the lack of appropriate terms in the momentum equations at the pipe/vessel junction.

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TRAC-PF1/MOD1 has been exercised by several international users as a part of the ICAP Program. Participants are requested to prepare a report summarizing the results of their work. These assessment reports contain discussions of the code accuracy, errors and deficiencies, new user guidelines, and recommendations for code upgrades and modifications.

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