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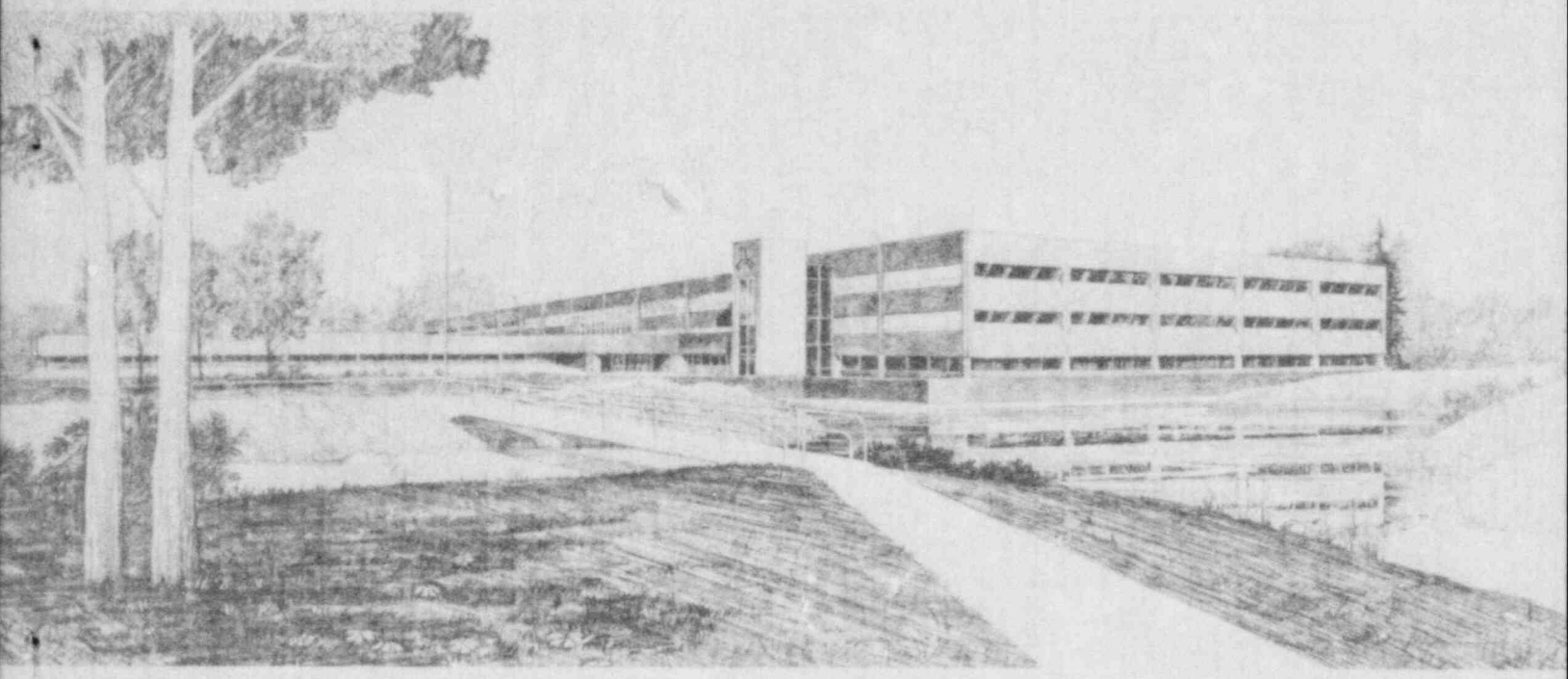

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Overview of TRAC-BD1 (Version 12) Assessment Studies

Craig M. Kullberg

April 1985

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OVERVIEW OF TRAC-BD1 (VERSION 12) ASSESSMENT STUDIES

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ABSTRACT

A series of simulations were performed at Idaho National Engineering Laboratory (INEL) to continue the advancement of Boiling Water Reactor (BWR) safety research, with the TRAC-BD1 (Version 12) computer code. The principal motivation for performing these simulations was to assess the code's capability to calculate Loss-of-Coolant Accident (LOCA) related phenomena. The results of a number of TRAC-BD1 (Version 12) simulations, which cover a broad range of conditions during different types of LOCA scenarios, are summarized in this document. Selected comparisons between calculated and measured results are presented. Conclusions derived from those comparisons are given.

FIN No. A6047—Code Assessment and Application (Transient Analysis)

SUMMARY

The analyses of a series of simulations performed with the TRAC-BD1 (Version 12) computer code are summarized in this report. All of the simulations, with one exception, focused on assessing the code capability to simulate transient behavior in various test facilities. Simulations of separate effects and system response tests were performed. The separate effects tests included two blowdown experiments, a bundle natural circulation stability test, a bundle forced circulation test, one radiation heat transfer test, and one reflood test. The system test transients included four small break LOCAs and nine large break LOCAs performed in several different test facilities. Additionally, a BWR audit calculation was performed. Although direct comparisons to data were not made in the audit calculation, useful conclusions were derived from these simulations in regard to optimizing input models. These conclusions reinforced similar findings derived from the assessment calculations.

The conclusions in this report do not fully reflect the current status of TRAC-BD1 since additional improvements have been implemented in the latest version of the code (TRAC-BD1/MOD1).

Conclusions resulting from the analyses are summarized as follows:

1. TRAC-BD1 (Version 12) can adequately simulate most BWR LOCA phenomena when the correct modeling techniques are employed. In particular, calculated system pressure and break flow responses as well as event timings were generally adequately calculated.

2. TRAC-BD1 (Version 12) contains certain inherent limitations and deficiencies which are being addressed in future code versions. Specifically, the needed improvements include (a) developing more generalized sets of countercurrent flow limiting (CCFL) input options for arbitrary geometries, (b) upgrading the interfacial heat transfer package, and (c) improving the water packing model.

3. The estimated calculational peak clad temperature (PCT) two sigma uncertainty and mean temperature difference between the calculated and measured PCT were 226 K and -28 K, respectively. Differences between the measured and calculated timing events were not significant contributors to the calculated PCT discrepancies. The principal cause of calculated PCT discrepancies was the consequence of implementing the TRAC CCFL model. Because of limited modeling options, the implementation of the CCFL model caused the calculated drainage of liquid from the core or upper plenum to be retarded. In most simulations the calculated drainage from the core region was sufficiently retarded to result in an undercalculated PCT.

4. Code performance relative to central processor unit (CPU) to real time ratios was a strong function of both model size and transient type. Large models (150 to 230 cells) had CPU to real time ratios which ranged from 60 to 250. Small models (60 cells or less) had CPU to real time ratios which ranged from 10 to 50. The CPU to real time ratios tended towards the higher values during the refill/reflood phase of a transient.

Several important conclusions were made relative to user modeling guidelines needed to reduce code uncertainties:

1. Numerical diffusion problems which produce unrealistic mass convection rates can be improved with finer nodalization; however, the level tracking model available in future code versions will be a more cost effective means of addressing these problems.

2. In general, modeling of system stored energy or heat losses are important if the system pressure response is to be correctly simulated.

3. There is not a set of universal break parameters that can be used to model all break configurations. In particular, a reliable data base for geometrical data and measured discharge coefficients is needed when simulating a test facility blowdown.

4. Facilities with inherently multi-dimensional vessel geometries cannot always be accurately simulated when modeled with a one dimensional approximation. This is particularly true if such phenomena as core multi-channel flow dynamics are to be accurately simulated during the refill/reflood phase of a LOCA.

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OVERVIEW OF TRAC-BD1 (VERSION 12) ASSESSMENT STUDIES

1. INTRODUCTION

TRAC-BD1 (Version 12)[1] is a Boiling Water Reactor (BWR) code version which is part of a code series being developed at the Idaho National Engineering Laboratory (INEL). This code is based on earlier TRAC-BD1 versions with additional modifications and models developed at INEL. This code will not be the final INEL TRAC version but will continue to evolve as additional models and enhancements are implemented. The TRAC-BD1 development at INEL has been carried out under the BWR TRAC Loss of Coolant Accident (LOCA) Program sponsored by the U.S. Nuclear Regulatory Commission.

This report describes the assessment of TRAC-BD1 (Version 12) by comparing code simulations with data from a variety of experimental separate effects and system tests.[a] The separate effects tests focused on simulating specific LOCA related phenomena. In contrast, the system response tests simulated a complete spectrum of BWR LOCA phenomena. The system response tests were performed with scaled facilities which simulated BWR LOCA scenarios.

These tests were conducted at a number of different facilities around the world including the General Electric (GE) Two Loop Test Apparatus (TLTA), the GE Steam Sector Test Facility (SSTF), the Japan Atomic Energy Research Institute (JAERI) Rig of Safety Assessment (ROSA-III) facility, the Hitachi Two-Bundle Loop (TBL) facility, and the Swedish Marviken, GOTA, and FRIGG separate effects facilities. A series of BWR audit calculations and sensitivity studies were performed with a model of the Dresden-III BWR plant. These audit calculations did not entail code-data comparisons.

Section 2 presents a summary of the assessment objectives. Section 3 presents a brief description of the TRAC-BD1 (Version 12) computer code. Section 4 contains a short description of the tests and test facilities. Results of the assessment analyses are presented in Section 5. User experience is detailed in Section 6 and code runtime statistics in Section 7. Conclusions are given in Section 8 and references given in Section 9.

a. Some of the simulations were performed with TRAC-BD1 (Version 11). Version 11 was a prerelease version of Version 12.

2. OBJECTIVES

The objective of the assessment analyses was to evaluate the capability of TRAC-BD1 (Version 12) to realistically simulate the governing phenomena and key events during BWR thermal-hydraulic transients. The principal focus of these analyses dealt with simulating LOCA scenarios. The methodology used to approach this objective is broken down into the following steps.

1. Quantify uncertainty of the code using key parameters such as Peak Clad Temperature (PCT).

2. Identify the principal phenomena governing a BWR LOCA.

3. Simulate a set of test transients which are representative of BWR LOCA scenarios.

4. Prepare best estimate code input models for the tests to be simulated. Implement a model review procedure to ensure that the optimum scheme for nodalization, boundary conditions, and code options are chosen.

5. Perform the test simulations and compare calculated results with data. In particular, make one-to-one comparisons with key measurement parameters, note areas of agreement and disagreement, and determine reasons for any discrepancies.

6. Perform appropriate sensitivity studies by implementing changes to the code (via updates) or input model to further evaluate any noted discrepancies between data and calculated results.

7. Provide recommendations, when necessary, for code improvements or modeling strategies based on results Items 5 and 6.

3. CODE DESCRIPTION

TRAC-BD1 (Version 12) is an advanced best-estimate code (Reference 1) designed for the thermal-hydraulic analysis of BWR transients. TRAC-BD1 (Version 12) was developed at the Idaho National Engineering Laboratory (INEL) and is based on the transient reactor analysis code (TRAC) originally developed at Los Alamos National Laboratory. TRAC-BD1 (Version 12) provides the capability to simulate the blowdown, refill, and reflood stages of a BWR LOCA. The code contains a full two-fluid model of two-phase flow. This model allows for both interfacial momentum and heat transfer to be calculated within a hydrodynamic cell. The code provides the capability to model the reactor vessel with one-, two-, or three-dimensional geometry options. Other components are treated one-dimensionally.

TRAC-BD1 (Version 12) has models to represent nonhomogeneous critical flow and countercurrent flow limiting (CCFL) at the upper tie plate (UTP) and side entry orifice (SEO) in a BWR. The code can calculate reactor power with a point kinetics model which includes the effects of reactivity feedback. The code has models to simulate BWR control systems. TRAC-BD1 (Version 12) has a detailed heat transfer model which includes bundle-to-bundle radiation heat transfer.

Several different types of hydrodynamic components including PIPE, VALVE, CHAN, PUMP, JETP, TEE, BREAK, and FILL components are available in TRAC-BD1 (Version 12). These components are used to represent different types of hardware such as pipes, jet pumps, etc. Boundary conditions can be modeled with FILL and BREAK components.

4. FACILITY AND TEST DESCRIPTIONS

This section presents a brief description of the facilities and transients used to assess TRAC-BD1 (Version 12) in this report. A summary of the test descriptions are presented in Table 1. Further facility and test details are given in Appendices A-J. The separate effects and systems tests are detailed in the following paragraphs.

4.1 Separate Effects Facilities and Test Descriptions

The separate effects tests used to assess TRAC-BD1 (Version 12) (Table 1) covered a number of different phenomena. These tests provided information that enhances the understanding of specific BWR-LOCA behavior. Since the number of interactions in these experiments were limited, cause and effect relationships were readily identified. This ease in identification allowed a systematic assessment approach which challenged particular TRAC-BD1 (Version 12) models for accuracy.

The GOTA separate effects test facility was used to evaluate the effectiveness of the emergency core cooling system (ECCS) used in Swedish boiling water reactors.[2] The facility consisted of a pressure vessel, a pressurizer, a recirculation pump, and other peripheral equipment needed to perform reflood experiments. Diagrams for this facility are presented in Figures 1 and 2 of Appendix A. The pressure vessel contained a single electrically heated fuel bundle. Allowances were made so that a number of different ECC configurations could be tested. The principal physical effects which were measured in Tests 11 and 42 were: radiation heat transfer, core reflood heat transfer, and fuel bundle quenching.

The Marviken separate effects facility was used to perform full-scale critical flow tests.[3,4,5,6,7] The separate effects facility consisted of a pressure vessel, a discharge pipe, various test nozzles, and a rupture disc assembly. Diagrams of the vessel and associated piping are shown in Figures 1 through 5

of Appendix B. The objectives of Tests 15 and 24 were to obtain critical flow data for subcooled and saturated blowdown conditions.

FRIGG was a separate effects test facility used to gather hydrodynamic data on the Marviken Boiling Heavy Water Reactor fuel bundle mockup.[8,9] The facility consisted of a pressure vessel with a simulated fuel bundle, steam separator, condenser and natural circulation loop with a forced circulation bypass on the downcomer. Diagrams of the test configuration are presented in Figures 1 through 5 of Appendix C. Tests conducted at FRIGG measured fuel bundle heat transfer behavior with varying power loads during both natural and forced convection conditions. Tests 301047 and 613130 were conducted under natural and forced convection conditions, respectively.

4.2 Integral Test Facilities and Test Description

The integral system LOCA tests were all performed in BWR scaled facilities. Those tests, summarized in Table 1, provided useful information in assessing transients where many different thermal-hydraulic phenomena were coupled. Presented in Figure 1 is a generic diagram incorporating hardware common to all these facilities.[a] These test transients allowed assessment of the following:

1. Multi-coupled thermal-hydraulic effects, such as multi-channel flow dynamics.
2. Capability of code analytical models to simulate particular phenomena such as critical flow, CCFL, bundle heat transfer, etc.
3. Capability of the code to simulate key events such as time of PCT, ECCS activation, bundle quenching, etc.

Three of the integral test facilities (ROSA-III, TBL, and TLTA) shared a number of common features which included:[10,11,12,13,14,15,16]

1. Two loop recirculation line configuration
2. Volumetric vessel scaling
3. Mock-up of BWR-ECCS
4. Electrically heated bundles
5. Mock-up of key BWR hardware including
   a. Jet pumps
   b. Recirculation pumps
   c. Vessel internals
   d. Safety relief valves (SRV)
6. Automatic depressurization systems (ADS).

The BWR vessel scaling for those facilities were 1/424, 1/624, and 2/764 for the ROSA-III, TLTA, and TBL facilities, respectively. The ECCS included low pressure core spray (LPCS), high pressure core spray (HPCS), and low pressure coolant injection (LPCI). Additional details and facility diagrams for those three facilities are given in Appendices D-G. One limitation common to those facilities was the inability to fully simulate multichannel flow phenomena in a full scale BWR during the refill/reflood phase of a LOCA. This was because the subscale facilities' core configurations were limited to four or fewer fuel bundle mockups.

The GE SSTF facility was designed to fill that experimental data gap.[17,18,19,20] In particular, the SSTF tests demonstrated the importance of multichannel flow dynamics, a key governing phenomena during the refill/reflood phase of a LOCA. The main features of the SSTF facility include:

1. Full scale 30-degree sector mockup of a BWR/6 vessel
2. Mockup of ECCS systems
3. Simulated vessel heat transfer with appropriate radial steam injection profiles.

Overall volume scaling was generally 1/1 with 30°/360° or 1/12 sector of a full scale BWR/6 simulated. Additional details of the SSTF facility and test are presented in Appendices H and I.

The full scale Nuclear Steam Supply System (NSSS) simulation employed a model of the

a. The particular ECCS configuration shown in Figure 1 is characteristic of a BWR/6 plant.

Dresden, Unit 3, BWR/3 power plant.[21] A spectrum of different LOCA scenarios were performed plus several sensitivity studies. Details of the plant model and LOCA transients are discussed in Appendix J. The results of those simulations provided useful information which reinforced certain conclusions relative to assessing TRAC's capability to simulate refill/reflood behavior.

5. CALCULATIONAL RESULTS

Accurately simulating global system response during a BWR-LOCA is contingent on correctly simulating specific localized thermal-hydraulic phenomena. Those localized phenomena are simulated with one or more code process models. This section identifies the principal phenomena controlling a BWR LOCA and assesses the associated code models used to simulate those phenomena. The assessments were done comparing, where relevant, test data and calculated results.

The comparisons were made to challenge key code models, including:

1. Critical flow
2. CCFL
3. Interfacial heat transfer
4. Water packing.

In particular, those models will be discussed relative to how well overall system response was calculated. Several key calculated parameters are presented here and compared with data. Three parameters judged to be good indicators of the code's predictive capability were pressure response, break flow response, and core heat transfer. Those parameters are discussed in the following paragraphs.

5.1 Pressure Response

During a BWR-LOCA the system pressure is controlled by the complex collective interaction of a number of phenomena. The most important relative to the BWR analyses discussed in this report include:

1. Break flow
2. Event timings
   a. ECCS
   b. ADS
   c. SRV
3. Flashing/condensation
4. Heat transfer
   a. Environmental heat transfer
   b. Stored energy
   c. Bundle to liquid heat transfer

Examples of how some of the above phenomena control system pressure and their relevance to code accuracy are discussed below. Because pressure is strongly coupled to many separate phenomena, it serves as a good parameter to assess code performance in simulating overall system behavior. Key measured and calculated event timings which are strongly coupled to the pressure response are presented in Table 2. Table 3 presents a summary of code performance versus data for system pressure response. Generally, pressure trends were adequately calculated; however, some discrepancies did exist.

In certain simulations the calculated volumetric break flow rate deviated from that measured, resulting in commensurate deviations between the calculated and measured depressurization rates. As an example consider Figure 2, which presents the measured and calculated pressure responses for TLTA test 6423. Prior to 35 s, both the measured and calculated pressures agreed closely; however, at 35 s the calculated break transitioned from two-phase to single-phase steam conditions. The subsequent increase in volumetric flow caused a significant but temporary increase in the calculated depressurization rate.[a] By 150 s the calculated and measured pressures were again in good agreement.

a. There was not a direct volumetric measurement. Using other test data, it was inferred that the calculated volumetric flow rate temporarily exceeded that measured.

One example of how different subsystem operations (event timings) effect the pressure response is shown in Figure 3, which compares the measured and calculated pressure responses for ROSA-III Run 912. Both the measured and calculated responses agreed closely until the calculated LPCS initiation at 327 s (318 s in test). Initially, both the measured and calculated pressures rapidly decreased until main steam isolation valve (MSIV) closure at 23 s. Following MSIV closure, the pressure increased and was held below 8.47 MPa by the SRV. The ADS was calculated to open at 164 s (158 s in test), which induced a rapid system blowdown.

After LPCS activation, feedwater line flashing and bundle heat transfer were identified as key phenomena controlling system pressure. In the experiment, the system pressure after LPCS initiation exceeded the calculated values. Also, LPCS drainage into the core region was undercalculated.[a] In the test, feedwater flashing and steam generation caused by LPCS fluid contacting heater rod surfaces held up the pressure.

In certain simulations, condensation was identified as an important phenomena controlling system pressure. In the simulation of SSTF test Run 111, ECCS-induced condensation caused the calculated depressurization rate to exceed that measured. This is demonstrated in Figure 4 during the time interval from approximately 5 to 20 s. During that interval, subcooled LPCI fluid mixed with saturated steam. The calculated steam condensation rate exceeded the actual rate, which resulted in overcalculating the depressurization rate.[b] It was concluded that improvements in the TRAC interfacial heat transfer package would mitigate the effects of overcalculating condensation. It was also found that improved ECCS modeling methods (discussed in Section 6) would improve the calculated pressure response.

a. The principal cause of calculated upper plenum hold-up was related to the interfacial shear package. A further discussion is given in Appendix D.

b. Steam condensation rates were not measured. This statement is a judgment made by the analyst.

From several simulations, it was concluded that overall system pressure response was significantly affected by modeling of stored energy and/or ambient heat losses. These difficulties are not necessarily a function of code technology but are rather a function of accuracy in the data base used to model a particular facility. However, the code does have some limitations in modeling heat structures. The principal limitation is that nonuniform heat losses cannot be modeled for a specific TRAC component. In particular, nonuniform heat losses in a VESSEL component become significant in modeling subscale facilities like ROSA-III, TLTA, and TBL. One major cause of heat loss variation is instrumentation penetrations. Such penetrations are generally selective and are very local pathways for ambient heat losses.

Large nonuniform heat loss variations are not peculiar to full scale BWR plants. Also, ambient heat losses are generally not important for full-scale BWR plants. However, stored metal mass thermal energy can be very important for both BWR plants and subscale facilities. It is suspected that inherent uncertainties in modeling stored energy in the SSTF simulations may have contributed to undercalculating pressure response. The consequence of an under estimated vessel metal mass (therefore stored thermal energy) was to undercalculate steam production from metal to liquid heat transfer. A lower steam inventory would in turn lead to a lower pressure.

The following conclusions were made relative to the code's capability to simulate system pressure response:

1. Generally, the code adequately calculated overall pressure trends and event timings such as ECCS activation.

2. The principal causes of data versus calculated pressure differences were attributed to

   a. Differences between measured and calculated break flow behavior.

   b. Shortcomings in the code's interfacial heat transfer package, resulting in overcalculated condensation.

   c. Limitations or uncertainties in modeling stored energy and/or environmental heat losses.

5.2 Break Flow Response

Summarized in Table 4 are the conclusions as to how well the break flow was calculated relative to test data. The most important phenomena relative to accurately calculating the break discharge included:

1. Break plane upstream conditions

   a. Void fraction

   b. Subcooling

2. Choking plane location

3. Event timings of ECCS, ADS, SRV, etc.

Examples of how some of the above phenomena related to accurately calculating break flow behavior are presented in the following paragraphs.

Correctly simulating break junction upstream conditions is a fundamental requirement for calculating blowdown rates since the upstream conditions directly determine the choking criteria at the break plane. When this criteria is met, a direct evaluation of the code choking model can be made. In the course of performing the assessment (with the prereleased version), problems were identified with the code choking model relative to simulating choked subcooled mass flow behavior (Appendix B). Those computational problems were characterized in certain simulations by mass flow oscillations at the break plane. [Those problems were corrected in the subsequently released TRAC-BD1 (Version 12) code.] Also, modeling uncertainties in the break configurations were present that could significantly change calculated results. User experience dealing with break modeling are discussed in Section 6.

There are a number of simulations where differences in measured and calculated break flows existed as a consequence of models unrelated to the break flow choking model. As an illustration, Figure 5 presents a comparison of calculated and measured suction line break flow for TLTA Test 6425. The initial blowdown was at single phase liquid conditions. After 9 s and 7 s respectively, the measured and calculated break flow transitioned to two phase conditions. In both the test and simulation, that transition was characterized by a rapid drop in mass flow rate because of density and velocity reductions at the break junction. In this case the measured and calculated values were generally within acceptable uncertainty bands of the measurement. In contrast to the good agreement shown in Figure 5, poor agreement in break flow rates occurred when break upstream conditions were incorrectly calculated. This is illustrated in Figure 6, which shows the measured and calculated break mass flow rates for SSTF Test EA3.1 Run 111. Relative to the test data, it took several seconds longer for the simulated break flow to transition to single phase steam conditions. The longer calculated transition time is the consequence of numerical diffusion. Too much liquid was donored from the annulus region to the break. By 20 s numerical diffusion effects again came into play as unrealistic amounts of liquid reached the break plane via the upper plenum region.

The following conclusions were made relative to the code's capability to simulate break flow response:

1. The code generally demonstrated the capability to accurately simulate two-phase and single-phase steam break flow when break plane upstream conditions were correct.

2. Code problems relative to simulating subcooled break flow were identified and subsequently corrected in later versions.

5.3 Core Heat Transfer

Key measured and calculated bundle heat transfer parameters are shown in Table 5. Table 6 summarizes overall comparisons between measured and calculated trends. The most important phenomena affecting the bundle heater response are summarized as follows:

1. System pressure

2. Event timings

3. Vessel liquid mass distribution

   a. UTP CCFL

   b. SEO CCFL

4. Multi-channel flow dynamics.

System pressure (discussed in Section 5.1) is important because it determines the timing of key subsystem operations such as ECCS activation and resultant vessel mass distribution. Core mass distribution is critical in determining the timing of key events such as rod dryout, PCT, and rod quenching. Generally, event timings were well simulated. It was concluded that calculated key events such as ECCS activation or jet pump uncovery did not significantly contribute to differences observed between the measured and calculated temperature responses or key parameters such as PCT. During the reflood/refill stage of a large break BWR LOCA, multi-channel dynamics become an important phenomena controlling regionalized bundle temperature behavior.

Certain simulations showed that correctly simulating bundle temperature response is strongly dependent on correctly simulating bundle CCFL at the UTP or SEO junctions. As an illustration of bundle temperature response being driven by UTP flooding, consider the heater rod temperature responses in Figure 7 for TLTA Test 6424. Generally, the measured and calculated bundle temperatures were in good agreement. However, at approximately 100 s a temporary anomalous heatup was calculated. It was determined that, during this period, calculated UTP flooding retarded drainage of liquid through the upper plenum/bundle interface. That in turn retarded bundle cooling. In a subsequent sensitivity calculation with the CCFL option turned off at the UTP, there was sufficient liquid drainage to prevent the anomalous heatup. As an additional example of anomalous behavior related to CCFL at the SEO, consider Figure 8 which presents peak cladding temperatures for TBL Test LR1. In this case the measured PCT exceeded that calculated because of the higher calculated core mass inventory. This higher mass inventory was a direct consequence of a slower drainage rate through the bundle SEOs relative to data. Again, it was concluded that the CCFL model applied at the SEO tended to produce an undercalculation of the fluid drainage rate. In general, application of the CCFL model at the UTP yielded calculated PCTs which exceeded those measured because of retarded liquid drainage into the core. Application of the CCFL model at the SEOs yielded calculated PCTs which were less than those measured because of retarded liquid drainage out of the core. However, it was concluded the code's CCFL package was sound and that the principal shortcoming was the limited number of CCFL parameter options available to the code user. A further discussion is presented in Section 6.5.

It was concluded that the most significant differences between the measured and calculated PCTs were a consequence of CCFL modeling limitations. As explained above, those differences were biased in one direction depending on the nature of the test facility and test scenario. Using the data from Table 5, the mean difference between the calculated and measured PCTs was -28 K; the two sigma standard deviation was 226 K. That data reduction is not statistically rigorous but was judged sufficient to define an estimated PCT calculational uncertainty for TRAC-BD1 (Version 12).[a]

During the refill/reflood stage of a BWR LOCA, multichannel dynamics become important phenomena governing bundle temperature response. In particular, different flow regimes develop in different bundles depending on the radial location of the bundle. The different flow regimes in turn control localized heat transfer characteristics and resultant cladding temperatures. The three principal regimes identified relative to the SSTF tests were:[b]

1. Co-current upflow in the central, high power bundles

2. CCFL limited flow at the SEO and UTP located in the middle, average powered bundles

3. Liquid down flow located in the peripheral, low powered bundles.

In one channel BWR mockups such as TLTA, the absence of multichannel flow effects can cause the timing for lower plenum and bundle bottom reflood to significantly differ from an equivalent test performed on the SSTF facility.[c]

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a. If it is assumed that the PCT deviation is calculated from a sample of a normally distributed population, then one is 95% confident that the mean deviation between the calculated and measured PCTs occurs in the interval from -120 to 64 K.

b. The SSTF bundle mockups are not powered; thus, rod temperatures were not considered. The SSTF tests are still relevant to bundle heat transfer in the context of measuring temperature-controlling phenomena (namely, multichannel flow dynamics).

c. These differences do not invalidate overall experimental results from few or single channel BWR subscale facilities. Rather, the differences show that specific multichannel phenomena during the reflood/refill phase of a LOCA are an existing experimental data gap in one or few bundle test facilities.

In the course of simulating SSTF tests Runs 26 and 111, code problems related to interfacial heat transfer and water packing were encountered. These two computational problems distorted the calculated vessel mass distribution, resulting in the premature termination of both simulations. Despite those difficulties, the code demonstrated a limited capability to correctly calculate qualitative multichannel flow trends (Appendix H). Because additional computational problems related to numerical diffusion helped to inhibit upper plenum drainage in the Run 111 simulation, that observation applies to the simulation of Run 26 but not to Run 111.[a] Although numerical diffusion affected both SSTF simulations, the degree of severity was larger in the simulation of Run 111 because of differences in ECCS configurations between Runs 111 and 26. Numerical diffusion is further discussed in Section 6.1 as well as nodalization requirements for simulating multi-channel dynamics.

The following conclusions were made relative to the code's capability to simulate bundle temperature response:

1. TRAC-BD1 demonstrated the capability to accurately simulate bundle temperature responses provided bundle liquid mass inventories are correctly simulated.

2. Further improvements in the water packing model are needed to ensure that bundle mass distributions are correctly calculated during BWR LOCA scenarios.

3. Additional input options relative to CCFL modeling are needed to enable the analyst to input additional CCFL coefficients for specific geometries. It was concluded that this limitation was the principal cause of significant differences between the measured and calculated PCTs.

a. In particular, UTP CCFL break down for Run 26 was calculated to occur at 20 s (18 s in test) in the peripheral channels.

6. USER EXPERIENCE AND GUIDELINES

Presented in this section are modeling recommendations to improve the accuracy of a BWR LOCA simulation. The recommendations address the following subjects: numerical diffusion, break modeling, ECCS modeling, water packing, CCFL options, and bundle refill/reflood heat transfer. The recommendations derive from the user experience gained in doing the simulations listed in Table 1.

6.1 Numerical Diffusion

Numerical diffusion is characterized by the artificial convection of fluid between hydrodynamic cells. Moreover, numerical diffusion is inherent to the finite difference solution scheme employed in TRAC-BD1 to solve the hydrodynamic field equations. Coarse nodalization generally exacerbates numerical diffusion problems and can render the simulated results invalid. Minimizing numerical diffusion is especially important if the following key LOCA phenomena are to be correctly simulated:

1. Vessel and piping liquid distribution.

2. Bundle temperature response (which is strongly dependent on Item 1).

3. Break flow behavior (since Item 1 determines upstream break conditions).

Sensitivity studies with finer nodalization (Appendixes B and J) consistently produced better computational results. However, the attendant increase in computational costs can, under some circumstances, make this approach unrealistic. The two-phase level tracking model proposed to be implemented in the next code version (TRAC-BD1/MOD1) is expected to be a more cost effective means of addressing this problem.

Numerical diffusion is thought to be a key contributing factor responsible for earlier calculated jet pump and recirculation line uncovery times (see Table 2). The maximum percentage time deviations between the measured and calculated results for the jet pump and recirculation line uncovery were both approximately 40%.

6.2 Break Modeling

A wide variety of different break configurations were used in the simulated test facilities. It was concluded that no one particular break modeling approach has general applicability. In particular, each break configuration has specific discharge characteristics peculiar to its geometry. In modeling a certain facility, it is therefore important that an empirical data base exist which allows the analyst to judge when break discharge characteristics are important. The TRAC-BD1 choking model is inherently one dimensional and as such cannot account for the complex three dimensional flow fields which can form in the break plane region. The multidimensional effects can significantly change the effective flow area at the break plane. Engineering judgment must also be exercised in determining the nodalization detail of a particular break assembly and regions upstream of the break. If the nodalization is too coarse, numerical diffusion may significantly distort the fluid conditions upstream of the break plane (Appendix B).

6.3 ECCS Modeling

In this particular code version, ECCS modeling required the use of PIPE/FILL combinations to inject fluid into a vessel cell. Generally, when ECCS systems were activated in a simulation, subcooled liquid penetrated into the pipes which were steam filled. The induced condensation in the PIPE components can cause computational difficulties (Appendixes H and G) which can invalidate a simulation. One modeling approach used (Appendix H) to mitigate this problem was to stop the simulation program at the point of ECCS activation, change the fluid conditions in the PIPE component from a steam to a liquid state, and then restart the simulation program. However, that approach is considered an interim solution. Over calculation of depressurization rates caused by unrealistic condensation rates are thought to be a major contributor to the earlier calculated LPCI and LPCS activation times (see Table 2). Maximum percentage time deviations between the measured and calculated ECCS times for HPCS, LPCS, and LPCI are 4%, 20%, and 28% respectively. In future code versions, improvements will be made to the interfacial heat transfer package to reduce the severity of these problems.

6.4 Water Packing

Water packing problems were characterized by a particular hydrodynamic volume transitioning to single-phase liquid conditions accompanied by localized pressure spikes lasting one or more time steps. Sufficiently large pressure spikes can artificially generate appreciable mass flow surges. Moderate flow surges are readily damped out causing relatively little disruption. Relatively large flow surges tend to effect the overall system response and render the simulation invalid. Water packing in its most severe manifestation will cause a simulation to abort (Appendixes E, H, and I). One identified method of reducing the severity of water packing is to reduce the time step on a simulation restart slightly before the onset of water packing. Smaller time steps generally will enable the code user to proceed with the simulation with reduced computational difficulties. However, upgrading the water packing model in future TRAC-BD1 versions is the more realistic approach to solve this problem.

6.5 CCFL Options

In the course of doing the simulations listed in Table 1, it was determined that a broader set of CCFL modeling options are needed. Currently, the TRAC-BD1 CCFL model is restricted to two sets of modeling options which characterize prototypical BWR geometric configurations at SEO or UTF junctions. The CCFL process model employs two sets of Kutateladze-type correlations for those junction types. Moreover, in those correlations the constants which characterize a specific geometry are fixed. Because of the unique geometric differences in junction configurations at the UTP, SEO, bypass/upper plenum, and guide tube/bypass interfaces, CCFL options peculiar to each of those junctions should be available to the code user. In particular, the code user should have the option of inputting geometry-specific constants into the supplied CCFL correlations. Examples of how these limitations affect calculated results are given in Appendixes F and I.

6.6 Bundle Refill/Reflood Heat Transfer

User experience related to modeling bundle heat transfer indicated that simulation of the

refill/reflood stages of a LOCA was the weakest area of code performance. Lessons learned included the following:

1. Relatively coarse nodalization that is adequate for the blowdown stage of a transient may be totally inadequate for refill/reflood conditions. Additional nodalization detail (both radial and axial) may be required to accurately simulate bundle heat transfer during this period.

2. Radiative heat transfer during extended core dryout periods is a significant mechanism for heat removal and must be correctly modeled. In particular, the details of rod-to-rod radiative heat transfer must be accounted for.

Regarding Item 1, finer axial nodalization is required during refill/reflood to suppress numerical diffusion (Section 6.1). Detailed radial nodalization of the vessel internals is required to capture multichannel flow effects. A radial nodalization sensitivity study conducted in Appendix J demonstrated that inherently multichannel facilities (such as the Dresden-III reactor) cannot be approximated with single-channel models during the refill/reflood phase of a LOCA. Figure 9 presents the bundle midplane temperature simulated with both a detailed and a single channel model. The single channel scoping model yielded significantly lower temperatures because of differences in UTP drainage dynamics. In the detailed model, preferential drainage via the peripheral channels produced a more rapid increase in the lower plenum mass inventory (Figure 10) with less cooling in the middle channel region.[a] The single channel model did not adequately simulate bundle temperate responses characteristic of either high or low powered core regions. As a consequence, the single channel approximation is not realistic if PCTs are to be accurately predicted.

With regard to Item 2, sensitivity studies conducted in Appendix A demonstrated that failure to model bundle radiation heat transfer during extended core dryout periods can cause overprediction of bundle temperatures by as much as 200%. It was also shown that, in an 8 x 8 bundle, five rod groups accurately simulate radiation heat transfer. It was judged that the TRAC-BD1 radiative heat transfer package was sound.

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a. Preferential peripheral channel drainage is peculiar to BWR refill/reflood multichannel flow dynamics during most modes of ECCS operation. This was shown in the SSTF test data for test Runs 26 and 111.

7. RUN TIMES

Presented in Table 7 are the run time statistics for the simulations discussed in this paper. The central processor unit (CPU) to real time ratios were a function of both model detail and transient conditions. Because separate effects facilities were modeled with fewer volumes and heat slabs, the associated CPU to real time ratios were smaller. Generally, large break LOCA scenarios had CPU to real time ratios exceeding those of small breaks. The large break LOCAs were characterized by a higher degree of nonequilibrium mixing of subcooled ECCS with saturated steam and higher localized steam velocities. Those two phenomena tended to reduce the numerical time steps in all the LOCA simulations.

By making purely empirical observations from Table 5, the following estimates relative to run time statistics were made:

1. Large input models (150-230 cells) have CPU to real time ratios in the range of 60-250.

2. Medium sized models (with 60-150 cells) have CPU to real time ratios of 10-150.

3. Small models (with less than 60 cells) have CPU to real time ratios in the range 10-50.

Depending on transient conditions, the estimated CPU to real time ratios for large break LOCAs tended towards the higher estimates, especially during the refill/reflood transient phase.

8. CONCLUSIONS

The TRAC simulations of various test transients revealed that overall calculated trends generally can be adequately simulated when the correct modeling strategy is employed. With the correct modeling constraints, TRAC-BD1 (Version 12) calculates reasonable results for a wide range of conditions typically encountered in various BWR LOCA scenarios.

The TRAC-BD1 code is continuing to evolve to meet the analytical requirements for accurately simulating BWR transients. The code's strongest areas of performance are in simulating pressure response, event timings, and break flow behavior. The code also demonstrates the capability to simulate multi-channel flow phenomena. Areas requiring additional improvement include interfacial heat transfer, water packing, and CCFL input options. Also, a level tracking model should be added to reduce the effects of numerical diffusion. These improvements have or will be incorporated into future versions of TRAC-BD1.

Observations concerning code accuracy relative to key code parameters are:

1. The estimated calculational PCT two sigma uncertainty and mean temperature difference between the calculated and measured PCT were 226 K and -28 K respectively.

2. Application of the CCFL model was judged to be the principal reason for significant differences between measured and calculated PCTs.

3. Maximum percentage deviations between measured and calculated ECCS events for HPCS, LPCS and LPCI are 4%, 20% and 28% respectively.

4. Although ECCS event timings were generally in good agreement, in most simulations faster depressurization rates resulted in early activation of low pressure systems.

5. Overcalculation of ECCS induced steam condensation rates is thought to be a major cause of overcalculating depressurization rates.

6. Maximum percentage time deviations between calculated and measured jet pump uncovery and recirculation line uncovery were both approximately 40%.

7. Calculated uncovery rates generally occurred slightly sooner than those measured. Numerical diffusion was a major cause of the faster uncovery rates.

The following lessons were learned relative to user experience and modeling guide lines:

1. Finer nodalization will minimize numerical diffusion problems. This is particularly true if uncovery times for the jet pump suctions or recirculation lines are to be accurately simulated. However, the two phase level tracking model proposed to be implemented in future code versions is expected to be a more cost effective means of addressing this problem.

2. Generally, modeling stored energy or ambient heat losses is important if system pressure response is to be correctly simulated.

3. A more general set of CCFL modeling options are required to simulate liquid drainage at the vessel UTP or SEOs.

4. Model enhancements of the interfacial heat transfer package will improve the calculated pressure response.

5. Correctly modeling a particular break configuration is dependent on a reliable data base. The analyst should know the discharge coefficients associated with the particular break configuration.

6. Multi-dimensional BWR mockups or facilities cannot always be approximated with one dimensional models. In particular, multi-channel flow dynamics during the refill/reflood phase of a LOCA cannot be adequately simulated with one dimensional models.

7. CPU real time ratios (which ranged from 10 to 250) increased significantly with larger model cell numbers. The CPU to real time ratios tend toward higher values during large break LOCA simulations.

Significant reductions in code parameter uncertainties can be realized by implementing the above guidelines. Most importantly, improvements in the calculated PCT, time to PCT, ECCS timing, jet pump suction uncovery, and recirculation line uncovery will result. However, relative to TRAC-BD1 the calculated event timings for most simulations reported in this paper were not significant contributors to observed uncertainties in the calculated PCTs.

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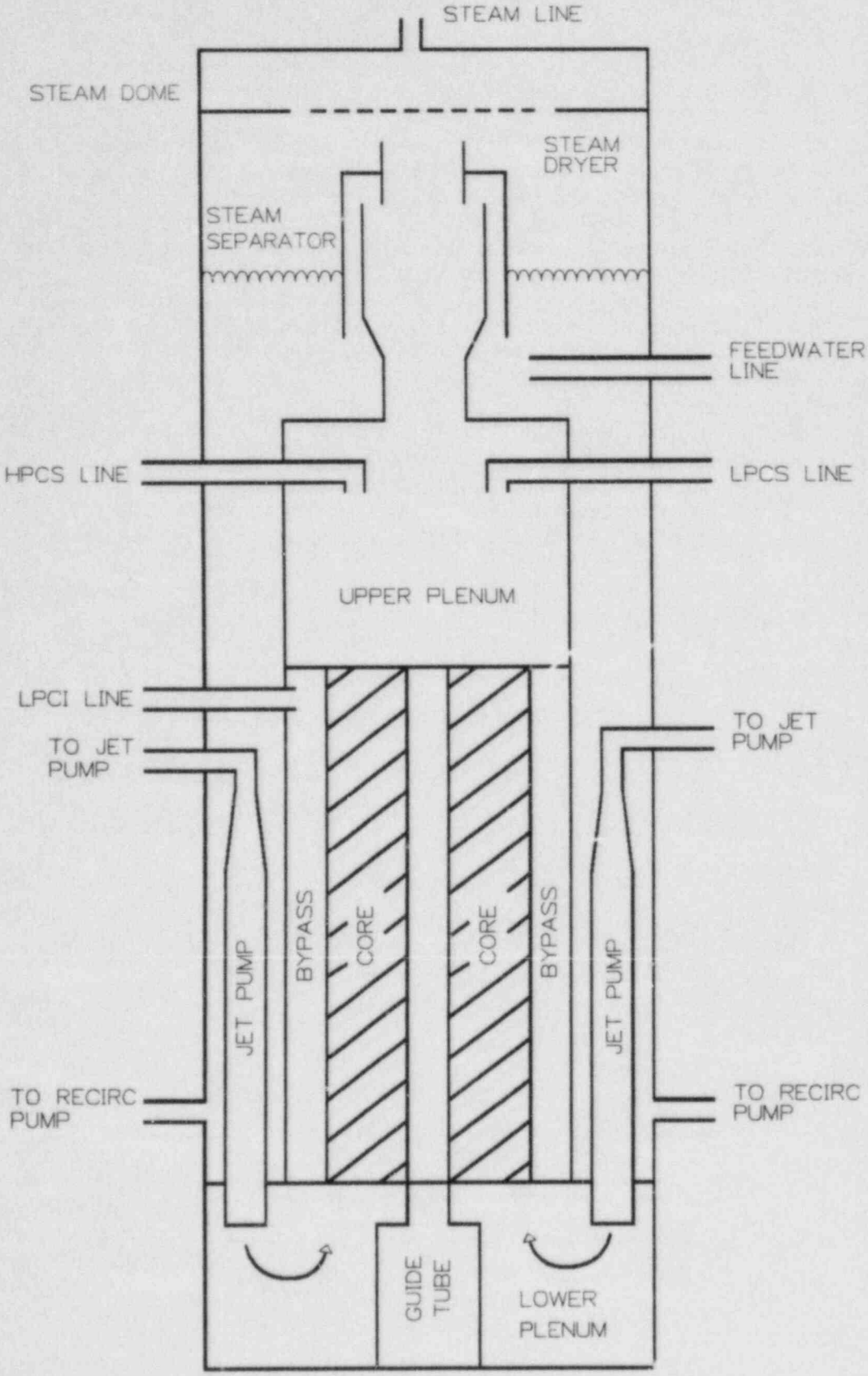


Figure 1. Generic BWR subscale facility diagram.

NST00082

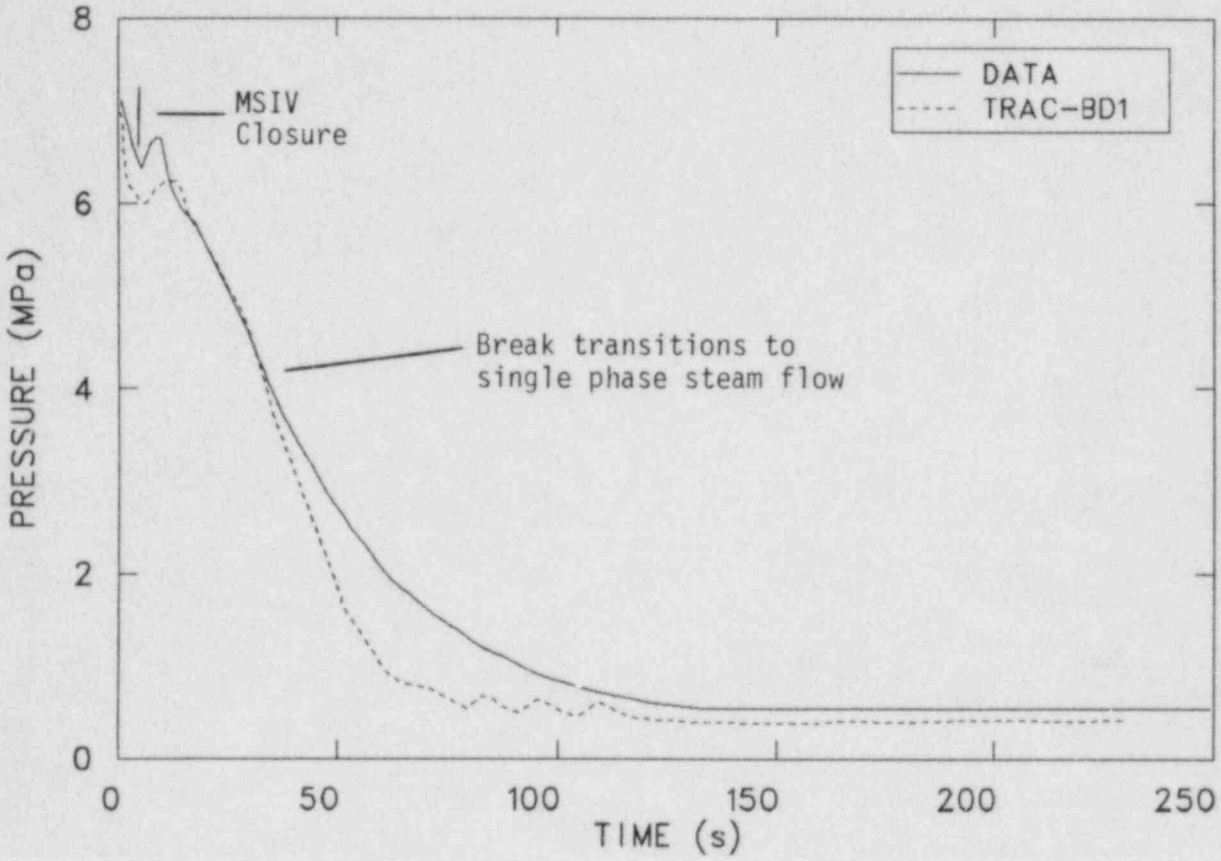


Figure 2. Comparison of measured and calculated steam dome pressures for TLTA Test 6423.

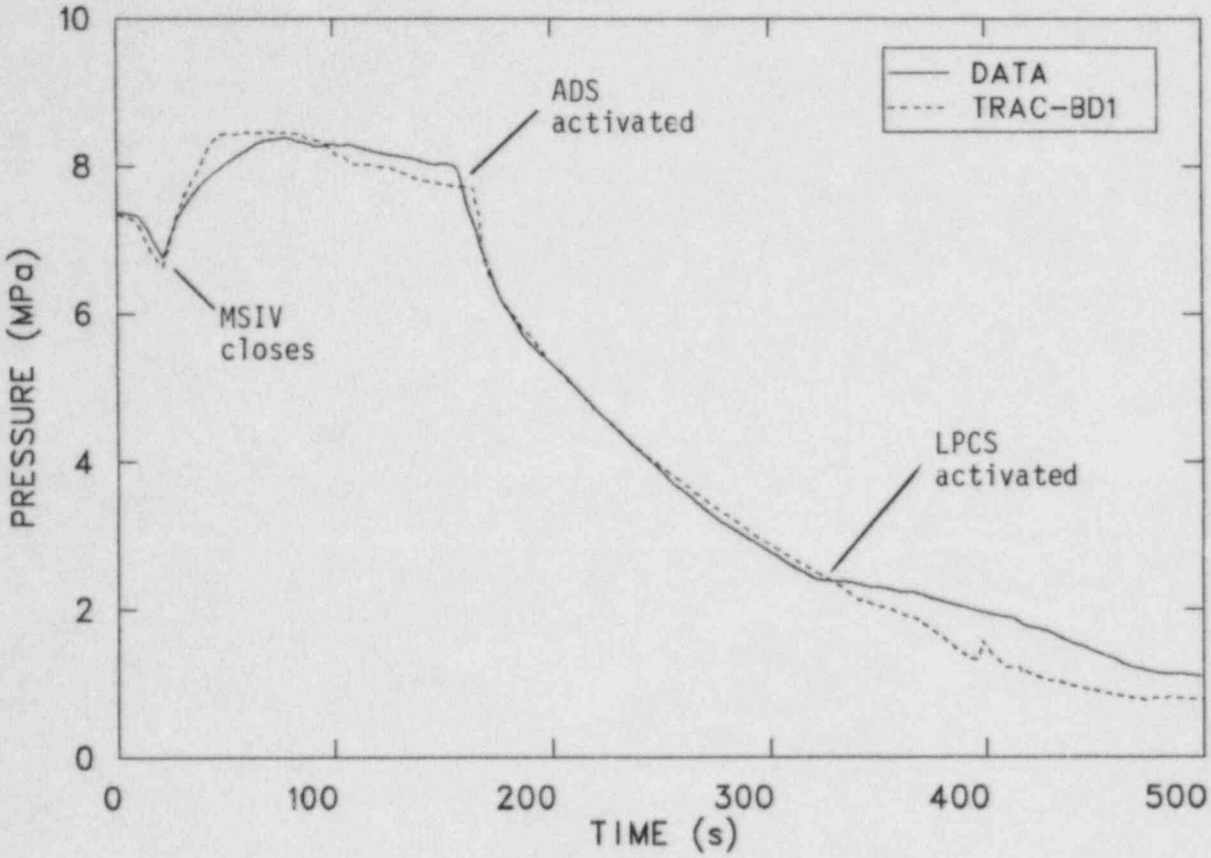


Figure 3. Comparison of measured and calculated steam dome pressures for ROSA-III Test 912.

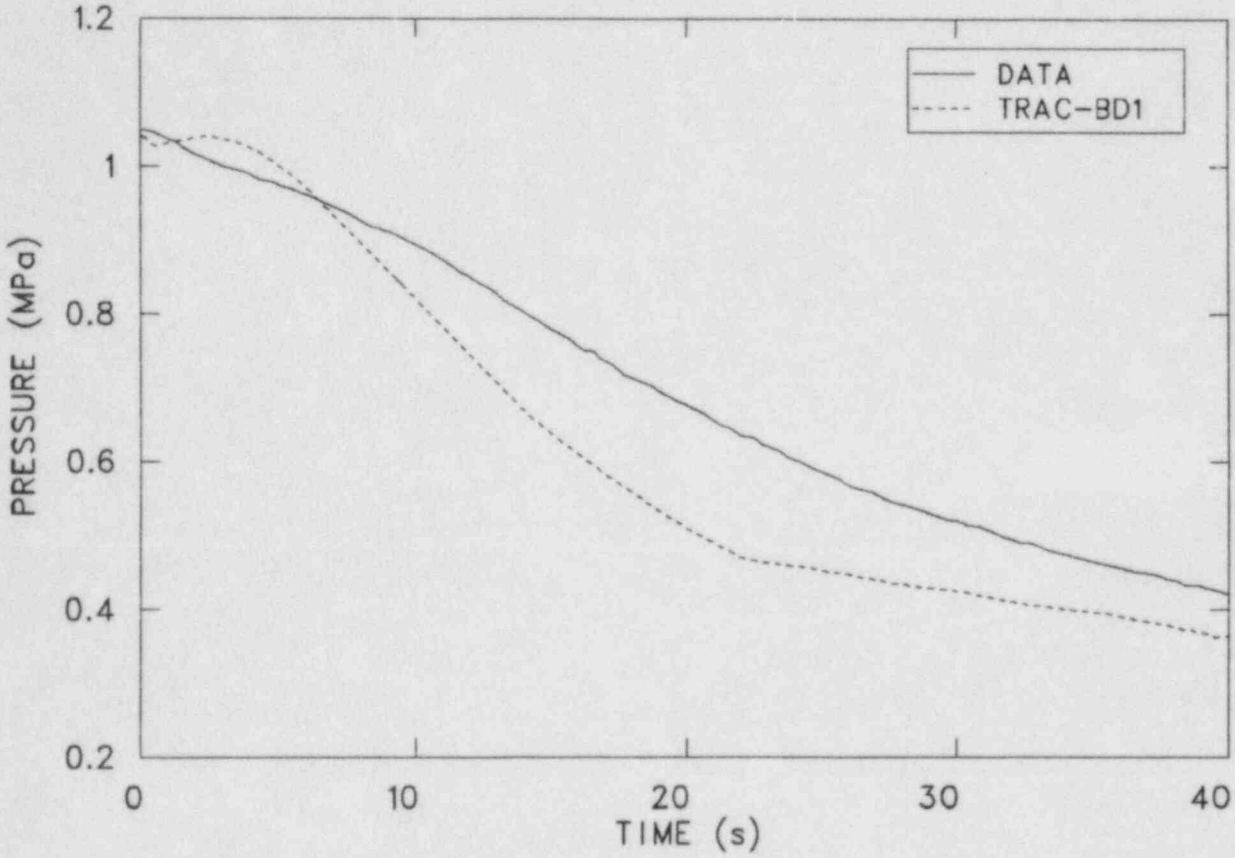


Figure 4. Comparison of measured and calculated upper plenum pressures for SSTF Test EA3.1 Run 111.

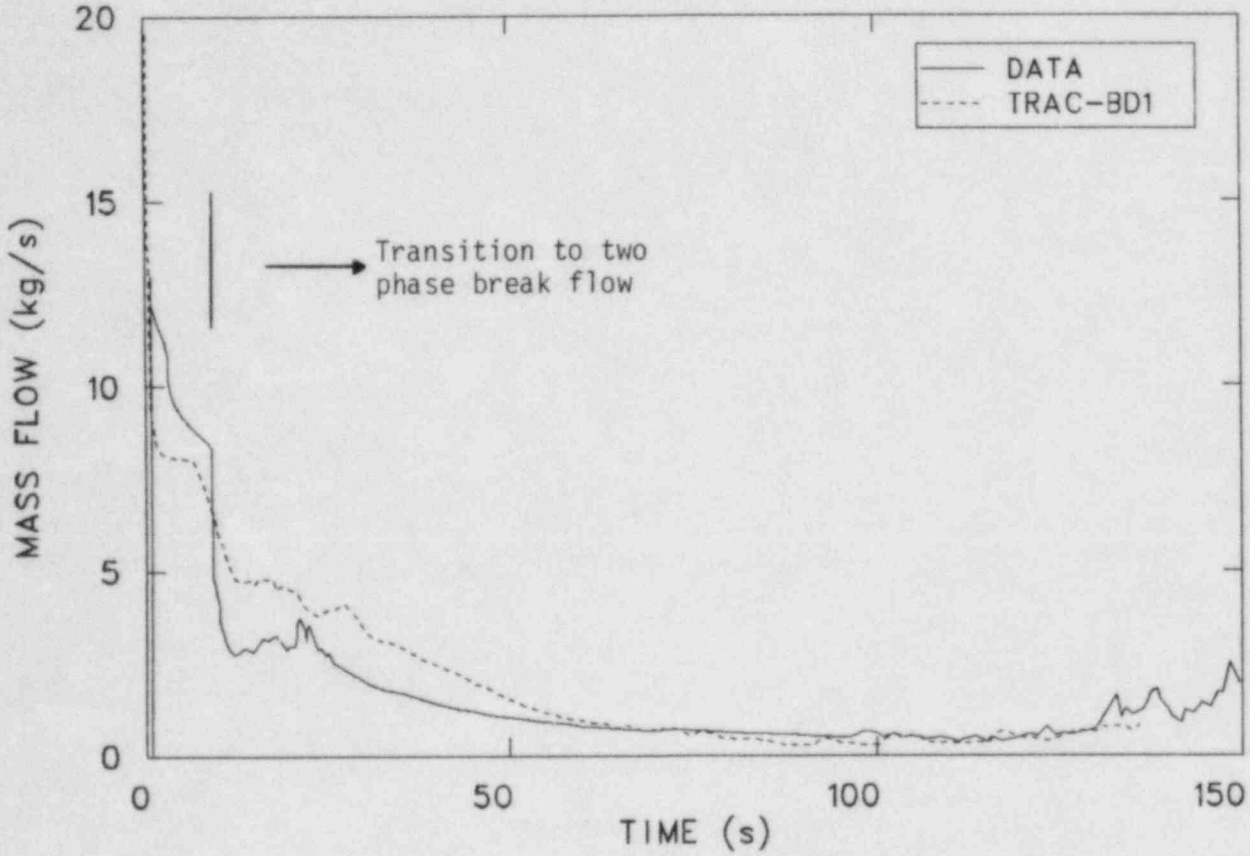


Figure 5. Comparison of measured and calculated suction side break mass flow rates for Test 6425.

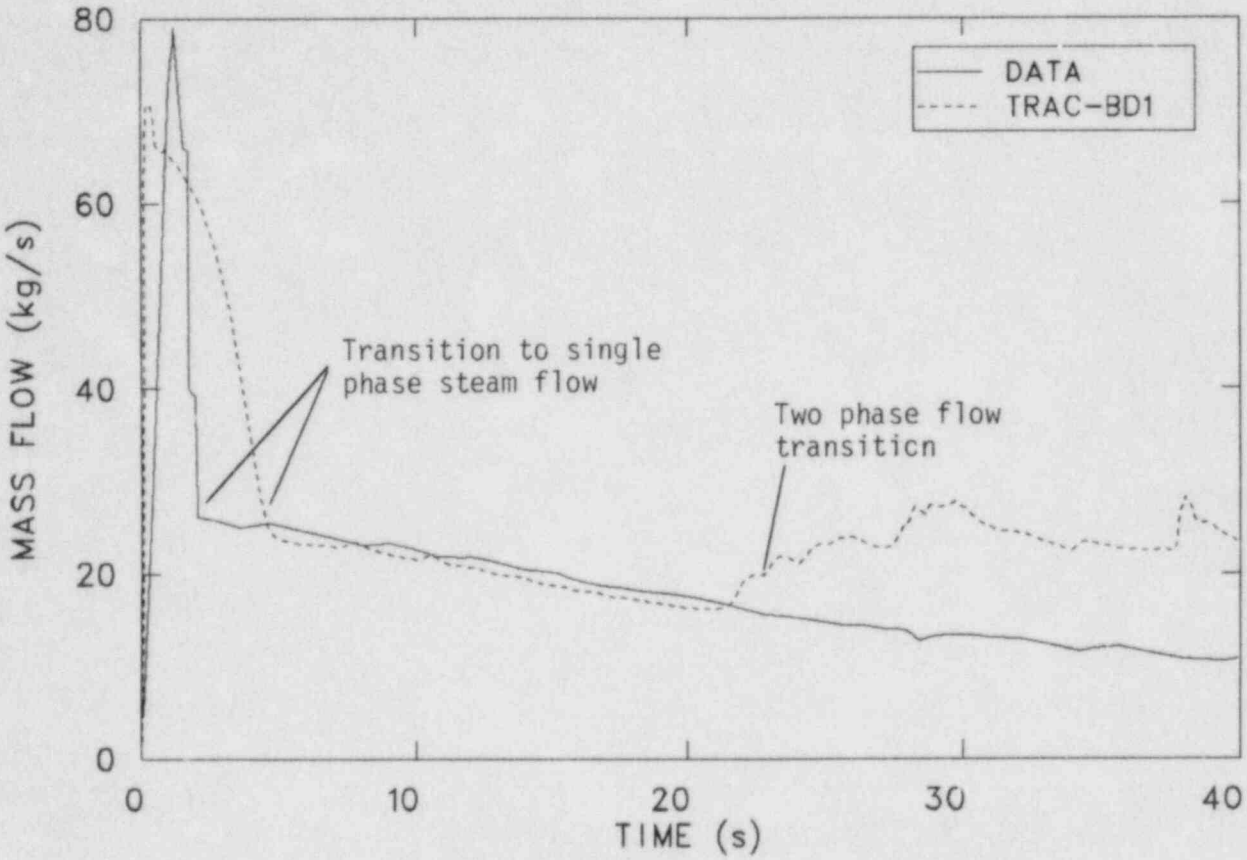


Figure 6. Comparison of measured and calculated break mass flow rates for SSTF Test EA3.1 Run 111.

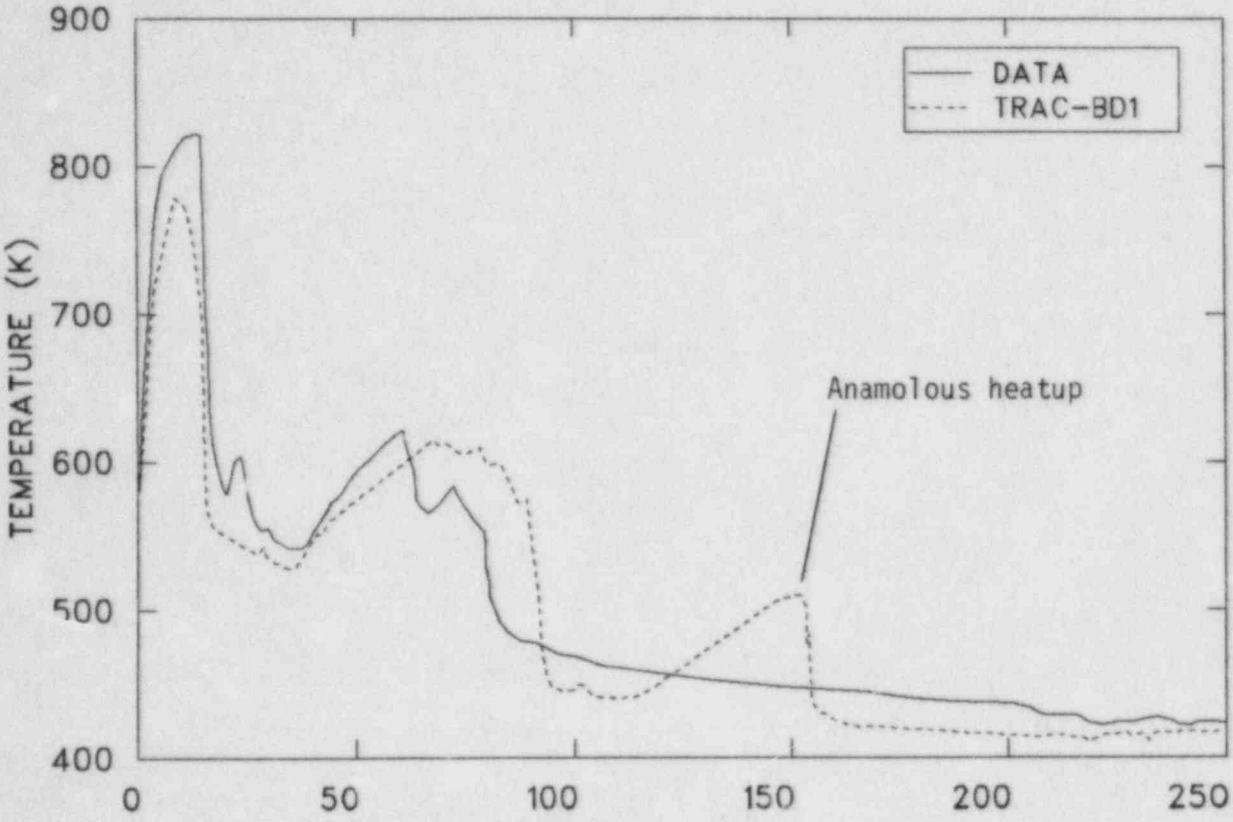


Figure 7. Comparison of measured and calculated rod temperatures at 3.05 m above BHL for TLTA Test 6424.

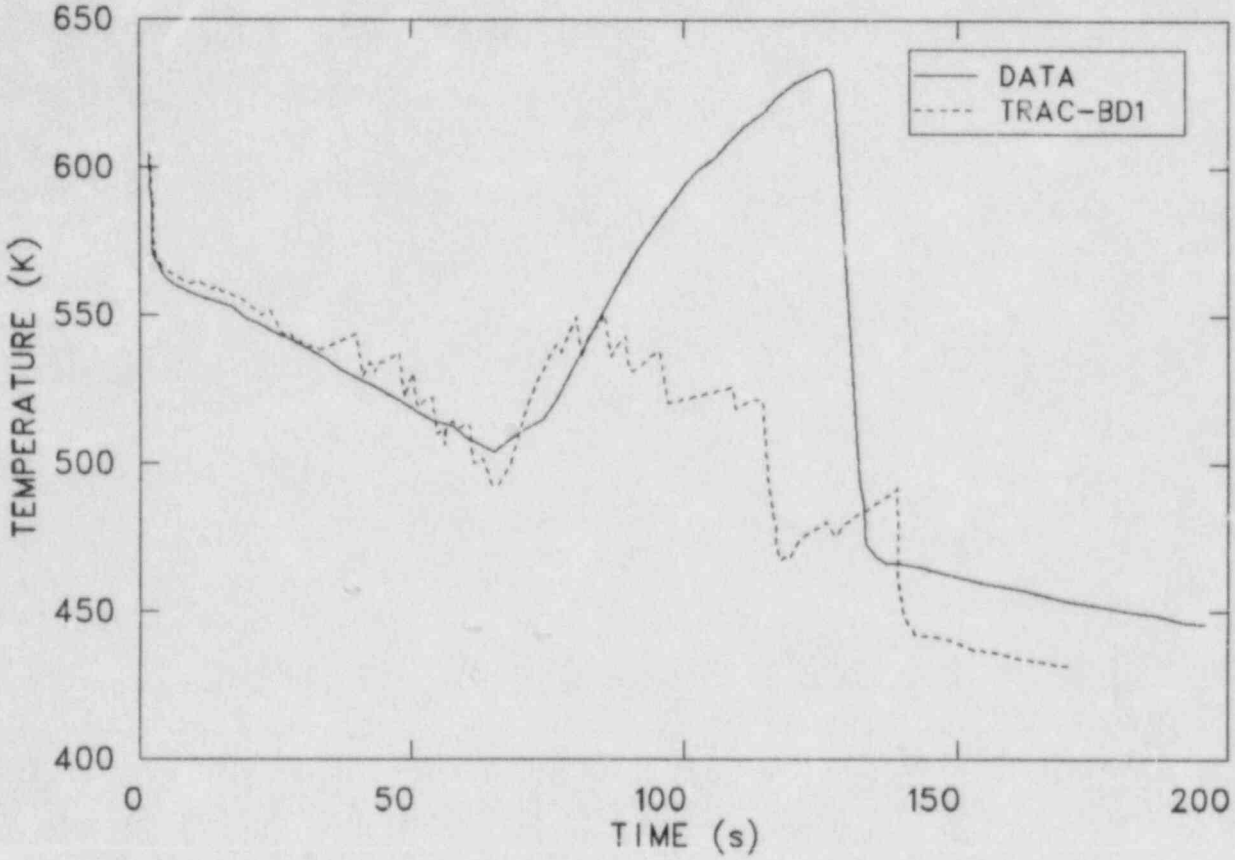


Figure 8. Comparison of measured and calculated cladding temperatures for TBL Test LR1.

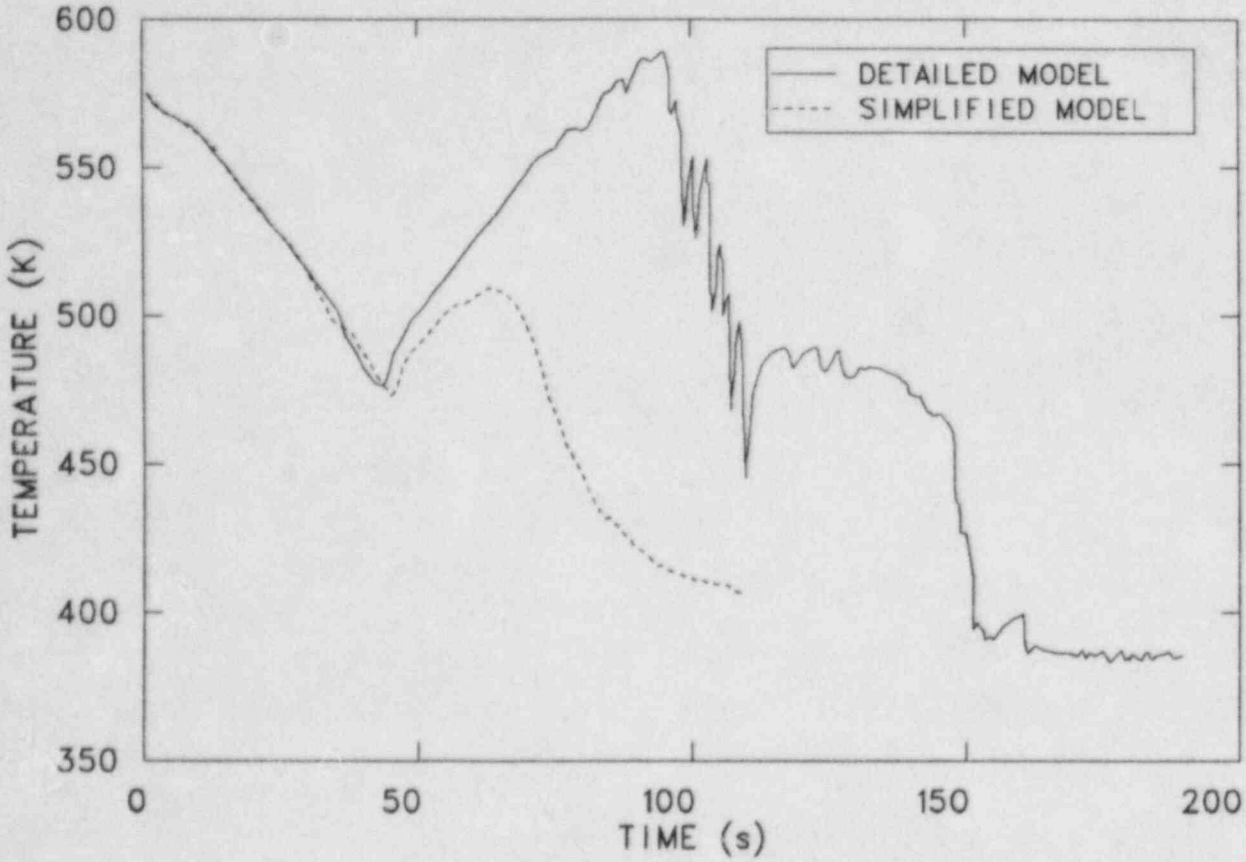


Figure 9. Comparison of mid plane cladding temperatures for detailed and simplified models for a 200% break.

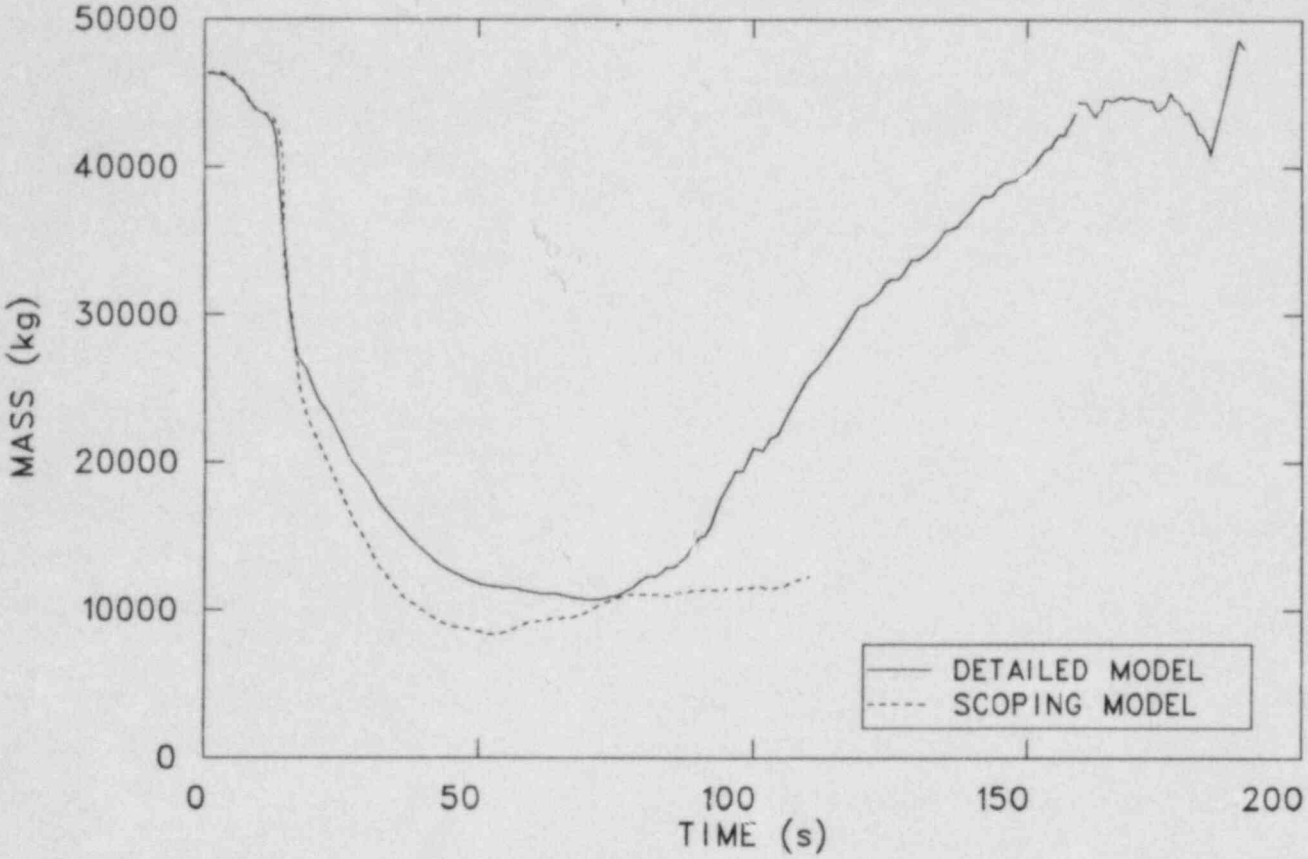


Figure 10. Comparison of lower plenum mass inventories for detailed and simplified models for a 200% break.

Table 1. Test descriptions

Facility	Test Designation	Test Description
GOTA bundle heat transfer (separate effects facility)	11	Bundle radiation heat transfer test.
	42	Reflood heat transfer test.
Marviken blowdown (separate effects) facility	15 and 24	Large break blowdown test for subcooled and saturated conditions.
FRIGG (fuel bundle forced/natural circulation separate effects)	301047	Natural circulation flow stability and burnout test.
	613130	Forced circulation fuel bundle void distribution test.
TBL (scaled BWR/5-251 integral facility)	LR1	Large recirculation line break test with HPCS, LPCS, LPCI.
	LR2	Large break recirculation line test, with LPCS and LPCI.
	SR1	Small break recirculation line test, with LPCS and LPCI.
	LR3	Large break recirculation line test with BWR/4 ECCS configuration, with LPCI.
TLTA (scaled BWR/6-218 integral facility)	6425	Large break (DBA) with average flow, average temperature ECCS (with HPCS, LPCS, and LPCI).
	6426	Large break (DBA) with no ECCS.
	6423	Large break (DBA) with high temperature, low flow ECCS (with HPCS, LPCS, and LPCI).
	6424	Large break (DBA) average temperature ECCS (with HPCS, LPCS, and LPCI).
TLTA	6431	Small break recirculation line test with HPCS.
	6432	Small break recirculation with LPCS and LPCI.
ROSA-III (scaled BWR facility)	RUN 912	Small recirculation line break with LPCS and LPCI.

Table 1. (continued)

Facility	Test Designation	Test Description
SSTF (scaled BWR/6 30° sector integral facility)	SRT-3 RUN 26	Large break DBA reflood/refill test BWR/6 ECCS configuration with HPCS, LPCS, and LPCI.
	EA3.1 RUN 111	Large break DBA reflood/refill test BWR/4 ECCS configuration with LPCS and LPCI.

Table 2. Summary of key event timings

Test[a]	Time to HPCS (s)		Time to LPCS (s)		Time to LPCI (s)		Time to Jet Pump Suction Uncovery (s)		Time to Recirculation Line Uncovery (s)	
	Measured	Calculated	Measured	Calculated	Measured	Calculated	Measured	Calculated	Measured	Calculated
912 (ROSA-III small break LOCA)	Not used	Not used	318	327	406	367	100	80	150	111
LR1 (TBL large break LOCA)[b]	30	30	93	93	116	116	6	7	15	16
LR2 (TBL large break LOCA)	Not used	Not used	81	65	93	71	5	7	15	16
SR1 (TBL small break LOCA)	Not used	Not used	508	481	593	547	165	155	420	360
LR3 (TBL large break LOCA)	Not used	Not used	Not used	Not used	65	47	4	4	12	9
6423 (TLTA DBA LOCA)	27	27	65	53	72	56	8	8	11	10
6424 (TLTA DBA LOCA)	27	28	63	52	71	56	7	6	11	9
6425 (TLTA DBA LOCA with ECC)	27	26	63	52	75	56	7	6	7	4
6426 (TLTA DBA LOCA without ECC)	Not used	Not used	Not used	Not used	Not used	Not used	7	8	9	9
6431 (TLTA small break LOCA)[c]	26	27	Not used	Not used	Not used	Not used	—	—	—	—
6432 (TLTA small break LOCA)	Not used	Not used	433	438	458	458	—	—	—	—

a. The SSTF simulations were initiated from conditions such that the ECCS systems had been activated and the jet pump suction and recirculation line were uncovered.

b. Time dependent trips were employed so that ECCS was automatically activated at times which ECCS was activated in the experiment.

c. Jet pump and recirculation line uncovery did not occur.

Table 3. Summary of simulated pressure responses

Test	Results	Comments
RUN 912 (ROSA-III small break LOCA)	Pressure response generally well calculated. Pressure somewhat undercalculated after LPCS initiation.	LPCS fluid held up in upper plenum caused undercalculation in steam inventory and resultant pressure response. Additional steam would have been generated via rod to fluid heat transfer if additional LPCS had drained into the bundle region.
RUN 26 (SSTF DBA LOCA)	Pressure response not adequately calculated. Initial overcalculation in the depressurization rate resulted in undercalculated pressure.	Underestimating vessel metal mass stored energy identified as one possible cause for undercalculation of pressure response. Additional metal mass to liquid heat transfer would increase vapor production and therefore pressure.
RUN 111 (SSTF DBA LOCA)	Pressure response not adequately calculated. Initial overcalculation in the depressurization rate resulted in undercalculated pressure.	Excessive steam condensation triggered by LPCI operation was identified as additional cause of overcalculated depressurization rate. Overcalculated steam condensation was believed to be due to deficiencies in the code interfacial heat transfer package.[a]
LR1 (TBL large break LOCA)	Generally pressure trends well calculated relative to data. Following HPCS initiation depressurization rate was overcalculated.	Suspect limitations in code interfacial heat transfer model resulted in overcalculated steam condensation during period of overcalculated depressurization.[a]
LR2 (TBL large break LOCA)	Generally pressure trends well calculated relative to data. After 50 s the depressurization rate was overcalculated.	Suspect code interfacial heat transfer model is overcalculating steam condensation during period of overcalculated depressurization rate.[a]
SR1 (TBL small break LOCA)	Pressure response well calculated relative to data.	Slight differences in measured and calculated pressures existed as a consequence of SRV operation. More flow was calculated to exit through the SRV as a consequence of probably undercalculating ambient heat losses.
LR3 (TBL large break LOCA)	Depressurization rate was overcalculated.	Water packing severely distorted calculated results and produced a premature code abort.
6425 (TLTA DBA with ECC)	Generally, pressure response adequately calculated. Initial depressurization rate slightly overcalculated.	Most probable cause of initial overcalculated depressurization rate was an overcalculated initial volumetric break flow rate.[a]

Table 3. (continued)

Test	Results	Comments
6426 (TLTA DBA without ECC)	Generally, pressure response adequately calculated. Initial depressurization rate overcalculated.	The simulated pressure trends between Tests 6425 and 6426 qualitatively matched the experimental trends. Namely, the test without ECC depressurized at a faster rate.
6423 (TLTA DBA LOCA)	Pressure response adequately calculated for most of transient. Between 35 and 120 s pressure was undercalculated.	The undercalculation in system pressure during the period from 35 to 120 s was a consequence of a larger break volumetric flow during this period.[a]
6424 (TLTA DBA LOCA)	Pressure response adequately calculated for most of transient.	Temporary period of initially overcalculated depressurization caused by overcalculation in volumetric break flow rate.[a]
6431 (TLTA small break LOCA)	Pressure response adequately calculated for most of the transient.	Suspected overcalculation of the break volumetric flow rate caused a more rapid depressurization at the end of the transient.[a]
6432 (TLTA small break LOCA)	Pressure response adequately calculated for most of the transient. After 165 s calculated pressure was slightly higher than the measured.	The higher calculated pressure was a consequence of the measured break mass flow rate being slightly larger than the calculated.

a. This conclusion was inferred from the data since a direct one to one comparison for this parameter did not exist.

Table 4. Summary of simulated break flow responses

Test	Results	Comments
15 and 24 (Marviken separate effects large break)	Two-phase saturated break mass flow rate well calculated. Subcooled blowdown mass flow rate was not adequately calculated.	Errors were identified in subcooled choking model.[a] Break flow results are sensitive to choke plane location and nodalization.
Run 912 (ROSA-III small break LOCA)	Calculated break mass flow rate was within experimental uncertainties.	Because of large data uncertainties in the break flow measurement, reasons for deviations between measured and calculated results could not be clearly defined.
Run 26 (SSTF, DBA, LOCA)	Initial break mass flow rate overcalculated. After both measured and calculated break flows transitioned to single phase steam the mass flow rates were in good agreement.	Numerical diffusion prolonged the initial period during which the calculated break flow was at two-phase conditions.
Run 111 (SSTF, DBA, LOCA)	Break mass flow rate adequately calculated for single phase steam conditions. During substantial part of calculation breakflow not correctly calculated because break upstream conditions were wrong.	Numerical diffusion caused unrealistic amounts of liquid convection to the break junction during a substantial part of the simulation.
LR1 (TBL large break LOCA)	Generally, calculated results compared well with data. There were some periods of overcalculated break mass flow rate.	Calculated break junction upstream conditions were affected by liquid convection through the steam separator and jet pump during lower plenum flashing. This caused a temporary period of overcalculated break mass flow rate.
LR2 (TBL large break LOCA)	Generally, break mass flow rate adequately calculated. Although after 45 s the calculated break mass flow rate was somewhat less than measured.	Differences in measured and calculated break mass flow rates were consequence of differences in calculated and measured break upstream conditions. Most probable cause was undercalculation of liquid convection from the vessel to the break junction.
SR1 (TBL small break LOCA)	No break flow measurement available to make comparisons with calculated results.	—
LR3 (TBL large break LOCA)	—	Water packing problems caused a premature code abort, making comparisons between measured and calculated mass break flow rates questionable.

Table 4. (continued)

Test	Results	Comments
6423 and 6424 (TLTA DBA LOCA)	Generally, breakflows adequately calculated.	Calculated conditions upstream of break junction transitioned to two-phase conditions too soon. This caused calculated volumetric breakflow to initially exceed the measured.
6425 and 6426 (TLTA DBA with ECC)	The subcooled mass flow rate was undercalculated and the two-phase mass flow rate overcalculated. The calculated subcooled and two-phase break flow rates were judged to be adequate since they were within data uncertainty bands. Single phase vapor break mass flow rate was well calculated.	Principal cause of noted differences consequence of differences in calculated break junction upstream conditions, particularly the void fraction.
6431 (TLTA small break LOCA)	Generally breakflow was adequately calculated. Slight undercalculation of break mass flow rate occurred between 50 and 300 s. Suspected overcalculation of break volumetric rate occurred at end of calculation.	Most probable cause of calculated break flow differences was a too coarsely noded break assembly.
6432 (TLTA small break LOCA)	Generally breakflow was adequately calculated. The break mass flow rate was slightly under calculated.	Most probable cause of undercalculated break mass flow rate was a too coarsely noded break assembly.

a. These coding errors in the prerelease version were corrected in released TRAC-BD1 (Version 12) code.

Table 5. Summary of measured and calculated key bundle parameters[a]

Test	Time to Dryout (s)		Peak Clad Temperature (K)		Time to PCT (s)		Time to Core Quench (s)	
	Measured	Calculated	Measured	Calculated	Measured	Calculated	Measured	Calculated
912 (ROSA-III small break LOCA)	200	7	776	665	330	397	444	410
LR1 (TBL large break LOCA)	38	40	663	624	140	77	155	158
LR2 (TBL large break LOCA)	36	48	802	682	165	111	220	130
SR1 (TBL small break LOCA)	300	162	852	785	635	554	690	595
6423 (TLTA DBA LOCA)	30	40	652	840	232	182	230	230
6424 (TLTA DBA LOCA)	1.3	0.7	830	875	5	12	150	160
6425 (TLTA DBA LOCA with ECC)	23	46	575	612	45	112	150	124
6426 (TLTA DBA LOCA without ECC)	22	42	1077	923	295	294	—[b]	—[b]

a. Inherent to discrete volume modeling, the code calculates volume average parameters. To provide meaningful comparisons, the experimental data must also be of the same form. Thus, the measured data shown on this table represents volume averages where the volumes were defined by the model nodalization. For example, if a specific volume in the model encompasses a geometric region of the core which contained three experimental thermocouples, then the measured PCT would be derived as the peak temperature of the average of those three thermocouples. It should be noted that this data reduction technique becomes less and less satisfactory as the number of thermocouples in a volume approach one, because each thermocouple represents a very local condition within each volume.

b. No quench developed since no ECC was used.

Table 6. Summary of simulated bundle temperature responses

Test	Results	Comments
301047 and 613130 (FRIGG separate effects test)	Subcooled boiling model allowed code to adequately simulate bundle void distributions.	There was evidence that the code interfacial heat transfer model may produce premature condensation.
42 (GOTA separate effects bundle quench test)	Calculated heater rod quenching occurred approximately 20 s earlier relative to the experiment.	The premature calculation of of quenching was the consequence of overcalculating steam generation in the bundle region. The calculated rod quench was accompanied by unrealistic vapor velocities which enhanced bundle cooling. Finer bundle nodalization would help to reduce these computational distortions.
11 (GOTA separate effects bundle radiative heat transfer)	Radiative heat transfer can be correctly simulated if the correct modeling techniques are employed.	A single rod group should not be used when significant radiative heat transfer is expected. Five rod groups have produced good results.
912 (ROSA-III small break LOCA)	Calculated bundle temperature response not adequately calculated.	Anomalous heatups occurred as consequence of undercalculating upper plenum liquid drainage into bundle region. Errors in interfacial shear package were identified as the cause of this difficulty.[a]
LR1 (TBL large break LOCA)	Most trends adequately calculated.	CCFL at the SEOs inhibited bundle drainage. This caused undercalculation of PCT. Calculated bundle multichannel flow trends were well calculated.
LR2 (TBL large break LOCA)	Calculated heatup times agreed with data but quench times were too early.	Early calculated depressurization activated low pressure ECCS too soon, causing earlier quench (and lower PCT) during reflood. CCFL model tended to inhibit liquid downflow at bundle SEOs.
SR1 (TBL small break LOCA)	Temperature trends adequately calculated for most of transient.	Early reflood caused lower PCT and earlier rod quench times.
LR3 (TBL large break)	Prior to water packing difficulties, timing of rod dryouts and heatup rates were calculated well.	Later in transient water packing problems distorted calculated temperature responses.

Table 6. (continued)

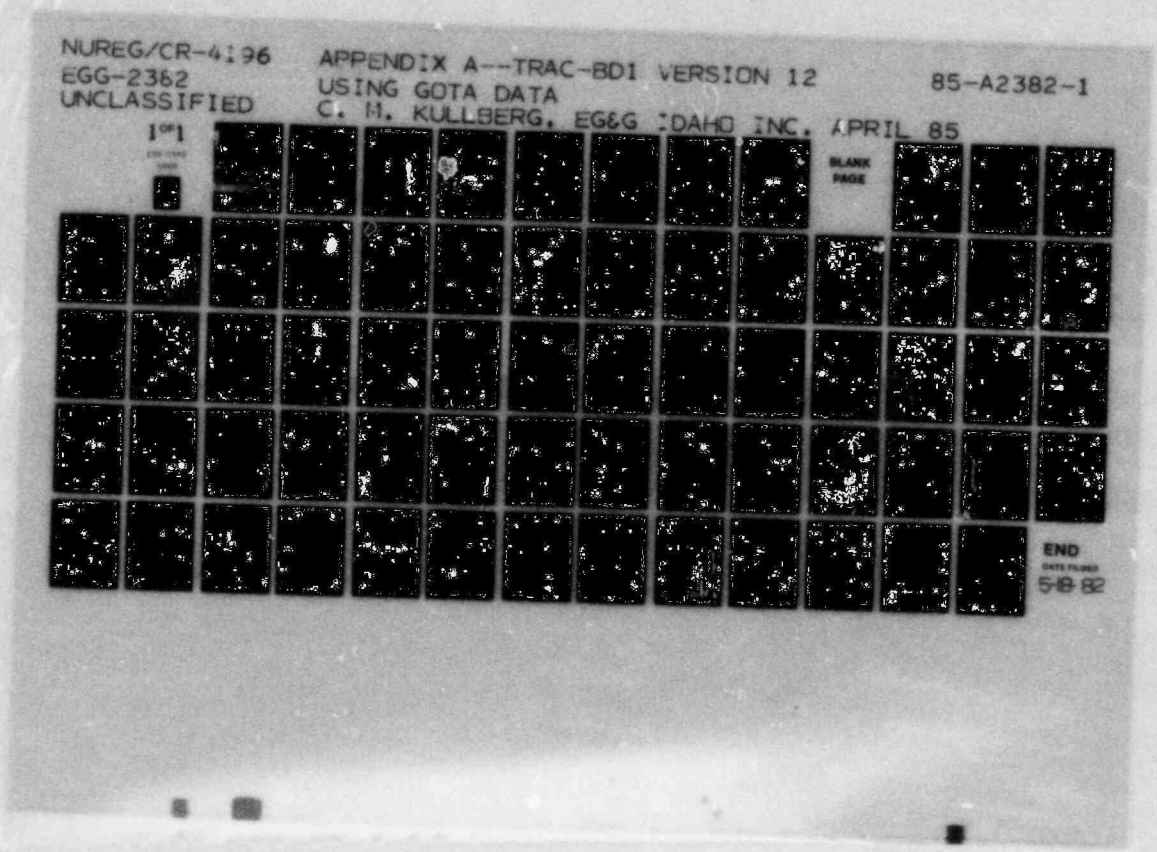
Test	Results	Comments
6423 (TLTA DBA LOCA)	Temperature responses at most rod locations adequately calculated.	CCFL at the UTP tended to limit liquid downflow relative to data. This caused some simulated temperatures to exceed test data.
6424 (TLTA DBA LOCA)	Temperature responses at most rod locations were adequately calculated.	Calculated limitations in UTP CCFL downflow triggered a spurious rod heatup. This heatup was avoided when simulation was restarted with UTP CCFL option turned off.
6425 (TLTA DBA with ECC)	Calculated temperatures slightly below measured. Generally trends were adequately calculated.	Undercalculation of temperatures was in part due to identified coding errors in heat transfer package.[a]
6426 (TLTA DBA without ECC)	Calculated timing events and heater rod temperatures generally matched test data.	Simulated bundle heat transfer for highly voided core was judged to be good.
6431 (TLTA small break LOCA)	Temperature responses at most rod locations were somewhat above test data but still adequately simulated.	Simulated CCFL UTP drainage tended to produce less down flow into the bundles. This produced higher calculated temperatures.
6432 (TLTA small break LOCA)	Temperature responses were adequately calculated.	CCFL limitations tended to retard ECCS drainage from the UTP to fuel bundles. Despite overcalculated UTP holdup sufficient bundle liquid existed to prevent spurious rod heatups.

a. This analysis was performed with a prerelease code version. These identified errors were corrected the released version of TRAC-BD1 (Version 12).

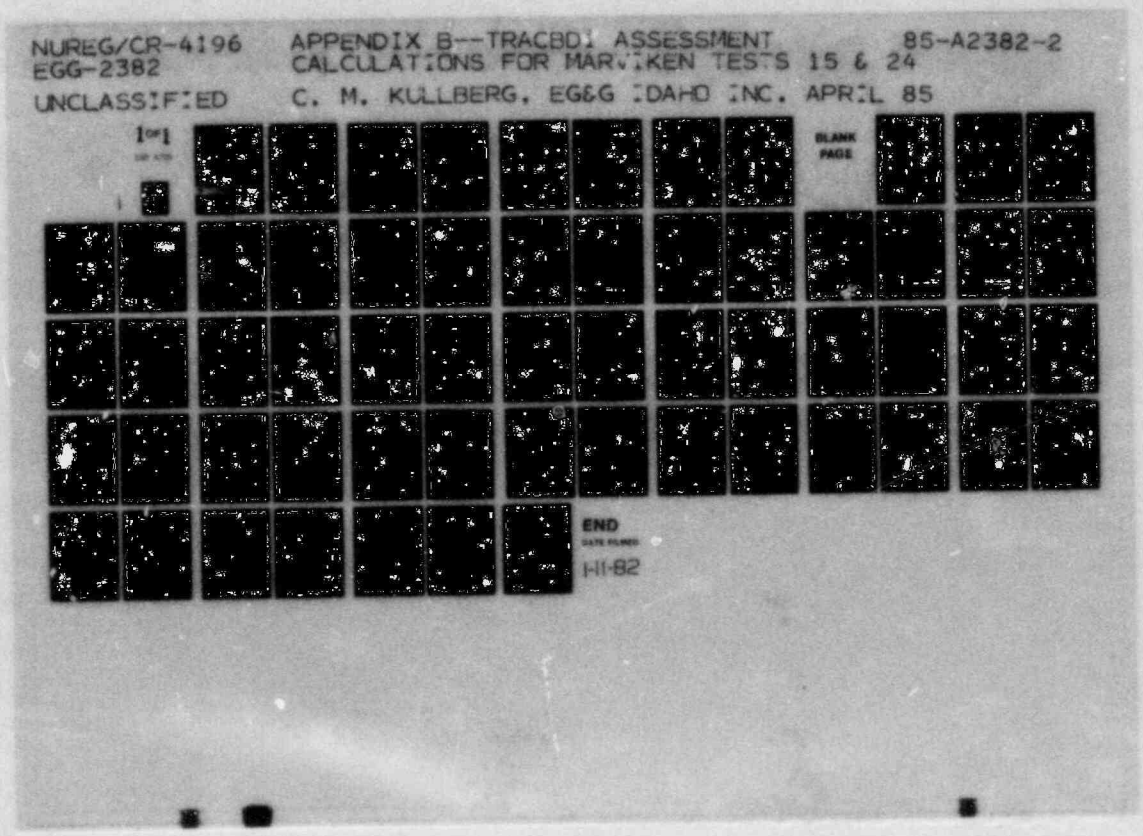
Table 7. TRAC-BD1 Code Assessment timing statistics (all calculations performed on a CDC 176 computer)

Facility and Test No.	Type of Test	Transient Length (s) (RT)	Number of Cells 1-D	Number of Cells 3-D	Total (c)	Number of Heat Transfer Surfaces	Number of Time Steps (DT)	Total CPU Time (s)	CPU RT	CPU (100) (RT) (c)	CPU (1.E6) (RT) (c) (DT)	CPU (1000) (c) (DT)
TLTA 6423	DBA	230	68	26	94	110	67,568	18,951	82	88	13	2.98
TLTA 6431	Small break	1500	80	32	112	150	52,812	16,504	11	10	2	2.79
ROSA-III 912	Small break	500	106	36	142	131	84,116	32,500	65	46	5	2.72
TBL LR1	Large break	170	157	76	233	282	41,857	37,744	222	95	23	3.87
TBL LR2	Large break	163	157	76	233	282	43,251	40,040	245	105	24	3.97
TBL SR1	Small break	600	151	57	208	198	57,537	33,853	56	27	5	2.83
SSTF SRT-3 Run 26	Large break reflood	37	65	40	105	102	8,242	5,038	136	130	157	5.82
SSTF EA3.1 Run 111	Large break reflood	40	63	40	103	102	9,303	6,172	154	150	161	6.44
BWR/3	200% break	190	108	52	160	206	27,150	32,300	170	106	39	7.44
GOTA 42	Core spray reflood	176	21	26	47	60	41,178	8,273	47	100	24	4.27
MAR-VIKEN 15	Hot vessel blowdown	60	56	0	56	0	7,995	589	10	18	22	1.32

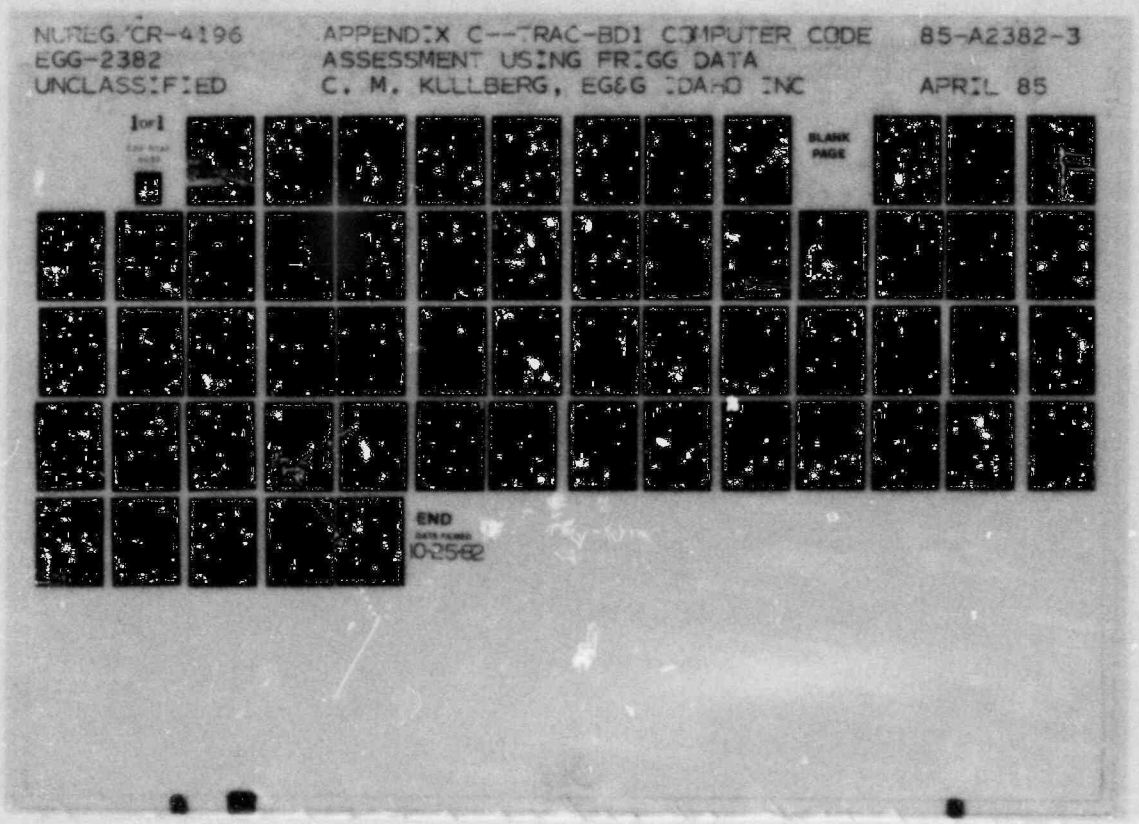
APPENDIX A
TRAC-BD1 VERSION 12 ASSESSMENT USING GOTA DATA



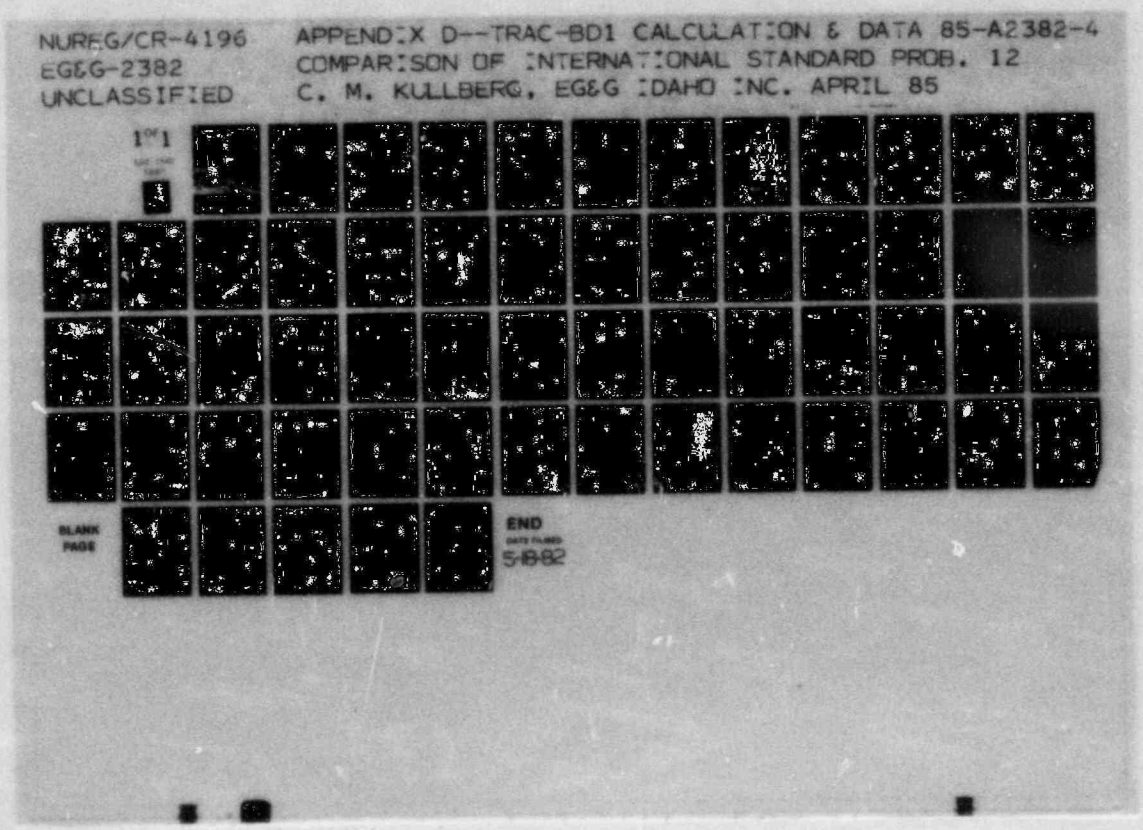
APPENDIX B
TRAC-BD1 ASSESSMENT CALCULATIONS FOR MARVIKEN TESTS 15 and 24



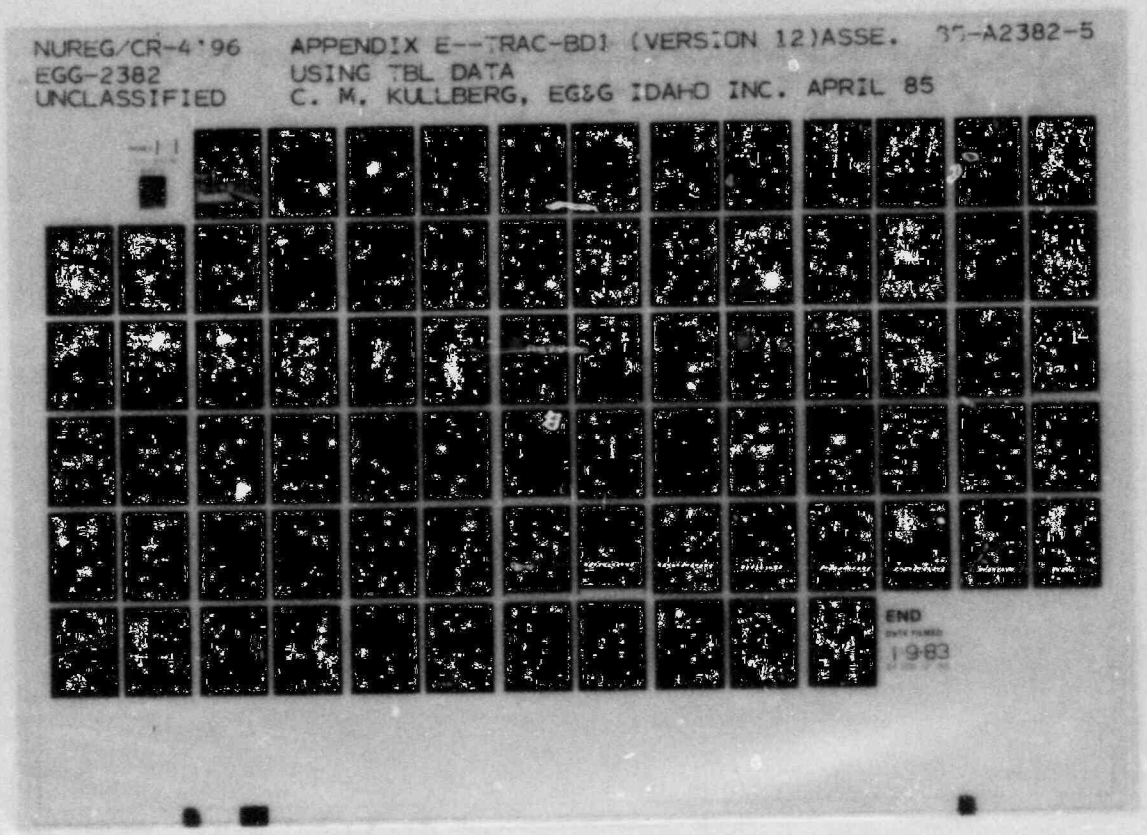
APPENDIX C
TRAC-BD1 COMPUTER CODE ASSESSMENT USING FRIGG DATA



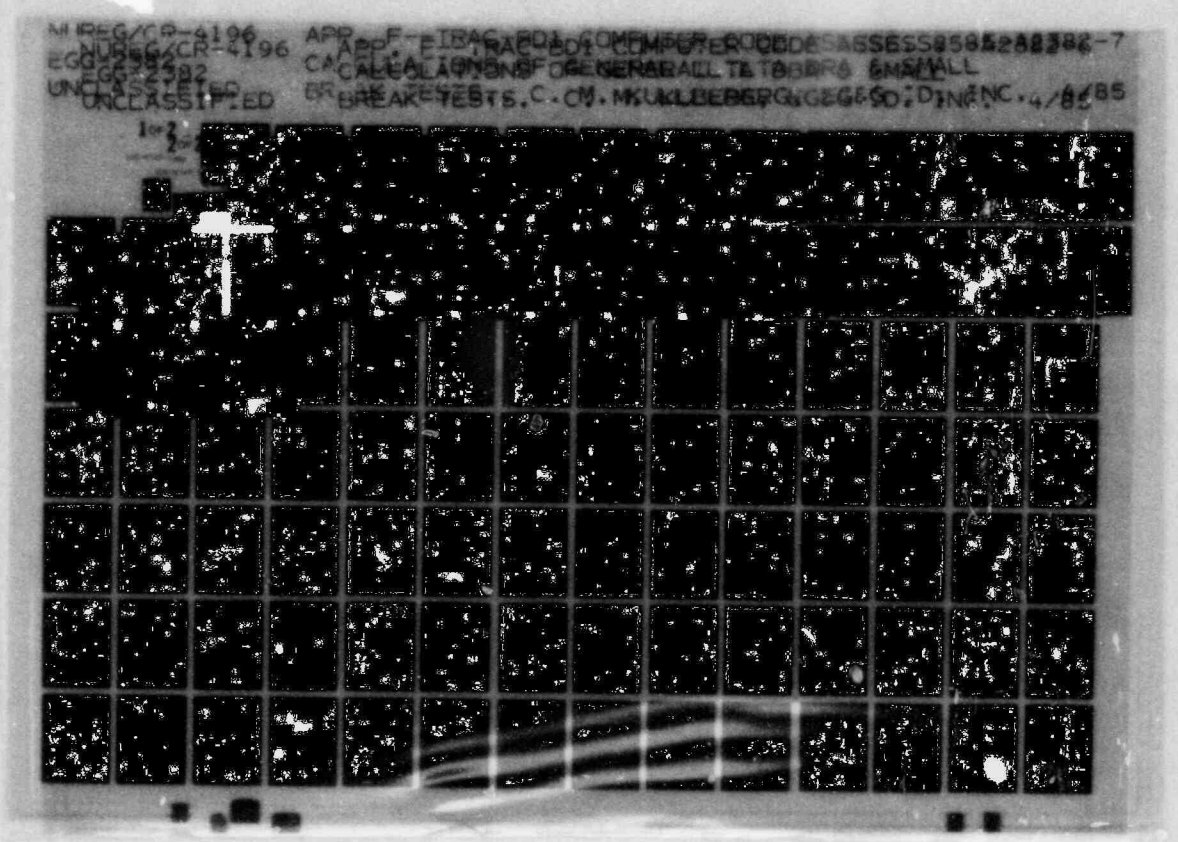
APPENDIX D
TRAC-BD1 CALCULATION AND DATA COMPARISON OF INTERNATIONAL STANDARD PROBLEM 12



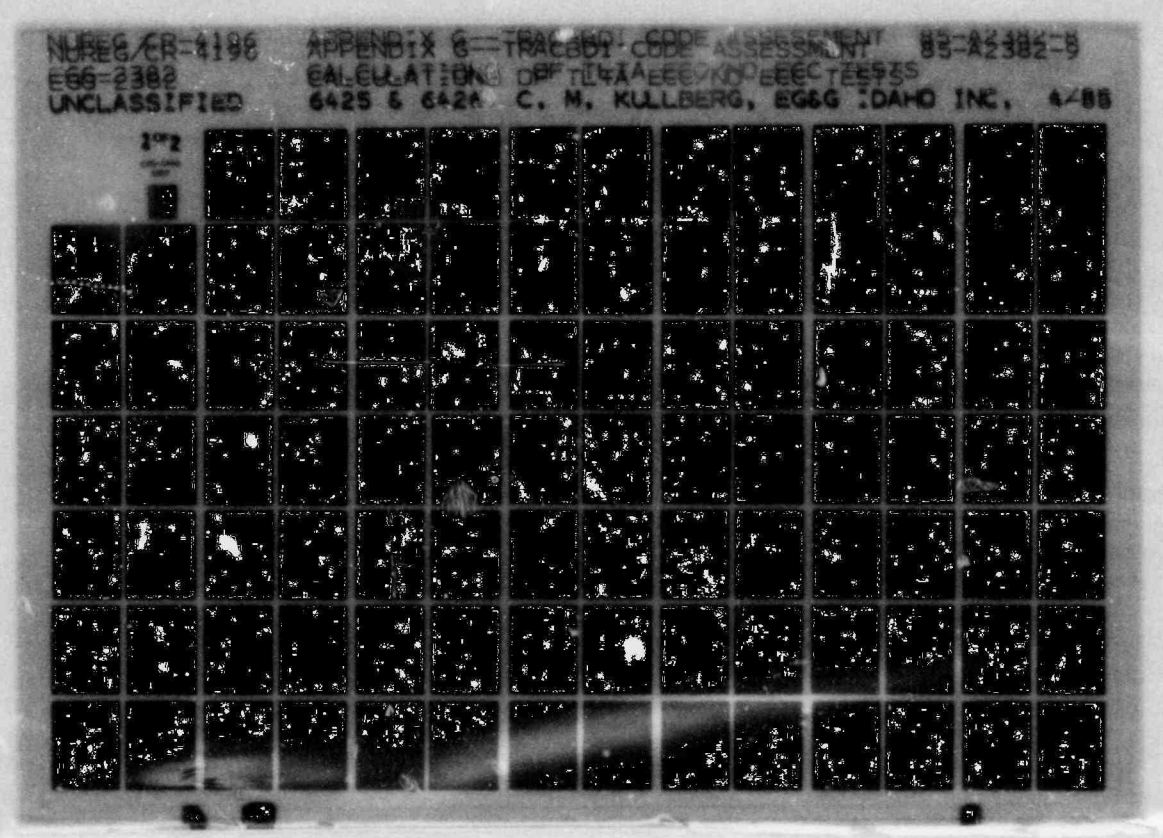
APPENDIX E
TRAC-BD1 (VERSION 12) ASSESSMENT USING TBL DATA



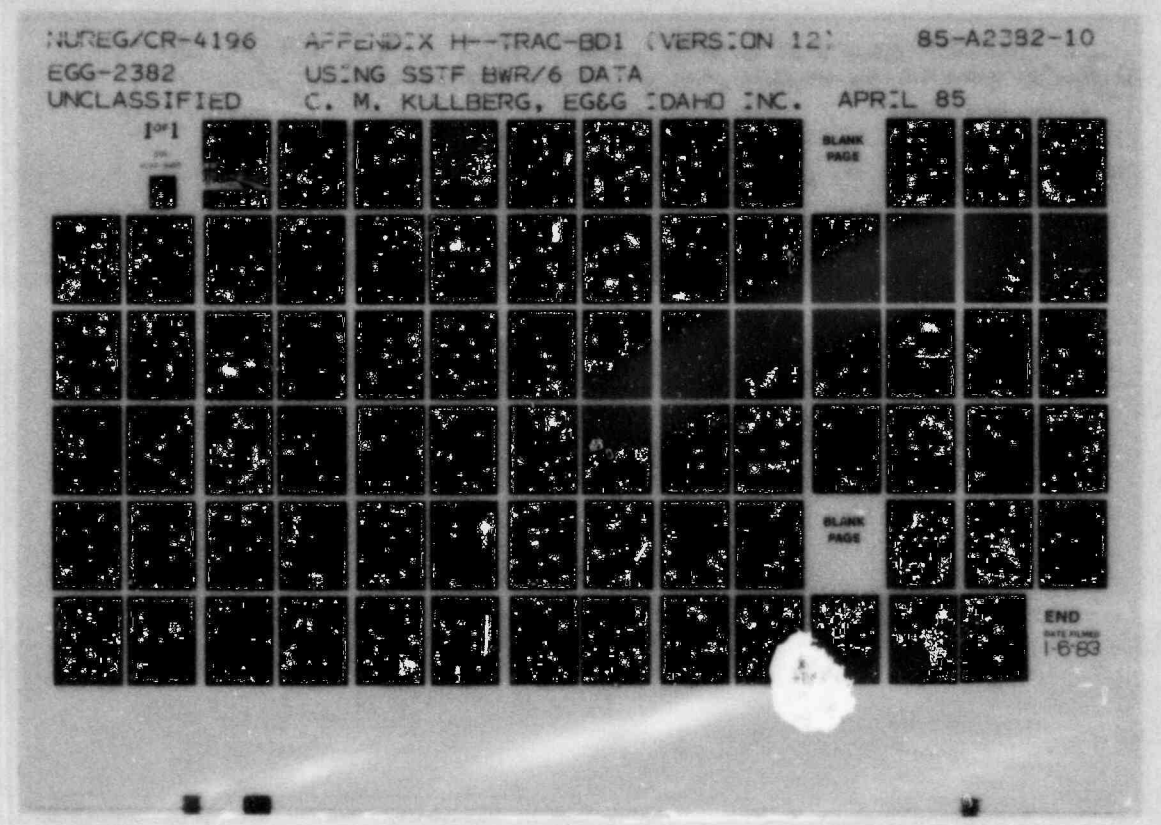
APPENDIX F
TRAC-BD1 COMPUTER CODE ASSESSMENT CALCULATIONS OF GENERAL ELECTRIC TLTA DBA AND SMALL BREAK TESTS



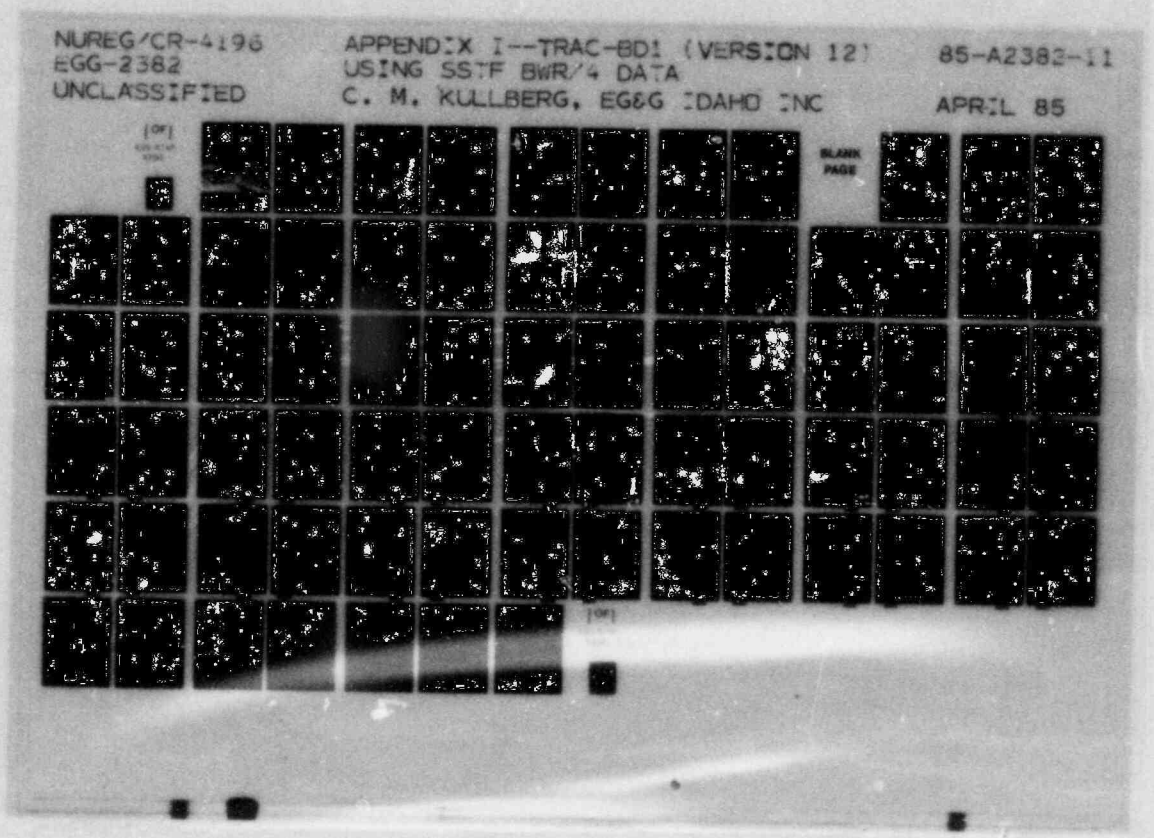
APPENDIX G
TRAC-BD1 CODE ASSESSMENT CALCULATIONS OF TLTA ECC/NO ECC TESTS 6425 AND 6426



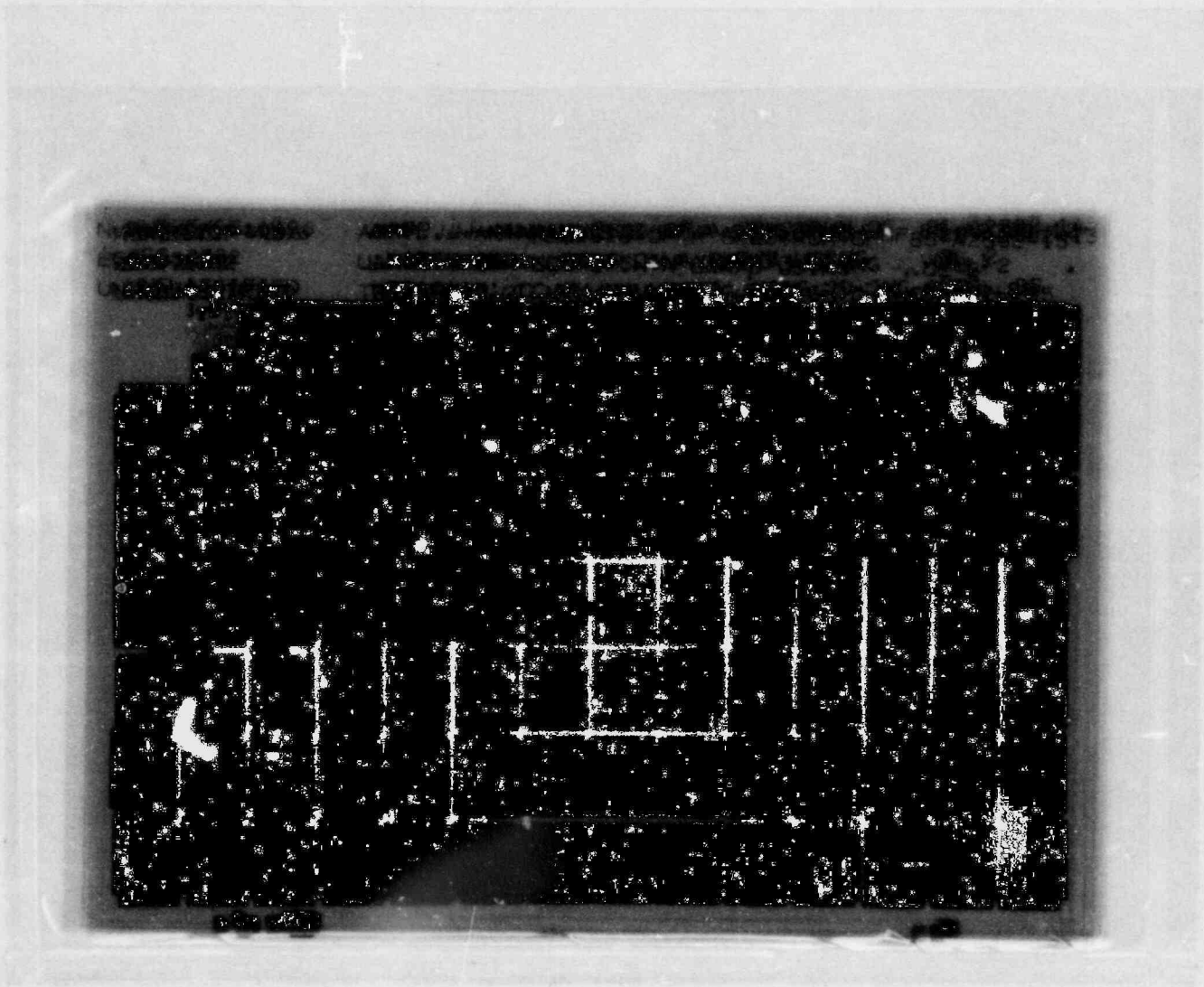
APPENDIX H
TRAC-BD1 (VERSION 12) ASSESSMENT USING SSTF BWR/6 DATA



APPENDIX I
TRAC-BD1 (VERSION 12) ASSESSMENT USING SSTF BWR/4 DATA



APPENDIX J
AN ANALYSIS OF A SPECTRUM OF LARGE-BREAK LOCAS IN A BWR/3 USING TRAC-BD1



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13. ABSTRACT (200 words or less)

A series of simulations were performed at Idaho National Engineering Laboratory (INEL) to continue the advancement of Boiling Water Reactor (BWR) safety research, with the TRAC-BD1 (Version 12) computer code. The principal motivation for performing these simulations was to assess the code's capability to calculate Loss-of-Coolant Accident (LOCA) related phenomena. The results of a number of TRAC-BD1 (Version 12) simulations, which cover a broad range of conditions during different types of LOCA scanrios, are summarized in this document. Selected comparisons between calculated and measured results are presented. Conclusions derived from those comparisons are given.

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