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TECHNICAL SUPPORT TO THE NUCLEAR REGULATORY COMMISSION FOR THE BOILING WATER REACTOR BLOWDOWN HEAT TRANSFER PROGRAM

RICHARD E. RICE

PREPARED BY AEROJET NUCLEAR COMPANY FOR

U. S. NUCLEAR REGULATORY COMMISSION

AND

ENERGY RESEARCH AND DEVELOPMENT ADMINISTRATION

IDAHO OPERATIONS OFFICE UNDER CONTRACT E(10-1) -1375

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ANCR-NUREG-1277 – TECHNICAL SUPPORT TO NUCLEAR
REGULATORY COMMISSION FOR THE BOILING
WATER REACTOR BLOWDOWN HEAT
TRANSFER PROGRAM

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**TECHNICAL SUPPORT TO THE NUCLEAR REGULATORY COMMISSION
FOR THE
BOILING WATER REACTOR BLOWDOWN HEAT TRANSFER PROGRAM**

by

Richard E. Rice

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ABSTRACT

This report presents the results of studies conducted by Aerojet Nuclear Company (ANC) in FY 1975 to support the Nuclear Regulatory Commission (NRC) on the boiling water reactor blowdown heat transfer (BWR-BDHT) program. This program is jointly sponsored by the NRC and General Electric Company (GE) and mutually funded by the NRC, GE, and the Electric Power Research Institute (EPRI).

The support provided by ANC is that of an independent assessor of the program to ensure that the data obtained are adequate for verification of analytical models used for predicting reactor response to a postulated loss-of-coolant accident. The support included reviews of program plans, objectives, measurements, and actual data. Additional activity included analysis of experimental system performance and evaluation of the RELAP4 computer code as applied to the experiments.

SUMMARY

The Aerojet Nuclear Company (ANC) support to the Nuclear Regulatory Commission (NRC) on the boiling water reactor blowdown heat transfer (BWR-BDHT) program, conducted by General Electric Company (GE), is provided in the following five categories:

- (1) Review of program plan
- (2) Review of operations and measurements
- (3) Analytical support
- (4) Review of two loop test apparatus (TLTA) data
- (5) RELAP4 code evaluation.

Significant results and findings in these categories are as follows.

PROGRAM PLAN REVIEW

The code verification needs for the boiling water reactor (BWR) loss-of-coolant accident were examined as part of the program plan review. This review indicated that additional experiments are necessary for verification of thermal-hydraulic codes used for analysis of the emergency core cooling period. These experiments should be conducted in a facility which allows interaction between core spray water, bottom reflood water, and the core as affected by flow paths and elevations of the complete system.

GE has proposed that the TLTA be modified to allow conduct of these experiments. ANC supports this proposal.

OPERATIONS AND MEASUREMENTS

An analysis of the accuracies of selected TLTA measurements has been completed. Findings of this study were that most of the measurements were adequate for purposes of model verification. Exceptions are the accuracy of all flow rates at low values. This problem, which arises after lower plenum flashing, limits the diagnosis of code problem areas. Greater flow measurement resolution in TLTA measurements would be beneficial in providing a code-verification data base and is recommended as one of the areas in which improvement should be sought.

ANALYTICAL SUPPORT

Pertinent TLTA areas of interest have been investigated using the RELAP4 computer code. Significant results of these studies included the following:

- (1) Wall heat transfer will be of significance in the TLTA and must be factored into evaluation of the test results.
- (2) The alternate lower plenum geometry proposed for Test 18 is not expected to have significant effect on TLTA performance.
- (3) Elevation and momentum differences between the TLTA and BWR will result in a nontypical TLTA core flow coastdown. This nontypical coastdown, which will affect core temperature response, must be accounted for in relating TLTA performance to that of a BWR.

REVIEW OF TLTA DATA

Data from all Bundle 1 tests have been reviewed. Emphasis was placed on evaluating the impact of the various Bundle 1 test parameters and on identifying new or unexpected phenomena. Significant results are as follows:

- (1) Variations in bundle power have little effect on overall system performance but substantially affect rod temperatures. A threshold for an early (less than one second) critical heat flux (CHF) exists at power levels between 4.55 and 6.05 MW.
- (2) Initial downcomer fluid mass, which was not repeatable from test to test, has a significant effect on system performance.
- (3) Test-to-test repeatability appears to be good for tests run close together in time.
- (4) The test of an alternate power decay curve was inconclusive.
- (5) Changes in break area affect system response and event timing.
- (6) Minor changes in bundle performance follow the system changes as expected.
- (7) Liquid fallback from the upper plenum may play an important role in holding rod temperatures down in the postflashing period.

On the basis of these observations, several recommendations have been made. A better control of initial downcomer mass should be established. The CHF threshold should be pinpointed by additional testing. Another test with an alternate power decay profile should be scheduled. An additional long-term repeatability test should be scheduled. The need for additional model development and evaluation work is indicated to account for observed experimental trends in bundle performance.

RELAP4 CODE EVALUATION

RELAP4 calculations for three experiments (Tests 1, 3, and 6) have been compared with the experimental results in order to assess adequacy of the code for application to BWR systems and to suggest areas of code improvement. Improvement areas indicated relate to critical flow calculations, jet pump modeling, bundle heat transfer, horizontal slip, and vertical phase separation.

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TECHNICAL SUPPORT TO THE NUCLEAR REGULATORY COMMISSION FOR THE BOILING WATER REACTOR BLOWDOWN HEAT TRANSFER PROGRAM

I. INTRODUCTION

In the interest of improving the understanding of the phenomena occurring in a light-water reactor during a postulated loss-of-coolant accident (LOCA), the water reactor safety research program has been established. This program is administered by the Office of Nuclear Regulatory Research of the Nuclear Regulatory Commission (NRC). The overall effort consists of a series of programs to develop computer codes to predict the thermal-hydraulic phenomena during a LOCA and to provide representative experimental data to assess these codes. These programs are being conducted by several of the Energy Research and Development Administration (ERDA) laboratories, nuclear reactor vendors, universities, and independent contractors.

The anticipated end result of this undertaking is verified computer codes with established confidence levels which can be used to predict nuclear plant performance for a wide variety of postulated LOCAs. These codes will be used in the NRC licensing activities.

Industry cooperative test programs are an integral part of this overall effort. These programs are jointly sponsored by the NRC and reactor vendors. To ensure that the needs of code verification are met by the industry cooperative programs, Aerojet Nuclear Company (ANC) has been placed in an independent technical advisory role. Specific ANC duties as NRC's advisor include:

- (1) Review of overall experimental program direction and results
- (2) Review of specific facilities including measurements, test plans, test conduction, test results, etc.
- (3) Analytical support for experimental programs, including investigations of scaling effects, test parameters, and modeling sensitivities
- (4) Comparison of computer code results with experimental data to assess code capability.

This topical report summarizes ANC activities in FY 1975 as advisor on the boiling water reactor (BWR) blowdown heat transfer (BDHT) program^[1] being conducted by General Electric Company (GE) in San Jose. This program is jointly sponsored by the NRC and GE and mutually funded by the NRC, GE, and EPRI^[a]. The experiments are being conducted in the two loop test apparatus (TLTA) which is a scaled simulator of a boiling

[a] Electric Power Research Institute.

water reactor. The system has been designed to provide BWR blowdown conditions in the test bundle, so that investigations can be made of time to critical heat flux (CHF), post-CHF heat transfer, and the effect of lower plenum swell on bundle thermal performance. The TLTA utilizes a full-length bundle of 49 electrically heated rods representing the BWR core region. This scaled facility features all major BWR components including two external recirculation loops with a single jet pump in each loop.

Several loss-of-coolant experiments (LOCE) with variation of key parameters have been conducted in the TLTA to determine the influence of the individual parameters on system blowdown response^[a]. In each test, numerous measurements reflecting system performance were taken. These measurements included major flow rates, local fluid state, and rod bundle temperatures.

[a] As of the end of FY 1975, eight tests were completed on the first bundle, and testing of the second bundle was in progress.

II. PROGRAM PLAN REVIEW

Emergency core cooling (ECC) tests have been identified as an extension to the blowdown heat transfer experiments conducted in the GE two loop test apparatus. The purpose of these ECC tests will be to explore the effect of interactions between core spray and reflood water with the total system during a simulated LOCA. In formulating a policy with respect to these proposed tests, the NRC requested Aerojet Nuclear Company to establish a position on these proposed experiments and provide recommendations regarding the future of such a program. This section describes the results of the requested evaluation.

1. MODEL VERIFICATION BACKGROUND

ANC's interest in the ECC time regime for BWRs arises from the present efforts to develop and verify best-estimate codes for prediction of peak cladding temperature. The presently planned experimental programs must be carefully evaluated to ensure that sufficient information is obtained for complete verification of the best-estimate codes.

Table I presents the results of a systematic review of the major ECC phenomena occurring in BWRs during a LOCA and summarizes the current best-estimate ECC analysis and experimental verification situation. The table is divided into two regimes during ECC, namely the core spray-refill regime and the reflood regime. The core spray-refill period begins during system blowdown as the high-pressure core spray starts and ends when water first enters the core and reflood starts.

Individual components, or groups of related components, are discussed in the table. This form of presentation was selected to correspond to the method of model verification in which models are evaluated separately for components or groups of components which exhibit similar influences or phenomena. A special category of "systems interactions" is also included, which denotes the interactive influence of the components upon each other. These interactions often require unique modeling techniques to provide the proper analytical interface between components.

The discussion in the table indicates that many aspects of the BWR LOCA analysis for the ECC period will be verified adequately through ongoing or completed experimental programs. However, several critical areas exist in which additional experimental investigation appears to be needed. The primary concern is the lack of confirming data to provide quantitative limits on the systems interactions capability of the codes. The interactions of importance include those among the core spray, core, and upper plenum and between the low-pressure coolant injection (LPCI) and the core bypass region and lower plenum.

TABLE I

BWR MODEL VERIFICATION FOR ECC TIME PERIOD

Component	Regime	Topic	Discussion
Core	Core Spray-Refill	Phenomena Occurring	<p>The core spray period is characterized by unequal velocity, unequal temperature (UVUT) separated flow patterns within the core superimposed on a three-dimensional rod bundle temperature distribution. Core spray, introduced at the top of the core, will collect and penetrate into the core and quench the channel walls and fuel rods. The quenching process results in violent local boiling which separates the core spray liquid into steam and subcooled liquid droplets which continue to interact with the rods, channel wall, and updraft flow through the core. Updraft flow comes from boiloff in the lower plenum and spray evaporation. Updraft flow may provide better cooling than spray. As demonstrated in the BWR-FLECHT experiments^[2,3], the channel walls will quench well before the fuel rods at a given axial location and eventually a liquid film will form. This will provide a radiant heat sink for the outermost rods. The radiation cooling will eventually reverse the rod temperature rise, but complete quenching of the rods for their full length does not generally occur until after reflood is initiated.</p>
		Predictive Model	<p>Current ECC core models have been derived from the BWR-FLECHT experimental program. The core is not analytically linked with a system calculation because presently no system model exists which can properly account for interaction between core spray, reflood water, and the core. Core flow, pressure, and enthalpy calculations are thus presently not made. Work is progressing on a RELAP4^[4] model for BWR analysis which will allow system calculations but will be limited by assumptions of equilibrium between phases. Additional analytical capability will be provided with new versions of the SCORE^[5] code which will eventually allow simultaneous solution of the two-phase UVUT core hydraulics and bundle and channel</p>

TABLE I (contd.)

BWR MODEL VERIFICATION FOR ECC TIME PERIOD

Component	Regime	Topic	Discussion
Core (contd.)	Core Spray-Refill (contd.)	Predictive Model (contd.)	wall heat transfer in three dimensions. Currently, SCORE is available in an equal velocity, equal temperature (EVET) version but has not been linked with empirical ECC film coefficients nor a radiation model.
		Supporting Data for Model Verification	BWR-FLECHT is the only publicly available source of ECC core heat transfer data for BWRs. In this program, simulated BWR rod bundles were tested over a wide range of core spray and reflood, flow, temperature, and power conditions. Combined core spray/reflood conditions were examined, and pressure effects were investigated. Most of the tests were conducted with stainless steel rods, but core spray tests were also conducted on a limited basis with zircaloy bundles. Inasmuch as the present analytical models are based completely on the BWR-FLECHT data, these models cannot really be verified with the currently available data. The models are shown to be consistent with the FLECHT data, as they should be, but complete verification will require confirming test data from a separate facility. Limited verification of the SCORE code could be made with data from the BWR-FLECHT program.
		Effect of Model Inadequacies	Inadequacies have a direct effect on calculated core fluid conditions and heat transfer coefficients. These boundary conditions directly affect calculated rod temperature. Peak temperature of many rods in a BWR core will occur during this time period.
		Conclusions	Assessment of a present code and planned codes used for core analysis requires confirming core spray data from a separate facility.

TABLE I (contd.)

BWR MODEL VERIFICATION FOR ECC TIME PERIOD

Component	Regime	Topic	Discussion
Lower Plenum	Core Spray-Refill	Phenomena Occurring	During core spray-refill, the lower plenum will experience a varying mixture level due to the combined effects of boiloff losses and liquid addition from core spray running down the bypass channel walls and from the LPIS. Quench of the lower plenum will occur when sufficient ECC water accumulates, resulting in a cessation of steam updraft.
		Predictive Model	The lower plenum can be represented as a distributed volume in RELAP4. Empirically determined coefficients used with a bubble rise and slip model allow calculations of local fluid conditions, mixture level, and phase slip.
		Supporting Data for Model Verification	No lower plenum data exist for the core spray-refill time regime. The lower plenum can be verified, however, with data from TLTA blowdown experiments, as the lower plenum phenomena are similar in both regimes. Other supporting data will be available from LOFT[6] and Semiscale[7].
		Effect of Model Inadequacies	Model is believed to be adequate. Effect of inadequacies would be improper timing of start of reflood.
		Conclusions	Model verification can be completed through presently planned programs.
Jet Pumps	Core Spray-Refill	Phenomena Occurring	Reverse flow through the jet pumps carries fluid from the lower plenum into the lower downcomer region and to the break.
		Predictive Model	The jet pumps are represented by the RELAP4 two-stream mixing model, which allows momentum exchange between mixing streams of fluid.

TABLE I (contd.)

BWR MODEL VERIFICATION FOR ECC TIME PERIOD

Component	Regime	Topic	Discussion
Jet Pumps (contd.)	Core Spray- Refill (contd.)	Supporting Data for Model Verification	No jet pump data are available for core spray-refill; however, blowdown data from the TLTA will provide a base for jet pump model verification.
		Effect of Model Inadequacies	Model is believed to be adequate for this time period when the jet pumps are relatively inactive. Inadequacies will only have minor effect on system performance.
		Conclusions	Model verification can be completed through presently planned programs.
Recirculation Pumps, Piping, Break	Core Spray-Refill	Phenomena Occurring	The intact loop elements are passive during the core spray-refill time periods. The broken loop piping provides a flow path to the containment. High quality flow is choked at the break.
		Predictive Model	The elements are modeled as in the blowdown period using homologous pump curves, two-phase friction models, user input from loss coefficients and the critical flow models for break flow.
		Supporting Data for Model Verification	These elements are to be verified by data from BWR-BDHT, LOFT, Semiscale, and other tests.
		Effect of Model Inadequacies	Models are believed to be adequate. Inadequacies will only have minor effect on system performance.
		Conclusions	Model verification can be completed through presently planned programs.
Downcomer, Steam Dome	Core Spray-Refill	Phenomena Occurring	Flow into and through these elements is at relatively low rate and of high quality.

TABLE I (contd.)

BWR MODEL VERIFICATION FOR ECC TIME PERIOD

Component	Regime	Topic	Discussion
Downcomer, Steam Dome (contd.)	Core Spray- Refill (contd.)	Predictive Model	Conventional RELAP4 phase separation models are used to represent the downcomer and steam dome.
		Supporting Data for Model Verification	Many programs are to be used to verify these elements of the code, including BWR-BDHT, LOFT, and Semiscale.
		Effect of Model Inadequacies	Models are believed to be adequate. Inadequacies will only have minor effect on system performance.
		Conclusions	Model verification can be completed through presently planned programs.
∞ ECC Injection Systems	Core Spray-Refill	Phenomena Occurring	Both core spray and LPCI systems pump cold water from reservoirs into the reactor vessel. Flows are relatively steady and single phase.
		Predictive Model	These elements can be represented conventionally in RELAP4 using the homologous curves (single phase) for the pump and volume/junction representations of the piping with single-phase form loss and friction loss models.
		Supporting Data for Model Verification	Verification of elements of RELAP4 models (piping, pumps) for ECC injection systems will be made through numerous experimental programs (LOFT, Semiscale, pump tests, etc.).
		Effect of Model Inadequacies	Models are believed to be adequate. Effect of inadequacies will have minor influence on system performance.
		Conclusions	Model verification can be completed through presently planned programs.

TABLE I (contd.)

BWR MODEL VERIFICATION FOR ECC TIME PERIOD

Component	Regime	Topic	Discussion
Upper Plenum	Core Spray-Refill	Phenomena Occurring	Flow patterns in the upper plenum are characterized by nonhomogeneous, nonequilibrium separated phases. Subcooled droplets of core spray may be entrained through this volume by steam exiting from the core. Entrainment would delay spray cooling and reflooding. The degree of mixing and heat exchange between the phases affects the quantity of steam condensed. The spray droplet size and path length will affect the rate of condensation. Condensation of steam will locally reduce pressure in the upper plenum which may alter basic flow patterns throughout the BWR. Core spray may accumulate and form a mixture level at the bottom of the upper plenum, prevented from penetrating the core by the steam updraft.
		Predictive Model	The homogeneous assumptions of RELAP4 do not permit an accurate definition of the UVUT flow patterns and mixing within the upper plenum. Analysis could be performed with RELAP4, but complete mixing and thermal equilibrium would be assumed. The validity of this assumption is not currently known. Present core spray-refill analyses do not consider core spray interactions in the upper plenum. Improvement in modeling capability will be provided upon completion of advanced codes which will allow UVUT solutions in volumes of this type.
		Supporting Data for Model Verification	No upper plenum data exist specifically for the BWR upper plenum during core spray-refill. Spray tests ^[8] performed on the Semiscale suppression tank have provided data for nonflowing conditions, to investigate spray effectiveness in pressure suppression. These tests have demonstrated the nonhomogeneity of the spray-steam mixture. These data could be used to partially verify the codes, but complete verification would require data from an interactive test with the plenum coupled to other system elements through typical flow paths.

TABLE I (contd.)

BWR MODEL VERIFICATION FOR ECC TIME PERIOD

Component	Regime	Topic	Discussion
Upper Plenum (contd.)	Core Spray-Refill (contd.)	Effect of Model Inadequacies	The major effect of inadequate prediction of events in the upper plenum will be errors in system flow rates, as affected by local pressure suppression and entrainment. These errors in turn will result in errors in core thermal-hydraulic calculations and rod temperature histories.
		Conclusions	Upper plenum data from an interacting system with core spray are required to assess the limitations of present code methods and to verify the accuracy of improved codes with UVUT capability.
System Interactions	Core Spray-Refill	Phenomena Occurring	Introduction of cold core spray into the upper region of the vessel results in several systems interaction phenomena. The core spray will condense steam in the upper plenum and at the core exit, resulting in a local pressure suppression which can potentially increase core flow. The core spray can accumulate and form a mixture level at the bottom of the upper plenum if steam updraft is sufficient to prevent penetration into the core. Once penetration occurs, the core spray will interact with the hot rod bundles and channel walls resulting in a quench front moving down through the core. Some of the spray may be carried back out of the core to the break by the updraft while a portion will reach the lower plenum, affecting the mixture level and core inlet enthalpy. The time at which reflood starts is affected by the quantity of core spray accumulated in the lower plenum in addition to the LPCI water. LPCI penetration to the lower plenum may be affected by local interactions with the core bypass fluid which could cause geysering and/or spillover.
		Predictive Model	The RELAP4 analytical code currently used for system analysis is not capable of handling the complex two-phase, thermal-hydraulic interactions between BWR components during the ECC time regimes. The limiting assumption in

TABLE I (contd.)

BWR MODEL VERIFICATION FOR ECC TIME PERIOD

Components	Regime	Topic	Discussion
System Interactions (contd.)	Core Spray-Refill (contd.)	Predictive Model (contd.)	RELAP4 is that of homogeneous volumes, with no separate calculations of the phase velocities and temperature. As a result, the BWR system interaction studies are presently limited to blowdown regime only, where this assumption can be made. Near-term improvements to RELAP4 are expected to allow limited use for BWR ECC problems but will not fully satisfy the analytical requirements. Advanced codes with UVUT capabilities are currently being developed. These codes, when available, will provide the capability to link the BWR components during ECC and permit calculation of coupled BWR performance history.
		Supporting Data for Model Verification	No data base is available to provide verification data on systems interactions for BWRs during the core spray-refill period.
		Effect of Model Inadequacies	With the lack of an accurate interactive systems calculation, thermal-hydraulic boundary conditions to and within the core cannot be correctly determined. As a consequence, rod temperature calculations must be made with empirically derived (BWR-FLECHT) core heat transfer correlations. The applicability of this approach to BWRs has not been verified. Confident application of advanced codes with UVUT capabilities depends on their verification through use of systems data typical of BWR-ECC conditions.
		Conclusions	Systems level ECC tests are necessary to provide a data base to assess the limitations of present codes and to verify new codes presently being developed. These tests are also desired to identify potential unexpected phenomena.
Core	Reflood	Phenomena Occurring	The core spray is still active during this regime, and all processes associated with core spray, described previously, are superimposed upon the reflooding effects. Core reflooding is initiated when the water level in the lower plenum reaches the core. As the reflood water contacts the hot rods, violent boiling occurs.

TABLE I (contd.)

BWR MODEL VERIFICATION FOR ECC TIME PERIOD

Components	Regime	Topic	Discussion
Core (contd.)	Reflood (contd.)	Phenomena Occurring (contd.)	The upward flow of steam and entrained subcooled liquid will result in cooling above the reflood front. Turn-around of the cladding temperature of the hottest rods is expected to occur after reflooding commences. The boiling front will advance up the bundle as the lower regions are quenched until, eventually, the entire bundle is quenched.
		Predictive Model	The predictive models used during reflood are similar to those used in core spray-refill analyses. They are based on BWR-FLECHT data and are subject to the same limitations.
		Supporting Data for Model Verification	As for core spray-refill, BWR-FLECHT is the only available source of reflood data.
		Effect of Model Inadequacies	Inadequacies affect core fluid conditions and heat transfer coefficient calculations. This directly affects peak clad temperature calculations and time of rod quench.
		Conclusions	Assessment of present codes used for core analysis requires confirming reflood data from a separate facility.
Lower Plenum	Reflood	Phenomena Occurring	During reflood, the lower plenum remains full of subcooled liquid. Flow enters the lower plenum from the LPIS and exits through the core and the jet pumps.
		Predictive Model	The lower plenum can be modeled as described for the core spray-refill period.

TABLE I (contd.)

BWR MODEL VERIFICATION FOR ECC TIME PERIOD

Component	Reflood	Topic	Discussion
Lower Plenum (contd.)	Reflood (contd.)	Supporting Data for Model Verification	No specific BWR reflood data are currently available. However, BWR-BDHT, LOFT, and Semiscale blowdown data can be used for verification.
		Effect of Model Inadequacies	There will be minor effects on reflood rate.
		Conclusions	Model verification can be completed through presently planned programs.
Jet Pumps, Recirculation Pumps, Piping, Downcomer, Steam Dome, Break, Upper Plenum, and ECC Injection	Reflood	Phenomena Occurring	Flow in these elements is generally single phase and readily analyzed.
		Predictive Model	These elements can be modeled as described for the core spray-refill period.
		Supporting Data for Model Verification	No specific BWR reflood data are currently available. However, BWR-BDHT, LOFT, and Semiscale blowdown data can be used for verification.
		Effect of Model Inadequacies	There will be minor effects on reflood rate.
		Conclusions	Model verification can be completed through presently planned programs.
Systems Interactions	Reflood	Phenomena Occurring	The reflood flow rate is a function of the eight-foot head of water in the jet pumps and the flow resistance which depends on the interaction of the reflood water and the hot rod bundles. A flow oscillation potential exists, influenced by the opposing forces of pressure generated by flashing in the core and the water head in the

TABLE I (contd.)

BWR MODEL VERIFICATION FOR ECC TIME PERIOD

Component	Regime	Topic	Discussion
Systems Interactions (contd.)	Reflood (contd.)	Phenomena Occurring (contd.)	jet pumps. Core spray is still active during this time period. All spray interactions previously described continue with an added interaction between the core spray and the reflood flow within the core.
		Predictive Model	As for core spray-refill, systems interaction analyses are not presently conducted for the reflood time period.
		Supporting Data for Model Verification	The PWR FLECHT-SET ^[9] , LOFT, and Semiscale experiments will provide PWR code verification data for the reflood period. The differences in system design, operating conditions, as well as the lack of concurrent core spray, will not allow complete verification of the codes for BWR application. No information is currently available to fill this need.
		Effect of Model Inadequacies	As for core spray-refill, the core model cannot be coupled to an interactive system model. Resulting core calculations are based on unverified empirical relationships.
		Conclusions	Systems level ECC tests are necessary to provide a data base to assess the limitations of present codes and to verify new codes presently being developed. These tests are also desired to identify potential unexpected phenomena.

Interactions occur in the bypass region where LPCI is injected (geysering and spillover) and in the lower plenum where LPCI mixes with saturated fluid (lower plenum quench). Some unique component data requirements during ECC are also outstanding. These include hydraulic and heat transfer processes within the core and two-phase flow mixing in the upper plenum regions.

The conclusion reached from this review is that the lacking information can only be acquired through additional testing in which systems interaction effects can be simulated. Measurements should be made of these effects simultaneously with measurements of the performance of related components. These experiments can be conducted in a scaled system such as the TLTA in which all major flow elements of the BWR are represented.

2. TLTA DESIGN CONSIDERATIONS

Several design features of the TLTA have been identified as potentially capable of distorting TLTA performance during ECC testing with respect to BWR behavior. These features include:

- (1) The TLTA jet pump suction is three feet above the core inlet (versus eight feet for the BWR) which would affect head for core reflood.
- (2) The upper electrode plate splits the upper plenum into two volumes and physically blocks introduction of core spray at the bundle top. Spray would be injected through the sides of the unheated part of the bundle or above the electrode plate which may affect simulation of spray-system interactions in the upper plenum region.
- (3) The TLTA channel wall is much heavier and of a different material than that of the BWR. Wall rewetting would thus be nontypical in the TLTA which could affect rod bundle temperature response.
- (4) The core bypass design in TLTA does not simulate BWR geometry. The current TLTA design could affect the timing of reflood coolant reaching the lower plenum.
- (5) The TLTA heater rods are limited to 1,500°F to prevent damage to the thermocouples. ECC temperatures in the BWR, prior to quench, could exceed this limit.

Modifications to the TLTA to permit the conduct of ECC interaction experiments have been proposed by GE. To cope with the above mentioned problems, while providing information on a timely basis, a three-part program has been formulated. Each part utilizes a specific TLTA configuration and addresses only certain ECC interaction questions.

The first portion of the proposed program uses the TLTA essentially as now constructed. The only modifications are the addition of high- and low-pressure core spray and low-pressure coolant injection systems. Objectives of the tests with this configuration are to assess the influence of ECC delivery systems on the fluid flow and heat transfer processes during the early blowdown.

For the second part of the program, the TLTA would be modified to provide more representative upper plenum, channel wall, jet pump, and core geometries. High temperature, low-power heater rods would also be utilized. Tests on this configuration would explore the ECC system interaction processes starting from the latter stages of blowdown through reflood.

During the third portion of the program, integral tests would be conducted from rupture through reflood to provide data in the regime between those covered by the first and second portions of the program. These tests would probably require development of a new high-power heater rod capable of withstanding temperatures in excess of 1,500°.

The proposed three-part program is tentatively endorsed by ANC as an alternative to complete integral systems tests. However, many potential BWR model verification problems may remain after completion of such a program. The models must be verified over the total integral LOCA regime from data obtained from several nonintegral tests. Subsequently, these models must be extrapolated from a 1/560-scale TLTA facility to predict performance of a full-scale plant.

3. RECOMMENDATIONS

The ECC systems interaction program proposed by GE should be adopted and schedules established for its completion.

A series of scoping studies should be defined and conducted to clarify the influences and importances of various factors affecting BWR cladding temperature during the ECC period. Subjects of interest would include core spray pressure suppression effects, flow and pressure oscillation potential, and nonequilibrium steam-water interaction throughout the system. In addition, the studies should scope the magnitude of updraft flow and cooling, the potential for spray entrainment, the potential delay in reflooding due to ECC entrainment, and interaction between LPCI fluid and the core bypass region.

Similar studies for the TLTA should parallel the development of the ECC program plan. These studies should be directed toward obtaining an understanding of TLTA response to various scaling compromises and hardware design options. Results from these studies should be compared with expected BWR behavior during the ECC period to assess typicality of expected TLTA experimental results.

The proposed test program should be continuously reviewed in light of the results of these studies and, as available, experimental results. Model verification progress and needs should also be continuously reviewed to determine current applicability of the experimental results and future requirements.

III. OPERATIONS AND MEASUREMENTS

One of ANC's primary assignments in connection with the BWR-BDHT program was to independently appraise the capability of the TLTA to provide accurate and meaningful results. This task was carried out by (a) conducting an analysis of the accuracies of selected key TLTA measurements, and (b) witnessing a selected TLTA test and reviewing pre- and posttest operations by the GE test conduction team.

Details of these two activities are covered in the following sections.

1. MEASUREMENT ACCURACY EVALUATION

1.1 Background

The primary purpose of this evaluation was to numerically define selected measurement accuracies to assist in the ultimate specification of TLTA data confidence levels and to identify potential problem areas which could be remedied. Emphasis was placed on evaluation of the accuracies of the transient measurements of quality, mass, void fraction, internal energy, mass flow, and density. Since most of these parameters will vary significantly during a typical experiment, their accuracies were evaluated at various time points to determine the effects of flow conditions on the accuracies. TLTA Test 3, the reference case, was used as a baseline for this study.

Results of these studies were originally presented in Reference 10. Since completion of the original analysis, several improvements were incorporated by GE in the measurement approach. These changes have been accounted for by an updated analysis. In addition, a more thorough treatment was given to flow rate uncertainties and bias errors to improve and add to those calculations described in Reference 10.

1.2 Analysis Description

The parameters investigated in this study are all derived from one or more direct measurements of pressure or pressure difference (ΔP). This relationship between measurements and derived quantities is shown in Figure 1. The locations of the measurement stations selected for this evaluation are shown in Figure 2.

Uncertainties exist in the basic measurements as well as in other variables used to calculate the parameter of interest. The evaluation of the total uncertainty in each parameter follows the approach outlined in Reference 11 for single sample experiments. For a parameter $m = f(v_1, v_2, \dots, v_n)$, the uncertainty in m , δm , was determined as a function of the known uncertainties in each of the variables (δv) by

Fig. 1 Calculation of TLTA derived data.

Fig. 2 TLTA measurement locations.

$$\delta m = \pm \left[\left(\frac{\partial m}{\partial v_1} \delta v_1 \right)^2 + \left(\frac{\partial m}{\partial v_2} \delta v_2 \right)^2 + \dots + \left(\frac{\partial m}{\partial v_n} \delta v_n \right)^2 \right]^{1/2} .$$

In addition to these uncertainties, bias errors will exist in the derived quantities. Typical sources of bias errors are transducer and data system response lags and neglected flow effects. Since these errors were not random, they were treated separately from the uncertainties. The bias errors in m , Δm , were determined from the known functional relationships for m , and the known bias errors, Δv , in each of the variables v by

$$\Delta m = f \left[(v_1 + \Delta v_1), (v_2 + \Delta v_2), \dots, (v_n + \Delta v_n) \right] - f(v_1, v_2, \dots, v_n) .$$

Table II summarizes the functional relationships used by GE to determine the parameters of interest and the uncertainty and bias error sources considered in this accuracy analysis.

Density is determined in the various TLTA regions through measurement of a pressure difference between two vertically separated points which form the boundaries of the volume (or node) of interest. The equation for density shown in Table II is given in two forms. The first form is derived directly from the momentum equation, assuming one-dimensional homogeneous flow. The three quantities in the bracket represent acceleration, momentum, and friction effects. In the large volumes (lower plenum, downcomer) where density measurements are made, GE assumes that these effects are negligible, and the measured pressure difference is simply the difference between cold leg and volume hydrostatic heads. The density equation then simplifies to the second form:

$$\bar{\rho} = \rho_c - \frac{\Delta P_T}{L}$$

which is the relationship used to compute local experimental densities.

The evaluation of density accuracy has considered the static and dynamic transducer and data system errors. In addition, uncertainties in the node length (L) and in cold leg density were considered. A scoping analysis was also made of possible bias errors introduced by neglecting the acceleration, momentum, and friction terms.

With exception of flow rate, all remaining quantities are calculated directly from measured density as shown in Table II. Uncertainties and bias errors in these parameters are based on the corresponding density uncertainties and biases. In addition, other error sources due to volume uncertainties and measured pressure uncertainties were considered as applicable.

TABLE II

UNCERTAINTY AND BIAS ERROR SOURCES

Parameter	Functional Relationship	Uncertainty Sources	Bias Error Sources
Density	$\bar{\rho} = \frac{\rho_c - \frac{\Delta P_T}{L}}{1 + \frac{1}{g} \left(\frac{\partial u}{\partial t} + \frac{\partial u^2}{\partial x} + \frac{fu^2}{2D} \right)} = \rho_c - \frac{\Delta P_T}{L}$	Transducer, data system, cold leg density, cold leg height	Transducer lag, data system lag, neglected terms $\left(\frac{\partial u}{\partial t}, \frac{\partial u^2}{\partial x}, \frac{fu^2}{2D} \right)$
Mass	$\bar{m} = \bar{\rho} v$	Density, volume	Density
Quality	$\bar{x} = \frac{\frac{1}{\bar{\rho}} - v_f}{v_f - v_g}$	Density, pressure (effect on v_f , v_g)	Density
Void fraction	$\bar{\alpha} = \frac{\rho_f - \bar{\rho}}{\rho_f - \rho_g}$	Density, pressure (effect on ρ_f , ρ_g)	Density
Internal energy	$\bar{e} = \left(\frac{\frac{1}{\bar{\rho}} - v_f}{v_f - v_g} \right) e_g + \left(1 - \frac{\frac{1}{\bar{\rho}} - v_f}{v_f - v_g} \right) e_f$	Density, pressure (effect on v_f , v_g , e_f , e_g)	Density
Flow rate	$W = C_1 A \sqrt{\bar{\rho}_g \left(\Delta P_T - \bar{\rho} L - \frac{1}{g} \frac{L}{A} \frac{\partial W}{\partial t} \right)} = C_1 A \sqrt{\bar{\rho}_g \Delta P_T}$	Density, transducer, data system, calibration factor	Transducer lag, data system lag, neglected terms $\left(\bar{\rho} L, \frac{1}{g} \frac{L}{A} \frac{\partial W}{\partial t} \right)$, density

Symbols: ρ_c = Density of cold leg water (lb/ft³) ΔP_T = Measured ΔP (lb/ft²) g = Gravitational constant (ft./sec²) L = Volume height (ft) u = Velocity within volume (ft./sec) t = Time (sec) x = Distance along volume centerline (ft) f = Two-phase friction factor D = Volume hydraulic diameter (ft) V = Volume (ft³) v_f, v_g = Phase specific volume (ft³/lb) ρ_f, ρ_g = Phase density (lb/ft³) e_f, e_g = Phase internal energy (Btu/lb) C_1 = Orifice calibration factor A = Flow area (ft²)

Experimental flow rates in the TLTA are calculated from measured pressure drops through flow resistance or form loss regions. The general relationship used for experimental flow rate is

$$W = C_1 A \sqrt{\rho g \Delta P_T} = C \sqrt{\rho \Delta P}$$

As in the case of the density measurement, this relationship is a simplified case of the complete form shown in Table II. Neglected in this form are effects of elevation head and fluid acceleration on the ΔP measurement.

The coefficient C is determined empirically from in-place flow calibration runs at various steady state flow rates, and, for core flow, at various void fractions.

Accuracy of these flow measurements has been evaluated for three flow stations considered most important for code verification. These are the core inlet, the intact loop jet pump, and the broken loop jet pump. The locations of these measurement stations are shown in Figure 2. Accuracies of the flow rates were evaluated at several times in the transient, each representing a unique flow condition.

The uncertainties considered in the analysis included those due to measured local density, measured flow station ΔP , and uncertainties in the calibration coefficient, C .

In GE's published calibration description^[12] it is recommended that the following calibration coefficients be used:

$$\text{bundle inlet: } C = 2.34$$

$$\text{jet pump, forward: } C = 0.935 + 2.45 \left(\frac{T}{10,000} \right)$$

$$\text{jet pump, reverse: } C = 0.511 + 8.4 \left(\frac{\log Re}{100} \right)$$

where

$$T = \text{fluid temperatures (}^{\circ}\text{F)}$$

$$Re = \text{Reynolds number.}$$

The value of C for core inlet flow is based on two-phase flow from 5 to 50 lb/sec with void fractions up to 9%. Locally measured two-phase density is used in solving for flow. Upon examination of the GE two-phase data, it appears that a $\pm 6.2\%$ scatter exists in various determinations of C for the bundle. This is assumed to represent the uncertainty in C for this analysis throughout the transient.

No uncertainty information was available on the jet pump coefficients. However, the jet pump flow calibrations were conducted under conditions similar to the bundle calibrations. It is believed that the resultant jet pump flow calibration accuracy is similar to

that of the bundle. It is therefore assumed that the jet pump calibration coefficients will also have $\pm 6.2\%$ uncertainty levels.

Bias errors were also calculated for the flow rate measurements. Sources of these bias errors were transducer and data system response lags and bias errors in the average density. Scoping analyses of the fluid acceleration and elevation effects were also made to determine their influence on the measured flow ΔP s.

1.3 Accuracy of Basic Measurements

The evaluation of TLTA measurement accuracies was initiated by examining GE's measurement system approach to determine uncertainty levels and bias errors in the basic pressure and ΔP measurements. This examination has indicated that GE did a good job in defining and confirming direct measurement uncertainties and bias errors. The resultant uncertainty and bias levels are also good and agree favorably with the accuracy of other experimental systems with which ANC is familiar.

1.3.1 Uncertainties. Table III summarizes the static transducer uncertainties determined in the evaluation. The figures given represent the root-mean-square (RMS) of linearity, hysteresis, repeatability, temperature shift, and excitation accuracy errors. The table includes an error determined from information provided by the supplier. Also included are errors determined from full-scale calibration tests performed by GE on numerous transducers. These latter data confirm the validity of the supplier error specifications for use of the transducer over its full range.

In ANC's previous analysis (Reference 10), the maximum full-scale errors were used in the uncertainty analysis. GE has since updated their calibration approach, defining a calibration factor only over the range of interest. This approach, as shown graphically in Figure 3, can improve the accuracy of individual transducers. The most significant improvements were observed in the Satham ΔP transducers, which are used for most flow and density measurements. Typically, these instruments were ranged to approximately twice the maximum measurement. Upon examination of the typical calibration traces available, it appeared that the calibration error could be reduced to about 50% of the full-scale value using the revised technique. The analysis was thus updated by using an uncertainty of 50% of the supplier-specified value for the Satham transducers.

Another component of uncertainty not covered by the manufacturer's specifications is zero shift of the differential pressure transducers with system pressure. This uncertainty is found during calibration and is seen in actual data as a measured zero shift from pretest to posttest conditions. GE compensates for zero shift through application of a pressure dependent correction factor in their data reduction code. This approach appears reasonable and, accordingly, zero shift uncertainties are assumed negligible.

Potential errors from the data acquisition system include gain and zero variations and analog-to-digital conversion errors. According to the manufacturer, fixed gain accuracy is

TABLE III

STATIC TRANSDUCER UNCERTAINTIES

Transducer	Supplier	Range (psi)	Used For	Uncertainty - Percent Full Scale [a]			
				Supplier Specification	Measured Minimum	Measured Maximum	Measured Average
Pressure	Straindyne	0 to 1,000	System pressure	± 0.24	± 0.12	± 0.25	± 0.18
ΔP	Statham	0 to 2.5 0 to 5 0 to 10 0 to 25 0 to 50	Flow orifice ΔP s, nodal density ΔP s, system pressure drops	± 0.78	± 0.21	± 0.67	± 0.29
ΔP	BLH	0 to 1.8	Nodal density ΔP s, system pressure drops	± 0.60	± 0.29	± 0.53	± 0.39

[a] Errors include repeatability, combined linearity and hysteresis, and temperature shift. Number of transducers analyzed: 7 Straindyne, 22 Statham, 7 Baldwin Lima-Hamilton.

Fig. 3 Transducer calibration options.

$\pm 0.1\%$ of the reading. Zero variations are believed negligible as they are calibrated out along with the transducer zero shifts. Analog-to-digital conversion errors are also believed to be negligible as the sample rate is generally several times the transducer bandwidth.

The transducer calibration accuracy is dependent upon the accuracy of a group of digital voltmeters and a set of pressure gauges. The RMS accuracy of the calibration tests, taken from manufacturer's specifications on these instruments, is $\pm 0.1\%$ of full scale. GE maintains the calibration of these instruments through periodic intercomparisons.

All measurements of pressure and ΔP must be corrected to remove the head generated by cold water in the vertical transducer lines. An uncertainty can be introduced in this cold leg correction due to uncertainties in the cold leg height ($\pm 1/8$ inch assumed) and variations in the cold water density due to ambient temperature changes ($\pm 20^\circ\text{F}$ assumed). The net effect of these uncertainties was found to be negligible for the pressure measurements. For the ΔP measurements, these uncertainties ranged from $\pm 0.27\%$ for low-range ΔP transducers to $\pm 0.10\%$ for high-range ΔP transducers.

1.3.2 Bias Errors. Dynamic bias errors are introduced by the finite response time of the transducers and the data system. These errors can be expressed as the product of the delay time for a ramp input and the slope of the pressure or ΔP response:

$$\text{error} = \text{delay time} \times (-dp/dt).$$

These errors will always be biased, either positive or negative depending on the sign of dp/dt .

The delay time for the data system is calculated to be 9 msec with the filters set at the nominal 30 Hz bandwidth. The "as installed" transducer delay times were experimentally determined by GE from dynamic response tests. The values obtained were about 2 msec for the Straindyne transducers used for pressure measurement and a maximum of 100 msec for the ΔP transducers.

1.4 Accuracy of Derived Quantities

The results of this measurement accuracy analysis are presented in Tables IV, V, and VI. A summary of these results follows. Note that all results are presented as a percentage of the instantaneous reading. This applies to both the uncertainties and bias errors.

TABLE IV
LOWER PLENUM NODE 2 MEASUREMENT ACCURACIES

Volume Condition		Subcooled Liquid (5 sec)	Flashing Two-Phase Mixture (10 sec)	Gradual Boiloff Two-Phase Mixture (15 sec)
Density	Value (lb/ft^3)	47	40	30
	Uncertainty (%)	± 1.8	± 2.1	± 2.8
	Bias (%)	-4.8	10.6	0.2
Mass	Value (lb)	45	38.3	28.7
	Uncertainty (%)	± 4.6	± 4.7	± 4.7
	Bias (%)	-4.8	10.6	0.2
Quality	Value	0	0.008	0.015
	Uncertainty (%)		± 15.4	± 5.6
	Bias (%)		-78.8	-5
Void Fraction	Value	0	0.142	0.428
	Uncertainty (%)		± 13.4	± 3
	Bias (%)		-66.4	-0.2
Internal Energy	Value (Btu/lb)	525.3	543	433
	Uncertainty (%)	± 0.8	± 0.2	± 0.2
	Bias (%)	0	-0.7	-0.1

1.4.1 Lower Plenum Node 2. The accuracy of parameters associated with Node 2 in the lower plenum is contained in Table IV. It is shown that these measurements are within acceptable limits throughout most of the transient. Exceptions are observed in density, quality, and void fraction bias errors during the flashing period. Though relatively large in

TABLE V
DOWNCOMER NODE 6 MEASUREMENT ACCURACIES

Volume Condition		Two-Phase Mixture Low Quality (6 sec)	Partially Full Two-Phase Mixture (9 sec)	Two-Phase Mixture High Quality (30 sec)
Density	Value (lb/ft ³)	42	22	0.9
	Uncertainty (%)	±1.1	±2.1	±55.6
	Bias (%)	-1.2	+15.4	+14.4
Mass	Value (lb)	90.2	42.2	1.7
	Uncertainty (%)	±2.6	±3.2	±55.7
	Bias (%)	-1.2	+15.4	+14.4
Quality	Value	0.005	0.056	0.98
	Uncertainty (%)	±11.8	±4	±56.6
	Bias	+12.9	-25.5	-12
Void Fraction	Value	0.098	0.552	0.999
	Uncertainty (%)	±10.6	±1.9	±1
	Bias (%)	+11.2	-13.9	-0.1
Internal Energy	Value (Btu/lb)	541.3	570.4	1,096.2
	Uncertainty (%)	±0.1	±0.2	±36.9
	Bias (%)	+0.1	-1.4	-6.7

magnitude, these errors only persist for a few seconds as influenced by fluid acceleration effects during flashing.

1.4.2 Downcomer Node 6. The results for Node 6 are shown in Table V. It is noted that uncertainties for the downcomer parameters are relatively small during the first part of the transient. Later in the transient when this volume contains saturated steam, substantial uncertainties are observed in measurements of density, because the density of the steam approaches the resolution limit of the transducers. The resultant large uncertainties in density are propagated into large uncertainties in most of the other derived quantities. These large uncertainties are not considered a major problem, however, since it is possible to use a backup measurement of local pressure to determine saturated steam properties.

Bias errors were found to be moderate for several of the parameters at various points in the transient. Most noticeable of these are the -25.5% bias error in quality as Node 6 is emptying. This error does not appear, however, to pose a significant problem in code verification studies. The errors only persist for a brief time and are in parameters of secondary importance in code comparisons.

1.4.3 Flow Rates. Table VI presents the calculated measurement accuracies for bundle flow rate and flow rates in both jet pumps. The results indicate that, initially, the accuracies

TABLE VI

FLOW RATE MEASUREMENT ACCURACIES

Flow Conditions		Initial Conditions	Decaying Flow of Subcooled Liquid (5 sec)	Flashing -- Two Phase Low Quality (10 sec)	Residual -- Two Phase High Quality (15 sec)
		Steady Flow of Subcooled Liquid			
Core Inlet Flow	Value (lb/sec)	40	5	15	~1
	Uncertainty (%)	±5.3	±21	±6.6	>±100
	Bias (%)	~0	-1.4	15	~0
Intact Loop Jet Pump Flow	Value (lb/sec)	21.5	13	Near 0	~0.5
	Uncertainty (%)	±6.2	±7	High	>±100
	Bias (%)	~0	3.7	High	~0
Broken Loop Jet Pump Flow	Value (lb/sec)	21.5	-10	-10	~2
	Uncertainty (%)	±6.6	±11.6	±11.6	>±100
	Bias (%)	~0	2.6	10	~0

are relatively good. However, as the transient progresses, many of these flow measurements develop significant uncertainties as the absolute values of the measurements drop. At five seconds, a moderate uncertainty of 21% was calculated in core flow which had dropped from 40 to about 5 lb/sec. During flashing, the flow has increased and the calculated uncertainty drops to 6.6%. Up through 10 seconds, uncertainties in the jet pump flow rates are moderate, with the exception of the intact loop jet pump during flashing. Flow stalls in this jet pump and remains near zero during flashing. The calculated uncertainties are thus a high percentage of the absolute flow rate.

Beyond 15 seconds, none of the flow rates can be measured within any reasonable uncertainty band, when the $\Delta W P$ measurements fall below the transducer sensitivity limits. ANC considers this area to be the most significant TLTA measurement problem. Lack of the postflashing flow information has restricted diagnosis of code problem areas.

Bias errors in the flow rates were not generally found to be serious. Most persist only for short periods of time during conditions of rapid flow rate change. A typical bias error, calculated for core inlet flow during the flashing period, is put into perspective in Figure 4. The error is shown as a difference between measured flow and a corrected flow where the bias was analytically removed. As shown, the maximum error is only 15% and appears only for a brief period. ANC does not consider errors of this type a serious detriment to the code verification activity.

2. OBSERVATION OF TESTS

An ANC representative witnessed Matrix Test 6, which was designated by NRC as Standard Problem 4[a].

In addition to witnessing the actual Test 6 experiment, the pretest and posttest operations were also viewed. In general, it was observed that the entire procedure was conducted quite professionally, with no obvious problems which would affect the quality of the data. GE has developed a systematic procedure for setting up and conducting the tests. The Hewlett-Packard computer in the control room is used extensively prior to the test to monitor and verify the measurements and initial flow conditions. This computer is also used to record the test data for immediate playback in engineering units. Specific procedures are summarized in the following paragraphs.

[a] The Standard Problems are a continuing series of code predictions made by the reactor vendors for various experiments to provide a basis for code evaluation and comparison.

Fig. 4 TLTA bundle flow bias error.

(1) Measurements

- (a) With the transducers on balance (valved off from the TLTA), the zero readings are recorded before and after the test. These zero readings are used to correct the transient experimental measurements, assuming a linear variation between pre- and posttest zero readings.
- (b) Measurements are checked several times during the hours leading up to the experiment, while the TLTA is hot and pressurized. The procedure includes a comparison of actual and expected nodal ΔP s and comparison of supposedly equal ΔP sums taken over several paths. In the Test 6 procedure, this careful double-checking revealed a faulty ΔP channel amplifier which was subsequently replaced to eliminate a potential problem.

(2) Operations

- (a) Automatic control systems are used to maintain proper system pressure and subcooling and to coordinate the

timing of all test initiation events. These systems were all checked several times prior to the tests.

- (b) Initial system flows are established by adjusting flow in both jet pumps until bundle flow reaches the desired value. This adjustment is accomplished with manual control valves in each of the jet pump drive lines.
 - (c) Downcomer mixture level starts to fall in the 60 seconds or so prior to initiation of the test when full power is applied to the bundle and steam generation rate increases. To achieve the proper initial mixture level, the test is started when the falling level reaches the desired value. This action is taken by the operator, based on his observation of a control room ΔP gauge indicating downcomer elevation head.
- (3) Blowdown Experiment

A typical experiment lasts 45 to 60 seconds. The progress of the blowdown can be followed by observing numerous control room displays which include mixture level, system pressure, flow rates, and bundle power. In addition, alarm bells are used to signal critical mixture level points and bundle temperature thresholds.

(4) Posttest

Within five minutes after the test, data retrieval operations begin with the printing of transient data on the control room printer. These data appear in engineering units. Quick-look examinations may be made of bundle flow, bundle temperature levels, and timing of various blowdown events as desired. A preliminary evaluation of the test results is also possible from this information.

3. CONCLUSIONS AND RECOMMENDATIONS

This evaluation has led to the following conclusions:

- (1) The accuracy of the various transducers used has been well defined and verified.
- (2) The conduct of the experiments was very thorough with numerous checks for measurement anomalies. No obvious problem areas are evident in these procedures.

- (3) Most of the measured parameters are considered to be of acceptable accuracy.
- (4) Bias error problems were found in several measurements of flow, density and void fraction, and quality during or near the flashing period. Inasmuch as these errors are short lived and not extremely high, they are not considered a major problem in using TLTA data for code verification.
- (5) Uncertainties were found to be relatively high in measured density and related parameters in steam-filled regions. These uncertainties pose no major problem in model verification, because properties of saturated steam are known from backup measurements of local system pressure.
- (6) System flow rates beyond the lower plenum flashing period are below the threshold of measurement system sensitivity. This is considered a significant problem area in utilizing TLTA performance data to assess, diagnose, and verify LOCA computer codes.

Based on this final conclusion, it is recommended that GE continue to seek improved methods of measuring these low flow rates.

IV. ANALYTICAL SUPPORT

Several analytical tasks have been completed to further the understanding of TLTA performance. These studies have focused on the relationship of TLTA performance to that of a BWR as affected by various scaling compromises and techniques. Consideration has been given to wall heat transfer effects, elevation effects, and effects of fluid inertia. An additional study has examined potential TLTA performance differences due to an alternate lower plenum geometry planned for use later in the test program.

These studies were all conducted with the RELAP4^[4] transient thermal-hydraulic computer code. A typical TLTA analytical model used in conjunction with RELAP4 is shown in Figure 5. Numerous, similar versions were developed during the course of these studies and in the code evaluation studies discussed in Section VI. A thorough description of the TLTA model is given in Section VI.

1. WALL HEAT TRANSFER EFFECTS

In thermal-hydraulic analyses of BWR systems during a postulated LOCA, wall heat effects are generally ignored. This assumption is believed to be valid, as the full-scale plant has a relatively low heat transfer surface area-to-fluid mass ratio. (In typical plants, this ratio is about $0.008 \text{ ft}^2/\text{lbm}$.) As a consequence, heat transfer to the fluid from the vessel structure is expected to be negligible. In the TLTA, which is a 1/560 scaled version of a BWR, this assumption may no longer be valid, as the TLTA surface-to-mass ratio is about $0.09 \text{ ft}^2/\text{lbm}$, an order of magnitude larger.

The purpose of this study was to evaluate the significance of TLTA wall heat effects to aid in interpreting TLTA performance and to provide guidance in modeling the TLTA system. The study was conducted with a version of the TLTA model which consisted of 14 volumes and 22 flow junctions connecting the volumes. Sensible wall heat effects were represented in the model by ten one-dimensional wall conduction models, interfacing with one or more of the TLTA regions through appropriate heat transfer correlations. These correlations are selected by RELAP4 to correspond to the instantaneous wall and fluid conditions prevailing in each region.

The model was set up to represent a typical TLTA blowdown experiment. Initial power, flow, pressure, and enthalpy distribution for Matrix Test 3, the reference case, were selected to initiate the problem. The blowdown analysis was based on expected TLTA valve phasing, which simulates a double-ended recirculation loop pipe break. The analysis was conducted with RELAP4/Mod 1, version 64.

Figure 6 presents the calculated wall heat flux to the fluid in the lower plenum. Also included is the calculated wall to fluid temperature difference (ΔT_w). The response shows a relatively low heat transfer rate early in the transient when a low ΔT_w exists. A threshold

Fig. 5 GE-BDHT-TLTA base case analytical model.

point is observed at about seven seconds when the suction line uncovers and the vessel begins to rapidly depressurize. As the pressure falls, the local fluid temperatures follow the saturation line, resulting in a rapid buildup of ΔT_w , hence increasing rates of heat transfer.

A forced convection heat transfer mode is predicted in the initial few seconds, when ΔT_w is low, with relatively low heat transfer rates. At about five seconds, the heat transfer mode is predicted to switch into a nucleate boiling regime, where it remains for the duration of the 30 seconds analyzed. Heat transfer rates increase throughout this period as ΔT_w increases, reaching a peak of 85,000 Btu/ft²-hr at 30 seconds.

Fig. 6 Heat transfer—lower plenum vessel wall.

The relative effect of the lower plenum wall heat transfer can be determined from the quantity of liquid boiled off by the wall heat compared to the total vapor generated in the lower plenum. The integral of energy transferred from the lower plenum walls in the 30-second interval, with the Figure 6 fluxes, was 7,300 Btu. This energy transfer is sufficient to boil off about 10 pounds of lower plenum water. This quantity is about one-third of the total of 30 pounds of vapor generated in the lower plenum during this interval.

The relative effect of wall heat on TLTA performance was established through two comparative runs, one with and one without the wall heat option. The calculated steam dome pressure decay and core flow rate for these two cases are shown in Figure 7.

Figure 7 shows that the predicted wall heat effects on system performance are significant. Wall heat transferred to the fluid contributes to the vapor generation rate, which holds vessel pressure up relative to the case with no wall heat. This effect is seen to become significant at about seven seconds when the wall heat transfer rates begin to rise. This difference in pressure increases with time and reaches about 130 psi at 30 seconds,

Fig. 7 Wall heat effect on TLTA.

lengthening the blowdown time by six to eight seconds. Core flow is also influenced by the wall heat. The most obvious difference occurs in the 10- to 15-second time period, where the local wall heat transfer effects are increasing rapidly. The heat addition to the lower plenum fluid results in local boiloff which forces more fluid through the core.

2. TLTA ELEVATION EFFECTS

In scaling the TLTA from the reference BWR, certain distortions in elevations were apparently unavoidable. Of particular interest are those elevation differences between the TLTA and the BWR which may affect core flow simulation in the TLTA. Specifically, these include the relative height of the jet pump suction and downcomer mixture level with respect to the core. Both elevations are significantly higher in the BWR.

To isolate and evaluate the potential effect of these differences, two comparative RELAP4 /Mod 3, version 66 computer runs have been used. One run representing a base case was made for TLTA Test 3, the reference test. The model used to make this run was then modified and rerun representing BWR rather than TLTA elevations, volume heights, and mixture levels for regions above the beginning of the bundle heated length. These regions include the jet pumps, downcomer, steam dome, upper plenum, and upper portions of the recirculation loops. Friction losses, inertias, heat transfer geometries, and initial fluid masses were kept the same as in the base case.

The results of the TLTA analytical model with BWR elevations are compared to those from the TLTA base case model results in Figures 8 and 9. The effect of the higher BWR elevations was to increase core flow as shown in Figure 8. The higher BWR elevations increase the head in the broken loop jet pump which decreases the flow from the lower plenum through the broken loop jet pump. The decrease in flow from the lower plenum through the broken loop jet pump results in the corresponding increase in core flow.

Fig. 8 TLTA-BWR elevation comparison - core flow.

Soon after the jet pump suction is uncovered, the core flows from both analytical models converge to nearly equal values. The flows remain nearly the same during the rest of the transient because the liquid level in the downcomer and jet pumps is depleted which negates any elevation differences between the two systems.

Surface temperatures of an average power rod at the axial center of the core are compared in Figure 9. The high core flow with the BWR elevation provides better cooling and keeps the temperature about 40°F lower than the base case during the initial 8 to 9 seconds. Although the rod surface temperatures converge at about 9 seconds, the stored energy and the average temperature of the rod in the base case is higher at this time. Dryout occurs slightly earlier for the base case which, along with the higher stored energy, results in the slightly higher surface temperature.

Fig. 9 TLTA-BWR elevation comparison - rod temperature.

3. TLTA FLUID INERTIA EFFECTS

Another potential distortion in TLTA simulation results from scaling compromises in the design of the TLTA recirculation loop. These compromises in TLTA piping and jet pump lengths and relative flow areas were necessary to avoid unacceptably high friction losses. These geometrical distortions result in lower initial TLTA fluid velocities and stored momentum. As an example, the initial fluid velocity in the TLTA intact loop suction line is about 4.6 ft/sec, whereas in a BWR it is about 27.4 ft/sec. The lower stored momentum would be expected to allow transient flow events in the TLTA to occur much faster than in the BWR.

The evaluation of the fluid inertia effects has been made through a comparison of RELAP4 core flow predictions for the TLTA and a BWR. The TLTA calculation used was that described as the base case in Section 2. Results from previous BWR analyses, described in Reference 13, were used for BWR core flow.

This comparison is shown in Figure 10 for the first 6 seconds of blowdown. The differences in flow rate are due to the combined effects of inertia and elevation differences. During the first second, the comparison shows the TLTA core flow rate decreasing much more rapidly than that for the BWR due to the lower TLTA inertias. The TLTA broken

Fig. 10 TLTA-BWR loop momentum comparison – core flow.

loop jet pump reverses flow direction more rapidly than it does for the BWR, which is the primary cause of the sharper decrease in core flow rate. Once the inertia effects are dissipated, the higher elevations of the BWR maintain a higher core flow, consistent with the results discussed in Section 2.

4. ALTERNATE LOWER PLENUM GEOMETRY

TLTA Test 18, to be conducted with the second bundle, will utilize an alternate lower plenum and guide tube configuration. The primary objective of this test will be to assess experimentally the sensitivity of TLTA performance to a variation in lower plenum and guide tube geometry.

The alternate lower plenum and guide tube configurations are shown in Figure 11, along with the reference design. The alternate configuration has a higher length-to-diameter (L/D) ratio as compared to the reference configuration. In addition to a different L/D, the alternate lower plenum volume is substantially higher. It was originally intended that the lower plenum and guide tube volumes be identical for both designs. An apparent design change resulted in the larger alternate configuration volume.

Fig. 11 Lower plenum and guide tube configurations.

The RELAP4 analysis described herein was conducted to determine the effect of the alternate lower plenum geometry on TLTA system performance. Three RELAP4/Mod 3, version 66 blowdown calculations were compared for the following conditions:

- (1) Baseline case with nominal lower plenum and guide tube geometry
- (2) Alternate lower plenum and guide tube geometry with L/D and volume as shown in Figure 11
- (3) Alternate geometry with L/D changed, but with volumes maintained identical to the baseline case.

The baseline case was generated for the Test 3 posttest calculation as described in Section 2. The two change cases were analyzed with an identical model except for minor changes to account for the alternate lower plenum and guide tube flow area, length, and volume.

The primary feature of RELAP4 affected by changes to the lower plenum and guide tube geometry is the bubble rise model. This model calculates a vertical distribution of bubble mass and enthalpy and an overall bubble mass balance in vertically oriented volumes.

The following paragraphs contain a discussion of the results obtained in the analysis.

Figure 12 compares the predicted average lower plenum quality for the three cases. The lowest quality occurs in the baseline case, with higher values in the change cases. This behavior is attributed to the smaller lower plenum cross-sectional area of the two change cases. Using the same bubble rise velocity (3 fps), a lower bubble mass escape rate is calculated in the change cases, leaving behind a higher percentage of voids in the lower plenum mixture. Where only the L/D is changed, the effect on average quality is more pronounced due to the reduced lower plenum liquid mass in this case.

Fig. 12 Lower plenum study - average lower plenum quality.

Figure 13 compares core inlet flow predictions for the three cases. The differences in quality discussed above affect core flow only to a minor degree.

Figure 14 compares the magnitude of flows in the broken loop jet pump. The two change cases both predict a lower quality fluid entering the jet pump due to the reduced bubble escape rate from the lower plenum. The lower quality entering the jet pump results in a higher mass flow in the change cases as shown in the figure. This is expected because the flow is choked in the broken loop jet pump at the drive nozzle and critical flow rate is strongly dependent on quality.

Figure 15 presents the predicted lower plenum pressure history for the three cases. The combined effects of slightly different predictions of wall heat transfer, break flow, and

Fig. 13 Lower plenum study — core inlet flow.

Fig. 14 Lower plenum study — broken loop jet pump flow.

Fig. 15 Lower plenum study - lower plenum pressure.

Lower plenum bubble escape rate result in only relatively minor differences in predicted system depressurization time.

These results show several minor performance differences between the two alternate lower plenum designs and the baseline case. With respect to the baseline, both alternate design cases show somewhat higher average lower plenum qualities, but only minimal changes in resultant flow rates out of the lower plenum. Slight differences in the system depressurization rate are also observed in the change case predictions.

In comparing the predictions for the two alternate configurations, it appears that the case with just the L/D changed results in the greatest departure in predicted performance from the base case.

5. CONCLUSIONS AND RECOMMENDATIONS

The studies described in Section 1 through 4 have led to the following conclusions regarding TLTA performance:

- (1) Wall heat transfer effects in the TLTA will be significant. The resultant effect on TLTA performance must be accounted for analytically.
- (2) The elevation and component height differences between the TLTA and a BWR significantly affect TLTA core flow simulations during the initial part of the transient. The lower TLTA core flow would tend to cause higher peak heater rod surface temperatures in the TLTA, compared to those in a BWR.
- (3) Fluid inertias are lower in the TLTA and result in a faster initial core flow rate decay relative to a BWR. This faster decay would tend to cause higher peak heater rod surface temperature in the TLTA.
- (4) The influence of the alternate lower plenum geometry on TLTA system behavior is expected to be small. To maximize the behavior difference, an alternate design is recommended in which L/D is the only parameter changed.

V. REVIEW OF TLTA DATA

The experimental program developed for the TLTA by GE revolves about a reference test. Conditions of the reference test were selected to represent an average power bundle experiencing a double-ended offset shear BWR recirculation line break. In the remaining tests in the TLTA series, a single parameter was usually varied from the reference test to isolate the influence of each parameter on TLTA performance. This section presents the results of a review of the data from all tests conducted on the first TLTA bundle. Emphasis was placed on determination of: (a) influence of each parameter on TLTA system behavior, (b) significance of the influence with respect to future model development and verification plans, and (c) potential improvements or additions to the GE test program to provide more useful results relative to code verification.

1. BUNDLE 1 TEST CONDITIONS

The conditions of the tests from the first TLTA bundle are summarized in Table VII. The major parameters which have been varied include:

Bundle power (Tests 1, 3, 4, and 10)

Break area (Tests 2, 3, and 6)

Power decay (Tests 4 and 7).

Tests 8 and 9 were dropped from the test matrix, as their objective (determination of power decay rate sensitivity) had been judged fulfilled by Test 7. An additional consideration by GE in developing the test plan was test-to-test repeatability. This question was addressed through a second run of the reference test, shown in the table as Matrix Test 5.

The data for the first bundle tests were obtained from GE in References 12 and 14 through 20.

2. EFFECT OF BUNDLE POWER

The effect of bundle power on system and bundle performance was assessed by comparing the results of Tests 1, 3, 4, and 10 which had bundle powers of 3.0, 4.55, 6.1, and 6.5 MW, respectively. An additional experiment, Test 4903, Run 16 (designated Test 3R) was also considered. This test, which was not included in the test matrix, was a rerun of Matrix Test 3 with a revised steam line valve closing time. All other test parameters were

TABLE VII

BUNDLE 1 TEST CONDITIONS

Matrix Test Number	Description	Test and Run Number	Bundle Power (MW)	Relative Break Area	Power Decay Rate
1	Low Power, Nominal Break	4901 Run 13	3.0	100%	Nominal
2	Nominal Power, Intermediate Break	4902 Run 9	4.55	50%	Nominal
3	Reference	4903 Run 9	4.55	100%	Nominal
4	Peak Power, Nominal Break	4904 Run 45	6.1	100%	Nominal
5	Repeatability Test	4903 Run 4	4.55	100%	Nominal
6	Nominal Power, Oversize Break	4906 Run 14	4.55	120%	Nominal
7	Peak Power, ANS + 20% Power Decay	4907 Run 10	6.1	100%	ANS + 20%
8	Nominal Power, ANS + 20% Power Decay	Not Run	4.55	100%	ANS + 20%
9	Nominal Power, Intermediate Break, ANS + 20% Power Decay	Not Run	4.55	50%	ANS + 20%
10	Overpower, Nominal Break	4910 Run 10	6.5	100%	Nominal

essentially the same in this group of experiments with the exception of initial downcomer mass. This parameter did not appear to be repeatable from test to test.

System performance parameters such as depressurization rate and system flows were not significantly affected by bundle power. Those differences that were observed between the tests are explained by other factors. For example, differences are observed in timing of lower plenum flashing, shown by bundle inlet flow in Figure 16. Flashing occurs earliest in Test 10, followed in succession by Tests 3, 4, 3R, and 1. Flashing occurs in exactly the same order as increases in initial downcomer masses for these five tests. Obviously, the quantity of initial mass determines the time to suction line uncover and subsequent lower plenum flashing.

Fig. 16 Effect of bundle power on bundle inlet flow.

Rod temperatures did show marked differences among the tests at varying power level. Temperatures in the 6.1 and 6.5 MW tests ran at consistently higher levels than the nominally powered cases, and the 3 MW test temperatures were consistently lower — both effects as expected. Of primary interest is the effect shown in Figure 17. Here, the rods in the high-powered tests experienced a rapid temperature rise immediately, whereas the temperatures of the rods in the lower power tests did not rise until after lower plenum flashing, when dryout occurred. This indicates a threshold bundle power, where an early critical heat flux occurs causing a change from nucleate to film boiling. It would be of interest to compare results of tests at intermediate bundle powers between 4.55 and 6.1 MW to closer determine the CHF threshold.

Fig. 17 Effect of bundle power on rod temperatures.

3. EFFECTS OF BREAK AREA

The effects of break area have been examined by comparing the results of Tests 2, 3, and 6. These tests had break areas of 50, 100, and 120% with respect to the reference case. Break area was found to have a significant effect on system performance as shown in Figure 18. The depressurization rate was much slower in the 50% break area test than in the nominal test and slightly faster with the 120% break area. The differences in break flow also affected downcomer mixture level history, time of suction line uncover, and subsequently, the timing of lower plenum flashing. This difference is shown by the bundle inlet flows in Figure 19. In the 50% break area test the lower plenum fluid flashed several seconds later than either the 100 or 120% cases. The nearly identical time of flashing for these latter cases is attributed to compensating differences in break area and initial downcomer mass.

In comparing rod temperatures, few consistent trends were found with respect to break area. Typical rod temperature results are shown in Figure 20. Generally, the rods dried out later in the small (50%) break case as expected from the later flashing and dryout in this test. The nominal break test had consistently higher rod temperatures than the 50% case, which follows from the differences in dryout times. However, at many locations the nominal test also showed higher rod temperatures than did the 120% case. This trend is not readily explained but could be attributed to the randomness of the rewetting process due to fallback, coupled with the limited quantity of thermocouple measurements available for comparison.

Fig. 18 Effect of break area on depressurization rate.

Fig. 19 Effect of break area on bundle inlet flow.

Fig. 20 Effect of break area on rod temperature.

4. EFFECT OF POWER DECAY RATE

In establishing the nominal power decay for the TLTA heater rods, GE used their own design values for decay heat based on BWR scram characteristics. To simulate the fuel rod, the heater rod must be programmed to follow a decay profile that combines both stored and decay heat of the fuel. The approach used in deriving this power profile is described in Reference 21.

The alternate decay profile was based on the ANS + 20%^[22] curve for decay heat rather than the GE design values. Stored energy considerations were identical in both cases. The resultant heater rod power profiles for the two cases were found to differ by only a few percent throughout the transient as shown in Figure 21. On the basis of this comparison, one would expect only a minor difference between tests programmed with the two power decay profiles.

The effect of power decay rates was evaluated by comparing the results of Tests 4 and 7, which used nominal and ANS + 20% decay heat assumptions, respectively. The decay heat had no perceptible effect on system performance depressurization, and bundle flow rates matched very closely. However, rod temperatures showed a very definite trend; the ANS + 20% power decay curve test resulted in consistently higher rod temperatures. In several cases, such as shown typically in Figure 22, the temperatures in the ANS + 20% test seemed disproportionately higher. It does not seem reasonable that such large temperature differences could be caused by the very small power difference. This apparent anomaly is thus far unexplained.

Fig. 21 Power decay rate - Tests 4 and 7.

ANC-A-6692

Fig. 22 Effect of power decay rate on rod temperature.

ANC-A-6697

The power decay test is considered inconclusive due to the apparent inconsistency of the results and the relatively minor differences between the programmed decay rates. It is thus suggested that power decay rate be considered again as a parameter in future tests. In running these tests, a wider difference in programmed decay rates is recommended to better establish rod temperature performance differences.

5. EFFECT OF THERMOCOUPLE LOCATION

In view of the apparent inconsistencies observed in bundle performance, the effect of thermocouple location on measurement values was examined. Two such comparisons are shown in Figures 23 and 24. The figures each present several temperature measurements from Test 3 taken at common axial positions and power levels. These results isolate the effect of radial position on rod thermal performance. Both figures show that temperature differences in excess of 400°F exist on rods with identical power levels and axial elevations. These results clearly indicate a three dimensionality and randomness in the bundle dryout and rewetting processes.

Fig. 23 Effect of thermocouple location - 1.11 power factor.

Fig. 24 Effect of thermocouple location - 1.25 power factor.

6. REPEATABILITY

Test-to-test repeatability was assessed by reviewing the data from Tests 3 and 5. These tests started from nearly identical initial conditions and were operated under similar valve phasing and power decay profiles.

Depressurization rates in the two tests were found to match almost exactly. Some minor differences in system flow rates were observed between the two tests, as shown by bundle flow in Figure 25. This difference is apparently due to slight differences in initial downcomer mass, initial bundle flow, and timing of the transient initiation.

Bundle performance was also found to be generally repeatable between these two tests as evidenced by Figure 26. The minor temperature differences shown are attributed to the bundle flow difference. In a few instances, some notable differences were observed in bundle temperatures. Typical of these are the results presented in Figure 27. The rod dryout and rewetting process does not appear to be consistent, demonstrating certain randomness in this phenomenon.

Some inconsistencies which could not be readily explained have been pointed out in comparisons in previous sections. Further, the repeatability tests were conducted within a few days of each other, whereas all other tests were conducted from several days to months apart. One question which has not been fully resolved is experiment repeatability over periods of times approaching the bundle lifetime. Lack of repeatability should be eliminated as a possible cause of data inconsistencies by running identical tests several months apart.

Fig. 25 Bundle flow repeatability.

ANC-A-6700

Fig. 26 Bundle temperature repeatability - 71-inch elevation.

ANC-A-6701

Fig. 27 Bundle temperature repeatability - 118-inch elevation.

7. CONCLUSIONS AND RECOMMENDATIONS

This review of the TLTA data has led to the following direct conclusions:

- (1) Bundle power level has only a minor effect on TLTA system performance.
- (2) Initial downcomer masses, which were not repeatable from test to test, have a significant effect on system behavior. The most severe bundle temperature conditions were associated with the lower initial mass values.
- (3) Rod temperatures were significantly affected by bundle power; a CHF threshold exists at initial powers some place between 4.55 and 6.1 MW.
- (4) Break area impacts system performance in an expected manner, influencing depressurization rates, flows, and mass inventories.
- (5) Results of the power decay profile tests are considered inconclusive.

- (6) Many inconsistencies are observed in bundle heat transfer processes. Some of the inconsistencies may be explained by the random nature of rod rewetting due to liquid falling back into the bundle from the upper plenum. Other inconsistencies defy explanation and indicate, perhaps, a high system performance sensitivity to an unknown variable.
- (7) Test-to-test repeatability was judged to be good for tests run close together in time. Repeatability over longer time intervals has not been established.

Based on these observations, it is recommended that the following steps be taken:

- (1) A criterion (such as ± 5 lb) should be established within which downcomer initial masses should be constrained on all future tests. Failure to meet the criterion should be cause to rerun the test.
- (2) Additional testing to precisely establish the CHF power threshold in TLTA should be considered.
- (3) A new alternate power decay profile which provides a significant departure from the reference case should be established and used.
- (4) A repeatability test to examine test-to-test consistency over the life of a bundle should be scheduled.
- (5) Analytical efforts to provide improved analyses of BWR rod bundle thermal-hydraulic performance should be expanded. Such models will require phase slip and distribution capability to account for fallback effects and standing bundle mixture level. The models should also consider three-dimensional interactions within the bundle combined with channel wall effects.

VI. RELAP4 CODE EVALUATION

This section presents the results of comparisons of data from selected TLTA tests with corresponding RELAP4 calculations. The objective of these comparisons was to evaluate the RELAP4 code and user methodology as applied to conditions similar to the blowdown portion of a BWR LOCA. The evaluation has been conducted in a systematic manner, concentrating on performance of individual TLTA components. Components considered include the break, downcomer, recirculation pump, jet pump, lower plenum, and the core.

Three tests were considered in the code evaluation process. These were Matrix Tests 1, 3, and 6, which were described generally in Table VII. Test 1 was the initial TLTA blowdown. It represented a low-power, low-flow rate bundle typical of those found on the periphery of a BWR core. Some measurement problems, unique to this test, were encountered in the data. These problems, which limited some of the Test 1 RELAP4 comparisons, were corrected by GE for subsequent tests. Test 3 represented the "reference case," in which all test parameters and initial conditions were at their nominal values. The flow and power conditions were representative of those in an average BWR bundle. Test 6 was designated as Standard Problem 4 by the NRC. Initial conditions and most other test parameters were similar to those of Test 3. The relative break area was 120% of the reference break area which resulted in a more rapid blowdown transient.

The bulk of the data comparisons were made with data from Test 3. However, Test 1 and 6 data were used in several instances to check and verify conclusions reached from the Test 3 comparisons. Sources of the data used are listed as References 12 and 14 through 20.

1. RELAP4 MODEL DESCRIPTION

1.1 System Model

The analytical model of the TLTA, illustrated in Figure 5, was derived by considering current large BWR modeling methods as they apply to the test facility. The physical model, including volumes, flow areas, elevations, flow rates, pressure, and enthalpy distribution was derived primarily from drawings supplied by GE and the Preliminary System Design Description^[1].

In general, Figure 5 is self-explanatory; however, the following items are considered pertinent to understanding the model and evaluating the results of the data comparisons:

- (1) The upper plenum and steam separator volumes are modeled as a common volume (Volume 2). The volumes surrounding the steam separator deflector and collector and a portion of the downcomer were included in the steam dome volume (Volume 3).

- (2) The junction (Junction 3) between the steam dome (Volume 3) and downcomer (Volume 4) separates a step change in initial downcomer fluid enthalpy at the feedwater injection location.
- (3) The blowdown and recirculation lines in the break loops were combined into common volumes (Volumes 5 and 7) using the blowdown line flow resistance.
- (4) Momentum flux has been included at all junctions except the core inlet (Junction 24) and outlet (Junction 1) as required to permit separate single channel analyses in the core.
- (5) Choking criteria are tested at the jet pump mixing junctions (Junctions 7, 12, 14, and 15), the break junctions (Junctions 26 and 27), and the venturi (Junction 4).
- (6) The bypass is modeled by a single volume (Volume 14) which contains the total volume of the four bypass tubes. The hydraulic diameter of the volume and connecting junctions (Junctions 16 and 17) is that of the actual hardware, and hence the flow resistance and pressure drop are conserved in the model.
- (7) Several heat slabs have been provided to account for sensible wall heat transfer to the TLTA fluid. To minimize the number of inputs for the heat slabs, some of the vessel structural elements have been combined into single heat slabs. Heat Slabs 1, 2, 3, 17, and 18 are the ceramic and stainless steel channel wall. These heat slabs interface with both the core and main vessel volumes. The surface areas and volumes of the upper plenum and steam separator were combined into Heat Slab 4. Heat Slabs 5, 6, and 7 represent the combined main vessel wall. The break loop recirculation pump and the suction side piping are represented by Heat Slab 9. Heat Slab 10 represents the break loop jet pump and the discharge side piping. Heat Slabs 8 and 11 represent the intact loop. The recirculation pump and the jet pump were combined with the piping as in the break loop. Heat Slabs 12, 13, 14, 15, and 16 represent the core heater rods at five axial locations. Each of these heat slabs represents an axial segment of 49 rods. The resultant calculation of temperature response is that of an average radial power rod.

1.2 Core Model

An analytical model of the core was developed to investigate the thermal-hydraulic response of single TLTA rods and the adjacent fluid. The model, shown in Figure 28,

Fig. 28 GE-BDHT-TLTA heater rod model.

permits a more detailed evaluation of a rod than is economically justified in the system analysis. The subchannel model uses the results of the system analysis as boundary conditions. Separate versions of this model were used to represent rods with different radial peaking factors. The following items are considered pertinent to understanding the heater rod model and evaluating the results of the data comparisons:

- (1) Volume 1 represents the unheated inlet section to the core.
- (2) Volume 2 represents the upper plenum.
- (3) The pressure and temperature or quality of Volumes 1 and 2 are taken from a system analysis and are used as boundary conditions for the core analysis.
- (4) Heat transfer is confined to the heater rods and the circulating fluid. Heat transfer to the channel wall is neglected.
- (5) The centers of Volumes 4, 6, 8, 10, and 12 correspond to the axial location of the thermocouples in the rods.

1.3 Model Evolution

The code comparisons described herein were based on an "evolutionary" code and user input model. Both the code and the TLTA model were changed several times during the course of the study to incorporate better modeling and techniques, to eliminate code errors, and, in some cases, to aid the diagnosis of problem areas. These changes are documented in References 23, 24, and 25. It is emphasized that the vast majority of these changes were minor in nature and had little impact on the TLTA calculations. Those that were of significance to the code evaluation are summarized in Table VIII.

Generally, the changes to the model were made to improve the calculations in a specific region of the TLTA. The CHF correlation change, the jet pump drive flow modification, and the critical flow model revisions were made to correct an indicated calculational problem. These changes are discussed in more detail in the following sections.

The core model described in Section 1.2 was not available when the Test 1 prediction was made but was available later for Tests 3 and 6. This model provided additional detail in rod temperature calculations. The Test 1 and 6 calculations were made prior to the test and used GE-prescribed initial and trip conditions.

TABLE VIII
MAJOR DIFFERENCES BETWEEN TEST CALCULATIONS

	Test	Test	Test
	1	3	6
CHF Correlation Used	Barnett	$X_{CHF} = 0.95$	$X_{CHF} = 0.95$
Jet Pump Model Used	As Coded	Modified Drive Flow	Modified Drive Flow
Critical Flow	Moody $C = 0.6$	Match Test 3	Moody $C = 0.6$
Core Model	Integral Average Rod	Separate Local Rod	Separate Local Rod
When Run	Pretest	Posttest	Pretest
RELAP4 Version Used	MOD 2, Version 3	MOD 3, Version 66	MOD 3, Version 56

2. DATA COMPARISONS

2.1 Break

2.1.1 Design and Performance Considerations. The simulation of a BWR LOCA is initiated by two quick-opening valves in the TLTA broken loop. As these valves open, flow in the loop very quickly departs from the initial conditions, as mass is forced out both sides of the loop into the suppression tank. Choking occurs at two points in the system: (a) at the broken loop jet pump drive nozzle and (b) at a venturi placed in the broken loop suction line. The areas of these two choking points were scaled from the BWR so that the relative mass expulsion rate would be simulated in the TLTA.

2.1.2 Model Considerations. The critical flow calculations for the Test 1 and Test 6 predictions utilized the Moody model with multipliers of 0.6 and 0.74, respectively. These calculations were considered unsatisfactory because they did not properly account for the relatively high flow rates observed during the subcooled portion of the blowdown. As a result of the improper break flow calculation, the timing of events during the transient was not properly predicted, and comparisons in other parts of the system were made with difficulty.

To overcome this problem in evaluating RELAP4 calculations for Test 3, the break flow was forced to match roughly the trends observed in the data. This was accomplished with the following critical flow model:

- (1) Subcooled - Henry model x 1.4
- (2) Saturated low quality - Moody model x 0.9
- (3) Saturated high quality - Moody model x 0.74.

2.1.3 Data Comparisons. Figure 29 presents information extracted from a GE analysis of net mass depletion in the TLTA for conditions similar to Test 3^[a].

Fig. 29 Tests 3 and 6 break flow.

These results were obtained by summing instantaneous local masses throughout the transient from numerous individual local density measurements. The figure represents total break flow, combining flows through the suction line and jet pump drive nozzle. The results of the RELAP4 calculations made for Tests 3 and 6 are also shown with the experimental data. Since actual break flows differed in these two tests, relative rather than actual flow is plotted.

The experimental trends in Figure 29 show several interesting effects. Initially, the experimental flows are high as subcooled liquid flows out of the system. The transition to low quality break flow is seen in the 2- to 4-second period as a substantial drop in the total break flow. At about 8 seconds, the flow again drops abruptly as the jet pump suction uncovers, and break flow through the drive nozzle changes from low to high quality. At 10 seconds, the sharp drop in flow is observed as the suction line uncovers, and flow here changes from low to high quality.

The degree of compliance of the Tests 3 and 6 calculations with these data is also evident in Figure 29. In Test 6, where a constant multiplier was used with the Moody

[a] The information presented in Figure 29 was taken from Test 4903, Run 16, which was very similar to Test 3.

model, the agreement was poor during the early, subcooled portion. The Test 3 case with adjusted models and multipliers exhibits more consistent trends throughout the transient.

Figures 30 and 31 show comparisons of Test 3 downcomer mass and steam dome pressure. Both parameters are directly affected by the break flow calculation. The calculated and experimental downcomer mass inventories, compared in Figure 30, indicate that the prescribed critical flow is reasonable. The calculated mass inventory is shown to be very close to the Test 3 data except for the 7- to 10-second time period, during which the mixture level in the downcomer is near the suction line opening. This discrepancy is partially attributed to drawdown within the test apparatus and the lack of a horizontal slip flow model at the suction line inlet. As the mixture level reaches the suction line opening, drawdown near the break is thought to allow high quality flow before the average volume mixture level has reached the opening. This effect, which would reduce the rate of change of the mixture level and mass inventory, is not accounted for in the analysis. During the uncovering process, significant slip between phases is expected at the suction line inlet, which would also reduce the mass inventory rate of change.

Fig. 30 Test 3 downcomer mass.

Fig. 31 Test 3 steam dome pressure.

The predicted steam dome pressure decay generally agrees with the test data as shown in Figure 31. The small difference in pressures in the 0- to 10-second time period may indicate that the prescribed break flow was slightly high. The minor differences in the latter part of the transient may also be due to the break flow calculation and/or wall heating effects. The effect of overpredicting wall heat or underpredicting break flow would be identical in their influence on steam dome pressure. Experimental wall temperature measurements, planned in future testing, are expected to provide additional information, which can be used to verify or improve the wall heat transfer model.

2.1.4 Discussion. It is generally conceded that improvements were required in the RELAP4 critical flow model. This problem was treated in a recent version of RELAP4^[26]. Until this model improvement was available, the approach used in the Test 3 analysis was followed. This procedure allowed a proper calculation of break flow-dependent variables such as steam dome pressure and downcomer mass, eliminating several problems in the evaluation of other code variables.

One area which should be examined further is the potential effect on break flow of drawdown and slip in the vicinity of the flow tube inlet. Neither is presently accounted for in the RELAP4 model but may be significantly affecting break flow. These effects may be even more pronounced in a BWR where flow exits the vessel through a 28-inch pipe.

2.2 Downcomer

2.2.1 Design and Performance Considerations. The downcomer is an annular region bounded by the outer vessel wall and the core channel wall. The jet pumps are submerged in the lower portion of the downcomer. During normal operations, steam separator effluent enters the downcomer in the upper portion of the vessel and exits through the suction line and jet pump suction. Highly subcooled feedwater is introduced into the downcomer, at an elevation which separates saturated liquid from subcooled liquid.

The downcomer mixture level is initially 10 to 15 feet above the bottom of this region. As the simulated LOCA is initiated, flow out the break begins to deplete the downcomer liquid inventory. At about 10 seconds, the liquid level has fallen below the suction line elevation, where it remains for the duration of the blowdown.

2.2.2 Model Considerations. The RELAP4 bubble rise model is used in the downcomer to determine local enthalpy, bubble escape rate, and mixture level. User-specified inputs of bubble rise velocity and a bubble gradient parameter control the calculated conditions in the downcomer region. In the TLTA analysis, the recommended values of these parameters have been used^[4], as determined from analyses of various vessel blowdowns.

The downcomer region is modeled with two separate volumes. One represents the initially subcooled region below the feedwater sparger. The other combines the upper portion of the downcomer with the steam dome region.

2.2.3 Data Comparisons. The predicted downcomer mixture level, shown in Figure 32, agrees with the data except at the initial time and for a few seconds thereafter. This difference is due to a minor modeling anomaly related to the nonuniform cross section of the test vessel in the upper flange region. Once the level falls below this region, the experimental and predicted levels agree closely, consistent with the downcomer mass comparison. Most importantly, the level is predicted to reach the jet pump suction and recirculation loop elevations at essentially the correct time.

The downcomer average fluid density comparison in Figure 33 shows the RELAP4 predicted value for the region below the feedwater sparger and the volume average values calculated from the three density measurements in this region. The initial values agree quite well. However, from shortly after the break until six seconds, when the mixture level in the downcomer drops below the feedwater spargers, a discrepancy exists which is believed to be due to temperature stratification related to carryunder. From six seconds until the mixture level is near the suction line, good agreement is shown. During the time the suction line is uncovering, the discrepancy is related to the drawdown effect and the lack of a slip flow model, as discussed in Section 2.1.

2.2.4 Discussion. The primary discrepancy shown in the downcomer calculations lies in predicted density in the first six seconds. This discrepancy could affect local enthalpy and

Fig. 32 Test 3 downcomer mixture level.

Fig. 33 Test 3 downcomer average fluid density.

resultant flow rate calculations at the jet pump suction and flow tube inlet. The discrepancy is apparently due to unaccounted stratification in the lower part of the downcomer. It is currently believed that the calculation could be improved if more detail were provided in the downcomer model. It is recommended that follow-on studies be conducted to investigate this potential by additional volumes in this region.

2.3 Recirculation Pump

2.3.1 Design and Performance Considerations. Both the broken and intact loop BWR recirculation pumps are simulated in the TLTA. The broken loop pump is valved off and isolated from the system in the initial part of the transient to protect it from potential damage. Therefore, only the intact loop pump is of significance for model evaluation.

The intact loop drive pump is a horizontally mounted, high pressure, single stage, centrifugal pump with a 3-inch-diameter inlet and 1-1/2-inch-diameter discharge. The impeller is 13 inches and consists of three vanes.

The TLTA pump performance is compared to performance of a typical BWR pump in Table IX.

TABLE IX

TLTA AND TYPICAL BWR RATED PUMP PERFORMANCE

<u>Parameter</u>	<u>TLTA</u>	<u>BWR</u>
Head (ft)	680	600
Flow (gpm)	140	47,000
Speed (rpm)	3,550	1,700
Specific speed	320	3,000

The TLTA pump has a shorter coastdown time than its BWR counterparts. To better simulate the BWR pump, a flywheel is attached to the TLTA pump shaft. As a result, the TLTA pump coastdown time constant is about seven seconds, which is believed consistent with the BWR pumps. Pump power is tripped at the onset of the LOCE which results in an exponential decay of the pump output.

2.3.2 Model Considerations. Single-phase pump performance curves were obtained from United Centrifugal Pumps and converted to the standard, four-quadrant, homologous curves for use in RELAP4. Two-phase effects are accounted for through use of Semiscale-derived degradation curves.

2.3.3 Data Comparison. Measured intact loop pump flow is compared to that predicted by RELAP4 for Test 6 in Figure 34. Pump speed and head for Test 3 are compared in Figures 35 and 36, respectively. The RELAP4 prediction of all three variables agrees quite well with the test data until shortly after lower plenum flashing. At this time, the RELAP4 calculation is affected by a check valve which was used to stop flow through the jet pump drive line. This valve has been included in recent models as an interim correction to a jet pump modeling problem. This point is discussed further in the next section. The closing of this valve adversely affects the predicted recirculation pump performance, and comparison with data beyond this time is precluded. However, it appears the recirculation pump model would provide a reasonably accurate prediction if not affected by the jet pump model.

2.3.4 Discussion. It is concluded from this evaluation that the RELAP4 pump model provides a reasonable prediction. It is recommended, however, that this comparison be repeated when an improved jet pump model is provided in RELAP4.

2.4 Jet Pumps

2.4.1 Design and Performance Considerations. Each of the two TLTA jet pumps is scaled to simulate 10 BWR jet pumps, representing the broken and unbroken loops, respectively. The TLTA jet pump is about 3-1/2 feet long with a tail pipe diameter of 2-1/2 inches. In comparison, the BWR jet pump height is 19 feet with a tailpipe diameter of about 20 inches.

Flow in both jet pumps is initially in the nominal direction, with the drive flow inducing additional liquid from the downcomer, with the mixture discharging into the lower plenum. During the LOCE, this flow pattern is maintained for several seconds in the intact loop jet pump. Eventually, as the drive pump output drops to zero, flows are expected to reverse in the intact loop. Flows are expected to quickly reverse in the broken loop jet pump as liquid is drawn up through the jet pump to the drive line side of the simulated break. Choking is expected at the drive nozzle, which is the minimum area point of this flow path to the pressure suppression system.

2.4.2 Model Considerations. The jet pump is modeled with the RELAP4 two-stream mixing model. This model utilizes a mixing region to allow mixing of two parallel flow streams, such as at the jet pump suction. Several forms of the model are provided to allow solutions for conditions of normal flow in the jet pump, as well as for situations where flow is reversed at any or all of the jet pump flow junctions.

2.4.3 Data Comparison.

(1) Intact Loop Jet Pump. The predicted intact loop jet pump flow is compared to Test 1 flow data in Figure 37. The predicted jet pump flow is similar to but slightly less than the test data through lower plenum flashing. RELAP4 correctly predicts the sharp flow decay as the jet pump suction uncovers. At lower plenum flashing, fluid is forced up into the jet pump resulting in a momentary jet pump flow reversal. This effect is also observed in the RELAP4 calculation.

Fig. 34 Test 6 intact loop pump flow.

Fig. 35 Test 3 intact loop pump speed.

Fig. 36 Test 3 intact loop pump head.

Fig. 37 Test 1 intact loop jet pump flow rate.

Following lower plenum flashing, the measured flow appears to recover from the flow reversal and stabilizes near zero. The predicted flow reverses again to a relatively high positive jet pump flow rate at this time. The difference between the predicted intact flow and the test data after lower plenum flashing suggests that a problem exists in the RELAP4 two-stream mixing model. This problem appears to be tied to flow reversals and off-design conditions in the jet pump. At the onset of the problem, RELAP4 has predicted the occurrence of a flow reversal and selected an alternate form of the two-stream mixing model.

In subsequent analyses, it was discovered that this jet pump problem is propagated through the system calculation, resulting in an overprediction of core flow in the postflashing period. The successful diagnosis of potential modeling problems in the core was thus precluded. To overcome this problem on an interim basis, a user-specified "fix" to the jet pump was developed. This "fix" required the use of a RELAP4 check valve at the jet pump drive nozzle, set to isolate the jet pump from the drive loop when flow reversed in the jet pump.

This approach was used in the Test 3 and 6 calculations. The results of this calculation for Test 6 are compared to Test 6 data in Figure 38. Up to lower plenum flashing, the

Fig. 38 Test 6 intact loop jet pump flow rate.

results are very similar to the Test 1 comparison. Following flashing, the use of the check valve in Test 6 is observed to correct the flow rise observed in the Test 1 calculation.

(2) Broken Loop Jet Pump. Figure 39 presents a comparison of the RELAP4 prediction and data from Test 3 for flow through the broken loop jet pump. RELAP4 is observed to correctly predict the early flow reversal as liquid is drawn from the lower plenum to the broken loop jet pump drive nozzle. The magnitude of the reverse flow is overpredicted up to the time the suction line uncovers. Following suction line uncover, the reverse flow is underpredicted. The reasons for these apparent problems are not presently clear. The possibility exists that, as shown for the intact loop, some problems may be present in the basic jet pump model under off-design flow conditions. It is also possible that the prediction of jet pump flow is being adversely influenced by calculated conditions in the lower plenum. Additional comparisons, with improvements made to other portions of RELAP4, are indicated to complete the diagnosis of this component.

2.4.4 Discussion. Some problem areas are indicated in the calculations of flow in the TLTA jet pumps. While flows appear to be well predicted during normal flow conditions, the trends and accuracy of off-design calculations are not considered satisfactory. Additional work is recommended to thoroughly review the two-stream mixing model under off-design conditions. Separate calculations with the jet pump model isolated from the system model and driven by experimental boundary conditions are also recommended to further diagnose problems in the two-stream mixing model approach.

Fig. 39 Test 3 broken loop jet pump flow rate.

2.5 Lower Plenum

2.5.1 Design and Performance Considerations. The TLTA lower plenum is constructed of a 16-inch-diameter pipe, about 3-1/2 feet deep. Four guide tube simulators are enclosed in this region, occupying about 50% of the lower plenum volume. The two jet pumps discharge into the lower plenum at the top. The core and guide tube inlet orifices are about one foot below the top of the lower plenum.

Initially the lower plenum is filled with subcooled water. As the system depressurizes, the conditions approach the saturation point. Flashing generally occurs in the lower plenum when the system depressurization rate accelerates after the suction line uncovers and quality develops rapidly in this region. Following the short-lived flow surge due to flashing, the lower plenum fluid remains in a two-phase state and continues to boil, venting through the core and jet pumps.

The TLTA lower plenum geometry is substantially different from that of the BWR. Those differences that are most significant include the lower plenum depth and relative elevations of the jet pump exhaust, core inlet, and guide tube inlet. These differences may have some influence on TLTA lower plenum performance with respect to the BWR.

2.5.2 Model Considerations. As in the downcomer region, the RELAP4 bubble rise model is used to determine local conditions in the lower plenum. A single fluid volume is used to represent this region. Nominal bubble rise parameters have been specified in the lower plenum calculations to date.

2.5.3 Data Comparisons. In Figure 40 the predicted density at the core inlet is compared with the measured density from Test 3. The predicted density is observed to drop at about 8.5 seconds when lower plenum flashing occurs. The measured density is not presented during the flashing period as it is adversely biased by fluid acceleration effects. Immediately after lower plenum flashing, the predicted density is about 5 lb/ft³ lower than the test data. The uncertainty of the measurement is about ± 3.5 lb/ft³ in this time period. After about 20 seconds, the predicted density converges within the density measurement uncertainty.

Fig. 40 Test 3 bundle inlet density.

The predicted lower plenum volume average density is compared to an equivalent experimental density in Figure 41. In addition, measured local densities of Nodes 1, 2, and 3 in the lower plenum are included in the figure. The predicted average density is higher than the experimental density after lower plenum flashing. During this time, there is a significant density gradient in the lower plenum as indicated by the local experimental densities. The difference between the predicted and experimental densities suggest that the single volume lower plenum representation combined with the bubble rise model used in the prediction may not provide sufficient analytical detail for this region.

Fig. 41 Test 3 lower plenum density.

2.5.4 Discussion. These comparisons show that RELAP4 is moderately successful in predicting the trends in lower plenum thermodynamic conditions. Some discrepancies are observed in the absolute density values, however. These differences may impact calculation of flow rates out of the lower plenum which are all dependent on local conditions. Additional work is thus recommended to evaluate potential model improvements such as inclusion of more nodal detail in the lower plenum and investigation of more suitable bubble rise constants. The inclusion of slip in this region may also offer a potential model improvement.

2.6 Core

2.6.1 Design and Performance Considerations. The TLTA heater rod bundle simulates a single, 7 x 7 rod BWR fuel bundle. Geometrically, the simulation is quite close, with exact TLTA reproduction of BWR rod diameter, pitch, and length. BWR decay heat and stored heat conditions are simulated in the TLTA directly heated rods by programming an appropriate electrical power decay rate. Typical BWR radial and axial peaking factors are both included in the TLTA bundle design.

Flow normally enters the bundle at the bottom in a subcooled condition and exits the bundle at the top with moderate quality (10 to 25%) which depends on the total bundle power level. During a typical LOCE, bundle flow immediately drops to 25 to 50% of rated flow as broken loop pumping action is lost. Thereafter, flow decays gradually as maintained by the intact loop pump until lower plenum flashing occurs. Flashing results in a momentary restoration of core flow, which lasts for several seconds. Following this event, all pumping action has ceased, and only a low residual flow is maintained by fluid boil-off from the lower plenum.

Heat transfer within the bundle can vary from well-cooled, nucleate boiling conditions to nearly zero heat flux. The occurrence of thermal transitions between these modes depends on time, flow conditions, and bundle position. Resultant rod temperatures are quite varied and require detailed interpretation.

Fig. 42 Test 6 bundle flow rate.

2.6.2 Model Consideration. As described in Section 1.2 a separate model was developed for the TLTA bundle. The model employs the basic RELAP4 conservation equations in one dimension. Two-phase friction effects are treated through quality-dependent multipliers. Heat exchange between the bundle and fluid is accounted for by the RELAP4 heat transfer model. This model includes logic to select one of nine separate heat transfer regimes which depend on the instantaneous flow and fluid conditions adjacent to the heater rods. Internal rod heat transfer is accounted for through one-dimensional, finite-element radial conduction models.

2.6.3 Data Comparisons. The core flow rate is compared to the Test 6 data in Figure 42. The rapid initial drop in core flow is successfully predicted by RELAP4. Following this drop, the experimental flow rate is significantly higher than that predicted during most of the initial nine seconds of the transient. RELAP4 predicts that lower plenum flashing begins at about nine seconds, and its effect is seen in the core by the flow rate spike which lasts less than one second. The measured flashing effect on core flow starts shortly after nine seconds, but rises at a slower rate and is sustained over a longer period than is predicted by RELAP4. Following the flashing period, the measured flow subsides to a near zero value, below its resolution threshold, which precludes further meaningful comparisons with the prediction. Generally, the prediction hovers between 0 and 2 lb/sec in the postflashing period, which is within the measurement accuracy limits. In attempting to determine the causes of the differences in core flow calculations, it must be recognized that the core is subject to influences propagated throughout the system from other components. Comparisons of jet pump flows, suction line uncover time, and lower plenum parameters have shown potential inconsistencies in the modeling of these regions. It is presently believed that the fundamental flow model of the core is essentially correct and that the core flow anomalies are produced by the problems in other portions of the model. In turn, these core flow problems potentially contribute to inaccuracies in calculation of heater rod temperatures.

Figure 43 presents the comparison of a typical thermocouple from Test 1 with a corresponding RELAP4 prediction. This prediction was made with the overall system model, rather than the detailed core model developed for Tests 3 and 6. The obvious difference between the data and prediction is due to an early prediction of a CHF condition by RELAP4. CHF is not observed in the data until much later in the transient when the core dries out. This unrealistic result is partly due to the underprediction of core flow by the code. The primary cause, however, is believed to lie in the CHF correlation. RELAP4 uses a correlation developed by Barnett^[27] which is believed to be conservative under the flow, pressure, and enthalpy conditions encountered at the time of the predicted CHF.

To provide a more reasonable calculation on an interim basis, the Barnett correlation was bypassed in RELAP4, and the core was allowed to dry out and go into a film boiling condition when local quality exceeded 95%. The results of this approach are shown in Figures 44, 45, and 46 for three typical locations on high-power rods in Test 3.

Fig. 43 Test 1 heater rod temperature.

Fig. 44 Test 3 heater rod temperature - 71-inch elevation.

Fig. 45 Test 3 heater rod temperature – 98-inch elevation.

The results show a more realistic temperature response prediction; however, significant differences are still observed in the comparisons.

Several notable effects are observed in the comparisons of predicted and actual rod temperatures:

- (1) Shortly after initiation of the transient, a minor rise is observed in predicted rod temperature. This rise is not seen in the thermocouple data. It occurs as RELAP4 changes from a nucleate boiling condition to the “forced convection vaporization” mode (which is based on a correlation developed by Shrock and Grossman^[28]) where heat transfer is slightly reduced from the nucleate boiling case. This trend is believed to be tied to the underprediction of core flow in this time period.

- (2) The rapid rise in rod temperature associated with core dryout always occurs earlier in the prediction than in the TLTA. In cases where this dryout is predicted before flashing (Figure 46) the low predicted core flow is believed responsible for the discrepancy. When dryout is correctly predicted to occur after lower plenum flashing (Figures 44 and 45), it is still earlier than in the test. This follows from the earlier predicted decay of flow as lower plenum flashing subsides.
- (3) The peak temperatures predicted after dryout are always higher than in the experiment. This trend is due to the earlier predicted dryout, which results in a higher power level and stored energy content of the rod at the time of dryout.
- (4) Following the temperature peak, the predicted temperatures show a gradual cooling trend not observed in the data. During this period, the RELAP4 heat transfer logic has selected the pool film boiling mode, which is based on a correlation developed by Berensen^[29]. Additional work is required to complete the diagnosis of this problem area. Possible causes include an improper core flow prediction or nonapplicability of Berensen's correlation.

Local effects are most obvious in these high-power rod data. The temperature at the axial midpoint of Rod 25-7 (shown in Figure 44) rises rapidly at 15 seconds, levels off at about 26 seconds, and rises slowly through the remainder of the transient. As shown in Figure 46, at 47 inches above this point, this same rod shows a small temperature increase and then appears to rewet at least twice. This behavior, which occurs in many areas in the core, is attributed to fallback of liquid from the upper plenum, rewetting rods at random locations. Even with improved, multidimensional codes, it will be difficult to model this phenomenon.

Also shown in Figure 46 are the temperatures of two thermocouples on a single rod (Rod 25-9) at the same elevation. They are separated circumferentially by 90 degrees. The difference between the time at which the temperatures rise sharply is about two seconds. It is also noteworthy that these two thermocouples have significantly different temperatures until about 42 seconds after the beginning of the transient. This indicates significant radial effects, either in the rod or in the local thermal boundary conditions.

The effect of radial rod location is also evident in the experimental data. In both Figures 44 and 45, rods with identical powers but located in different bundle positions exhibit significant differences in temperature history.

2.6.4 Discussion. Although the RELAP4 core model predictions are encouraging, additional effort is required to improve the calculations. It is believed that many of the

Fig. 46 Test 3 heater rod temperature - 118-inch elevation.

problem areas were propagated into the core model from other regions of the TLTA system. The core model should be separated from the system calculation and driven with experimental boundary conditions to remove these influences.

It is further noted that several changes to the RELAP4 heat transfer model have been proposed in forthcoming best estimate versions^[26] of the code. These changes may include the substitution of more appropriate heat transfer relationships in place of the Shrock and Grossman, Barnett and Berensen correlations discussed in Subsection 2.6.3.

The experimental evidence of fallback into the bundle and the three dimensionality of bundle phenomena indicate the need for improved model detail. This potential is offered by the slip option which has been implemented in RELAP4 and three-dimensional core codes currently being developed under NRC sponsorship.

3. CONCLUSIONS AND RECOMMENDATIONS

The results of this data comparison have provided an initial assessment of the capability of the code. From these comparisons, guidance is obtained for planning future RELAP4 development and verification activities. Successful completion of the next phase will require a systematic evaluation and correction of various problems indicated by this comparison in the RELAP4 code and user methodology.

The overall accuracy of the RELAP4 calculation can be expressed in terms of heater rod temperature. The model is shown to overpredict Test 3 peak rod temperature by 200 to 400°F. The peak occurs shortly after bundle dryout in the prediction but is usually observed at the end of blowdown in the experiment. The model is shown to underpredict the temperature of some rods at the end of blowdown. The temperature level at this time is especially important because it influences subsequent bundle behavior during the core spray, reflood, and refill periods of the LOCA.

These discrepancies would have been even greater if the RELAP4 CHF logic had not been bypassed, the jet pump drive flow had not been altered after flashing, and the break flow calculations had not been adjusted to fit Test 3 experimental break flow.

No primary cause of the data-prediction mismatch on bundle temperature is apparent. Rather, the mismatch is believed to result from an accumulation of relatively small anomalies, each having an important impact on system and bundle performance. Many of these problem areas are readily identified; however, some are masked by complex thermal-hydraulic interactions between components in the TLTA and will require additional studies to isolate causes and determine corrective actions.

Table X presents the findings of this comparison for major components within the TLTA. Included in the table are a synopsis of the analytical model used for each component, a summary of the data comparison, and conclusions reached from the study. On the basis of these results, a number of recommendations for future work are made. Specifically, studies are suggested in the following areas:

- (1) Bundle flow and heat transfer
- (2) Separation effects in vertically oriented volumes
- (3) Jet pump performance
- (4) Horizontal slip and drawdown
- (5) Critical flow
- (6) Wall heat transfer.

These recommendations should be used as a guide for the NRC as well as ANC in setting priorities and defining BWR safety analysis activities in the future. The recommendations cover code development needs, model verification tasks, and improvements required in the experimental measurements.

TABLE X

OVERVIEW OF RELAP4 COMPARISONS WITH TLTA DATA

Component	RELAP4 Model Description	Summary of Comparison	Conclusions	Recommendations
Core	Single channel and average power rods used to simulate bundle in system calculation. Single, closed channel and single rod used in separate calculation of individual rod performance. CHF logic bypassed to avoid early, unrealistic CHF.	Predicted bundle flow rates are less than actual through lower plenum flashing. Postflashing flow rates cannot be compared due to data limitation. Early prediction of dryout in bundle results in early rod temperature excursion. Peak temperature predicted was generally higher than observed. Postdryout temperature predictions show cooling trend not observed in data. Predicted temperature at end of blowdown was generally lower than observed.	Exact cause of data-prediction mismatch in bundle temperature cannot be pinpointed due to systems interaction effects. Most likely causes may be any or all of the following: Improper prediction of bundle boundary conditions (flows and α_F) from system model. RELAP4 heat transfer logic and empirical relationships used for film coefficient and CHF. Subchannel effects not accounted for in one-dimensional analysis. Fallback cooling provided by liquid from upper plenum, not accounted for in homogeneous model.	The comparisons should be repeated when the best-estimate version of the code becomes available, driving the bundle model with experimental (rather than predicted) boundary conditions. Calculations should also be made to investigate potential benefits of using a separation model with slip in the core. GE should consider alternate methods for provision of postdryout bundle flow rates to aid in the diagnosis.
Lower Plenum and Downcomer	Both regions are modeled with a single volume representing average fluid conditions. Separation effects considered through RELAP4 bubble rise model which assumes one-dimensional flow. User-specified inputs control bubble rise velocity and vertical density distribution.	In both regions, average density is overpredicted and quality is underpredicted. Local densities at flow junctions are also not in complete agreement with data. This may influence calculated flows out of these regions. The test data at times show a significant stratification within these regions, with some portions subcooled and others saturated. The prediction does not allow stratification to occur within a single volume.	The single volume model cannot fully account for the stratification and as a result, average and local properties are incorrectly calculated at times. The errors in local density may bias flow rate calculations for the downcomer and lower plenum.	Consideration should be given to improving the predictions in these regions through more detailed models and incorporation of the RELAP4 slip option. The various constants used with the bubble rise and slip models should be reviewed for their applicability to this problem.

TABLE X (contd.)

OVERVIEW OF RELAP4 COMPARISONS WITH TLTA DATA

Component	RELAP4 Model Description	Summary of Comparison	Conclusions	Recommendations
Jet Pump	RELAP4 contains a two-stream flow mixing model which is used for jet pump analysis. The model allows complete mixing of the two streams (drive and induced flow) in a separate mixing section, where energy, continuity, and momentum relationships are satisfied. Several mixing options are available for use which are automatically selected depending on the instantaneous direction of flow at the mixing junctions.	Predictions compare favorably with test data where drive flow, induced flow, and total flow are in normal operating directions. These conditions are maintained in the intact loop jet pump until lower plenum flashing occurs, but flow reverses within one second in the broken loop pump. During off-design flow conditions where flow has reversed at one or more junctions in the jet pump, the predictions and data generally do not agree. These anomalies in predicted jet pump behavior in both loops are believed to affect flow rates in other regions of the TLTA.	Present RELAP4 jet pump model needs to be improved during off-design flow conditions.	RELAP4 two-stream mixing model should be thoroughly reviewed with emphasis on isolating cause of anomalies during off-design flow conditions. A separate TLTA jet pump model should be developed and run with boundary conditions determined from TLTA tests and other available jet pump data. Predicted jet pump performance should be compared with experimental performance. Consideration should be given to development of a "black box" jet pump model similar in concept to the recirculation pump model presently used in RELAP4. The need for this approach would be identified through steps mentioned above.
Recirculation Pump	The centrifugal pump interaction with system fluid is accounted for through the four quadrant curves. These curves which define head and torque as functions of flow and speed for single-phase liquid are derived from measured TLTA pump performance and input to RELAP4 by the user. Degradation of pump head and torque from two-phase effects is accounted for through characteristic curves, also supplied by the user. Pump speed calculations require user-specified pump inertia and friction torque.	Pump performance predictions during coastdown closely match TLTA test data. As predicted flows in the intact loop jet pump begin to deviate from the data, recirculation pump performance predictions also show disagreement. This trend is believed due to the jet pump problem being propagated into the recirculation loop and pump.	The pump model is believed adequate when appropriate pump model inputs are available (four quadrant curves, two-phase degradation, pump inertia, and friction torque).	Review predicted recirculation pump performance again when improvements are made in RELAP4 jet pump model.

TABLE X (Contd.)

OVERVIEW OF RELAP4 COMPARISONS WITH TLTA DATA

Component	RELAP4 Model Description	Summary of Comparison	Conclusions	Recommendations
Wall Heat Transfer	Heat transfer from the vessel walls to the contained fluid is based on the same logic and correlations as used in the rod bundle.	No direct comparisons were made on wall heat transfer rates. Based on system pressure comparisons, it is suspected that an overprediction of wall heat transfer is retarding the predicted postflashing pressure decay rate.	Wall heat transfer rates may be overpredicted with current RELAP4 methodology.	RELAP4 heat transfer logic should be critically reviewed to determine applicability of rod bundle analysis methods for large vessel surfaces. Using TLTA vessel wall temperature histories (to be provided by GE on a future test), compare predicted and experimental wall heat transfer conditions.
Recirculation Line Flow Tube	Flow into this 2-1/2-inch-diameter volume from the downcomer is controlled by a "vertical junction". This junction option allows flow to occur in two phases as the downcomer mixture level falls across the vertically-oriented entrance to the flow tube. Assuming no slip, liquid and vapor volumetric flows are computed based on relative junction area above and below the mixture level.	Observation of the experimental mixture level as it passes through the flow tube entrance region suggests that significant drawdown and slip occurs here during the uncovering period. RELAP4, which does not account for these effects, predicts a much higher flow rate during this interval. Full uncovering of the flow tube entrance is predicted in about 0.1 second compared to over 1 second in the experiment.	The lack of a slip model and neglect of drawdown in situations such as this can result in significant differences between predicted and actual system flow rates. Relative to the TLTA, these may be even more significant in a full-size BWR recirculation line.	Consideration should be given to providing a slip model at horizontal junctions intersecting large volumes with varying mixture levels. A method should be developed to consider the effects of drawdown.
Break	Critical flow is calculated by user-specified models (Henry, Moody, Sonic choking) with user input flow multipliers. Logic is available to change from Henry model in subcooled flow to Moody model under saturated conditions.	Break flow model was forced to match the TLTA Test 3 data. Other calculations with best-estimate flow multipliers under-predicted break flow considerably, resulting in improper timing of major events such as suction line uncovering and flashing.	Present RELAP4 critical flow model does not accurately predict break flow unless empirical multipliers are used. These multipliers appear to be strongly dependent on fluid state (subcooled, saturated low quality, saturated high quality). Further, they are believed only applicable to the TLTA geometry and flow conditions.	These comparisons should be repeated with the RELAP4 best-estimate version of the code, which will have improved critical flow models.

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