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TRAC-M Validation Test Matrix

Los Alamos National Laboratory

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ABSTRACT

This document briefly describes the elements of the United States Nuclear Regulatory Commission's (NRC's) software quality assurance program leading to code qualification and identifies and proposes specific tests for qualifying the modernized TRAC code (TRAC-M) for a broad spectrum of pressurized- and boiling-water reactor accidents and transients such that the requirements of the NRC's software quality assurance program are satisfied.

Verification is the process of ensuring that the products and process of each major activity of the software life cycle meet the standards for the products and objectives of that major activity. Examples of verification activities include formal major life-cycle reviews and audits, formal peer reviews, and informal tests such as unit and integration testing. Verification efforts are not discussed in this report.

Validation is the process of demonstrating that the as-built software meets its requirements. Testing is the primary method of software validation. We have subdivided the TRAC-M validation test matrix into four elements. The first set of validation activities compares code-calculated results with data from tests other than those employing experimental data, designated Other Standard Tests. The second set of validation activities compares code-calculated results with data from Separate Effect Tests. The third and fourth sets of activities compare code-calculated results with data from Component Effect Tests and Integral Effect Tests, respectively. The four elements identified above constitute the TRAC-M Validation Test Matrix.

CONTENTS

CONTENTS (cont)

APPENDICES

Page

FIGURES

TABLES

TABLES (cont)

TABLES (cont)

TABLES (cont)

Page

EXECUTIVE SUMMARY

INTRODUCTION

This document briefly describes the elements of the United States Nuclear Regulatory Commission's (NRC's) software quality assurance program leading to software (code) qualification and identifies a test matrix for qualifying the modernized Transient Reactor Analysis Code (TRAC-M) to the NRC's software quality assurance requirements. Code qualification is the outcome of several software life-cycle activities, specifically, (1) Requirements Definition, (2) Design, (3) Implementation, and (4) Validation Testing. The major objective of this document is to define the TRAC-M Validation Testing effort.

WORKING CONCEPTS

We first present several concepts that are important to the remainder of the summary.

Validation Testing: The process that allows the sponsor to determine whether a software product complies with its requirements. Validation Testing demonstrates and assures that the code and its models and methods satisfy the code's design objectives and are both applicable to and qualified for usage in specified targeted applications.

Verification: The process of demonstrating that the products and process of each major activity of the software life cycle satisfy the objectives and standards set forth for that major activity. Examples of Verification activities include formal major life-cycle reviews and audits, formal peer reviews, and informal tests such as unit and integration testing. Verification activities are not discussed in this report

TRAC-M Validation Test Matrix: The collection of separate effect tests (SETs), component effect tests (CETs) integral effect tests (IETs), and other standard tests (OSTs) selected to ensure that all important code features, models, and integrated calculation capabilities are tested. To ensure completeness, we have taken four-element structured approach to identifying the individual tests to be included in the TRAC-M Validation Test Matrix. First, we have identified the basic equation models, flow-field models and engineering correlations, equipment component models, and special-purpose models in TRAC-M that must be validated. Second, we have identified local, component, and system level processes and phenomena that must be modeled by TRAC-M. Third, we have identified the set of targeted applications associated with plant type and event scenarios that must be modeled. Fourth, we have identified candidate tests for incorporation in the TRAC-M validation test matrix.

TRAC-M CODE

The TRAC-M code comprises operational features that are the user's interface with the code, mathematical models for the phenomena, components and equipment that make up the physical system, and numerical solution methods for the mathematical models.

Each of these structural elements comprises many individual subelements. Operational features include the basic input and output functions that make the code useful to the users. The mathematical models include

- basic equation models for fluid flow, heat conduction, and power generation (for example),
- flow field and engineering correlation closure models for mass, momentum, and energy exchange,
- models for physical equipment components such as the pressurizer (for example), and
- special purpose models for phenomena and equipment, such as countercurrent flow limiting and critical flow.

Numerical solution methods are associated with each of the mathematical models.

The contents of these basic TRAC-M structural elements are further expanded by category, subcategory, and model as described in Section 3.

PHENOMENA IDENTIFICATION AND RANKING TABLE (PIRT) USAGE

A PIRT identifies and ranks the processes/phenomena occurring in a particular plant during a particular transient scenario, e.g., plant event, transient, or accident. Three contemporary pressurized-water-reactor (PWR) PIRTs and BWR PIRTs covering a variety of accidents and transients were reviewed and summarized to develop a consolidated PIRT for PWR and BWR applications.

CODE VALIDATION

We have subdivided the validation element into four elements: validation tests using standards other than those that employ experimental data from OSTs and validation tests comparing code-calculated results with SET, CET, and IET test data.

Validation Using OSTs. This sub-element of validation contributes to code qualification by comparing code-calculated results with standards that do not employ experimental data. It encompasses tests of specific code features or functions; comparisons to equilibrium, concept problems with known outcomes, or analytical problems with known solutions; and problems to test the properties of the numerical solution methods. The other standard tests recommended for validation of TRAC-M are presented in Section 6 of this report.

Validation Using SETs. SETs generally focus on a few processes or phenomena within a single component test fixture. SETs are experiments in which a very limited number of physical phenomena are of interest and detailed, high-quality data are obtained. The SETs data recommended for validation of TRAC–M are presented in Section 7 of this report.

Validation Using CETs. CETs investigate behavior in a plant component. Comparisons of code-calculated predictions to data from CETs provide the mechanism for an important aspect of the code qualification effort. Comparisons to CET data are necessary to assess the capability of thermal-hydraulic (T-H) code to predict component-level processes identified in PWR and BWR PIRTs. The CETs recommended for validation of TRAC-M are presented in Section 8 of this report.

Validation Using IETs. IETs generally focus on multiple, coupled processes and components in facilities that have numerous hardware components. IET data are most useful for assessing performance and qualifying the integrated T-H code for its targeted applications. The IET data recommended for validation of TRAC-P are presented in Section 9 of this report.

TRAC-M VALIDATION TEST MATRIX

Given the four-coverage-element approach, we developed the test matrix presented in Sections 6-9. Relative to previous TRAC validation matrices, the TRAC Validation Test Matrix presented in this document places a much greater emphasis on validating individual TRAC-M models and methods using SET data, particularly fundamental test data. There are TRAC-M models for which no direct SET data exist (i. e., data do not exist that can be used directly to validate these models because the effect of the processes/phenomena that they model cannot be isolated). The most important of these models are associated with the interfacial transport processes for mass, momentum, and energy. The direct consequence of this circumstance is that validation must proceed at present by indirect means.

For this release of the document, candidate validation tests have been identified and recommended for PWR and BWR large-break loss-of-coolant accident phenomena only at the local, component and system level. Tests have also been recommended for a variety of PWR and BWR plant types and accidents and transients.

ACKNOWLEDGMENTS

The authors express their appreciation to Dr. F. Odar of the United States Nuclear Regulatory Commission for his thorough review and suggestions for improving this document.

D. Hughes, a co-author of an earlier version of this document ("TRAC-P Validation Test Matrix," LA-UR-97-3900, September 1997), was instrumental in bringing this document to publication.

Finally, but no less important, are the contributions of the editorial staff who worked on this report throughout its preparation: L. Rothrock and A. Mascareñas.

ACRONYMS

1D	One dimensional
2D	Two dimensional
3D	Three dimensional
ADS	Automatic depressurization system
ATWS	Anticipated transient without scram
B&W	Babcock & Wilcox
BEM	Basic equation model
BETHSY	Boucle d'Etudes Thermohydrauliques Système
BWR	Boiling water reactor
CCFL	Countercurrent flow limiting
CCTF	Cylindrical Core Test Facility
CE	Combustion engineering
CET	Component effect test
CHF	Critical heat flux
CISE	Centro Informazioni Studi Esperienze
CL	Component level
CSAU	Code scaling, applicability, and uncertainty
CSNI	Committee on the Safety of Nuclear Installations
ECM	Equipment component model
EOS	Equation of state
FIST	Full Integral Simulation Test
FFEC	Flow-field models and engineering correlations
FLECHT-SEASET	Full Length Emergency Cooling Heat Transfer-Separate Effects And Systems Effects Test
GE	General Electric
GERDA	Geradrohr Dampferzeuger Anlage
IET	Integral effect test
INEL	Idaho National Engineering Laboratory
JAERI	Japan Atomic Energy Research Institute
LANL	Los Alamos National Laboratory
LB	Large break
LOBI	Loop for blowdown investigation
LOCA	Loss-of-coolant accident
LOFT	Loss-of-fluid test
LL	Local level
LOSP	Loss of offsite power
LSTF	Large Scale Test Facility
MIST	Multiple-Loop Integral System Test
MSLB	Main steam line break
NEA	Nuclear Energy Agency
NRC	United States Nuclear Regulatory Commission
NSM	Numerical solution methods

ACRONYMS (cont)

ODE	Ordinary differential equation
OECD	Organization for Economic Cooperation and Development
OST	Other standard test
OTIS	Once-through Integral Systems
OTSG	Once-through steam generator
PIRT	Phenomena identification and ranking table
PKL	Primarkreislaufe
PWR	Pressurized water reactor
ROSA	Rig of Safety Assessment
SB	Small break
SCTF	Slab Core Test Facility
SET	Separate effect test
SETS	Stability enhancing two-step method
SGTF	Steam generator test facility
SGTR	Steam generator tube rupture
SL	System level
SPES	Simulatore PWR per Esperienze di Sicurezza
SPM	Special-purpose model
SSTF	Steam Sector Test Facility
T-H	Thermal-hydraulic
THEF	Thermal Hydraulic Experimental Facility
THTF	Thermal Hydraulic Test Facility
TLTA	Two-Loop Test Apparatus
TPFL	Two-Phase Flow Loop
TPTF	Two-Phase Test Facility
TRAC	Transient reactor analysis code
TRAC-B	TRAC-boiling water reactor version
TRAC-M	TRAC-modernized version
TRAC-P	TRAC-pressurized water reactor version
UMCP	University of Maryland, College Park
UPTF	Upper-Plenum Test Facility
W	Westinghouse

1.0. INTRODUCTION

Thermal-hydraulic (T-H) systems codes, hereinafter called T-H codes, are specifically designed for a variety of targeted applications. Among these applications are (1) reactor safety analyses for both operating and planned reactors, (2) audits of licensee's calculations, (3) analyses of operating reactor events, (4) analyses of accident management strategies, (5) support for test planning and interpretation, (6) support for probabilistic risk assessments, (7) design analyses, and (8) nuclear plant training and instrument and control simulators. Given the significance of the applications for T-H codes, both envisioned and realized, it is important that they be qualified for their intended applications. Validation Testing demonstrates and ensures that the code and its models and methods satisfy the code's design objectives and are both applicable to and qualified for use in specified targeted applications.

1.1. Background

The United States Nuclear Regulatory Commission (NRC) has established an overall goal of maintaining core competencies in thermal hydraulics, reactor physics, and T-H codes to support regulatory decisions and the continuance of international exchanges. The NRC has elected to implement its T-H code development goals in a single code by executing the five-component development plan shown in Fig. 1-1. The Transient Reactor Analysis Code (TRAC)-Pressurized Water Reactor Version (-P), or TRAC-P, has been selected by the NRC as the base code for its T-H code development efforts. The current name for the single code under development is the modernized TRAC (TRAC-M) code.

1.2. Document Objectives

The objectives for this document are as follows:

- Briefly describe the elements of the NRC's software quality assurance program,[1-1] including validation efforts.
- Describe the concepts providing the foundation for development of the TRAC-M validation test matrix.
- Identify and propose specific validation tests for TRAC-M qualification that satisfy the requirements of the NRC's software quality assurance program. The set of tests thus identified constitutes the TRAC-M Validation Test Matrix.

1.3. TRAC-M Validation Test Matrix Concepts

TRAC-M is a state-of-the-art, best-estimate, transient, system analysis computer code for analyzing geometrically complex multidimensional T-H systems, primarily nuclear power plants. TRAC-M also can perform containment system analyses. However, this is a recently added capability; the containment features of the code are not treated in this release of the TRAC-M validation test matrix.

The TRAC-M computer code consists of two major functional elements. The first element consists of the individual, fundamental building blocks for the code. Examples of these building blocks are mathematical models of specific physical processes, such as heat conduction in a pipe wall or the friction between a moving fluid and the wall as fluid moves through a pipe. The former is a complete theoretical model, whereas the second requires experimental data to effect an engineering solution. The experimental insights are embodied in closure models, also called constitutive models. TRAC-M contains more than a hundred of these individual theoretical and closure models.

Taken one at a time, these building block models cannot simulate complex, multi-feature physical processes, e.g., the transient, systemwide, multiphase, thermal-hydraulic, and neutronic processes that arise in nuclear plants during accident and transient conditions. These models must be brought into a unified structure and must be integrated. Thus, the second element consists of the features that integrate the individual theoretical and closure models within the TRAC-M code such that it can be used for the broad applications to which it is targeted. Two primary integrating elements of the code are the basic two-phase equations describing mass, momentum, and energy transport and the numerical methods employed to obtain numerical solutions to these coupled transport equations and the building block models described above.

Within a nuclear power plant, as it undergoes either a transient or accident, processes are observed to occur at three phenomenological levels: the local level (LL), component level (CL), and system level (SL). Examples of local-level processes are interfacial heat and mass transfer, fluid shear at a fluid-wall interface, and fluid-to-surface heat transfer. Examples of component-level processes are coastdown of the reactor coolant pumps, liquid levels within a component, and multidimensional flows within a component. Component-level processes arise from a combination of local-level phenomena and processes. Examples of system level processes are oscillations, loop-to-loop asymmetries, and natural circulation. As with component-level processes, system-level processes arise from a combination of phenomena and processes at both the local and component level.

Clearly, if the TRAC-M code is to fulfill its design objectives, it must model the important phenomena and processes occurring at the local, component, and system levels. However, all phenomena and processes occurring within a nuclear power plant, whether at the local, component, or system level, do not have the same impact on the path and outcome of the accident or transient. Some phenomena and processes are more important than others in this regard. It is from this reality that the value of phenomena identification and ranking tables (PIRTs) derive. The essence of a PIRT is captured in its name: it first identifies all the processes and phenomena occurring in a specified nuclear power plant undergoing a specific accident or transient. It next ranks the identified processes and phenomena for importance relative to one or more primary evaluation criteria. The TRAC-M validation matrix uses all available pressurized-water-reactor (PWR) and boiling-water-reactor (BWR) PIRTs to construct a consolidated list of highly important processes and phenomena for which the adequacy of the TRAC-M code must be validated, including all LL, CL, and SL processes appearing in the consolidated PWR and BWR PIRT. PIRTs are the first driver in constructing the TRAC-M validation test matrix.

The code must also model a variety of plant types, e.g., Babcock & Wilcox (B&W), Combustion Engineering (CE), and Westinghouse (W) PWRs, a variety of General Electric (GE)-designed BWRs, and the individual designs of each of these vendors. For example, there are lowered-loop and raised-loop B&W designs, System 80 and System 80+ designs by CE, and two-loop, three-loop, and four-loop W designs. Core designs may also vary between different units within the same category, e.g., W four-loop and GE BWR/4 designs. For each of the above vendor, plant type, and category features, the code must be able to predict the behavior of the plant accurately under both accident and transient conditions. Accidents to be simulated include a spectrum of loss-of-coolant accidents (LOCAs), steam-generator tube ruptures, and main steam-line breaks. Transients to be simulated include pressurization, depressurization, and reactivity increases. The requirement to simulate a variety of plant, accident, and transient types adequately are requirements on the system-level or integrated performance of the code. It is not sufficient that a particular local-level phenomenon or component processes be well simulated if the simulation of key system-level parameters is inadequate. Plant design and targeted applications are the second driver in constructing the TRAC-M validation test matrix.

The final requirements on the TRAC-M validation test matrix derive from the need to represent and simulate accurately the highly important local-, component-, and system-level phenomena and processes identified by the PIRTs and system-wide processes associated with the targeted plant designs and applications.

1.4. Document Structure

The report contains nine sections. We have endeavored to provide brief, yet complete, coverage of the topics in each section. Where additional coverage is deemed necessary to demonstrate completeness, we have provided the needed information in appendices.

Section 2 of this report provides an overview of code qualification, as implemented by the NRC's software quality assurance program. Section 3 provides an overview of the current release version (Version 3.0) of TRAC-M. Section 4 culminates with a consolidated PIRT for the phenomena expected to occur during PWR and BWR accidents and transients. Each phenomenon is cross-correlated to the appropriate TRAC-M model previously defined in Section 3. Section 5 identifies the plant, accident, and transient scenarios that constitute the current set of targeted applications for the TRAC-M code.

Sections 6–9 describe the tests selected for the TRAC-M validation test matrix. Section 6 identifies validation tests other than those employing experimental data; these are designated Other Standard Tests (OST). Section 7 identifies the separate effect test (SET) data selected for the TRAC-M Validation Test Matrix; Section 8 identifies the component effect test (CET) data; and Section 9 identifies the integral effect test (IET) data. The relationship between the PIRT driver, plant and application driver, and the TRAC-M validation matrix is illustrated in Fig. 1-2.

The appendices contain either conceptual or detailed supporting information for the TRAC-M validation test matrix.

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1-1. Division of Information Support Services, "Software Quality Assurance Program and Guidelines," NUREG/BR-0167 (1993).

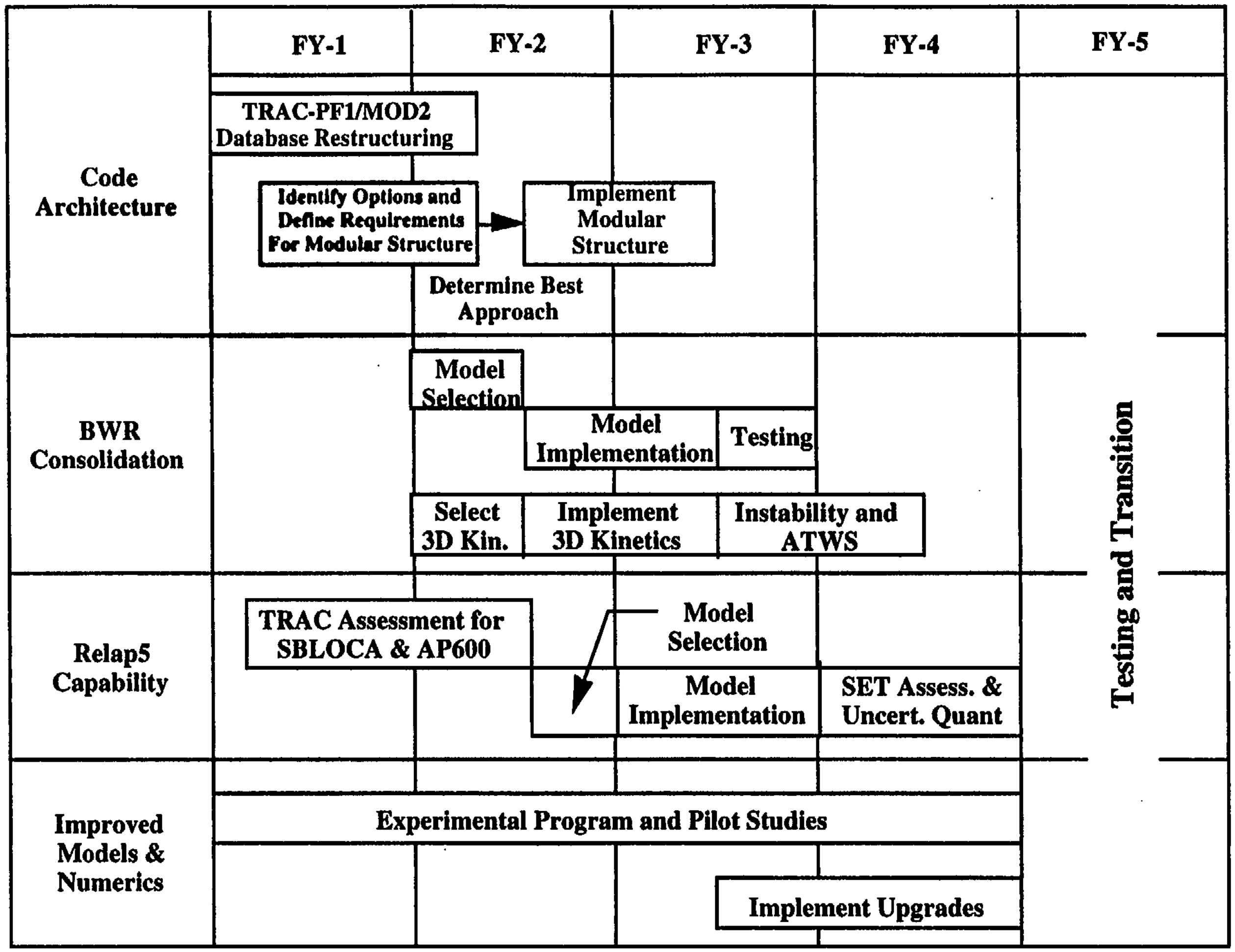

Fig. 1-1. Components of NRC's Thermal-Hydraulic Research Plan.[1-1]

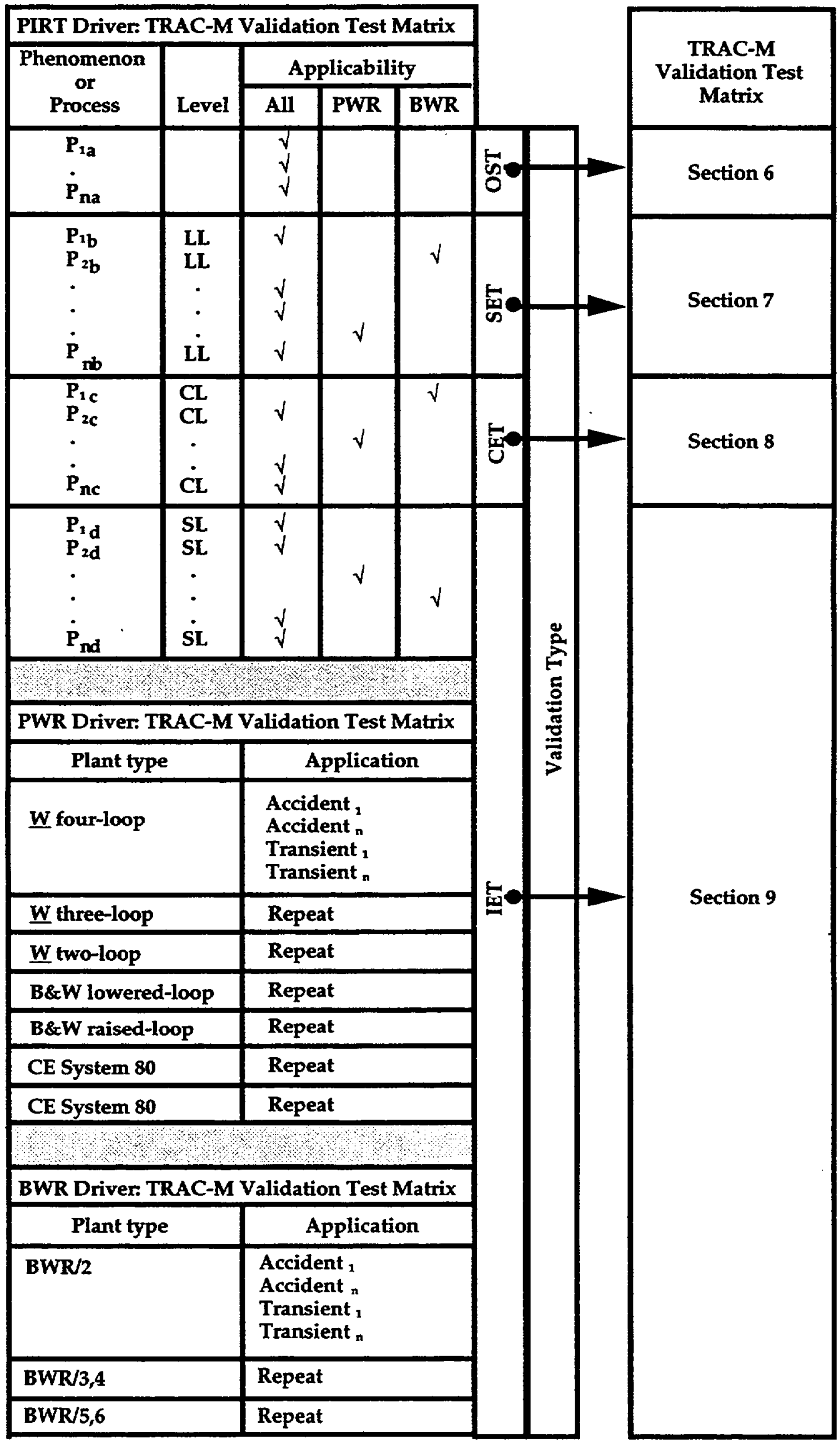

Fig. 1-2. Relationships of PIRT and plant and targeted applications to TRAC-M validation test matrix.

2.0. CODE QUALIFICATION OVERVIEW

Qualification is the process that allows the sponsor to determine whether a software product complies with its requirements. Completion of this process demonstrates and ensures that the code and its models and methods satisfy the code's design objectives and are both applicable and adequate for the specified targeted applications.

2.1. Code Qualification

Code qualification is the outcome of specific software life-cycle activities. The subset of software life-cycle activities culminating in code qualification is illustrated in Fig. 2-1. These activities are identical to those listed in Refs. 2-1 and 2-2. The life-cycle activities leading to code qualification are Requirements Definition, Design, Implementation, Verification, and Testing.

The life-cycle activities covered in Refs. 2-1 and 2-2 and shown in Fig. 2-1 assume creation and qualification of an entirely new code. Clearly, that is not the case for TRAC-M. Nevertheless, all of the life-cycle activities leading to code qualification will be described briefly here. The current status of TRAC-M within its software life-cycle is discussed in Section 3.6. The life-cycle activities are directed to the development of the following products: Requirements Definition, Design, Implementation and Testing.

- *Requirements Definition* is the set of activities that results in the specification, documentation, and review of the requirements that the software product must satisfy, including functionality, performance, design constraints, attributes, and external interfaces. The requirements form the basis for the software plans, products, and activities. Requirements should be necessary, complete, verifiable, consistent, unambiguous, modifiable, traceable, and technically feasible. Acceptance criteria that satisfy these requirements are defined during this life-cycle activity.

- *Design* is the set of activities that results in the development, documentation, and review of a software design that meets the defined requirements. Software design documentation specifies the overall structure of the software so that it can be translated into code.

- *Implementation* is the set of activities that produces the software. Implementation activities are conducted so that the software is developed in accordance with the design documentation and coding standards. It also includes informal unit and integration testing.

- *Testing* is the set of activities associated with formally testing, reviewing, analyzing, and documenting software performance.

Software quality assurance requires verification and validation of life-cycle products. The documentation that accompanies these software life-cycle activities is shown in Fig. 2-1 and is described further in Ref. 2-1.

- *Verification* is the process of ensuring that the products and process of each major activity of the software life cycle meet the standards for the products and the objectives of that major activity. Examples of verification activities include formal, major life-cycle reviews and audits, formal peer reviews, and informal tests such as unit and integration testing.[2-1]

- *Validation* is the process of demonstrating that the as-built software meets its requirements in accordance with selected acceptance criteria (success metrics). Testing is the primary method of software validation. The objectives of validation are to ensure that

  1. the as-built software correctly and adequately performs for all intended functions, e.g., targeted applications;

  2. the software does not perform any unintended function, either by itself or in combination with other functions that can degrade the entire system; and

  3. all nonfunctional requirements, e.g., performance, design constraints, attributes, and external interfaces, are met.

We have subdivided the validation effort into four elements: validation tests using OSTs, validation tests comparing code-calculated results with data from SETs, validation tests comparing code-calculated results with data from CETs, and validation tests comparing code-calculated results with data from IETs. This document provides a detailed description of the OSTs, SETs, CETs, and IETs that comprise the validation test matrix.

- *Validation Using OSTs*. This element of validation compares code-calculated results with standards that do not employ experimental data. It encompasses tests of specific code features or functions; comparisons to equilibrium, concept problems with known outcomes, or analytical problems with known solutions; and problems to test the properties of the numerical solution methods. An example of the first category, testing of code features, is a test to ensure that the input deck error checking is performing as designed. An example of the second category, equilibrium problems, is a test created by inducing a small imbalance in a U-tube manometer, followed by a return to equilibrium. An example of the third category, concept problems, is a test that checks whether the code returns a symmetrical result for a demonstrably symmetrical configuration. An example of the fourth category, analytical problems, is a comparison of code-calculated conduction results with the exact solution. An example of the fifth category, numerical method tests, is a problem that helps to characterize numerical diffusion.[2-3]

- *Validation Using SETs*. This element of validation compares code-calculated results with SET data. SETs are experiments in which a limited number of physical phenomena of interest occur and detailed, high-quality data are obtained under closely controlled conditions. SETs cover a spectrum of tests (Fig. 2-2), from the most fundamental to those investigating interactions between phenomena and components or equipment in a specific region of the physical system. Ideally, the fundamental, high-quality data should be used and the desired parameter measured directly. However, inherent to the basic two-fluid modeling approach used in TRAC-M is the requirement to provide closure models for wall-to-phase and interfacial heat, mass, and momentum exchange. This is a most challenging and difficult requirement because few complete and directly applicable sets of experimental data are available on which to base the mechanistic modeling of these exchange processes. Given this circumstance, only indirect validation at best is currently possible. The Organization for Economic Cooperation and Development (OECD), Nuclear Energy Agency (NEA), Committee on the Safety of Nuclear Installations (CSNI) has produced the most comprehensive review of SETs facilities.[2-4] The primary use of data from SETs is to assess the adequacy of the closure relationships used in the code. These data also are used to address scaling issues. Because code predictions are compared with data, the definition of a precise set of performance measurement standards or success metrics is essential. Such a set of success metrics has recently been used in the qualification of the RELAP5 code for AP600 small-break (SB) LOCA analyses.[2-5] We subscribe to these success metrics (see Appendix A). The selected SETs become part of the validation test matrix. Additional perspectives regarding SETs are presented in Appendix B.

- *Validation Using CETs.* This element of validation compares code-calculated results with data from CETs, including transients measured in real plants. CETs investigate behavior in a plant component, frequently (but not always) at full scale (Fig. 2-2). Comparisons of code-calculated predictions to data from CETs provide the mechanism for an important aspect of the code qualification effort. Comparisons to CET data are necessary to assess the capability of T-H code to predict component-level processes identified in PWR PIRTs. In this manner, CET data are used to determine whether the behavior of the integrated code (e.g., field equations, closure relations, component models, numerics, and special models) are adequate at the CL. Component testing can occur in either SET or IET facilities.

- *Validation Using IETs.* This element of validation compares code-calculated results with data from IETs, including transients measured in real plants. IETs investigate behavior in a full nuclear power plant, usually in a reduced-scale facility (Fig. 2-2). Comparisons of code-calculated predictions to data from IETs provide the mechanism for three important validation efforts. First, comparisons to IET data are necessary to assess the capability of T-H codes to predict system-level processes identified in PWR PIRTs. In this manner, IET data are used to determine whether the behavior of the integrated code (e.g., field equations, closure relations, component models, numerics, and special models) are adequate. Second, IET data are selected to ensure that the code-targeted applications are represented (i.e., plant types and accident scenarios). Third, IET data are selected to address scaling issues. If possible, the selected IET facilities should cover a sufficiently broad spectrum of facility scales and transient types to support arguments of code applicability for plants. The OECD/NEA/CSNI has produced a comprehensive review of IETs facilities.

Deficiencies exist in the current TRAC-M code,[2-6] some of which are associated with the use of heuristic models in the code. Numerous others are associated with use of specific engineering correlations (closure models) beyond the range of applicability justified by their pedigree. Given this reality, code validation using IET data provides confidence that the resultant integrated code adequately predicts real plant performance. Once again, we subscribe to the success metrics (see Appendix A) that have recently been used in the qualification of the RELAP5 code for AP600 SB LOCA analyses.[2-5] The selected IETs become part of the validation test matrix. Additional perspectives regarding IETs are presented in Appendix B.

Taken together and properly implemented, these elements (Requirements, Definition, Design, Implementation, and Testing) provide the basis for qualifying a code for its targeted applications.

2.2. Validation Test Matrix

Information from several sources is needed to create a comprehensive TRAC-M validation test matrix, as shown in Fig. 2-3. These sources include information about the TRAC-M models and about processes and phenomena occurring during plant events and accidents in PWR and BWR plants. The various test problems and experimental data needed to complete the validation test matrix are discussed in Sections 6–9.

A formal release version of the code, i.e., release of a fully qualified code and associated documentation, always should be preceded by full-scope testing of the code against the validation test matrix. Although there is no set interval between two formal release versions of a code, the time and effort expended to qualify the code are such that 2 years between formal releases is probably the minimum, with the norm approaching 3 years.

2.2.1. Data Characterization

An essential element of data selection is data characterization. The important characterizing factors are as follows:

- experiment characteristics,
- applicability of data,
- data availability,
- quality of data, and
- range and variety of data.

The first factor, experiment characteristics, focuses on the experimental scale, instrumentation, and availability of information to develop a database from which a facility input deck can be prepared. The second factor, applicability of data, focuses on phenomena and the associated code models, specifically those identified in the summary PIRT (Section 4, Table 4-5). This factor addresses whether the data can be used directly to validate a particular model or whether they can be used only in an indirect manner to infer the characteristic behavior of the model. This factor also addresses whether the data are fundamental or derived from single or several components test facilities. The third factor, data availability, addresses whether the data can be acquired. The fourth factor, quality of data, is evident; high-quality data are required if the validation part of code qualification is to reflect code capabilities and adequacy accurately. An important measure of quality is the extent to which the data have been accepted and used for other code validation efforts. The fifth factor, range and variety of data, addresses the pragmatic issue of the cost of preparing facility input decks. Given two SET facilities, which are equal in all aspects except that a broader range of conditions is covered in one, we would select the facility with the broader range and variety of data because overall program costs are reduced.

2.2.2. Existing TRAC-M and RELAP5 Models

For some specific model validation efforts, there are several candidate facilities and data sets from which to choose. For example, numerous facilities have simulated film boiling; therefore, choices must be made. For this initial release of the validation test matrix, our selections are made using the following selection criteria:

- Facilities for which up-to-date TRAC-M input decks exist are given priority.
- Facilities for which TRAC-M input decks for earlier code versions exist are assigned the next highest priority; the input decks must be updated to run on the latest code version.
- Facilities for which RELAP input decks and a sufficient document database exist to permit creation of a TRAC-M input deck are assigned the next highest priority.

2.2.3. Data Sources

Various sources of information have been used to identify potential SET validation tests, including the following.

- The OECD/CSNI compilation of 185 SET facilities.[2-4]
- Reports on validation of TRAC-M and other computer codes (Refs. 2-7 through 2-11).
- Electronic bibliographies of publications associated with the TRAC-M, RELAP5, and RETRAN computer codes.
- Citations identified as a result of performing computer-based searches of the scientific literature.

2.4. Standard Test Matrix

Because there is an extended interval between formal release versions, numerous interim versions of the code are created during the interval. Interim versions are created to incorporate on-going code modification or development efforts, user enhancements, and error corrections. Because numerous interim versions are anticipated, it is desirable to define a smaller matrix that tests many, but not all, code features, algorithms, and equations. The test matrix so defined is the Standard Test Matrix. It is a subset of the TRAC-M validation test matrix optimized in some manner to fulfill the contradictory requirements of maximizing coverage of code features, algorithms, and equations while minimizing the resource requirements, e.g., the number of problems to be calculated.

The Standard Test Matrix will not fulfill all testing needs for every interim version, e.g., when an enhanced or revised model is untested by the problems in the Standard Test Matrix. Thus, for each interim version, it will be necessary to review the assessment needs and define, if needed, additional specific tests for the modified code.

2.5. Completeness Issues

An important goal to be attained in developing the TRAC-M validation test matrix is that of complete coverage. Ideally, there should be complete coverage of all code features, algorithms, and equations while minimizing duplication.

One ideal of completeness is that the TRAC-M validation test matrix contains problems that represent all of the important plants, facilities, systems, components, processes, and phenomena that arise from the targeted applications for the code. This aspect of coverage is considered in Section 5.

A second ideal of completeness is that the TRAC-M validation test matrix exercises each elemental part of the code, the input, output, subroutines, and, indeed, every line of code. Software now exists to create this database.* With existing coverage software, it is possible to run individual problems within either the TRAC-M validation test matrix or the standard test matrix and determine which specific lines of code are activated by the problem. In addition, it is possible to combine the individual results to determine the lines of coding activated by any subset of the validation matrices or the totality of the validation matrices. This information can be obtained only by exercising (running) the code for each of the specific tests within the validation test matrix.

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* One example is Pure Atria Corporation's PureCoverage™ software, which provides a precise and accurate way to gather code coverage data. This and like software provide a means to identify what parts of the program were and were not tested.

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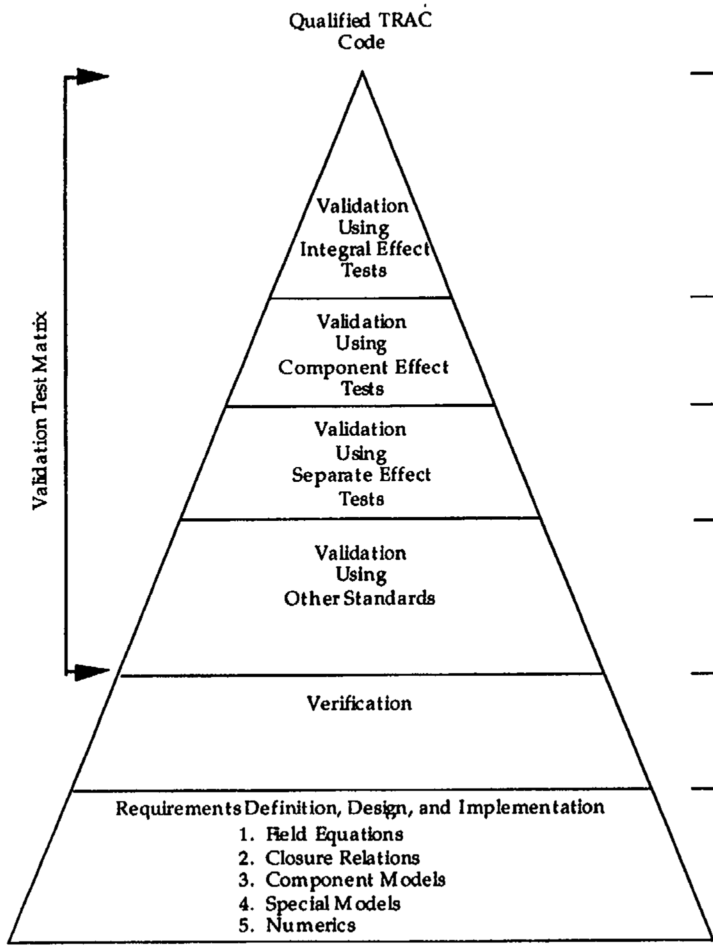
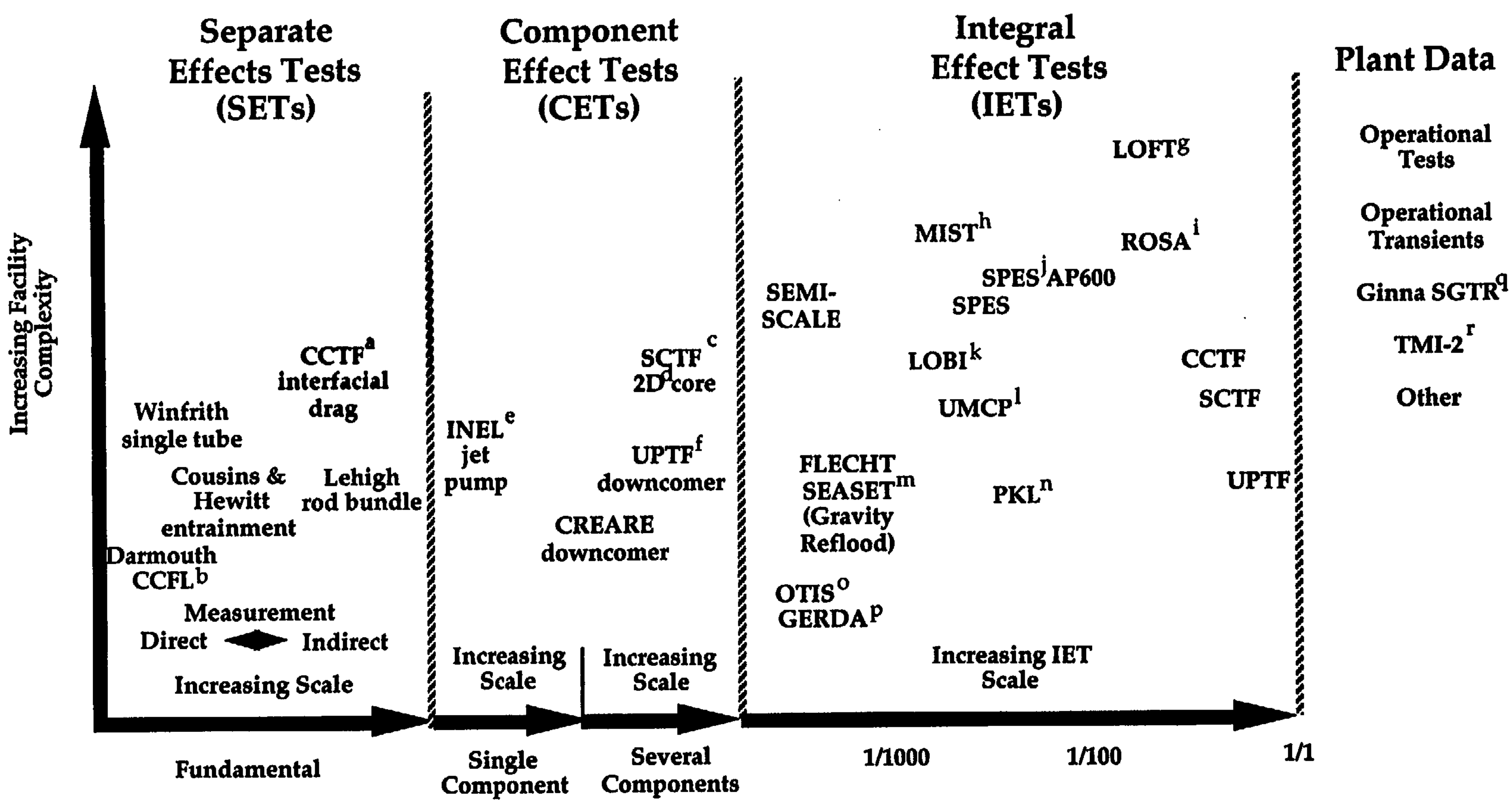


Description	Documentation
Integrated Code Behavior • Field Equations • Closure Relations • Component Models • Special Models • Numerics Scenario Applicability Scaling to Plant Conditions	Validation Test Plan Validation Test Procedures Validation Test Report Acceptance Test Plan Acceptance Test Procedures Acceptance Report User Documentation
Testing is variously performed using SET, CET, or IET data, depending on availability and applicability	
Focus on Closure Relationships (e.g., Correct Equations Used) Few Phenomena/Processes Simple Geometry Controlled Boundary Conditions	
Specified Design Features/Functions Equilibrium Problems Concept Problems Analytical Problems Numerical Method Tests	
Reviews Audits Peer Inspections Informal Tests	Verification and Validation Plan Review and Audit Packages Peer Inspection Packages Informal Test Plans, Procedures, Results
Analyze Requirements Develop Preliminary Design Develop Detailed Design Develop Code Units Inspections Reviews	Requirements Documents Verification and Validation Plan Software Project Plan Software Design Documentation Validation Test Plan and Procedures Acceptance Test Plan and Procedures

* For additional information see NUREG/BR-0167, "Software Quality Assurance Program and Guidelines," US NRC (February 1993)

Fig. 2-1. Code qualification overview.*



Note: Figure is illustrative and is not intended to include all SET, CET, and IET facilities in the test matrix.

[a] Cylindrical Core Test Facility.
[b] Counter current flow limitation.
[c] Slab Core Test Facility.
[d] Two dimensional.
[e] Idaho National Engineering Laboratory.
[f] Upper-Plenum Test Facility.
[g] Loss of Fluid Test.
[h] Multiloop Integral Test Facility.
[i] Rig of Safety Assessment.
[j] Simulatore PWR per Esperienze di Sicurezza.
[k] Loop for Blowdown Investigation.
[l] University of Maryland, College Park.
[m] Full Length Emergency Cooling Heat Transfer-Separate Effects And Systems Effects Test.
[n] Primarkreislaufe.
[o] Once-Through Integral Systems.
[p] Geradrohr Dampferzeuger Anlage.
[q] Steam-generator tube rupture.
[r] Three Mile Island, Unit 2.

Fig. 2-2. Spectrum of SET, CET and IET facilities.

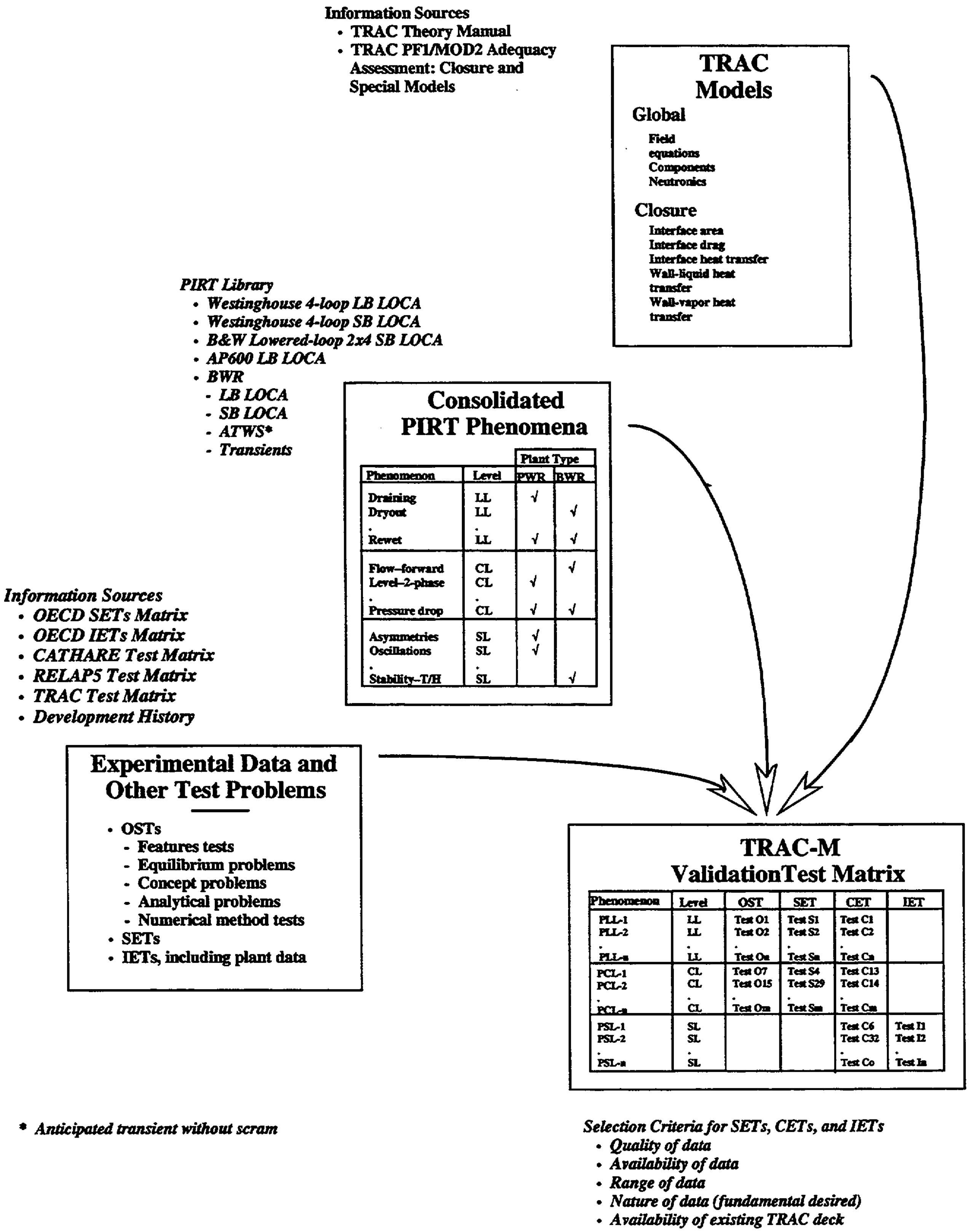


Fig. 2-3. Information sources supporting creation of TRAC-M validation test matrix.

3.0. TRAC OVERVIEW

The NRC is consolidating the capabilities of four of its T-H neutronics codes, i.e., TRAC P,[3-1]), TRAC-B,[3-2] RELAP-5,[3-3] and RAMONA,[3-4] into a single state-of-the art analysis code, TRAC-M. TRAC-M is a state-of-the-art, best-estimate, transient, system analysis computer code for analyzing geometrically complex multidimensional T-H systems, primarily nuclear reactor power plants. TRAC-M will be used by government and industry for design and safety analysis; phenomenological studies; operational transient analysis; evaluation of emergency operating procedures, simulator support and operator training; and assessment of data involving basic experiments, separate-effects tests, and plant operations. TRAC-M will calculate fluid flow involving gas, liquid, and mixture states in one-dimensional (1D) and three-dimensional (3D) rectilinear and cylindrical coordinates.

The TRAC-M computer code can be viewed as being based on two major theoretical elements. The first element is made up of the mathematical models that describe the physical processes/phenomena needed for the applications areas for which the code is designed. The second element is the numerical solution methods applied to the mathematical models. All aspects of both parts of TRAC-M must be tested during the verification, validation, and qualification procedures.

The mathematical models are further assigned to one of four categories, as shown in the following list:

1. basic-equations models (BEMs),
2. flow-field models and engineering correlations (FFECs),
3. equipment-component models (ECMs), and
4. special-purpose models (SPMs).

The details of the contents of the four mathematical model categories and the numerical solution methods (NSMs) are described further in the following paragraphs. The acronyms are defined to facilitate the information entered in various summary tables presented throughout the reminder of this document.

3.1. Basic Equation Models

The BEM category in TRAC-M includes the following subcategories:

- fluid mass,
- fluid momentum,
- fluid energy,
- noncondensable gas mass,
- dissolved solute in the liquid,
- 3D vessel,
- heat conduction,
- power generation in fuel,
- radiative energy exchange in the core,
- equation of state for fluids, and
- fluid thermophysical and transport properties.

Several of the subcategories are subdivided further into models. This decomposition of the BEM category into subcategories and models is presented in Table 3-1. This construct (category, subcategory, and model) is emphasized here because this format is utilized in Section 4 to cross-correlate the PWR and BWR PIRT phenomena and processes to TRAC-M models.

The fluid flow equations include mass, momentum, and energy equations for the vapor and liquid phases of the water plus mass conservation equations for noncondensable gases and dissolved solids. These model equations are applied in the 1D formulation to most of the physical system and in the 3D formulation for the reactor pressure vessel. A TRAC-M Fill component is used to apply a specified fluid velocity or flow at a boundary link, and a TRAC-M Break component is used to specify the pressure at a boundary.

The heat conduction model includes both 1D and 2D formulations for both rectangular and cylindrical solid structures. The 2D form generally is applied only to the modeling of reflood heat transfer in the fuel rods in the core. The conduction model can handle all three of the consistent boundary conditions for the parabolic heat conduction equation. A lumped-capacitance form of the conduction equation is also available.

The power generation in the core is modeled in three ways: the power can be (1) specified by the user, (2) modeled as point-kinetics decay heat, or (3) modeled by 3D neutron kinetics. Reactivity feedback is accounted for by changes in fuel and coolant temperature and coolant density. The power deposition in the fuel rods can be specified by the user as a function of position in the rod.

The 2D radiative energy exchange model is designed to handle radiative energy exchange between the heat structures assigned to hydro cells in a TRAC-M model of a physical system. The model includes accounting for the effects of a two-phase fluid mixture between the radiating surfaces.

The equation of state for water in TRAC-M uses the pressure and temperature as independent variables and returns all other fluid thermodynamic state properties plus various derivatives of these properties needed for the numerical solution methods. Properties for both the liquid and vapor phases are determined by polynomial fits to water property tabulations. All necessary thermophysical and transport properties for water are also available. The equation of state for the gases that can be included in the fluid flow model is based on the perfect gas model. The thermophysical properties of the gases are determined by derivatives of the equation of state, and transport properties are given by polynomial fits to data.

The material properties for the solid materials needed by the conduction equations are also available.

3.2. Flow Field Models and Engineering Correlations (Closure)

The basic fluid flow equations need various models to account for mass, momentum, and energy exchange between the flow-channel walls; between each phase in the flow field; and between the liquid and vapor phases. The models for these processes generally comprise correlations for heat, mass, and momentum exchange taken from the literature. These correlations account for the majority of the empirical correlations in the TRAC-M code.

The FFEC category in TRAC-M includes the following subcategories:

- regime maps
- fluid mass equation closure (mass exchange), including
  - subcooled boiling,
  - interfacial mass exchange, and
  - solute mass exchange;
- fluid momentum equation closure (momentum exchange), including
  - wall-to-phase momentum exchange,
  - interfacial momentum exchange, and
  - local pressure losses;
- fluid energy equation closure (energy exchange), including
  - wall-to-phase energy exchange and
  - interfacial energy exchange.

Although it is not clear that regime maps should be classified as closure models, they are so closely associated with the closure models that we have elected to include them with these models.

Several of the subcategories are subdivided further into models. This decomposition of the FFEC category into subcategories and models is presented in Table 3-1. This construct (category, subcategory, and model) is emphasized here because this format is utilized in Section 4 to cross-correlate the PIRT phenomena and processes to TRAC-M models.

In numerous cases, additional sublevels for the FFEC models are listed in Table 3-1. For completeness, these lower-level models are tabulated in Tables C-1 through C-6 in Appendix C. The information in Table 3-1 and Appendix C is extracted from Ref. 3-2. Verification and validation of TRAC-M ultimately will focus on the individual correlations given in Appendix C.

3.3. Equipment Component Models

Models for equipment components are usually developed and used when

- the equipment, and the phenomena that occur in the equipment, are so complex or too-little understood that a reliable mathematical description of the equipment and processes at a fundamental level is not possible; and
- the computational costs of using a more fundamental description of the equipment and processes would be too high for use in a systems-analysis computer code.

Equipment component models are usually based on an input-output type of model, and the details of the phenomena are not directly accounted for. The phenomena that occur in some equipment components require specialized modeling that cannot be easily obtained directly from the basic-equation models in TRAC-M.

The ECM in the TRAC-M code contains the following equipment components subcategories:

- centrifugal pumps (Pump component),
- jet pumps (Jetp component)
- steam-water separator (Sepd component),
- Plenum component,
- Valve component,
- turbine (Turb component), and
- pressurizer (Prizer component).

The ECM subcategories are not further subdivided into models; however, the decomposition of the ECM category into subcategories is repeated in Table 3-1 for completeness. This construct (category and subcategory) is emphasized here because this format is utilized in Section 4 to cross-correlate the PIRT processes/phenomena to TRAC-M models.

3.4. Special-Purpose Models

The SPM category in TRAC-M includes the following subcategories:

- countercurrent flow limitation model;
- critical flow model for fluid boundary conditions;
- trip and control system elements;
- reflood heat-transfer models, including
    - flow regime modeling,
    - wall-to-phase fluid drag,
    - interfacial fluid drag,
    - wall-to-phase fluid heat transfer,
    - interfacial fluid heat transfer, and
    - conduction heat transfer;
- two-phase mixture level tracking model;
- offtake model for Tee component; and
- fuel-cladding gap conductance.

With the exception of the reflood model, the SPM subcategories are not subdivided further into models. However, decomposition of the category into subcategories is repeated in Table 3-1 for completeness. The reflood heat-transfer model is subdivided further into models. This further decomposition of the reflood heat transfer subcategory into models is presented in Table 3-1.

In numerous cases, additional sublevels for the SPM are listed in Table 3-1. For completeness, these lower-level models are tabulated in Tables C-7 through C-9 in Appendix C. The information in Table 3-1 and Appendix C is extracted from Ref. 3-2.

3.5. Numerical Solution Methods

All of the mathematical models in the TRAC-M code must be integrated into the overall solution methods used to advance the model equations over a timestep. Generally, finite-difference approximations to the continuous equations are used to implement the solution methods. The resulting systems of algebraic equations are then solved to advance the time.

The NSM category in TRAC-M includes the following subcategories:

- fluid field equations, including
  - 1D stability enhancing two-step (SETS) method and
  - 3D SETS method; and
- conduction in solid materials, including
  - 1D rectangular and cylindrical,
  - 2D rectangular and cylindrical,
  - lumped capacitance method; and
- conduction boundary conditions;
- power generation in the fuel rods;
- trip and control system elements;
- fluid equation of state;
- fluid boundary conditions;
- equipment component models;
- special-purpose models;
- steady-state solution methods; and
- timestep size and control methods.

The steady-state solution methods have been developed to accelerate the solution of the transient equations to the steady-state condition. The timestep size and control methods are used to ensure the accuracy and stability of the solution method for the fluid flow equations.

The NSM subcategories are not subdivided further into models; however, the decomposition of the NSM category into subcategories is repeated in Table 3-1 for completeness. This construct (category and subcategory) is emphasized here because this format is utilized in Section 4 to cross-correlate the PIRT processes/phenomena to TRAC-M models.

3.6. Current Qualification Status

The TRAC-M code and it predecessors have been under development for approximately 25 years. Much of the rigorous structure and documentation envisioned in the NRC's software quality assurance program and guidelines, as summarized in Section 2.0, have not been realized. This is not to say that TRAC-M is found to be inadequate for its targeted applications. It is to state that its adequacy cannot be demonstrated to be in compliance with the NRC's software quality assurance program and guidelines. In the remaining paragraphs of this section, the current code qualification status of TRAC-M is reviewed briefly relative to each of the life-cycle activities leading to code qualification described in Section 2.1.

Requirements Definition, Design, and Implementation. Clearly, field equations, closure relations, component models, special models, and numerics have all been specified, selected, and incorporated into the present TRAC-M code. Some, but not all, of the documentation called for in the NRC's software quality assurance program and guidelines exist. However, requirements and specification documents, design reports, and independent review audits do not. A suite of TRAC-P documentation exists,[3-6–3-10] but a key document has remained in draft form for several years.[3-6] The primary code documentation is currently being updated to reflect the TRAC-M code.

Verification. Some verification has occurred during the years of TRAC development as documents such as the theory manual[3-6] and adequacy assessment document[3-7] were written or updated, code modifications were undertaken, and code problems were identified and resolved. However, these efforts constitute neither a complete or formal set of verification activities. The last comprehensive review of TRAC by the Advisory Committee on Reactor Safeguards, Reactor Safeguards Subcommittee on Thermal Hydraulic Phenomena was conducted on January 20–21, 1988.

Testing—Validation Using Other Tests. This type of validation of TRAC has taken place, but an expanded set of test problems is envisioned. Problems that test several pieces of coding, test various code features and functions, and evaluate code capabilities via comparison to concept and analytical problems have been employed. A set of such problems is described in Ref. 3-12.

Validation Using Separate Effect Tests. Various SET data have been used throughout the TRAC development history. However, these constitute, at best, a sparse subset of the SET validation (fundamental, component, and several components) needed to fully qualify TRAC-M for its targeted applications. The SET data used as part of the developmental validation of TRAC-M, Version 5.5[3-10, 3-11] are as follows: CCFL using Bankoff data, condensation model using Akimoto's data, critical flow model using Marviken data, core reflood model using Flecht-Seaset, Lehigh and Berkeley tube data, multiple models using UPTF Tests 6 and 8, and CCTF Run 14.

For the last two decades, the majority of validation testing performed for TRAC has used IET data. Although this extensive body of IET validation has shown that TRAC can generally reproduce the major trends and key processes/phenomena for a variety of transients, too little validation of the underlying models and correlations has been performed using SET data.

Testing—Validation Using Integral Effect Tests. As stated in the previous paragraph, numerous validations of various versions of TRAC have been performed using IET data. The majority of these were conducted with TRAC-PF1/MOD1. Because there have been significant changes to the code as it evolved from the MOD1 to the MOD2 version,[3-13] extrapolation of MOD1 assessments to the MOD2 code is problematic. The IET tests used as part of the developmental assessment of TRAC-M, Version 5.5,[3-10, 3-11] are as follows: LOFT L2-6 and L6-1, CCTF Run 54, and SCTF Run 719.

In summary, qualification efforts for the present TRAC-M code constitute a modest fraction of the qualification testing envisioned by NRC's current software quality assurance program and guidelines.[3-14] The validation test matrix, which is defined in subsequent sections of this report, is designed to fulfill the requirements of the NRC guidelines

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TABLE 3-1
TRAC ELEMENTS BY CATEGORY, SUBCATEGORY, AND MODEL

Category	Subcategory No.	Subcategory Description	Model
BEM	1	Fluid mass equation	Mass convection Mass exchange due to phase change
	2	Fluid momentum equation	Momentum flux Area change Pressure gradient Wall-to-phase momentum exchange Interfacial momentum exchange Momentum exchange due to mass exchange Local losses Gravity
	3	Fluid energy equation	Energy convection Pressure-work term Wall-to-phase energy exchange Interfacial energy exchange Direct energy deposition Energy exchange due to mass exchange
	4	Noncondensable gas and liquid solute	Mass convection Solute mass exchange
	5	3D Vessel model	Refer to the Fluid Mass, Fluid Momentum, Fluid Energy, Noncondensable Gas, and Liquid Solute models.
	6	Heat conduction equation	Lumped-capacitance model 1D radial 2D radial plus axial Reflood implicit Fuel-clad gap Metal-water reaction Material properties

TABLE 3-1 (cont)
TRAC ELEMENTS BY CATEGORY, SUBCATEGORY, AND MODEL

Category	Subcategory No.	Subcategory Description	Model

BEM (continued)	7	Power generation in fuel	Tabular power input
			Point kinetics
			3D kinetics
			Reactivity feedback
			  Fuel temperature
			  Coolant temperature
			  Void fraction
			  Boron concentration

	8	Radiative energy exchange in the core	Referenced at subcategory level
	9	Equation of state for fluids	Referenced at subcategory level
	10	Fluid thermophysical and transport properties	Referenced at subcategory level
FFEC	1	Regime maps (Also see Appendix C, Table C-1)	Bubbly flow Bubbly slug transition Bubbly slug flow Churn flow Annular-mist flow Transition to stratified flow Stratified flow Plug flow
	2	Fluid mass equation closure (mass exchange)	
	2a	Subcooled boiling (Also see Appendix C, Table C-2)	Referenced at subcategory level
	2b	Interfacial mass exchange (Also see Appendix C, Table C-2)	Referenced at subcategory level
	2c	Solute mass exchange (Also see Appendix C, Table C-2)	Referenced at subcategory level

TABLE 3-1 (cont)
TRAC ELEMENTS BY CATEGORY, SUBCATEGORY, AND MODEL

Category	Subcategory No.	Subcategory Description	Model
FFEC (continued)	3	Fluid momentum equation closure (momentum exchange)	
	3a	Wall-to-phase momentum exchange (Also see Appendix C, Table C-3)	Single phase Two phase, homogeneous Two phase, horizontal stratified
	3b	Interfacial momentum exchange (Also see Appendix C, Table C-4)	Bubbly flow Bubbly slug transition Bubbly slug flow Churn flow Annular-mist flow Transition to stratified flow Stratified flow Plug flow
	3c	Local pressure losses	Abrupt expansion Abrupt contraction Orifice plate User supplied
	4	Fluid energy equation closure (energy exchange)	
	4a	Wall-to-phase energy exchange (Also see Appendix C, Table C-5)	Natural convection to liquid Forced convection to liquid Nucleate boiling Critical heat flux Transition boiling Minimum stable film boiling temperature Film boiling Single-phase vapor Condensation Two-phase forced convection

TABLE 3-1 (cont)
TRAC ELEMENTS BY CATEGORY, SUBCATEGORY, AND MODEL

Category	Subcategory No.	Subcategory Description	Model
FFEC (continued)	4b	Interfacial energy exchange (Also see Appendix C, Table C-6)	Bubbly flow Bubbly slug transition Bubbly slug flow Churn flow Annular-mist flow Transition to stratified flow Stratified flow Plug flow Effect of noncondensables
ECM	1	Centrifugal pumps (Pump component)	Referenced at subcategory level
	2	Steam-water separator (Sepd component)	Referenced at subcategory level
	3	Plenum component	Referenced at subcategory level
	4	Valve component	Referenced at subcategory level
	5	Turbine (Turb component)	Referenced at subcategory level
	6	Pressurizer (Prizer component)	Referenced at subcategory level
SPM	1	Model for countercurrent flow limitation	Referenced at subcategory level
	2	Critical flow model	Referenced at subcategory level
	3	Trip and control elements	Referenced at subcategory level

TABLE 3-1 (cont)
TRAC ELEMENTS BY CATEGORY, SUBCATEGORY, AND MODEL

Category	Subcategory No.	Subcategory Description	Model
SPM (continued)	4	Reflood heat transfer models	
	4a	Flow regime modeling (Also see Appendix C, Table C-3)	Bubbly flow Inverted annular flow Dispersed flow
	4b	Wall-to-phase fluid drag (Also see Appendix C, Table C-3)	Single phase Two phase Homogeneous
	4c	Interfacial fluid drag (Also see Appendix C, Table C-8)	Subcooled boiling Smooth inverted annular flow Rough-wavy inverted annular flow Agitated inverted annular flow Post-agitated (dispersed) flow Highly dispersed flow
	4d	Wall-to-phase fluid heat transfer (Also see Appendix C, Table C-5)	Forced convection to a single-phase liquid Nucleate boiling Critical heat flux Transition boiling Minimum stable film boiling temperature Film boiling Convection to a single-phase vapor Convection to a two-phase mixture Condensation Natural convection to a single-phase liquid
	4e	Interfacial fluid heat transfer (Also see Appendix C, Table C-9)	Bubbly flow Inverted annular flow Dispersed flow
	4f	Conduction heat transfer	Referenced at subcategory level

TABLE 3-1 (cont)
TRAC ELEMENTS BY CATEGORY, SUBCATEGORY, AND MODEL

Category	Subcategory No.	Subcategory Description	Model
SPM (continued)	5	Two-phase level-tracking model	Referenced at subcategory level
	6	Offtake model for Tee component	Referenced at subcategory level
NSM		Fluid field equations	
		1D stability enhancing two-step (SETS) method	Referenced at subcategory level
		3D SETS	Referenced at subcategory level
		Conduction in solid materials	
		1D rectangular and cylindrical	Referenced at subcategory level
		2D rectangular and cylindrical	Referenced at subcategory level
		Power generation in fuel rods	Referenced at subcategory level
		Trip and control system elements	Referenced at subcategory level
		Fluid equation of state	Referenced at subcategory level
		Fluid boundary conditions	Referenced at subcategory level
		Equipment component models	Referenced at subcategory level
		Special-purpose models	Referenced at subcategory level
		Steady-state methods	Referenced at subcategory level
		Timestep size and control methods	Referenced at subcategory level

4.0 PIRT OVERVIEW

Phenomena Identification and Ranking Tables (PIRTs) were first developed during the pioneering Code Scaling, Applicability, and Uncertainty (CSAU) study.[4-1] They have since provided useful support for a number of code-related activities. For the purposes of this report, we focus on the utility of PIRTs in identifying needed code improvements and supporting code development decisions.[4-2]

The purpose of a PIRT is to identify the phenomena that are important to the T-H behavior of a particular plant during a particular transient scenario, e.g., plant event, transient, or accident. In addition, each phenomenon that is deemed of significance is assigned a relative importance ranking, either high, medium, or low, for example. The information obtained through the application of the PIRT process supports the identification of requirements to be imposed on transient T-H codes used to simulate given scenarios.

4.1. PIRT Concepts and Utility

PIRT development proceeds through the following steps:[4-2] (1) specification of the plant design; (2) specification of the scenario(s); (3) establishment of the primary evaluation criteria that will be used to judge the relative importance of phenomena during the scenario; (4) identification, acquisition, and review of all available experimental and analytical data; (5) definition of high-level basic system processes; (6) partitioning of the scenario into characteristic time phases; (7) partitioning the plant design into components; (8) identification of plausible phenomena by phase and component; and (9) ranking component and phenomena importance. Details are provided in Ref. 4-2.

The linkage of the PIRTs and code requirements is evident. First, a given PIRT, i.e., one for a specified plant and scenario, identifies all the components and phenomena that influence the course of the scenario. Second, there is a presumption that all such components and phenomena must be modeled in a transient T-H code used to simulate the scenario so that this information identifies a portion of the code design requirements. Third, some components and phenomena more strongly affect the course of the scenario than others. In fact, some components and phenomena play such a minor role in the progression of the scenario that the course of the scenario is quite insensitive to the details of the component or phenomena. Therefore, the same can be said, about related requirements imposed on the code. The PIRT provides the needed ranking information. Fourth, the ranking information found in a PIRT can also be used as the basis for programmatic decisions about the sequencing of development activities.

A schematic representation of PIRT usage to support development of the Assessment Test Matrix was provided in Fig. 2-3. The PIRT summary discussed in Section 4.3 provides information about phenomena occurring at three levels: local, component, and system. Phenomena occurring at the LL are usually associated with SET data sets (Fig. 2-1), whereas phenomena occurring at the SL are naturally associated with IET data sets. Phenomena occurring at the CL are associated with either SET or IET data sets on a case-by-case basis. Entries in the OST category are most frequently used to test various code features or functions. They are also used to test physical models and the local and CL, although the number of OSTs for this usage is limited.

4.2. PIRT Library

An ideal library would contain PIRTs for each plant type of each U.S. vendor and selected scenarios for each plant type. Unfortunately, such an extensive PIRT library is not available at this time.

The first PIRT was completed in 1989.[4-1] Since that time, a number of additional PIRTs have been completed for PWRs and BWRs; these constitute the current PIRT library for the TRAC-M validation test matrix. The contents of the PWR and BWR PIRT library are identified in the Table 4-1; this table applies only to operational light water reactors within the U.S. A reference to the citation for each PIRT is also provided in Table 4-1.

PIRTs have also been developed for advanced reactors such as the AP600 and the simplified boiling water reactor (SBWR). An AP600 large-break (LB) LOCA PIRT is found in Ref. 4-6. PIRTs for an AP600 SB LOCA, main steam line break (MSLB), and steam SGTR are found in Ref. 4-7. These are not discussed further in this report. PIRTs for SBWR LOCAs are found in Ref. 4-8. Finally, PIRTs have also been developed for other reactor types;[4-2] however, these are not discussed further in this report.

The validation matrix is to cover both PWR and BWR plants, i.e., it is being developed for the consolidated TRAC-M code which has both PWR and BWR capabilities. Given the different design and operating characteristics of PWRs and BWRs, three types of validation tests are envisioned. Tests of the first type are plant-type independent. It is expected, for example, that numerous OSTs and SETs can be used to assess the adequacy of basic models and constitutive relations that are used for both PWR and BWR calculations. Tests of the second type are PWR-specific tests. Tests of the third type are BWR-specific tests. The TRAC validation matrix is an evolutionary validation matrix; the consolidated validation test matrix is expected to evolve with time.

For this release of the matrix documentation, the elements of the PWR validation test matrix are specific to the LB LOCA and SB LOCA applications in Westinghouse plants[4-1,4-3,4-6] and the SB LOCA application in B&W lowered-loop plants.[4-4] Brief descriptions of each PWR and BWR reactor system and scenario included in the PIRT library are provided in Appendix D. The elements of the BWR validation test matrix cover a broader spectrum of events, including the LB LOCA, SB LOCA, and transient events divided into categories based on certain common attributes such as pressurization, depressurization, rapid reactivity increase, coolant temperature decrease, power oscillations, and an ATWS.

Having compiled the individual PWR and BWR PIRT currently available, the next logical step is to develop several summary PIRT tables. The first of these is a PWR summary PIRT. The second is a BWR summary PIRT. Finally, and most importantly, a consolidated PWR and BWR PIRT is developed. The development of these three summary PIRT tables is described in Section 4.3.

TABLE 4-1
PWR AND BWR PIRT LIBRARY

	PWR			BWR[d]		
Category	W[a]	B&W[b]	CE[c]	2	3,4	5,6
Accidents						
LB LOCA	X[4-1,4-6]			X[4-5]	X[4-5]	X[4-5]
SB LOCA	X[4-3]	X[4-4]		X[4-5]	X[4-5]	X[4-5]
SGTR						
MSLB						
ATWS				X[4-5]		
Transients						
Pressurization				X[4-5]		
Depressurization				X[4-5]		
Rapid reactivity increase				X[4-5]		
Coolant temperature decrease				X[4-5]		
Instability	Not Applicable			X[4-5]		

Notes

Number in superscript refer to reference numbers.

a. W plants are further differentiated as 2-loop, 3-loop and 4-loop plants. Additional variations include bundle design (14 x 14, 15 x 15, 16 x1 6, and 17 x 17), number of fuel assemblies and power level (high, medium and low).

b. B&W plants are further differentiated as lowered loop or raised loop. Additional variations include bundle design (15 x 15 and 17 x 17), number of fuel assemblies, and power level (high and low).

c. CE plants are further differentiated on bundle design (14 x 14, 15 x 15 and 16 x 16) and power level (high, low and unique).

d. Individual PIRTs have been produced for BWR/2, BWR/3,4 and BWR/5,6 designs for some accidents as noted, but general BWR PIRTs have been prepared for the ATWS and all the transients.

4.3. Summary Findings for PWR LOCAs

The highly ranked LB LOCA phenomena for W plants are presented in Table 4-2a; this table is based on the PIRTs in Refs. 4-1 and 4-6. The highly ranked SB LOCA phenomena for W plants are presented in Table 4-2b; this table is based on the PIRT in Ref. 4-3. The highly ranked SB LOCA phenomena for B&W lowered-loop plants are presented in Table 4-2c; this table is based on the PIRT in Ref. 4-4.

Our summary of highly ranked PWR LOCA phenomena is presented as Table 4-2d. This table summarizes highly ranked phenomena from Refs. 4-1, 4-3, 4-4 and 4-6; identifies whether the phenomena is evident at the LL, CL, SL, or in multiple levels; and identifies the associated TRAC models as organized and discussed in Section 3.

In previous efforts to prepare a summary PIRT for all PWR phenomena,[4-9] we encountered and addressed several issues. First, different phenomena names were used in the individual PIRTs to describe identical phenomena. For our summary tabulation, we selected a unique and consistent set of phenomena names and recast the individual PIRTs using this set of phenomena names. Our definitions for the highly ranked PWR LB LOCA PIRT phenomena identifiers in Table 4-2a-c and the summary tabulation of highly ranked PWR LOCA phenomena are provided in Table 4-3. In addition, Table 4-3 contains the definitions of the highly ranked BWR phenomena discussed in the next section.

PWR PIRTs have been developed for only LOCAs to date. They have not been developed for either non-LOCA accidents or transient sequences.

4.4. Summary Findings for BWR Events

Highly ranked LB LOCA phenomena for BWR plants are presented in Table 4-4a; this table is based on the PIRTs in Refs. 4-5. Highly ranked SB LOCA phenomena for BWR plants are presented in Table 4-4b; this table is also based on the PIRTs in Ref. 4-5. For the LB LOCA (Table 4-4a) and SB LOCA (Table 4-4b), the PIRTs have been developed for the following three types of BWRs: (1) BWR/2, (2) BWR/3 and /4, and (3) BWR/5 and /6. Highly ranked phenomena for BWR transients are presented in Table 4-4c, also based on the PIRTs in Ref. 4-5. The transient event categories covered are pressurization, depressurization, rapid reactivity increase, coolant temperature decrease, instability (power oscillation), and ATWS.

Our summary of highly ranked BWR phenomena is presented in Table 4-2d. This table summarizes highly ranked phenomena for the spectrum of PIRT scenarios presented in Ref. 4-5; identifies whether the phenomena is occurs at the LL, CL, SL; and identifies the associated TRAC models as organized and discussed in Section 3.

Our definitions for the highly ranked BWR PIRT phenomena identifiers in Table 4-4d are provided in Table 4-3.

4.5. Summary Findings for PWR and BWR Events

Finally, the summary PWR PIRT findings (Table 4-2d) and summary BWR PIRT findings (Table 4-4d) have been consolidated into a single table of highly ranked light water reactor phenomena (Table 4-5) for which PIRTs are available. We do note that PIRTs do not exist for all PWR plant types and accident sequence. Nevertheless, the list in Table 4-5 is believed to represent the majority of the highly important T-H processes occurring in light water reactors. The list can be easily updated as addition PIRTs are generated for other PWRs and accident sequences.

4.6. Application to TRAC-M Qualification

Table 4-2d lists the highly ranked phenomena for the PWR LOCAs. Table 4-4d lists the high-ranked phenomena for the BWR events described in Section 4.2. TRAC must model these phenomena. The phenomena identified in Tables 4-2d and 4-4d occur at different levels within a plant or facility. There is a natural association between LL phenomena and the flow field models and engineering correlations FFEC described in Section 3.2 and the SPM and associated tables described in Section 3.4. The appropriate cross-correlation or linkage between phenomena identified in the summary PIRT tabulation and the associated models for highly ranked phenomena in PWRs is provided in Table 4-2a-c. The appropriate cross-correlation or linkage between phenomena identified in the summary PIRT tabulation and the associated models for highly ranked phenomena in BWRs is provided in Table 4-4a-c.

There are two possible associations between CL phenomena and TRAC models. For some CL phenomena, there is no unique TRAC component model. Thus, the modeling capability is founded in more fundamental TRAC components and the underlying flow FFEC. For other CL phenomena, specific TRAC component models do exist, e.g., the Pump.

Some of the phenomena listed in Tables 4-2 and 4-4, are SL phenomena. These phenomena can invoke the entire hierarchy of TRAC models; basic equation models, as described in Section 3.1; flow field models and engineering correlations, as described in Section 3.2; equipment component models, as described in Section 3.3; and special-purpose models, as described in Section 3.4.

In summary, the cross–correlation of TRAC-M models at all levels, i.e., local, component, and system, with the summary PIRT phenomena and component lists serve to identify the associated TRAC models that must be provided and qualified.

REFERENCES

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4-4. M. G. Ortiz, "Uncertainty Analysis of Minimum Vessel Liquid Inventory during a Small Break LOCA in a B&W Plant: An Application of the CSAU Methodology," Idaho National Engineering Laboratory document NUREG/CR-5818 (December 1992).

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4-6. B. E. Boyack, "AP600 LB LOCA Phenomena Identification and Ranking Tabulation," Los Alamos National Laboratory document LA-UR-95-2718 (1995).

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4-8. P. G. Kroeger et al., "Preliminary Phenomena Identification and Ranking Tables for SBWR LOCA Scenarios," Brookhaven National Laboratory Technical letter report W-6092-5 6/95 (June 1995).

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TABLE 4-2a
SUMMARY TABULATION OF HIGHLY RANKED W PWR LB LOCA PHENOMENA[a]

Phenomena	Ref.[a]	Level	Phase[b]	TRAC Models[c] (category: subcategory: model)
Asymmetries	4-1	SL	1, 2	BEM:all:fluid flow equations
Boiling—film	4-1, 4-6	LL	1, 2, 3	FFEC:4a: film boiling
Boiling—transition	4-1, 4-6	LL	1, 2, 3	FFEC:4a:transition boiling
Condensation—interfacial	4-1	LL	2	FFEC:4b:all flow regimes
Draining	4-6	LL	4	BEM:all:fluid flow equations FFEC:3:all flow regimes
Entrainment/deentrainment	4-1	LL	2, 3	FFEC:3b:all flow regimes
Evaporation—interfacial	4-1, 4-6	LL	1, 2, 3	FFEC:4a:all flow regimes
Flashing—interfacial	4-1, 4-6	LL	1	FFEC:4b:all flow regimes
Flow—countercurrent	4-1	CL	2	FFEC:3b:all flow regimes
Flow—critical	4-1, 4-6	LL	1, 2	SPM:2:critical flow model
Flow—discharge	4-6	LL	2, 3	BEM:all:fluid flow equations FFEC:3:all flow regimes
Flow—multidimensional	4-1, 4-6	CL	2, 3	BEM:5:3D vessel model
Heat conductance—fuel-clad gap	4-1, 4-6	LL	1	BEM:6:fuel-clad gap model
Heat transfer—forced convection to vapor	4-1, 4-6	LL	2	FFEC:4a:single phase vapor
Heat transfer—stored energy release	4-1, 4-6	LL	1	BEM:6:conduction equation, fuel-clad gap
Interfacial shear	4-1, 4-6	LL	2, 3	FFEC:3b:all flow regimes
Level	4-1, 4-6	SL	3	BEM:all:fluid flow equations
Noncondensable effects	4-1	LL	3	FFEC:4b:effect of noncondensables
Oscillations	4-1, 4-6	SL,CL	3	BEM:all:fluid flow equations FFEC:3: all flow regimes FFEC:4: all flow regimes
Power—decay heat	4-1, 4-6	CL	2, 3, 4	BEM:7:power generation in fuel
Pump—performance, inc. degradation	4-1, 4-6	CL	1	ECM:1:centrifugal pump component
Reactivity—void	4-6	CL	1	BEM:7:power generation, reactivity feedback

[a] Based on Westinghouse 4-loop plant of CSAU study (Ref. 4-1) and AP600 plant (Ref. 4-6).
[b] Phase of the LB LOCA sequence: Blowdown = 1, Refill = 2, Reflood = 3, Long-Term = 4
[c] Per Section 3, there are five model categories. Each model category has subentries: BEM is Basic Equation Model, FFEC is Flow Field Model and Engineering Correlation (Closure), ECM is Equipment Component Model, SPM is Special Purpose Model, and NSM is Numerical Special Model.

TABLE 4-2b
SUMMARY TABULATION OF HIGHLY RANKED W PWR SB LOCA PHENOMENA[a]

Phenomena	Ref.[a]	Level	Phase[b]	TRAC Models[c] (category: subcategory: model)
Condensation—fluid to surface	4-3	LL	1,3	FFEC:4a:condensation
Condensation—interfacial	4-3	LL	4,5	FFEC:4b:all flow regimes
Entrainment/deentrainment	4-3	LL	3	FFEC:3b:all flow regimes
Flashing—interfacial	4-3	LL	3,4,5	FFEC:4b:all flow regimes
Flow regime—break inlet	4-3	CL	all	FFEC:1:all flow regimes
Flow—countercurrent	4-3	CL	2,3	FFEC:3b:all flow regimes
Flow—critical	4-3	LL	all	SPM:2:critical flow model
Flow—gap	4-3	CL	3	BEM:all:fluid flow equations
Heat Transfer—post-CHF	4-3	LL	4,5	FFEC:4a, 4b;transition boiling, film boiling
Interfacial shear	4-3	LL	3	FFEC:3b:all flow regimes
Level	4-3	SL	3,4,5	BEM:all:fluid flow equations
Oxidation	4-3	LL	4,5	BEM:6:metal-water reaction
Power—3D distribution	4-3	CL	4,5	BEM:7:3D kinetics
Power—decay heat	4-3	CL	all	BEM:7:power generation in fuel
Power—local peaking (fuel rod)	4-3	CL	4,5	BEM:7:3D kinetics
Pressure drop	4-3	CL	3	BEM:all:fluid flow equations FFEC:3,4;all
Rewet	4-3	LL	4,5	FFEC:4a SPM:4d
Stratification—horizontal	4-3	CL	3	BEM:1,2,3 FFEC:1:stratified flow

[a] Based on Westinghouse 4-loop plant; stated by PIRT panel to have extended applicability to conventional Westinghouse 3- and 4-loop plants (Ref. 4-3).
[b] Phase of the SB LOCA sequence: Blowdown = 1, Natural Circulation = 2, Loop Seal Clearance = 3, Boil-off = 4, and Core Recovery = 5.
[c] Per Section 3, there are five model categories. Each model category has subentries: BEM is Basic Equation Model, FFEC is Flow Field Model and Engineering Correlation (Closure), ECM is Equipment Component Model, SPM is Special Purpose Model, and NSM is Numerical Special Model.

TABLE 4-2c
SUMMARY TABULATION OF HIGHLY RANKED B&W PWR SB LOCA PHENOMENA[a]

Phenomena	Ref.[a]	Level	Phase[b]	TRAC Models[c] (category: subcategory: model)
Flow—critical	4-4	LL	1,2,4	SPM:2:critical flow model
Flow—high pressure injection	4-4	LL	3,4	BEM:all fluid flow equations FFEC:all
Flow—natural circulation	4-4	SL	2	BEM:all:fluid flow equations
Heat Transfer—primary to secondary	4-4	LL	4	BEM:all fluid flow equations BEM:6:1D radial FFEC:all
Level	4-4	SL	2	BEM:all:fluid flow equations
Power—decay heat	4-4	CL	2	BEM:7:power generation in fuel
Pump—performance, inc. degradation	4-4	CL	3	ECM:1:centrifugal pump component

[a] Based on Babcock & Wilcox 2x4-loop, lowered-loop plant (Ref. 4-4).
[b] Phase of the SB LOCA sequence: Blowdown = 1, Natural Circulation = 2, Loss of Natural Circulation = 3, and Boiler-Condenser = 4.
[c] Per Section 3, there are five model categories. Each model category has subentries: BEM is Basic Equation Model, FFEC is Flow Field Model and Engineering Correlation (Closure), ECM is Equipment Component Model, SPM is Special Purpose Model, and NSM is Numerical Special Model.

TABLE 4-2d
SUMMARY TABULATION OF HIGHLY RANKED PWR LOCA PHENOMENA

Phenomena	Level	Event Type: W LB LOCA	Event Type: W SB LOCA	Event Type: B&W SB LOCA
Boiling—film	LL	X		
Boiling—transition	LL	X		
Condensation—fluid to surface	LL		X	
Condensation—interfacial	LL	X	X	
Draining	LL	X		
Entrainment/deentrainment	LL	X	X	
Evaporation—interfacial	LL	X		
Flashing—interfacial	LL	X	X	
Flow—critical	LL	X	X	X
Flow—discharge	LL	X		
Flow—high pressure injection	LL			X
Heat conductance—fuel-clad gap	LL	X		
Heat transfer—forced convection to vapor	LL	X		
Heat transfer—post-CHF	LL		X	
Heat transfer—primary to secondary	LL			X
Heat transfer—stored energy release	LL	X		
Interfacial shear	LL	X	X	
Noncondensable effects	LL	X		
Oxidation	LL		X	
Rewet	LL		X	
Flow regime—break inlet	CL		X	
Flow—countercurrent	CL	X	X	
Flow—gap	CL		X	
Flow—multidimensional	CL	X		
Oscillations	CL	X		
Power—3D distribution	CL		X	
Power—decay heat	CL	X	X	X
Power—local peaking (fuel rod)	CL		X	
Pressure drop	CL		X	
Pump—performance, inc. degradation	CL	X		X
Reactivity—void	CL	X		
Stratification—horizontal	CL		X	
Asymmetries	SL	X		
Flow—natural circulation	SL			X
Level	SL	X	X	X
Oscillations	SL	X		

TABLE 4-3
CONSOLIDATED PIRT PHENOMENA DESCRIPTIONS[a]

PIRT Term	Description
Asymmetries	A difference in T-H behavior that can be attributed to the geometrically asymmetric arrangement of hardware.
Boiling—film	Boiling regime in which vapor blankets all or an appreciable portion of the heating surface.
Boiling—nucleate	A boiling regime in which bubble formation is at the liquid-solid interface which results in slow surface temperature increases for relatively large in creases in surface heat flux.
Boiling—transition	A boiling regime that spans the boiling surface between critical heat flux and minimum film boiling.
Boiling—subcooled	A boiling regime in beginning with the onset of nucleate boiling and continuing to the onset of saturated boiling, the boundary between the latter two regimes occurring when the bulk liquid temperature approaches saturation at the given pressure.
Condensation—fluid to surface	The process whereby steam is cooled due to contact with a colder surface, resulting in a change of phase from vapor to liquid at the surface.
Condensation—interfacial	The process whereby steam is cooled due to contact with a colder liquid, resulting in a change of phase from vapor to liquid at the interface between the two phases.
Draining	The downward flow of fluid on a surface under the influence of gravity.
Dryout-critical heat flux	Also variously called burnout, boiling crisis, and critical heat flux. The point in a heated channel with flowing two-phase flow at which there is no longer any liquid in contact with the heated surface, resulting in a rapid increase in surface temperature.

[a] If available, the descriptions are taken from Ref. 4-6. Additional terms are based on definitions found in the *Dictionary of Scientific and Technical Terms*, 2nd edition, McGraw-Hill Book Company (1978).

TABLE 4-3 (cont)
PWR PIRT PHENOMENA DESCRIPTIONS

PIRT Term	Description
Entrainment/deentrainment	The process whereby liquid is captured (entrained) by a high-velocity steam flow. The process whereby liquid departs (deentrained) from a steam flow.
Evaporation—interfacial	The process whereby a fluid changes from the liquid state to the vapor state by the addition of energy.
Flashing—interfacial	The process whereby fluid changes from the liquid state to the vapor state due to a reduction in the fluid pressure, which lowers the saturation temperature.
Flow regime—break inlet	The characteristics of the flow at the break entrance, e.g., subcooled liquid, saturated, two-phase, stratified, vapor, etc.
Flow—carryunder	The mass fraction of produced steam that is entrained via the separator liquid drain path.
Flow—countercurrent	The process whereby liquid flows opposite (counter) to the gas flow direction.
Flow—channel-bypass leakage	Flow via the channel-bypass leakage path.
Flow—critical	The maximum possible flow through a flow constricting item of hardware, usually a nozzle, orifice, or break in a pipe.
Flow—discharge	Flow leaving a component under the influence of an upstream forcing function.
Flow—distribution	The location of fluid (liquid and vapor) throughout a system
Flow—forward (jet pumps)	That part of the jet pump operating regime in which the outlet (discharge) flow is positive, i.e. forward.
Flow—gap	Flow through the hot leg to downcomer gap.
Flow—multidimensional	Flow that has two or more dominant velocity vectors. Examples are multidimensional flows in a PWR core during reflooding and spray induced flows in the upper plenum of a BWR.

TABLE 4-3 (cont)
PWR PIRT PHENOMENA DESCRIPTIONS

PIRT Term	Description
Flow—multi-channel T/H effect	Differences in the boiling-induced flows and pressure drop characteristics in parallel channels, e.g., fuel assemblies that may induce dynamic instabilities.
Flow—reverse (jet pumps)	That part of the jet pump operating regime in which the outlet flow is negative, i.e. reversed.
Heat conductance—fuel-clad gap	The overall thermal resistance to the flow of heat between the fuel pellets and cladding in a nuclear fuel rod.
Heat conductance—fuel	The overall thermal resistance to the flow of heat from the high temperature to lower-temperature parts of the fuel pellet.
Heat—stored	The total energy residing in a material at a given time; the amount being dependent on the material mass, heat capacity and temperature.
Heat transfer—forced convection to vapor	Process of energy transport by the combined action of heat conduction, energy storage, and mixing motion.
Heat transfer—post CHF	Heat transfer between the two-phase fluid and the heated surface in the liquid-deficient region downstream of the CHF point, i.e., the location at which the heat transfer condition of the two-phase flow substantially deteriorates.
Heat transfer—radiation	The transfer of energy from a higher temperature body to a lower temperature body without relying on the intervening medium, i.e., the transfer can take place in a vacuum.
Heat transfer—stored energy release	The process by which the energy within a solid structure is released to a lower energy state through one or more heat transfer processes, e.g., conduction and convection. Applies specifically to the transport of the energy residing in fuel rods operating at full power to the coolant following a reactor trip.
Interfacial shear	The friction caused by the velocity difference between two phases at their interface.
Level	The vertical height of a column of single- or two-phase fluid.

TABLE 4-3 (cont)
PWR PIRT PHENOMENA DESCRIPTIONS

PIRT Term	Description
Noncondensable effects	The impact of the presence of noncondensable gases upon heat transfer or any other phenomenon such as flow, condensation, flashing, and vapor volume expansion.
Oscillations	The periodic variation of any given hydraulic characteristic between two values.
Oxidation	A chemical reaction that increases the oxidation content of a material. Of specific interest is cladding oxidation, which occurs at elevated temperatures, which can occur only under accident conditions.
Power—3D distribution	The axial, radial and azimuthal power variation in a core.
Power—3D kinetics effect	Neutronic effect that takes place in space, i.e. three dimensions.
Power—decay heat	Heat produced by the decay of radioactive nuclides.
Power—local peaking (fuel rod)	The ratio of power at a location (specific fuel rod) to the core average power.
Pressure drop	The reduction in pressure with distance.
Pressure wave propagation	The movement of a compression or decompression wave through the coolant.
Pump—performance, including degradation	The behavior of a pump under all normal and off-normal conditions.
Reactivity—fuel temperature	Prompt reactivity feedback from fuel temperature changes, also known as Doppler feedback.
Reactivity—scram	Reactor trip initiates insertion of control rods and their associated negative reactivity into the core.
Reactivity—void	The change in core reactivity due to an increase or decrease in the amount of void in the moderating fluid.
Rewet	The post-dryout process in which liquid once again resumes intimate contact with a heated surface.

TABLE 4-3 (cont)
PWR PIRT PHENOMENA DESCRIPTIONS

PIRT Term	Description
Spray distribution	The radial and azimuthal distribution of flow in the upper plenum resulting from operation of the spray system.
Stability—neutronic and T/H interaction	Neutronic-T-H interaction between fuel channel boiling and nuclear reactivity feedback processes.
Stratification—horizontal	The variation of physical properties such as temperature or density across the vertical cross section of a fluid body having a primarily horizontal orientation, e.g., the cold leg of a nuclear steam supply system.
Subcooling—coolant	The difference between the saturation temperature at a given pressure and the temperature of the coolant. The degree of subcooling affects density-wave travel time and two-phase pressure drop via boiling boundary change.
Void collapse	The rapid reduction in void in the core.
Void distribution	The distribution (location) of two-phase fluid within the nuclear steam supply system.

TABLE 4-4a
SUMMARY TABULATION OF HIGHLY RANKED BWR LB LOCA PHENOMENA[a]

Phenomena	Ref.[a]	Level	Phase[b]	TRAC Models[c] (category: subcategory: model)
Boiling—film	4-5	LL	1,2,3	FFEC:4a: film boiling
Boiling—nucleate	4-5	LL	4	FFEC:4a:nucleate boiling
Condensation—interfacial	4-5	LL	1,2,3	FFEC:4b:all flow regimes
Dryout-critical heat flux	4-5	LL	1,2,3	FFEC:4a:critical heat flux
Flashing—interfacial	4-5	LL	1	FFEC:4b:all flow regimes
Flow—channel-bypass leakage	4-5	CL	1,2,3	FFEC:3b:all flow regimes
Flow—countercurrent	4-5	CL	1,2,3	FFEC:3b:all flow regimes
Flow—critical	4-5	LL	1	SPM:2:critical flow model
Flow—distribution	4-5	CL	1	FFEC:3b:all flow regimes
Flow—forward (jet pumps)	4-5	CL	1	FFEC:3b:all flow regimes
Flow—multidimensional	4-5	CL	1,2,3,4	BEM:5:3D vessel model
Flow—natural circulation	4-5	SL	2,3,4	BEM:all:fluid flow equations
Flow—reverse (jet pumps)	4-5	CL	1	FFEC:3b:all flow regimes
Heat transfer-fuel-clad gap	4-5	LL	1	BEM:6:fuel-clad gap model
Heat transfer—forced convection to vapor	4-5	LL	2,3	FFEC:4a:single phase vapor
Heat transfer—radiation	4-5	LL	2,3	BEM:8:radiative energy exchange in the core
Heat—stored	4-5	LL	1,2,3	BEM:6:material properties
Interfacial shear	4-5	LL	1,2,3	FFEC:3b:all flow regimes
Level	4-5	SL	1,2,3,4	BEM:all:fluid flow equations
Power—3D distribution	4-5	CL	2,3	BEM:7:3D kinetics
Power—decay heat	4-5	CL	1,2,3,4	BEM:7:power generation in fuel
Pressure drop	4-5	CL	1	BEM:all:fluid flow equations FFEC:3,4;all
Pump performance, inc. degradation	4-5	CL	1	ECM:1:centrifugal pump component
Rewet	4-5	LL	2,3,4	FFEC:4a SPM:4d
Spray distribution	4-5	CL	1,2,3,4	BEM:all:fluid flow equations, FFEC 4
Void distribution	4-5	CL	1,2,3,4	BEM:all:fluid flow equations FFEC:all SPM:4

[a] Based on BWR/2, BWR/3 and 4, and BWR/5 and 6 designs as discussed in Ref. 4-5.
[b] Phase of the LB LOCA sequence: Blowdown = 1, Refill = 2, Reflood = 3, Long-Term = 4.
[c] Per Section 3, there are five model categories. Each model category has subentries: BEM is Basic Equation Model, FFEC is Flow Field Model and Engineering Correlation (Closure), ECM is Equipment Component Model, SPM is Special Purpose Model, and NSM is Numerical Special Model.

TABLE 4-4b
SUMMARY TABULATION OF HIGHLY RANKED BWR SB LOCA PHENOMENA[a]

Phenomena	Ref.[a]	Level	Phase[b]	TRAC Models[c] (category: subcategory: model)
Boiling—film	4-5	LL	b,2,3	FFEC:4a: film boiling
Boiling—nucleate	4-5	LL	a,4	FFEC:4a:nucleate boiling
Condensation—interfacial	4-5	LL	b,2,3,4	FFEC:4b:all flow regimes
Dryout-critical heat flux	4-5	LL	b,3,4	FFEC:4a:critical heat flux
Flashing—interfacial	4-5	LL	b	FFEC:4b:all flow regimes
Flow—channel-bypass leakage	4-5	CL	b,3,4	FFEC:3b:all flow regimes
Flow—countercurrent	4-5	CL	b,3,4	FFEC:3b:all flow regimes
Flow—critical	4-5	LL	a,b	SPM:2:critical flow model
Flow—distribution	4-5	CL	b	FFEC:3b:all flow regimes
Flow—forward (jet pumps)	4-5	CL	a,b	FFEC:3b:all flow regimes
Flow—multidimensional	4-5	CL	b,2,3,4	BEM:5:3D vessel model
Flow—natural circulation	4-5	SL	b,2,3,4	BEM:all:fluid flow equations
Flow—reverse (jet pumps)	4-5	CL	b	BEM:all:fluid flow equations
Heat transfer–fuel-clad gap	4-5	LL	b	BEM:6:fuel-clad gap model
Heat transfer—forced convection to vapor	4-5	LL	3,4	FFEC:4a:single phase vapor
Heat—stored	4-5	LL	b,2,3	BEM:6:material properties
Interfacial shear	4-5	LL	a,b,2,3,4	FFEC:3b:all flow regimes
Level	4-5	SL	b,2,3,4	BEM:all:fluid flow equations
Power—3D distribution	4-5	CL	2,3	BEM:7:3D kinetics
Power—decay heat	4-5	CL	a,b,2,3,4	BEM:7:power generation in fuel
Pressure drop	4-5	CL	a,b	BEM:all:fluid flow equations FFEC:3,4;all
Pump–performance, inc. degradation	4-5	CL	a	ECM:1:centrifugal pump component
Reactivity—scram	4-5	SL	a	BEM:7
Rewet	4-5	LL	b,2,3	FFEC:4a SPM:4d
Spray distribution	4-5	CL	b,2,3,4	BEM:all:fluid flow equations, FFEC 4
Void distribution	4-5	CL	a,b,2,3	BEM:all:fluid flow equations FFEC:all SPM:4

[a] Based on BWR/2, BWR/3 and 4, and BWR/5 and 6 designs as discussed in Ref. 4-5.

[b] Phase of the LB LOCA sequence: Blowdown before ADS operation = a, Blowdown after ADS operation = b, Refill = 2, Reflood = 3, Long-Term = 4.

[c] Per Section 3, there are five model categories. Each model category has subentries: BEM is Basic Equation Model, FFEC is Flow Field Model and Engineering Correlation (Closure), ECM is Equipment Component Model, SPM is Special Purpose Model, and NSM is Numerical Special Model.

TABLE 4-4c
SUMMARY TABULATION OF HIGHLY RANKED BWR TRANSIENT PHENOMENA[a]

Phenomena	Ref.[a]	Level	Transient[b]	TRAC Models[c] (category: subcategory: model)
Boiling—film	4-5	LL	3,4,5	FFEC:4a: film boiling
Boiling—subcooled	4-5	LL	5	FFEC:4a:nucleate boiling
Condensation—interfacial	4-5	LL	4	FFEC:4b:all flow regimes
Dryout-critical heat flux	4-5	LL	3,4,5	FFEC:4a:critical heat flux
Flow—carry-under	4-5	SL	1,2,4,5,6	BEM:all:fluid flow equations
Flow—critical	4-5	LL	1,2,6	SPM:2:critical flow model
Flow—forward (jet pumps)	4-5	CL	1,2,4,5,6	FFEC:3b:all flow regimes
Flow—multi-channel T/H effect	4-5	CL	all	BEM:all:fluid flow equations
Flow—multidimensional	4-5	CL	4,5	BEM:5:3D vessel model
Flow—natural circulation	4-5	SL	5	BEM:all:fluid flow equations
Heat conductance—fuel-clad gap	4-5	LL	1,3,5,6	BEM:6:fuel-clad gap model
Interfacial shear	4-5	LL	all	FFEC:3b:all flow regimes
Level	4-5	SL	1,2,4,5,6	BEM:all:fluid flow equations
Power—3D distribution	4-5	CL	3,5	BEM:7:3D kinetics
Power—3D kinetics effect	4-5	CL	1,3,4,5,6	BEM:7:3D kinetics
Pressure drop	4-5	CL	all	BEM:all:fluid flow equations FFEC:3,4;all
Pressure wave propagation	4-5	SL	1,2,6	BEM:all:fluid flow equations
Pump-performance, inc. degradation	4-5	CL	5,6	ECM:1:centrifugal pump component
Reactivity—fuel temperature	4-5	CL	1,3,4,5,6	BEM:7:power generation, reactivity feedback
Reactivity—scram	4-5	SL	1,5,6	BEM:7
Reactivity—void	4-5	CL	All	BEM:7:power generation, reactivity feedback
Stability—neutronic and T/H interaction	4-5	SL	5	BEM:all:fluid flow equations BEM:7:power generation, reactivity feedback
Subcooling—coolant	4-5	SL	5	BEM:all:fluid flow equations
Void collapse	4-5	CL	1,3,4,6	BEM:all:fluid flow equations, FFEC 4
Void distribution	4-5	CL	all	BEM:all:fluid flow equations FFEC:all SPM:4
Void—subcooled liquid	4-5	CL	all	FFEC:2a:subcooled boiling

[a] Based on BWR/2, BWR/3 and 4, and BWR/5 and 6 designs as discussed in Ref. 4-5.
[b] Transients are pressurization = 1, depressurization = 2, rapid reactivity increase = 3, coolant temperature decrease = 4, instability (power oscillations) = 5 and anticipated transient without scram (ATWS) = 6.
[c] Per Section 3, there are five model categories. Each model category has subentries: BEM is Basic Equation Model, FFEC is Flow Field Model and Engineering Correlation (Closure), ECM is Equipment Component Model, SPM is Special Purpose Model, and NSM is Numerical Special Model.

TABLE 4-4d
SUMMARY TABULATION OF HIGHLY RANKED BWR PHENOMENA

Phenomena	Level	Event Type: LB LOCA	SB LOCA	Transient
Boiling—film	LL	X	X	X
Boiling—nucleate	LL	X	X	
Boiling—subcooled	LL			X
Condensation—interfacial	LL	X	X	X
Dryout–critical heat flux	LL	X	X	X
Flashing—interfacial	LL	X	X	
Flow—critical	LL	X	X	X
Heat conductance—fuel-clad gap	LL	X	X	X
Heat transfer—forced convection to vapor	LL	X	X	
Heat transfer—radiation	LL	X		
Heat—stored	LL	X	X	
Interfacial shear	LL	X	X	X
Rewet	LL	X	X	
Flow—channel-bypass leakage	CL	X	X	
Flow—countercurrent	CL	X	X	
Flow—distribution	CL	X	X	
Flow—forward (jet pumps)	CL	X	X	X
Flow—multi-channel T/H effect	CL			X
Flow—Multidimensional	CL	X	X	X
Flow—reverse (jet pumps)	CL	X	X	
Power—3D distribution	CL	X	X	X
Power—3D kinetics effect	CL			X
Power—decay heat	CL	X	X	
Pressure drop	CL	X	X	X
Pump–performance, inc. degradation	CL	X	X	X
Reactivity—fuel temperature	CL			X
Reactivity—void	CL			X
Spray distribution	CL	X	X	
Void collapse	CL			X
Void distribution	CL	X	X	X
Void—subcooled liquid	CL			X
Flow—carry-under	SL			X
Flow—natural circulation	SL	X	X	X
Level	SL	X	X	X
Pressure wave propagation	SL			X
Reactivity—scram	SL		X	X
Stability—neutronic and T/H interaction	SL			X
Subcooling—coolant	SL			X

TABLE 4-5
CONSOLIDATED TABULATION OF HIGHLY RANKED PIRT PHENOMENA

Phenomena	Level	Transient Type: W-P LB LOCA	W-P SB LOCA	B&W-P SB LOCA	GE-BWR LB LOCA	GE-BWR SB LOCA	GE-BWR TRANSIENT
Boiling—film	LL	X			X	X	X
Boiling—nucleate	LL				X	X	
Boiling—subcooled	LL						X
Boiling—transition	LL	X					
Condensation—fluid to surface	LL		X				
Condensation—interfacial	LL	X	X		X	X	X
Draining	LL	X					
Dryout–critical heat flux	LL				X	X	X
Entrainment/deentrainment	LL	X	X				
Evaporation—interfacial	LL	X					
Flashing—interfacial	LL	X	X		X	X	
Flow—critical	LL	X	X	X	X	X	X
Flow—discharge	LL	X					
Flow—high pressure injection	LL			X			
Heat conductance—fuel-clad gap	LL	X			X	X	X
Heat transfer—forced convection to vapor	LL	X			X	X	
Heat Transfer—post-CHF	LL		X				
Heat Transfer—primary to secondary	LL			X			
Heat transfer—radiation	LL				X		
Heat transfer—stored energy release	LL	X					
Heat—stored	LL				X	X	
Interfacial shear	LL	X	X		X	X	X
Noncondensable effects	LL	X					
Oxidation	LL		X				
Rewet	LL		X		X	X	
Flow—channel-bypass leakage	CL				X	X	
Flow—countercurrent	CL	X	X		X	X	
Flow—distribution	CL				X	X	
Flow—forward (jet pumps)	CL				X	X	X

TABLE 4-5 (cont)
CONSOLIDATED TABULATION OF HIGHLY RANKED PIRT PHENOMENA

Phenomena	Level	Transient Type W-P LB LOCA	W-P SB LOCA	B&W-P SB LOCA	GE-BWR LB LOCA	GE-BWR SB LOCA	GE-BWR TRANSIENT
Flow regime—break inlet	CL		X				
Flow—gap	CL		X				
Flow—multi-channel T/H effect	CL						X
Flow—multidimensional	CL	X			X	X	X
Flow—reverse (jet pumps)	CL				X	X	
Oscillations	CL	X					
Power—3D distribution	CL		X		X	X	X
Power—3D kinetics effect	CL						X
Power—decay heat	CL	X	X	X	X	X	
Power—local peaking (fuel rod)	CL		X				
Pressure drop	CL		X		X	X	X
Pump[a]—performance, inc. degradation	CL	X		X	X	X	X
Reactivity—fuel temperature	CL						X
Reactivity—void	CL	X					X
Spray distribution	CL				X	X	
Stratification—horizontal	CL		X				
Void collapse	CL						X
Void distribution	CL				X	X	X
Void—subcooled liquid	CL						X
Asymmetries	SL	X					
Flow—carry-under	SL						X
Flow—natural circulation	SL			X	X	X	X
Level	SL	X	X	X	X	X	X
Oscillations	SL	X					
Pressure wave propagation	SL						X
Reactivity—scram	SL					X	X
Stability—neutronic and T/H interaction	SL						X
Subcooling—coolant	SL						X

[a]centrifugal.

5.0. PLANT TYPES AND TARGETED APPLICATIONS

T-H codes are specifically designed for a variety of targeted applications. Among these applications are (1) reactor safety analyses for both operating and planned reactors, (2) audits of licensee's calculations, (3) analyses of operating reactor events, (4) analyses of accident management strategies, (5) support for test planning and interpretation, (6) support for probabilistic risk assessments, (7) design analyses, and (8) nuclear plant training and instrument and control simulators.

With respect to code qualification, the list of targeted applications can be distilled to two key elements: the need to accurately simulate plant type and event type. Thus, with respect to targeted applications, an important source of validation requirements arises from the need to accurately model the response of PWR and BWR plants currently operational in the United States for a spectrum of transient and accident scenarios.

5.1. Plant Type

A survey of commercial nuclear power plants was completed in 1992.[5-1] Similar plants designed by a given vendor were placed in groups characterized by coolant loop configuration, the number of fuel bundles, and bundle design. This information is summarized in Table 5-1 for PWRs; a similar summary is provided in Table 5-2 for BWRs.

5.2. Event Type

It is impossible to list all the potential event scenarios (accidents, transients, and operating events) and correlate these to the accident scenarios simulated in each IET. For our purposes, a more modest goal is set, namely, to create a table of the major PWR and BWR event scenarios for use in selection of IETs. This tabulation is provided in Table 5-3.

5.3. IET Selection Based on Scaling Issues

A significant amount of effort will be required to address the scaling issue. That effort is beyond the scope of the present document. However, a promising approach has been identified as part of the RELAP5 adequacy demonstration for AP600 SBLOCA analyses. Scaling analyses are used to demonstrate the relevancy and sufficiency of the collective experimental database for representing the behavior expected of a given plant design during a selected accident scenario. With this approach, an effort is made to demonstrate that the experimental database is sufficiently diverse that the expected full-plant response is included and that the code calculations are comparable with the corresponding tests in nondimensional space. This demonstration permits conclusions relating to code capabilities, drawn from assessments comparing calculated and measured IET test data, to be extended to the prediction of the full-plant behavior. This is a time- and labor-intensive effort. It appears to be generally applicable, if there are sufficient IET facilities. Some diversity in the scaling approaches used when designing the facilities appears desirable. For the AP600 demonstration just described, there were three such IET facilities.

REFERENCES

5-1. J. C. Determan and C. E. Hendrix, "Survey of Thermal-Hydraulic Models of Commercial Nuclear Power Plants," EG&G Idaho, Inc. document EGG-EAST-9031 (December 1992).

TABLE 5-1
SUMMARY OF PWR VENDOR AND REACTOR TYPES

Vendor Group	Group Description	Coolant Loops	Number of Bundles	Bundle Design
Westinghouse				
W1	High-power 4 loop	4	193	17 x 17
W2	Medium-power 4 loop	4	193	17 x 17
W3	Low-power 4 loop	4	193	15 x 15
W4	Unique 4 loop	4	157	15 x 15
W5	Unique 4 loop	4	76	16 x 16
W6	High-power 3 loop	3	157	17 x 17
W7	Medium-power 3 loop	3	157	15 x 15
W8	Low-power 3 loop	3	157	14 x 14
W9	2 loop	2	121	14 x 14
AP600	Advanced passive	2 x 4	145	17 x 17
CE				
C1	Unique	3	217	14 x 14
C2	High power	2 x 4	241	16 x 16
C3	Medium power	2 x 4	217	16 x 16
C4	Unique	2 x 4	217	16 x 16
C5	Low power	2 x 4	217	14 x 14
C6	Unique	2 x 4	204	15 x 15
C7	Unique	2 x 4	177	16 x 16
C8	Unique	2 x 4	133	14 x 14
B&W				
B1	High-power, raised loop	2 x 4	205	17 x 17
B2	Low-power, raised loop	2 x 4	177	15 x 15
B3	Low loop	2 x 4	177	15 x 15

TABLE 5-2
SUMMARY OF BWR REACTOR TYPES

Vendor Group	Group Description	Number of Bundles	Bundle Design
GE/BWR/1	G1	84	11x11
GE/BWR/2	G2	560	8x8
GE/BWR/3	G3, low power	484	8x8
	G4, medium power	580	8x8
	G5, high power	724	8x8; 9x9
GE/BWR/4	G6, low power	368	8x8
	G7, medium power	560; 548	8x8
	G8, high power	764	8x8; 9x9
GE/BWR/5	G9	764	8x8; 9x9
	G10, low power	624	8x8
	G11, medium power	748	8x8
	G12, high power	800	8x8

TABLE 5-3
PWR AND BWR EVENT SCENARIOS SUPPORTING THE SELECTION OF IETS

LWR Type	Scenario
Pressurized water reactor	Large-break LOCA
	Intermediate-break LOCA
	Small-break LOCA
	Steam-generator tube rupture
	Main-steam-line break
	Loss-of-offsite power
	Loss of feedwater
	Reactor trip
	Anticipated transient w/o scram
	Multiple-failure events
	Accident management scenarios
Boiling water reactor	Large-break LOCA
	Intermediate-break LOCA
	Small-break LOCA
	Transients
	Pressurization
	Depressurization
	Rapid reactivity increase
	Coolant temperature decrease
	Instability (power oscillation)
	Anticipated transient w/o scram

6.0. CODE QUALIFICATION—VALIDATION USING OTHER STANDARD TESTS

As discussed in Section 2.1, this element of validation is conducted by comparing code features and code-calculated results with standards not requiring experimental data. It encompasses tests of code features or functions; comparisons of code-calculated results with equilibrium, concept, and analytical solutions; and tests of the numerical methods used in the code.

The collection of tests selected for this element of the TRAC-M validation test matrix is limited in the sense that it does not now, nor will it ever, constitute a complete test of the TRAC-M code. For example, exact solutions, although setting the highest standard for code validation, exist for only a subset of the physical processes and conditions modeled in TRAC-M. Equilibrium, concept problems, and numerical methods also have limitations, as discussed in subsequent subsections.

The tests selected for the TRAC-M validation test matrix for this element are given in this section. The objective of these tests is to provide increased assurance that TRAC-M code features, algorithms, and equations are correctly programmed. Test problems that focus on specific code features, algorithms, and equations in TRAC-M are either devised or defined. Success metrics are established for each problem, and code output is examined to ensure that the expected results are obtained.

Additional test problems are expected to acquire the status of "other standard tests" as TRAC-M development continues under the multiple-team, multiple-site development format employed by the NRC. These should be added to the validation test matrix in a timely manner.

The categories of problems used in this element are

- features tests,
- equilibrium problems,
- concept problems with known outcomes,
- analytical problems (known solutions), and
- problems to test properties of the numerical solution methods.

Descriptions of each of the categories listed above are given in the following discussions, as well as specific recommendations for tests in each category.

6.1. Features Tests

Three code features have been identified for testing. These features, related to TRAC-M input and output, are

- input file error checking,
- output file (graphics) processing, and
- English units input/output.

The initial set of Features Tests, including development status, is presented in Table 6-1.

TABLE 6-1
FEATURES TEST PROBLEMS

Test	Status
Error checking for input decks	In progress
Graphics process	Input deck(s) to be developed
English units input/output	Input decks exist

6.2. Equilibrium Problems

Equilibrium is a condition of balance among various forces. Several types of equilibrium problems exist. First, there are problems with specified initial and boundary conditions such that all real forcing functions that could drive the system from its specified state are zero-valued. Therefore, as the problem is run, the system should remain in equilibrium, which is the success metric. Second, there are problems in which a small nonequilibrium condition is established and the system returns to equilibrium conditions.

An example equilibrium problem of the first type is a horizontal flow channel containing either single-phase vapor, single-phase liquid, or a mixture of subcooled liquid and a noncondensable gas. The channel is open at each end, and the identical pressure is specified at each end and throughout the channel. All fluid and wall temperatures are specified to be identical. The fluid is static, i.e., zero velocity everywhere and no power generation. A transient is run and the outcome examined. The success metric is that the problem should maintain its initial state (zero velocity and constant, specified temperature) for all timestep sizes and for all time. Deviations from the success metric are to be examined and the causes described.

There are three approaches to creating equilibrium problems that can be used to exercise the code. First, an equilibrium condition can be specified via the problem initial and boundary condition specifications as described in the previous paragraph. Second, small departures from equilibrium can be specified initially, and the problem should approach a known equilibrium state. Adjustment of the gravitational head in a vertical flow channel is an example. Following the initial adjustment, equilibrium is attained. Third, an equilibrium state calculated via a steady-state calculation is rerun as a transient restart using the previously calculated steady-state result.

In general, equilibrium problems test for the absence of coding errors that introduce spurious information into the solution. Ideally, each equilibrium problem is designed to test different features. The cause of the failure is sought if the success metric is not satisfied.

The initial set of Equilibrium Problems, including development status, is presented in Table 6-2.

6.3. Concept Problems

Concept problems are problems for which specific outcomes are known even though the exact solution may not be known. An exact but partial success metric can be defined

TABLE 6-2
EQUILIBRIUM TEST PROBLEMS

ID	Test	Status
O1.1	Horizontal pipe hydro equilibrium	Input decks to be developed
O1.2	Displaced vertical fluid column	Input decks to be developed
O1.3	Static vessel	Input deck exists
O1.4	TRAC-P MS#& Standard Test Matrix Problem[6-1]	Existing decks to be modified
O1.5	TRAC-P Conduction Developmental Assessment Problems[6-1]	Existing decks to be modified
O1.6	Air/water hydro equilibrium	Input decks to be developed
O1.7	Liquid/solute hydro equilibrium	Input decks to be developed
O1.8	Radiative energy exchange	Existing decks to be modified

defined. For example, a symmetric perturbation introduced in a symmetric hardware configuration should be preserved, although the precise propagation and attenuation of the perturbation are not known.Concept problems can be devised for most of the basic-equation models in TRAC-M, including the fluid flow equations (single and two phase), conduction equations, power generation model, control system, and component and special-purpose models. Examples of these problems are

- Simple symmetrical fluid flow situations in pipes and the reactor pressure vessel.
- More complex symmetrical fluid flow situations, such as the primary and secondary sides of a complete PWR at steady-state conditions.
- Symmetrical situations for conduction in solids.
- System descriptions that cause changes in the sign of the fluid speed.
- Restart problems to test that results obtained in an original run are exactly repeated after restart.
- Closed-container problems to test conservation of mass and energy.
- Conduction situations that cause a change in the sign of the heat flux.

All the problems that test fluid flow models and methods will be run with single-phase water, two-phase water, and noncondensable gases. Concept problems will be devised for the equipment-component models.

Concept problems are found in the current TRAC-P Standard Test Matrix.[6-1] One series of problems is an isothermal, abrupt flow-area change, vertical coolant-flow channel. This test series uses six different TRAC-hydraulic-component models, including the 3D vessel model to give the same flow channel geometry. The test is executed with single-phase liquid; single-phase vapor; and a two-phase, liquid-vapor mixture. The combinations of TRAC-hydraulic-component arrangements and fluid states give 18 separate problems. The specific known outcome is that all problems should give the identical result. The magnitude of the specific result may not be known analytically.

The problems already available in the Standard Test Matrix can be augmented by making the flow channels horizontal to eliminate gravity and adding an additional hydraulic node to the center of the flow channels. These modifications would allow additional testing as follows: (1) the horizontal channel models, as noted in Table 6-2 above, would allow equilibrium problems to be run; and (2) symmetric perturbation problems could be tested by initializing the central node at a pressure different from all the other nodes. Additional modifications, such as adding heat conductors and power generation, will expand the range of TRAC-M models and methods tested.

The initial set of Concept Problems, including development status, is presented in Table 6-3.

6.4. Analytical Problems

As used in this document, analytical problems have known, exact solutions. The success metric is both exact and complete in the sense that the precise values of all solution variables are known.

TABLE 6-3
CONCEPT TEST PROBLEMS

ID	Test	Status
O2.1	TRAC-P MS#& Standard Test Matrix Problem[6-1]	Existing decks
O2.2	Symmetric perturbations in the MS#& Standard Test Problems[6-1]	Existing decks to be modified
O2.3	HCOND# Standard Test Matrix Problem[6-1]	Existing decks
O2.4	DRAIN Standard Test Matrix Problem[6-1]	Existing deck
O2.5	ROD2 Standard Test Matrix Problem[6-1]	Existing deck
O2.6	Bubble rise problems	Existing decks
O2.7	Falling drop problems	Existing decks
O2.8	Boron transport problem	Existing decks
O2.9	Restart validation for 1D SET	Existing deck to be modified
O2.10	Restart validation for 3D SET	Input decks to be developed
O2.11	Restart validation for conduction	Input decks to be developed
O2.12	Restart validation for control system	Input decks to be developed
O2.13	Restart validation for equipment component models and methods	Input decks to be developed
O2.14	Restart validation for special purpose models and methods	Input decks to be developed
O2.15	Mass and energy conservation validation	Input decks to be developed

6.4.1. Basic Equation Models

6.4.1.1. Fluid Flow Equations. A number of analytical solutions exist for steady-state, single-phase flows in simple geometries, both with and without heat transfer. Some available analytical solutions include the following.

- Pressure gradient in simple, unheated flow channels (Ref. 6-2, pp. 188-190).
- Temperature gradient in a heated channel (Ref. 6-2, pp. 390-392).
- Flow in variable-area channels such as expanding and contracting nozzles (Ref. 6-2, pp. 485-486).
- Flow in channels with local pressure losses (Ref. 6-2, pp. 219-220).
- Flow in natural-circulation loops such as thermosyphons (Ref. 6-3, pp. 73-76).
- Flows in distribution manifolds (Refs. 6-4 and 6-5).
- Transport of a scalar by a constant-speed flow (Ref. 6-6).
- Transport of a void wave in a two-phase flow with noncondensable gas (Refs. 6-7 and 6-8).
- Transport of a void wave in a two-phase water flow (Refs. 6-7 and 6-8).
- Nusselt condensation on a vertical surface (Ref. 6-2, pp. 415-420).
- Transport of dissolved solids with a liquid (Ref. 6-6).

These problems can be run with subcooled liquid, superheated vapor, and noncondensable gases to check that the special cases are handled correctly. These problems also test the fluid equation of state and other properties of the fluids and the 1D SET numerical solution method. The fluid equation of state is validated in the sense that given the independent variables solved for by the code, a standard tabulation can be used to obtain the reference value for the dependent variables, and these compared with the values from the TRAC equation of state. This validation method can be used also for the fluid transport properties and the properties of the solids.

The information given in the cited references can be used to develop the problem specification. The success metric will be that the TRAC-M calculated results agree with the analytical solution (within prespecified limits) given in the references. Because these are steady-state problems, spatial resolution will be increased to demonstrate that convergence has been attained.

A few transient analytical solutions for the fluid flow equations are available including:

- Startup of the flow of an incompressible fluid in a simple channel (Ref. 6-3, pp. 21-28).
- Draining of liquid from a tank (Ref. 6-2, p. 237).

- The U-tube manometer problem (Ref. 6-2, pp. 229-230).
- The TRAC-P drain and fill test problem (Ref. 6-9).
- Problems that eliminate the momentum balance from consideration.

The last analytical solutions listed refer to the noncondensable gas capabilities in TRAC-M. The perfect gas with variable specific heat modeling for these gases allows derivation of both steady-state and transient analytical solutions. Many of these are given in thermodynamics textbooks. The analytical solution is obtained from the mass and energy equations. Specific examples include closed-container problems that allow testing of conservation of mass and energy and the work term in the energy equations. Other transient analytical solutions may be available in the literature and in reports describing verification and validation problems for other computer software.

As in the case of the steady-state problems, the cited references can be used to develop the problem specification and TRAC-M model. The success metric will be that the TRAC-M calculated results agree with the analytical solution given in the references. User guidance is provided in the form of the requirement to demonstrate temporal and spatial convergence of the TRAC-M numerical solution to the analytical solution.

6.4.1.2. Heat Conduction in Solids. There are numerous analytical solutions available for the heat conduction equation. The TRAC-P Standard Test Matrix report,[6-1] the TRAC Developmental Assessment Manual,[6-9,6-10] and TRAC-P Theory Manual[6-11] all contain a number of conduction equation solutions and comparisons with TRAC-P predictions. Problems for both one-and two-dimensions in both rectangular and cylindrical geometries are used for TRAC-M validation, including the fuel-clad gap model. These and other conduction problems will be used for TRAC-M validation. The test problems now used for TRAC-P assessment will be used for the validation test matrix. Problem specifications such as those in Appendix E will be developed; the success metric is that the TRAC-M calculated results agree with the analytical results. User guidance is the requirement to demonstrate temporal and spatial convergence.

6.4.1.3. Other Basic Equation Models. Analytical solutions for the radiative energy exchange models have been given by Lam[6-12] and these will be part of the TRAC-M validation test matrix. Analytical solution test problems for the 3D vessel model have not yet been devised.

The tabular input for the power generation in the fuel can be validated by outputting the table and comparing the values with the input values. The point-kinetics model and solution method will be validated by comparing TRAC results with results of a calculation with the ORIGEN2[6-13] isotope buildup and depletion computer code.

We are not aware of benchmark problems that isolate a single reactivity feedback mechanism.

6.4.1.4. Properties of Fluids and Solids. The equations used in TRAC to calculate the equation of state (EOS) and other properties of all the fluids and solid materials available in the code can be validated as a part of the analytical solutions as follows. The liquid and vapor EOS properties for water in TRAC, for example, are functions of the independent variables temperature and pressure. The pressure and temperature obtained during a calculation can be used in the equations for water properties used in TRAC to verify that these equations are correctly coded. A standalone version of the TRAC EOS equations can be used for this purpose. Additionally, the EOS properties given by the TRAC equations can be compared with tabulations of standard values to validate the equations used in TRAC. The transport properties for fluids can be verified and validated by use of the same technique.

This same method can be applied to the solid materials as well. The thermal conductivity of a solid uses the temperature as the independent variable, for example. The value of the solid temperature given by TRAC can be used in the equations for thermal conductivity and both results compared with tabulations of standard values.

6.4.2. Equipment Component and Special-Purpose Models

Currently, we don't have specific examples of analytical solutions for all the equipment component and special-purpose models. Additional literature review is needed to locate or help develop analytical solutions. Two analytical solutions for two special-purpose models are given here.

The critical speed for equilibrium single-phase fluid states is known. Problems that reproduce these known critical flow conditions will be executed with the code. The success metric is that the TRAC-M calculated results should agree with the known critical speed. For these steady-state problems, demonstration of spatial convergence provides user guidance.

The generality of the control system elements in TRAC-M allows a variety of situations with analytical solutions to be devised and tested. Simple ordinary differential equations, for example, can be simulated with control system elements. Ordinary differential equations (ODEs) with known analytical solutions have been used to validate some elements of the TRAC-M control system. These same problems will be selected for the validation test matrix. The success metric is that the TRAC-M calculated results must agree with the analytical solution. User guidance is provided by the requirement that convergence to the analytical solution must be demonstrated.

The initial set of Analytical Problems, including development status, is presented in Table 6-4.

6.5. Numerical Methods Test Problems

These tests are used to demonstrate stability and convergence of the numerical methods. Some of the numerical methods tests can be done in conjunction with the analytical solutions discussed in Section 6.4.1 above. The objective is to demonstrate that the numerical solution methods in TRAC-M are stable and will converge to a solution of the basic partial differential equations. The testing provides assurance that the equations are coded correctly and that the numerical method is stable for some conditions. The success metric will be that stability and convergence are demonstrated.

TABLE 6-4
ANALYTICAL AND NUMERICAL METHODS TEST PROBLEMS

ID	Test	Status
O3.1	Pressure gradient in unheated channel	Input decks to be developed
O3.2	Temperature gradient in heated channel	Input decks to be developed
O3.3	Flow in variable-area channel	Input decks to be developed
O3.4	Flow with local pressure loss	Input decks to be developed
O3.5	Flow in natural circulation loops	Input decks to be developed
O3.6	Flow in distribution manifold	Input decks to be developed
O3.7	Transport of a scalar	Input decks to be developed
O3.8	Void "wave" in noncondensable	Input decks to be developed
O3.9	Liquid enthalpy "wave" in two-phase flow	Input decks to be developed
O3.10	Nusselt condensation	Input decks to be developed
O3.11	Solute transport with liquid	Input decks to be developed
O3.12	Incompressible flow startup	Input decks to be developed
O3.13	Tank draining	Input decks to be developed
O3.14	U-tube manometer problem	Existing deck
O3.15	TRAC-P drain and fill problem	Existing deck
O3.16	Transient noncondensable gas problems	Input decks to be developed
O3.17	1D radial conduction solution	Existing decks
O3.18	2D radial plus axial conduction	Existing decks
O3.19	Radiative exchange	Existing decks
O3.20	Equilibrium critical flow	Input decks to be developed
O3.21	Control system solutions	Existing decks
O3.22	Validate Tabular Power Input	Existing decks
O3.23	Validate Point Kinetics Model	Input deck to be developed
O3.24	3D Neutron Kinetics Benchmarks	Input decks to be developed
O3.25	Numerical methods stability and convergence	Input decks to be developed

Convergence is tested by refining the spatial and timestep increments at a fixed ratio, e.g., one-third the Courant limit. Convergence is demonstrated by showing that as the number of spatial nodes increases, the difference between calculated results decreases. A straight flow channel will be used to help focus on the basic aspects of the numerical methods. Both single-phase and two-phase fluid states, with and without wall heat transfer, will be used in the testing.

An example problem is a straight flow channel, initially at constant pressure, and zero fluid speed. At time greater than zero, the pressure at the pipe inlet will be increased. At fixed locations along the channel, the pressure and fluid speed will be plotted as a function of time for each run. To demonstrate convergence, the plots from successive runs should approach a fixed value.

Accuracy of the spatial difference method will be demonstrated by setting up problems in which a scalar is transported by the motion of the fluid. A temperature "wave" will be used for single-phase flow and a void "wave" for two-phase flow. These flows have analytical solutions and have been included under Section 6.4.1 above. The success metric is that the TRAC-M results agree with the analytical results. User guidance is provided by the requirement that convergence be demonstrated.

The initial set of recommended Analytical and Numerical Methods Test Problems, including development status, is presented in Table 6-4.

6.6. Validation Test Matrix—Validation Using Other Standard Tests

The contributions to the TRAC-M validation test matrix by the Other Standard Tests element are summarized in Table 6-5. Generally, the Equilibrium and Concept Problems test that the equations are coded correctly. These tests do not generally point to specific parts of the equations. Successful completion of these tests generally indicates that nothing major is wrong, but the tests do not indicate that everything is right. They are useful as screening indicators that progressing to the next phase of testing is warranted.

The Analytical and Numerical Methods Test Problems test that, for the limited parts of the equations tested, the correct equations are coded. For steady-state, single-phase flow in a pipe, for example, the friction factor must be correct to calculate the analytical solution with the code.

As shown in Table 6-5, the parts of the TRAC-M coded tested by these validation tests consist mainly of the BEM and NSM. All EOS, transport, and thermal-physical properties for all fluids and solids will be validated as a part of these tests. Limited validation of the other models and methods occurs with these tests. As code development continues, tests for other models and methods by equilibrium and concept problems will evolve.

The SET data that will provide validation of some of the flow field models and FFEC, ECM, and SPM in TRAC-M are discussed in the next section of this report.

TABLE 6-5
VALIDATION OF TRAC-M USING OTHER STANDARDS

Category	Subcategory No.	Subcategory Description	Model	Validation by Other Standards Tests: Best	Validation by Other Standards Tests: Candidates
BEM	1	Fluid mass equation	Mass convection	√ **O3.1**	O1.1, O1.2, O1.4, O1.6, O1.7, O2.1, O2.2, O2.4, O2.8, O3.1-O3.16, O3.20, O3.24
			Mass exchange due to phase change		
	2	Momentum equation	Momentum flux	√ **O3.3**	O1.1, O1.2, O1.4, O1.6, O1.7, O2.1, O2.2, O2.4, O2.8, O3.1-O3.16, O3.20, O3.24
			Area change	√ **O3.3**	O3.3, O3.4, O3.6, O3.13
			Pressure gradient	√ **O3.1**	O1.1, O1.2, O1.4, O1.6, O1.7, O2.1, O2.2, O2.4, O2.8, O3.1-O3.16, O3.20, O3.24
			Wall-to-phase momentum exchange	√ **O3.1**	O1.1, O1.2, O1.4, O1.6, O1.7, O2.1, O2.2, O2.4, O2.8, O3.1-O3.16, O3.20, O3.24
			Interfacial momentum exchange		
			Momentum exchange due to mass exchange		
			Local losses	√ **O3.4**	O1.1, O3.4, O3.6
			Gravity	√ **O3.5**	O1.1, O1.2, O1.4, O1.6, O1.7, O2.1, O2.2, O2.4, O2.8, O3.5, O3.13, O3.14
	3	Fluid energy equation	Energy convection	√ **O3.2**	O1.1, O1.2, O1.4, O1.6, O1.7, O2.1, O2.2, O2.4, O2.8, O3.1-O3.16, O3.20, O3.24
			Pressure-work term	√ **O3.16**	O1.1, O1.2, O1.4, O1.6, O1.7, O2.1, O2.2, O2.4, O2.8, O3.1-O3.16, O3.20, O3.24
			Wall-to-phase energy exchange	√ **O3.2**	O3.2, O3.5, O3.10
			Interfacial energy exchange		
			Direct energy deposition		
			Energy exchange due to mass exchange		
	4	Noncondensable gas and liquid solute	Mass convection	√ **O3.8**	O1.7, O3.8
			Solute mass exchange	√ **O3.11**	O1.6, O2.8, O3.11
	5	3D Vessel model	As in BEM Subcategories 1-4		O1.3, O1.4
	6	Heat conduction equation	Lumped-capacitance model		
			1D radial	√ **O3.17**	O1.5, O2.3, O2.5, O3.17
			2D radial plus axial	√ **O3.18**	O1.5, O2.3, O2.5, O3.18
			Reflood implicit		
			Fuel-clad gap		
			Metal-water reaction		
			Material properties	√ **Any**	O1.5, O2.3, O2.5, O3.17, O3.18

TABLE 6-5 (cont)
VALIDATION OF TRAC-M USING OTHER STANDARDS

Category	Subcategory No.	Subcategory Description	Model	Validation by Other Standards Tests: Best	Validation by Other Standards Tests: Candidates
	7	Power generation in fuel	Tabular power input Point kinetics 3D kinetics Reactivity feedback Fuel temperature Coolant temperature Void fraction Boron concentration	√O3.22 √O3.23 √O3.24	O3.22 O3.23 O3.24
	8	Radiative energy exchange in the core	Referenced at subcategory level	√ O3.19	O1.8, O3.19
	9	Equation of state for fluids	Referenced at subcategory level		All that use fluids
	10	Fluid thermophysical and transport properties	Referenced at subcategory level		All that use fluids
FFEC	1	Regime maps	Bubbly flow Bubbly slug transition Bubbly slug flow Churn flow Annular-mist flow Transition to stratified flow Stratified flow Plug flow		
	2	Fluid mass equation closure (mass exchange)			
	2a	Subcooled boiling	Referenced at subcategory level		
	2b	Interfacial mass exchange	Referenced at subcategory level		
	2c	Plateout of dissolved solids	Referenced at subcategory level		

TABLE 6-5 (cont)
VALIDATION OF TRAC-M USING OTHER STANDARDS

Category	Subcategory No.	Subcategory Description	Model	Validation by Other Standards Tests: Best	Validation by Other Standards Tests: Candidates
FFEC (cont)	3	Fluid momentum equation closure (momentum exchange)			
	3a	Wall-to-phase momentum exchange	Single phase	√ O3.1	O1.1-O1.4, O1.6, O1.7, O2.1, O2.2, O2.4, O2.8, O3.1, O3.2, O3.5, O3.6, O3.12
			Two-phase, homogeneous		O2.1
			Two-phase, horizontal stratified		
	3b	Interfacial momentum exchange	Bubbly flow		O2.6
			Bubbly slug transition		
			Bubbly slug flow		
			Churn flow		
			Annular-mist flow		O2.7
			Transition to stratified flow		
			Stratified flow		
			Plug flow		
	3c	Local pressure losses	Abrupt expansion	√ O3.4	O1.1, O2.1, O2.2, O3.4
			Abrupt contraction	√ O3.4	O1.1, O2.1, O2.2, O3.4
			Orifice plate	√ O3.4	O1.1, O3.4
			User supplied	√ O3.4	O1.1, O3.4
	4	Fluid energy equation closure (energy exchange)			
	4a	Wall-to-phase energy exchange	Natural convection to liquid		
			Forced convection to liquid	√ O3.2	O3.2
			Nucleate boiling		
			Critical heat flux		
			Transition boiling		
			Minimum stable film boiling temperature		
			Film boiling		
			Single-phase vapor		
			Condensation	√ O3.10	O3.10
			Two-phase forced convection		

TABLE 6-5 (cont)
VALIDATION OF TRAC-M USING OTHER STANDARDS

Category	Subcategory No.	Subcategory Description	Model	Validation by Other Standards Tests: Best	Validation by Other Standards Tests: Candidates
FFEC (cont)	4b	Interfacial energy exchange	Bubbly flow Bubbly slug transition Bubbly slug flow Churn Flow Annular-mist flow Transition to stratified flow Stratified flow Plug flow Effect of noncondensables		
ECM	1	Centrifugal pumps (Pump component)	Referenced at subcategory level		
	2	Steam-water separator	Referenced at subcategory level		
	3	Plenum component	Referenced at subcategory level		
	4	Valve component	Referenced at subcategory level		
	5	Turbine	Referenced at subcategory level		
	6	Pressurizer	Referenced at subcategory level		
SPM	1	Model for CCFL	Referenced at subcategory level		
	2	Critical flow model	Referenced at subcategory level	√ O3.20	O3.20
	3	Trip and control elements	Referenced at subcategory level	√ O3.21	O3.21
	4	Reflood heat transfer models			
	4a	Flow regime modeling	Bubbly flow Inverted annular flow Dispersed flow		
	4b	Wall-to-phase fluid drag	Single phase Two-phase homogeneous		

TABLE 6-5 (cont)
VALIDATION OF TRAC-M USING OTHER STANDARDS

Category	Subcategory No.	Subcategory Description	Model	Validation by Other Standards Tests: Best	Validation by Other Standards Tests: Candidates
SPM (cont)	4c	Interfacial fluid drag	Subcooled boiling Smooth inverted annular flow Rough-wavy inverted annular flow Agitated inverted annular flow Post-agitated (dispersed) flow Highly dispersed flow		
	4d	Wall-to-phase fluid heat transfer	Forced convection to a single-phase liquid Nucleate boiling Critical heat flux Transition boiling Min. stable film boiling temperature Film boiling Convection to a single-phase vapor Convection to a two-phase mixture Condensation Natural convection to a single-phase liquid		
	4e	Interfacial fluid heat transfer	Bubbly flow Inverted annular flow Dispersed flow		
	4f	Conduction heat transfer	Referenced at subcategory level		
	5	Two-phase level-tracking model	Referenced at subcategory level		
	6	Offtake model for Tee component	Referenced at subcategory level		
NSM		Fluid field equations	Referenced at subcategory level		
		1D stability enhancing two-step (SETs) method	Referenced at subcategory level	√ O3.25	O1.1, O1.2, O1.4, O1.6, O1.7, O2.1, O2.2, O2.4, O2.8, O2.9, O2.15, O3.1-O3.16, O3.20, O3.25
		3D SETs	Referenced at subcategory level		O1.3, O1.4, O2.6, O2.7, O2.10

TABLE 6-5 (cont)
VALIDATION OF TRAC-M USING OTHER STANDARDS

Category	Subcategory		Model	Validation by Other Standards Tests	
	No.	Description		Best	Candidates
NSM (cont)		Conduction in solid materials			
		1D rectangular and cylindrical	Referenced at subcategory level	√ O3.17	O1.5, O2.3, O2.5, O2.11, O3.17
		2D rectangular and cylindrical	Referenced at subcategory level	√ O3.18	O1.5, O2.3, O2.5, O2.11, O3.18
		Power generation-fuel rods	Tabular power input Point kinetics 3D kinetics Reactivity feedback	- √O3.22 √O3.23 √O3.24	- O3.22 O3.23 O3.24
		Radiative energy exchange	Referenced at subcategory level	√ O3.19	O1.8, O3.19
		Fluid equation of state	Referenced at subcategory level	√	All that use fluids
		Fluid boundary conditions	Referenced at subcategory level	√	All that use fluids
		Equipment component models		-	-
		Pump component	Referenced at subcategory level		
		Steam-water separator	Referenced at subcategory level		
		Plenum component	Referenced at subcategory level		
		Valve component	Referenced at subcategory level		
		Turbine	Referenced at subcategory level		
		Pressurizer	Referenced at subcategory level		
		Special-purpose models			
		Model for CCFL	Referenced at subcategory level		
		Critical flow model	Referenced at subcategory level	√O3.20	O3.20
		Trip and control elements	Referenced at subcategory level	√ O3.21	O3.21
		Reflood heat transfer	Referenced at subcategory level		
		Steady-state methods	Referenced at subcategory level	√	All Steady-State Problems
		Timestep size and control	Referenced at subcategory level	√	All

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7.0. CODE QUALIFICATION—VALIDATION USING SEPARATE EFFECTS TEST DATA

As discussed in Section 2, this element of validation contributes to code qualification by comparing code-calculated results with SET data. SETs are experiments in which a limited number of physical phenomena of interest occur, and detailed, high-quality data are obtained under closely controlled conditions. SETs cover a spectrum of tests from the most fundamental, to those investigating interactions between phenomena and components or equipment in a specific region of the physical system. The primary use of data from SETs is to assess the adequacy of the closure models and closed form analytical models used in the code.

The summary PIRT (Section 4, Table 4-5 and the other PIRT tables upon which Table 4-5 is based) is the sole source of requirements for the SET element of the TRAC-M validation test matrix.

7.1. SET Element Completion Status

Several features of the TRAC-M validation test matrix reflect work in progress or yet to be accomplished. The objective of this section is to identify the areas of the SET element of the validation test matrix that are incomplete.

With respect to the coverage of PWR LL phenomena, potential validation tests have been identified only for the W-PWR LB LOCA (Table 4-2a). These derive from an earlier LB LOCA validation test matrix effort,[7-1] but do include the highly ranked phenomena from both the AP600 PIRT[7-2] and W four-loop PWR PIRT[7-3] efforts. As seen in the summary tabulation of highly ranked PWR phenomena (Table 4-2d), additional PWR phenomena arise from the other PWR PIRTs, namely the W and B&W SB LOCAs, e.g., transition boiling, condensation on surfaces, and post-CHF heat transfer. SET tests have not yet been identified for these phenomena. In addition, it is anticipated that additional phenomena will be added to the SET validation test matrix as PIRTs are completed for other plants, accidents, and transients.

With respect to the coverage of BWR LL phenomena, potential validation tests have been identified only for the BWR LB LOCA (Table 4-4a). As seen in the summary tabulation of highly ranked BWR phenomena (Table 4-4d), additional BWR phenomena arise from the other BWR PIRTs, namely the SB LOCAs and transient events. SET tests have not yet been identified for these phenomena.

At present, the number of tests entered in the SET validation test matrix may be larger than necessary. This situation exists because data availability is presently uncertain for a number of the tests currently included in the PWR SET element of the TRAC-M validation test matrix. As data availability is determined, it is expected that the SET matrix will be revised accordingly.

7.2. Data Selection Based on PIRT Summary

With a few exceptions, the present TRAC-M analytical and constitutive models used in both PWR and BWR applications derive from the TRAC-P code.[7-4] Work to improve the TRAC-M constitutive models is planned. As this work is completed, the constitutive models will be tested for both PWR and BWR applicability as appropriate.

Referring to the consolidated PIRT (Table 4-5), the LL phenomena can be assigned to one of three groups: highly ranked PIRT phenomena common to both PWRs and BWRs, highly ranked phenomena derived from PWR PIRTs only, and highly ranked phenomena derived from BWR PIRTs only.

The TRAC-M SET validation test matrix is based upon these three groups of PIRT phenomena and consists of three parts. The first part consists of common validation tests that apply to the entirety of the consolidated code, whether used in PWR or BWR application (Section 7.2.1). The second part consists of validation tests that are specific to PWR phenomena (Section 7.2.2). The third part consists of validation tests that are specific to BWR phenomena (Section 7.2.3).

7.2.1. Common SET Validation Tests

Validation tests that apply to the consolidated code, whether used in PWR or BWR applications are listed in Table 7-1. Additional details about the common validation tests included in the SET element of the TRAC-M validation are presented in Appendices F (PWR) and G (BWR), specifically the applicable literature or report citations and the testing ranges for key parameters, if available.

The first column in Table 7-1 identifies the PIRT phenomenon with which the validation tests are associated. The second column is an identifying number for each validation test of the form Sx.y, with the "S" denoting SET, "x" being a number common to all tests for the same PIRT phenomenon, and "y" being the individual identifying number within set "x". The third column identifies the facility, and if applicable, lead investigator. The fourth column contains a brief statement characterizing the key feature of the test. The fifth column contains a symbol to communicate a priority assessment, namely whether the test is deemed vital or desirable. The sixth column provides summary information about the existence of TRAC input models (decks). A "-" is entered if no input model exists. If an input model exists, the deck location, need for updating for use with the current version of the code, and availability of quality assurance documentation are summarized. The seventh column provides summary information about the availability of the test data to be used for the validation exercise. If the availability of the data is unknown, an "-" is entered. If the data are available, additional information about the data is summarized. The eighth and final column cross correlates the facility (column 3) with the corresponding table and reference in Appendix F, e.g., F-12=>1,2 refers to references 1 and 2 in Table F-12, and the identifying number of the facility in the OECD/CSNI separate effects test matrix for thermal-hydraulic code validation,[7-6] should the selected facility be described in that document. A listing of TRAC-M input decks for common SETs is provided in Appendix G.

7.2.2. Additional PWR SET Validation Tests

Additional validation tests that arise from phenomena found to be important only in PWRs are summarized in Table 7-2. The format for Table 7-2 is identical to that of Table 7-1.

Additional details about the additional PWR validation tests included in the SET element of the TRAC-M validation matrix are presented in Appendix F. A listing of TRAC-M input decks for PWR-specific SETs is provided in Appendix G.

7.2.3. Additional BWR SET Validation Tests

Additional validation tests that arise from phenomena found to be important only in BWRs[7-5] are summarized in Table 7-2. The format for Table 7-2 is identical to that of Table 7-1.

Additional details about the additional BWR validation tests included in the SET element of the TRAC-M validation matrix are presented in Appendix H, beginning with Table H-16. In several instances, BWR-specific tests are entered for a phenomenon identified in the common set validation matrix. A listing of TRAC-M input decks for BWR-specific SETs is provided in Appendix I.

REFERENCES

7-1. E. D. Hughes and B. E. Boyack, "TRAC-P Validation Test Matrix," Los Alamos National Laboratory document LA-UR-97-3990 (September 1997).

7-2. B. E. Boyack, "AP600 LBLOCA Phenomena Identification and Ranking Tabulation," Los Alamos National Laboratory document LA-UR-95-2718 (1995).

7-3. Technical Program Group, EG&G Idaho, Inc., "Quantifying Reactor Safety Margins: Application of CSAU to a LBLOCA," United States Nuclear Regulatory Commission report NUREG/CR-5249, 1989.

7-4. J. W. Spore, S. J. Jolly-Woodruff, T. K. Knight, J-C. Lin, R. A. Nelson, K. O. Pasamehmetoglu, R. G. Steinke, and C. Unal, "TRAC-PF1/MOD2 Theory Manual," Los Alamos National Laboratory document NUREG/CR-5673, Volume 1 (July 21, 1993).

7-5. M. Straka and L. W. Ward, "BWR PIRT and Assessment Matrices for BWR LOCA and Non-LOCA Events," Scientech, Inc. document SCIE-NRC-393-99 (1999).

7-6. Separate Effects Test Matrix for Thermal-Hydraulic Code Validation, Volume I, Phenomena Characterization and Selection of Facilities and Tests; Volume II, Facility and Experiment Characteristics, Committee on the Safety of Nuclear Installations OECD Nuclear Energy Agency report NEA/CSNI/R(93)14/Part 1, Part 2/Rev. (September 1993).

TABLE 7-1
COMMON SET VALIDATION TESTS

PIRT Phenomenon (Appendix Table)	No.	Facility/Originator	Test Feature	Assess. Need	TRAC Input	Data	Ref: Append. F; OECD/CSNI
Boiling–film	Sc1.1	UoO[a]/Stewart	Fundamental tube data	++	-	4	F-1=>2; -
(Table F-1)	Sc1.2	UoO/Laperriere	Fundamental tube data	+	-	4	F-1=>3; -
	Sc1.3	UoO/Fung	Fundamental tube data	+	-	4	F-1=>5; -
	Sc1.4	Winfrith	Fundamental tube data	++	1,4	2	F1=>4; 10.4
	Sc1.5	THEF[b]/INEL	Fundamental tube data	++	1,4	2	F1=>4; 11.3
	Sc1.6	Lehigh	Fundamental rod-bundle data	++	1,4	2	F1=>4; 11.42
	Sc1.7	TPTF[c]/JAERI[d]	BWR and PWR core geometries	+	-	-	F1=>4; 6.1
	Sc1.8	Blowdown HT/RS37	25-rod bundle	+	-	-	F1=>4; 4.5
Condensation–Interfacial	Sc2.1	Lee	Cocurrent stratified horizontal flow	++	-	4	F-3=>1; -
(Table F-3)	Sc2.2	Kim	Countercurrent steam-water stratified flow	++	-	4	F-3=>2; -
	Sc2.3	Akimoto	Water into flow steam at 90 degree angle	++	1,3,4	4	F-3=>3,4; -
	Sc2.4	Celata	Superheated steam on subcooled water surface	+	-	4	F-3=>5,6; -
Flashing–interfacial	Sc3.1	Critical Flow Facility/GE	Flashing discharge through pipe	++	-	1	F-7=>1; 11.54
	Sc3.2	GE Vessel Test 1004-3	small vessel test w/ void fraction <0.5	++	1	3	H-25=>3; 11.44
	Sc3.3	GE Vessel Test 5801-13	large vessel test	++	1	3	H-25=>3; -
(Table F-7 and H-25)	Sc3.4	Edwards Blowdown	Pipe blowdown	++	1,3,4	2, 4	F-7=>2; 3.15
	Sc3.5	Canon (Initial:Vertical:Super)	Pipe blowdown	++	2,3,4	4	F-7=>3; 3.3, 3.4
	Sc3.6	BNL[e] Nozzle	Converging-diverging nozzle	+	-	1	F-7=>4,5; -
	Sc3.7	Moby Dick, Super Moby Dick	Critical flow in tubes and nozzles	++	2,3,4	4	F-7=>3; 3.1, 3.2
	Sc3.8	OMEGA	Rod bundle blowdown	+	2,3,4	4	F-7=>3; 3.15
Flow–critical	Sc4.1	Super Moby Dick	Vertical upflow, three nozzle configurations	++	2,3,4	4	F-8=>1; 3.2
(Table F-8)	Sc4.2	Rebecca	Vertical downflow, two nozzle configurations	++	-	1	F-8=>1; 3.25
	Sc4.3	Marviken	Multiple nozzle configurations small to big	++	1,4	1,2	F-8=>1; 8.2
	Sc4.4	TPFL[f]/INEL	Tee critical flow	+	-	1	F-8=>1; 11.35

ASSESSMENT NEED:
++ = vital.
+ = desirable.

TRAC INPUT:
1 = exists/available at LANL[g] or ISL.[h]
2 = exists/outside LANL or ISL.
3 = deck will require updating.
4 = deck quality assurance documentation unavailable.

DATA:
1 = available NUREG/CR, NUREG, NRC or OECD/CSNI databank, or equiv.
2 = available at LANL.
3 = available at ISL.
4 = limited data: NUREG/IA, CAMP[i], journal, or conference proceedings.

[a] University of Ontario.
[b] Thermal Hydraulic Experimental Facility.
[c] Two-phase test facility.
[d] Japan Atomic Energy Research Institute.
[e] Brookhaven National Laboratory.
[f] Two-phase flow loop.
[g] Los Alamos National Laboratory.
[h] Information Systems Laboratories.
[i] Code Assessment and Maintenance Program.

TABLE 7-1 (cont)
COMMON SET VALIDATION TESTS

PIRT Phenomenon (Appendix Table)	No.	Facility/Originator	Test Feature	Assess. Need	TRAC Input	Data	Ref: Append. F; OECD/CSNI
Flow–critical (Table F-8) (cont)	Sc4.5	Critical Flow Facility/GE	Low quality critical flows using 7 nozzles	++	-	1	F-8=>8; 11.54
	Sc4.6	Edwards Blowdown	Simulates double-ended break of primary pipe	++	1,4	2,3,4	F-8=>9; -
	Sc4.7	Safety Valve/CISEa -SIET	ADS [b] valves tested	++	-	1	F-8=>1; 5.5
	Sc4.8	Valve Blowdown/CEGBc-MEL	Overpressure protection valves for Sizewell B	+	-	-	F-8=>1; 10.21
Heat conductance–fuel-clad gap (Table F-10)	Sc5.1	Modified Pulse Design	Low pressure	++	-	1	F-10=>3,4; -
	Sc5.2	Modified Pulse Design	High pressure	++	-	1	F-10=>5; -
	Sc5.3	Power Burst Facility	Gap conductance Test Series-2	+	-	1	F-10=>6; -
	Sc5.4	Halden Assembly IFA-226	USNRC-OECD Halden Fuel Behavior Test Prog.	+	-	1	F-10=>7,8; -
Heat transfer–forced convect-	Sc6.1	Babus'Haq	Tests with air rather than steam	++	-	4	F-11=>1; -
ion to vapor (Table F-11)	Sc6.2	Davies & Al-Arabi	Tests performed with water	+	-	-	F-11=>2; -
Interfacial shear (Table F-13 and H-11)	Sc7.1	Dadine	Heated tube	++	-	1	F-13=>2; 3.7
	Sc7.2	Pericles	Boil-off in a bundle w/ void fraction <0.9	++	2	3	H-11=>4; 3.8
	Sc7.3	Pericles Cylindrical	Cylindrical 368-rod core	+	-	-	F-13=>2; 3.7
	Sc7.4	Erset Rod Bundle	36-rod bundle	+	-	1	F-13=>2; 3.7
	Sc7.5	Rebecca	Critical Flow	+	-	1	F-13=>2; 3.7
	Sc7.6	TPTF d/JAERI	Horizontal two-phase flow and core heat transfer	+	-	4	F-13=>2; 3.7
	Sc7.7	SCTF/JAERI	2D eight fuel-rod bundle	++	1,4	1	F-13=>2; 3.7
	Sc7.8	CCTF/JAERI	3D 32 fuel-rod bundle	++	1,4	1	F-13=>2; 3.7
	Sc7.9	FRIGG/FROJA	Six-rod and 32-rod test sections	+	-	-	F-13=>2; 3.7
	Sc7.10	NEPTUN-1/NEPTUN-2 Reflood	33-rod test section	++	2,3,4	1	F-13=>2; 3.7
	Sc7.11	Achilles Reflood Loop	68-rod test section ballooned and unballooned	+	2,3,4	4	F-13=>2; 3.7
	Sc7.12	THETIS Bundle	7 x 7 rod test section	++	1,2,3,4	4	F-13=>2; 3.7
	Sc7.13	FLECHT-SEASET/W	17 x 17 rod bundle	++	1,4	1	F-13=>2; 3.7

ASSESSMENT NEED:
++ = vital.
+ = desirable.

TRAC INPUT:
1 = exists/available at LANL or ISL.
2 = exists/outside LANL or ISL.
3 = deck will require updating.
4 = deck quality assurance documentation unavailable.

DATA:
1 = available NUREG/CR, NUREG, NRC or OECD/CSNI databank, or equiv.
2 = available at LANL.
3 = available at ISL.
4 = limited data: NUREG/IA, CAMP, journal, or conference proceedings.

[a] Centro Informazioni Studi Esperienze, SpA.
[b] Automatic depressurization valve.
[c] Central Electricity Generating Board.
[d] Two-phase test facility.

TABLE 7-1 (cont)
COMMON SET VALIDATION TESTS

PIRT Phenomenon (Appendix Table)	No.	Facility/Originator	Test Feature	Assess. Need	TRAC Input	Data	Ref: Append. F; OECD/CSNI
Interfacial shear (Table F-13 and H-11) (cont)	Sc7.14	THTF/ORNL[a]	8x8 rod bundle, steady-state and transient	++	1,3,4	1	F-13=>5; 11.38
	Sc7.15	UPTF/KWU[b]	1:1 German PWR core simulator	++	1,4	1	F-13=>2; 3.7
	Sc7.16	1/30;1/15;1/5 Vessel/CREARE	1/15 and 1/30 vessel downcomer tests	++	2,3,4	1	F-13=>2; 3.7
Rewet (Table H-12)	Sc8.1	GOETA Test 42	Test 42; bottom and top reflood	++	2	3	H-11=>2; 8.1
	Sc8.2	NEPTUN	bottom reflood	+	1		H-11=>3; 9.2
	Sc8.3	BWR-FLECHT	Bottom reflood	+	1	3	H-11=>4; 11.23
	Sc8.4	FLECHT-SEASET/W	Bottom reflood	++	1	3	H-11=>5; 11.41

ASSESSMENT NEED:
++ = vital.
+ = desirable.

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2 = available at LANL.
3 = available at ISL.
4 = limited data: NUREG/IA, CAMP, journal, or conference proceedings.

[a] Oak Ridge National Laboratory.
[b] Kraftwerk Union.

TABLE 7-2
ADDITIONAL PWR SET VALIDATION TESTS

PIRT Phenomenon (Appendix Table)	No.	Facility/Originator	Test Feature	Assess. Need	TRAC Input	Data	Ref: Append. F; OECD/CSNI
Boiling-transition (Table F-2)	Sp1.1	UoC [a]/Wang	Fundamental tube and annulus data	++	-	4	F-2=>2,3; -
	Sp1.2	SGTF [b]/ANL	Fundamental tube data	+	-	4	F-2=>4; -
	Sp1.3	UoO/Cheng	Fundamental tube data	+	-	4	F-2=>5; -
	Sp1.4	Johannsen	Fundamental tube data	++	-	4	F-2=>7; -
	Sp1.5	Bennett	Fundamental tube data	++	1,3,4	4	F-2=>8; -
	Sp1.6	FZK [c] Single Rod	Single rod data	+	-	4	F-2=>9,10; -
	Sp1.7	NEPTUN	Rod bundle tests	++	2,3,4	1?	F-2=>9,11/9.2
Draining (Table F-4)	Sp2.1	Foster	Analytical formula for 4 tank geometries	++	-	NA	F-4=>1; -
	Sp2.2	Lubin and Springer	Test drain water from open-top cylinder	++	-	4	F-4=>2; -
	Sp2.3	GIT [d]/Ghiaasiaan	Draining sealed vertical cylinder	++	-	4	F-4=>3,4; -
	Sp2.4	ROSA-AP600	IET experiment	++	2	1	F-4=>5; -
Entrainment/Deentrainment (Table F-5)	Sp3.1	Cousins & Hewitt	Upward flow air-water vertical round tube	+	-	4	F-5=>1,3; -
	Sp3.2	Steen and Wallis	Downward flow air-water in tubes	++	-	4	F-5=>2,3; -
	Sp3.3	Lopez de Bertodano	Adiabatic upward flow air-water loop	++	-	4	F-5=>4,5; -
	Sp3.4	Parabas and Karabelas	Adiabatic horizontal air-water flow	++	-	4	F-5=>6; -
	Sp3.5	Williams	Adiabatic horizontal air-water flow in pipe	+	-	-	F-5=>7; -
Evaporation–interfacial (Table F-6)	Sp4.1	Allesandrini	Steam-water in round vertical tubes	+	-	-	F-6=>2; -
	Sp4.2	Wurtz	Steam-water in tubes and annuli	+	-	-	F-6=>3; -
	Sp4.3	Becker	Single tubes with different heat flux profiles	+	-	-	F-6=>5; -
	Sp4.4	Lehigh	Internal flow in tube using hot patch	++	-	4	F-6=>6,7; 11.57
	Sp4.5	THEF/INEL	Internal flow in heated tube using hot patch	++	1,4	2	F-6=>8,9; 11.3
	Sp4.6	Winfrith	Internal flow in heated tubes	++	1,4	2	F-6=>10-11; -
	Sp4.7	Lehigh	3x3 rod bundle using hot-patch	++	1,4	2	F-6=>12; 11.42

ASSESSMENT NEED:
++ = vital.
+ = desirable.

TRAC INPUT:
1 = exists/available at LANL or ISL.
2 = exists/outside LANL or ISL.
3 = deck will require updating.
4 = deck quality assurance documentation unavailable.

DATA:
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3 = available at ISL.
4 = limited data: NUREG/IA, CAMP, journal, or conference proceedings.

[a] University of Cincinatti.
[b] Steam generator test facility.
[c] Forschungszentrum Karlsruhe.
[d] Georgia Institute of Technology.
[e] Savannah River Laboratory.

TABLE 7-2 (cont)
ADDITIONAL PWR SET VALIDATION TESTS

PIRT Phenomenon (Appendix Table)	No.	Facility/Originator	Test Feature	Assess. Need	TRAC Input	Data	Ref: Append. F; OECD/CSNI
Flow–discharge (Table F-9)	Sp5.1	LOFT L3-1	Accumulator discharge	++	1,4	1	F-9->1; -
	Sp5.2	SRL[a] Gas Pressurizer	Pressurizer discharge	++	-	1	F-9->2; -
	Sp5.3	KMR-2	Gas-steam pressurizer	+	-	4	F-9->5; -
Heat transfer–stored energy release (Table F-12)	Sp6.1	Power Burst Facility	Test PCM-2; used unirradiated fuel	+	-	1	F-12->1,2; -
	Sp6.2	Power Burst Facility	Test LOC-11C	+	-	1	F-12->3,4; -
	Sp6.3	Phebus LB LOCA	Test 212	+	-	-	F-12->5; -
	Sp6.4	LOFT	Tests L6-8B01 and L6-8B-2	++	1,4	1	F-12->6,7;
Noncondensable effects (Table F-15)	Sp7.1	MIT Steam Condensation	Steam condensation with natural circulation	+	-	1	F-15->1; -
	Sp7.2	MIT[b] Single-Tube Experiment	Steam condensation with forced convection	++	-	1	F-15->2,3; -
	Sp7.3	UCB Steam Condensation	Steam condensation with natural circulation	++	-	1	F-15->4,5; -

ASSESSMENT NEED:
++ = vital.
+ = desirable.

TRAC INPUT:
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DATA:
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2 = available at LANL.
3 = available at ISL.
4 = limited data: NUREG/IA, CAMP, journal, or conference proceedings.

[a] Savannah River Laboratory.
[b] Massachusetts Institute of Technology.

TABLE 7-3
ADDITIONAL BWR SET VALIDATION TESTS

PIRT Phenomenon (Appendix Table)	No.	Facility/Originator	Test Feature	Assess Need	TRAC input	Data	Ref: Append. G; OECD/CSNI
Boilingfilm (Table H-1)	Sb1.1	THTF	Test 3.06.6B and Test 3.08.6C	++	1	3	H-1=>1; 11.38
Boiling–nucleate (Table H-2)	Sb2.1	ORNL	Test 3.07.9N	++	-	3	H-2=1; 11.38
Dryout–CHF (Table H-4)	Sb3.1	Biasi		-	-	-	H-4=>1; -
	Sb3.2	CISE		-	-	-	H-4=>2; -
	Sb3.3	Zuber	Apply to countercurrent flow	-	-	-	H-4=>3; -
Flashing–interfacial (Table G5)	Sb4.1	ROSA-III	Tests 901, 902, 924, 926, 905	++	-	3	H-5=>1; -
	Sb4.2	FIST[a]	Test 6DBA1B	++	2	3	H-5=>2; -
Heat–stored (Table H-10)	Sb5.1	See Table 7-1, Common SET Validation Tests: Heat conductance–fuel-clad gap					F-10=>3-8;-
Heat transfer–forced convection to vapor (Table G8)	Sb6.1	THTF bundle	Tests 3.09.10 I, J, K, L. M, N	++	-	3	H-8=>1; 11.38
	Sb6.2	H-2	336 rod bundle uncovery tests 718, 722, 727, 731	-	-	-	H-8=>2; 11.49
Heat transfer–radiation (Table H-9)	Sb7.1	GOETA Test 27	Steady-state experiment in 8x8 bundle	+	2	3	H-9=>1; 8.1
	Sb7.2	THTF	Rod-to-rod and wall during steady state boiloff	++	-	3	H-9=>2; 8.1
Interfacial shear (Table H-11)	Sb8.1	CISE adiabatic pipe	Void fraction>0.5 (CISE-R-291)	++	2	3	H-11=>1; -
	Sb8.2	GE level swell	Tests 1004-3 and 5801-13	++	1	3	H-11=>2; 11.44
	Sb8.3	TLTA[b]-5A	Test 6441	++		3	H-11=>3; -

ASSESSMENT NEED:
++ = vital.
+ = desirable.

TRAC INPUT:
1 = exists/available LANL or ISL.
2 = exists/outside LANL or ISL.
3 = deck will require updating.
4 = deck quality assurance documentation unavailable.

DATA:
1 = available NUREG/CR, NUREG, NRC or OECD/CSNI databank, or equiv.
2 = available at LANL.
3 = available at ISL.
4 = limited data: NUREG/IA, CAMP, journal, or conference proceedings.

[a] Full integral simulation test.
[b] Two-loop test apparatus.

8.0. CODE QUALIFICATION—VALIDATION USING COMPONENT EFFECT TEST DATA

As discussed in Section 2, this element of validation contributes to code qualification by comparing code-calculated results with CET data. Component effect tests investigate behavior in a plant component, frequently but not always at full-scale. Comparisons of code-calculated predictions to data from CETs provide the mechanism for an important aspect of the code qualification effort; these comparisons assess the capability of T-H code to predict component-level phenomena identified in the consolidated PWR and BWR PIRT (Table 4-5). CET data are used to assess the behavior of the integrated code (e.g., field equations, closure relations, component models, numerics, and special models) at the component level.

Component testing can occur in SET, CET or IET facilities.

The summary PIRT (Section 4, Table 4-5 and the other PIRT tables upon which Table 4-5 is based) is the sole source of requirements for the CET element of the TRAC-M validation test matrix.

8.1. CET Element Completion Status

Several features of the TRAC-M validation test matrix reflect work in progress or yet to be accomplished. The objective of this section is to identify the areas of the CET element of the validation test matrix that are incomplete.

With respect to the coverage of PWR CL phenomena, potential validation tests have been identified only for the Westinghouse-PWR LB LOCA (Table 4-2a). These derive from an earlier LB LOCA validation test matrix effort,[8-1] but do include the highly ranked phenomena from both the AP600 PIRT[8-2] and W four-loop PWR PIRT[8-3] efforts. As seen in the summary tabulation of highly ranked PWR phenomena (Table 4-2d), additional PWR CET phenomena arise from the other PWR PIRTs, namely the Westinghouse and B&W SB LOCAs, e.g., flow regime at the break inlet. CET tests have not yet been identified for these phenomena. In addition, it is anticipated that additional phenomena will be added to the CET validation test matrix as PIRTs are completed for other plants, accidents, and transients.

With respect to the coverage of BWR CL phenomena, potential validation tests have been identified only for the BWR LB LOCA (Table 4-4a). As seen in the summary tabulation of highly ranked BWR phenomena (Table 4-4d), additional BWR phenomena arise from the other BWR PIRTs, namely the SB LOCAs and transient events, e.g., multi-channel flows. CET tests have not yet been identified for these phenomena.

At present, the number of tests entered in the CET validation test matrix may be larger than necessary. This situation exists because data availability is presently uncertain for a number of the tests currently included in the TRAC-M validation test matrix. As data availability is determined, it is expected that the SET matrix will be revised accordingly.

8.2. Data Selection Based on PIRT Summary

Several of the TRAC-M plant components, e.g., steam generators and pressurizers, are assembled from more elemental TRAC components. Other components are present in TRAC-M as component models, e.g, pumps, valves and breaks.

Referring to the consolidated PIRT (Table 4-5), the CL phenomena can be assigned to one of three groups: highly ranked PIRT phenomena common to both PWRs and BWRs, highly ranked phenomena derived from PWR PIRTs only, and highly ranked phenomena derived from BWR PIRTs only.

The TRAC-M CET validation test matrix is based upon these three groups of PIRT phenomena and consists of three parts. The first part consists of common validation tests that apply to the entirety of the consolidated code, whether used in PWR or BWR application (Section 8.2.1). The second part consists of validation tests that are specific to PWR phenomena (Section 8.2.2). There are several additional components found in BWRs that are unique to the BWR; they are not present in PWRs. The jet pump is one such component. Also, the BWR fuel assembly configuration differs from that in a PWR; the fuel is contained within a container or can. A separate component model has been incorporated in TRAC-M to model the BWR fuel assembly. The third part consists of validation tests that are specific to BWR phenomena (Section 8.2.3).

8.2.1. Common CET Validation Tests

Validation tests that apply to the consolidated code, whether used in PWR or BWR applications are listed in Table 8-1. Additional details about the common validation tests included in the CET element of the TRAC-M validation are presented in Appendices F (PWR) and G (BWR), specifically the applicable literature or report citations and the testing ranges for key parameters, if available.

The first column in Table 8-1 identifies the PIRT phenomenon with which the validation tests are associated. The second column is an identifying number for each validation test of the form Cx.y, with the "C" denoting CET, "x" being a number common to all tests for the same PIRT phenomenon, and "y" being the individual identifying number within set "x". The third column identifies the facility, and if applicable, lead investigator. The fourth column contains a brief statement characterizing the key feature of the test. The fifth column contains a symbol to communicate a priority assessment, namely whether the test is deemed vital or desirable. The sixth column provides summary information about the existence of TRAC input models (decks). A "-" is entered if no input model exists. If an input model exists, the deck location, need for updating for use with the current version of the code, and availability of quality assurance documentation are summarized. The seventh column provides summary information about the availability of the test data to be used for the validation exercise. If the availability of the data is unknown, an "-" is entered. If the data are available, additional information about the data is summarized. The eighth and final column cross correlates the facility (column 3) with the corresponding table and reference in Appendix F, e.g., F-16=>1,2 refers to Refs. 1 and 2 in Table F-16, and the identifying number of the facility in the OECD/CSNI separate effects test matrix for thermal-hydraulic code validation,[8-4] should the selected facility be described in that document. A listing of TRAC-M input decks for common CETs is provided in Appendix G.

8.2.2. Additional PWR CET Validation Tests

Additional validation tests that arise from phenomena found to be important only in PWRs are summarized in Table 8-2. The format for Table 8-2 is identical to that of Table 8-1.

Additional details about the additional PWR validation tests included in the CET element of the TRAC-M validation matrix are presented in Appendix F. A listing of TRAC-M input decks for PWR-specific CETs is provided in Appendix G.

8.2.3. Additional BWR CET Validation Tests

Additional validation tests that arise from phenomena found to be important only in BWRs are summarized in Table 8-3. The format for Table 8-3 is identical to that of Table 8-1.

Additional details about the additional BWR validation tests included in the CET element of the TRAC-M validation matrix are presented in Appendix H, beginning with Table H-13. In several instances, BWR-specific tests are entered for a phenomenon identified in the common set validation matrix. A listing of TRAC-M input decks for BWR-specific CETs is provided in Appendix I.

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TABLE 8-1
COMMON CET VALIDATION TESTS

PIRT Phenomenon (Appendix Table)	No.	Facility/Originator	Test Feature	Assess. Need	TRAC Input	Data	Ref: Appendix F or G; OECD/CSNI
Flow–countercurrent (Table F-17)	Cc1.1	Dartmouth	Countercurrent flow: steam, subcooled water in vertical tube (fundamental test)	++	1,2,3,4	1,2,3	F-17=>1; 11.16
	Cc1.2	Bankoff	Countercurrent flow: horizontal perforated plate (fundamental test)	++	1,4	1,4	F-17=>5,6
	Cc1.3	1/15; 2/15 BCL[a]	Downcomer countercurrent flow	+	1,3,4	1,2	F-17=>2; 11.4
	Cc1.4	1/30;1/15;1/5 Vessel/CREARE	Downcomer countercurrent flow	++	1,3,4	1	F-17=>3; 11.13
	Cc1.5	1/1; UPTF	Downcomer countercurrent flow; Test 6	++	1	1	F-17=>4; 4.1
	Cc1.6	1/1; UPTF	Upper tie plate countercurrent flow; Test 10C	++	1	1	F-17=>4; 4.1
Flow–multidimensional (Table F-18)	Cc2.1	Rectangular clarifier	Dissertation, University of Windsor	+	-	1	F-18=>4,5; -
	Cc2.2	PERICLES	2D effects in rectangular facility	+	-	-	F-18=>1; 3.8
	Cc2.3	SCTF/JAERI	Runs 718, 719, 720 have multidimensional flow	++	1,2,3,4	1	F-18=>6; 6.14
	Cc2.4	CCTF/JAERI	Run 76 and 76	++	1,2,3,4	1	F-18=>7,8; 6.15
Power–3D distribution Table (H-20)	Cc3.1	ROSA-III	Test 926				H-20=>1; -
Power–decay heat (Table F-20)	Cc4.1	ANS[b] -5.1-1994	American National Standard	++	-	NA	F-5=>1; -
	Cc4.2	AESJ[c]	Proposed Japanese Standard	+	-	NA	F-5=>2; -
	Cc4.3	ISO[d]	Proposed International Standard	+	-	NA	F-5=>3; -
Pressure drop (Table H-22)	Cc5.1	Sher and Greer		++	-	3	H-22=>1; -
	Cc5.2	Muscettola		++	-	-	H-22=>2; -
	Cc5.4	ROSA-III	Test 926	++	-	3	H-22=>4; -
Pump performance (Table F-21)	Cc6.1	SEMISCALE	Radial-flow pump	++	1	1	F-21=>1; 11.39
	Cc6.2	EPRI[e]	Mixed-flow pump	++	-	1	F-21=>2
	Cc6.3	KWU	Axial and mixed-flow pumps; RS 111 project	+	-	4	F-21=>3

ASSESSMENT NEED:
++ = vital.
+ = desirable.

TRAC INPUT:
1 = exists/available at LANL or ISL.
2 = exists/outside LANL or ISL.
3 = deck will require updating.
4 = deck quality assurance documentation unavailable.

DATA:
1 = available NUREG/CR, NUREG, NRC or OECD/CSNI databank, or equiv.
2 = available at LANL.
3 = available at ISL.
4 = limited data: NUREG/IA, CAMP, journal, or conference proceedings.

[a] Batelle Columbus Laboratories.
[b] American Nuclear Society.
[c] Atomic Energy Society of Japan.
[d] International Standard Organization.
[e] Electric Power Research Institute.

TABLE 8-2
ADDITIONAL PWR CET VALIDATION TESTS

PIRT Phenomenon (Appendix Table)	No.	Facility/Originator	Test Feature	Assess. Need	TRAC Input	Data	Ref: Appendix F or G; OECD/CSNI
Oscillations (Table F-19)	Cp1.1	U-tube manometer	Analytical solution	++	1	2	F-19=>1; -
Reactivity–void (Table F-22)	Cp2.1	None identified					

ASSESSMENT NEED:
++ = vital.
+ = desirable.

TRAC INPUT:
1 = exists/available at LANL or ISL.
2 = exists/outside LANL or ISL.
3 = deck will require updating.
4 = deck quality assurance documentation unavailable.

DATA:
1 = available NUREG/CR, NUREG, NRC or OECD/CSNI databank, or equiv.
2 = available at LANL.
3 = available at ISL.
4 = limited data: NUREG/IA, CAMP, journal, or conference proceedings.

TABLE 8-3
ADDITIONAL BWR CET VALIDATION TESTS

PIRT Phenomenon (Appendix Table)	No.	Facility/Originator	Test Feature	Assess. Need	TRAC Input	Data	Ref: Appendix F or G; OECD/CSNI
Flow–channel bypass leakage (Table H-13)	Cb1.1	ROSA-III	Tests 901, 926	++	-	3	H-13=>1; -
	Cb1.2	FIST	Test 6DBA1B	++	-	3	H-13=>2; -
Flow–countercurrent (Table H-14)	Cb2.1	BD/ECC[a] /Tobin	Upper tie plate	++	2	3	H-14=>2; -
	Cb2.2	BD/ECC/Jones	Upper tie plate	++	2	3	H-14=>1,3; -
	Cb2.3	Naitoh	Upper tie plate	+	-	4	H-14=>4; -
	Cb2.4	GOTA	Upper tie plate	+	-	4	H-14=>1,3; -
	Cb2.6	BD/ECC/Jones	Side entry orifice	++	2	1	H-15=>1; -
Flow distribution (Table H-16)	Cb3.1	ROSA-III	Tests 901, 902, 926	++	-	3	H-16=>1; -
	Cb3.2	FIST	Test 6DBA1B	++	-	3	H-16=>2; -
	Cb3.3	TLTA	Tests 6422 (R3); 6423 (R3); 6426 (R1)	++	2	3	H-16=>3; -
	Cb3.4	SSTF[b]	Test EA2-2	++	-	3	H-16=>3; 11.28
Flow–forward (Table H-17)	Cb4.1	TLTA-5A	Test 6426/Run 1	++	-	3	H-17=>1; -
	Cb4.2	FIST	Test 6DBA1B	++	2	3	H-17=>2; -
	Cb4.3	INEL 1/6 jet pump (LSTF[c])	Forward and reverse flow performance	++	1	3	H-17=>3; 11.1
Flow–multidimensional (Table H-18)	Cb5.1	SSTF/UP[d]	Full scale upper plenum; spray into 2-phase mix	++	-	3	H-18=>1; 11.28
Flow–reverse (Table H-19)	Cb6.1	TLTA-5A	Test 6426/Run 1	++	-	3	H-19=>2; -
	Cb6.2	FIST	Test 6DBA1B	++	-	3	H-19=>3; -
	Cb6.3	INEL 1/6 jet pump (LSTF)	Forward and reverse flow performance	++	1	3	H-19=>1; 11.1
Pump performance (Table H-23)	Cb9.1	ROSA-III	Test 926	++	-	3	H-23=>1; -
	Cb9.2	FIST	Test 4DBA1	++	-	3	H-23=>2; -
Spray distrib. (Table H-24)	Cb10.1	SSTF	Full-scale upper plenum	++	-	1	H-24=>1; 11.28

ASSESSMENT NEED:
++ = vital.
\+ = desirable.

TRAC INPUT:
1 = exists/available at LANL or ISL.
2 = exists/outside LANL or ISL.
3 = deck will require updating.
4 = deck quality assurance documentation unavailable.

DATA:
1 = available NUREG/CR, NUREG, NRC or OECD/CSNI databank, or equiv.
2 = available at LANL.
3 = available at ISL.
4 = limited data: NUREG/IA, CAMP, journal, or conference proceedings.

[a] Blowdown/emergency core cooling.
[b] Steam sector test facility.
[c] Large-scale test facility.
[d] Upper plenum.

TABLE 8-3 (cont)
ADDITIONAL BWR CET VALIDATION TESTS

PIRT Phenomenon (Appendix Table)	No.	Facility/Originator	Test Feature	Assess. Need	TRAC Input	Data	Ref: Appendix F or G; OECD/CSNI
Void distribution (Table H-25)	Cb11.1	Frigg	Boiling in 6x6 bundle	+	-	-	H-25=>1; 8.3
	Cb11.2	GE level swell	Test 1004-3, test 5801-13	++	2	3	H-25=>3; 11.44
	Cb11.3	SSTF/LP[a]	Mixing in lower plenum	++	-	1	H-25=>4; -
	Cb11.4	TLTA	Test 6424/Run1	++	-	3	H-25=>6; -
	Cb11.5	FIST	Test 4DBA1	++	-	3	H-25=>7; -
	Cb11.6	ANL[b]/Marchaterre	Subcooled and saturated void (ANL-5735)	++	1	3	H-25=>5 -

ASSESSMENT NEED:
++ = vital.
\+ = desirable.

TRAC INPUT:
1 = exists/available at LANL or ISL.
2 = exists/outside LANL or ISL.
3 = deck will require updating.
4 = deck QA documentation unavailable.

DATA:
1 = available NUREG/CR, NUREG, NRC or OECD/CSNI databank, or equiv.
2 = available at LANL.
3 = available at ISL.
4 = limited data: NUREG/IA, CAMP, journal, or conference proceedings.

[a] Lower plenum.
[b] Argonne National Laboratory.

9.0. CODE QUALIFICATION—VALIDATION USING INTEGRAL EFFECT TEST DATA

As discussed in Section 2, IETs investigate behavior in a full nuclear power plant, often in a reduced-scale experimental test facility. Comparisons of code-calculated predictions to data from IETs provide the mechanism for three important code qualification efforts. First, IET data are selected to assess the capability of T-H codes to predict SL phenomena identified in the consolidated PIRT (Section 4, Table 4-5). In this manner, IET data are used to determine whether the behavior of the integrated code (e.g., field equations, closure relations, component models, numerics, and special models) adequately simulates highly ranked SL phenomena. Second, IET data are selected to ensure that the code targeted applications are represented (i.e., plant types and accident scenarios). Simulation requirements for plant and targeted application simulation requirements are presented in Section 5. Third, IET data are selected to address scaling issues. If possible, the selected IET facilities should cover a sufficiently broad spectrum of facility scales and transient types to support arguments of code applicability for full-size plants.

9.1. IET Element Completion Status

Several features of the TRAC-M validation test matrix reflect work in progress or yet to be accomplished. The objective of this section is to identify the areas of the IET element of the validation test matrix that are incomplete.

Identification of individual IETs for the TRAC-M validation test matrix arises from the fulfillment of two requirements. The first requirement is that the code be validated by comparison to SL data for highly ranked SL phenomena. The second requirement is that code adequacy be demonstrated for a representative collection of plant types and applications. The relationship between SL PIRT and plant type and targeted applications was illustrated in Fig. 1-2.

With respect to the coverage of PWR SL PIRT phenomena, potential validation tests have been identified for the Westinghouse-PWR LB LOCA (Table 4-2a). These derive from an earlier LB LOCA validation test matrix effort[9-1] but include the highly ranked phenomena from both the AP600 PIRT[9-2] and W four-loop PWR PIRT[9-3] efforts. As seen in the summary tabulation of highly ranked PWR phenomena (Table 4-2d), an additional PWR IET. It is anticipated that additional phenomena will be added to the IET validation test matrix as PIRTs are completed for other plants, accidents, and transients.

With respect to the coverage of BWR SL PIRT phenomena, potential validation tests have been identified only for the BWR LB LOCA (Table 4-4a). As seen in the summary tabulation of highly ranked BWR phenomena (Table 4-4d), additional BWR phenomena arise from the other BWR PIRTs, e.g., carry under flow, pressure wave propagation, and thermal-hydraulic stability. IET tests have not yet been identified for these phenomena.

At present, the number of tests entered in the IET validation test matrix via PIRT SL requirements may be larger than necessary. This situation exists because data availability is presently uncertain for a number of the tests currently included in the

TRAC-M validation test matrix. As data availability is determined, it is expected that the IET matrix will be revised accordingly.

The coverage of PWR and BWR plants and targeted applications in the IET portion of the TRAC-M validation test matrix is believed to be adequate.

9.2. Data Selection Based on PIRT Summary

Referring to the consolidated PIRT (Table 4-5), the SL phenomena can be assigned to one of three groups: highly ranked PIRT phenomena common to both PWRs and BWRs, highly ranked phenomena derived from PWR PIRTs only, and highly ranked phenomena derived from BWR PIRTs only.

The TRAC-M IET validation test matrix is based on these three groups of PIRT phenomena and consists of three parts, one of which contains no IETs at the present time. The first part consists of common validation tests that apply to the entirety of the consolidated code, whether used in PWR or BWR application (Section 9.2.1). The second part consists of validation tests that are specific to PWR phenomena (Section 9.2.2). The third part, if following the pattern of the SET and CET matrices, would consist of validation tests that are specific to BWR phenomena. However, all BWR specific IET phenomena in Table 4-5 arise from PIRTs other than a BWR LB LOCA. As discussed in the previous section, potential validation tests have been identified only for the BWR LB LOCA and thus there are no PIRT required BWR specific IET in this release of the TRAC-M validation test matrix.

Validation tests that apply to the consolidated code, whether used in PWR or BWR applications are listed in Table 9-1. Additional details about the common validation tests included in the IET element of the TRAC-M validation are presented in Appendices F (PWR) and H (BWR), specifically the applicable literature or report citations and the testing ranges for key parameters, if available. A listing of TRAC-M input decks for common and PWR-specific IETs is provided in Appendix G. A listing of TRAC-M input decks for BWR-specific IETs is provided in Appendix I.

The first column of Table 9-1 identifies the PIRT-related or application-related test type. The second column is an identifying number for each validation test of the form Ix.y, with the "I" denoting IET, "x" being a number common to all tests for the same PIRT phenomenon, and "y" being the individual identifying number within set "x". The third column identifies the facility, and if applicable, lead investigator. The fourth column contains a brief statement characterizing the key feature of the test. The fifth column contains a symbol to communicate a priority assessment, namely whether the test is deemed vital or desirable. The sixth column provides summary information about the existence of TRAC input models (decks). A "-" is entered if no input model exists. If an input model exists, the deck location, need for updating for use with the current version of the code, and availability of quality assurance documentation are summarized. The seventh column provides summary information about the availability of the test data to be used for the validation exercise. If the availability of the data is unknown, an "-" is entered. If the data is availability, additional information about the data is summarized. The eighth and final column cross correlates the facility (column 3) with the identifying number of the facility in the OECD/CSNI separate effects test matrix for thermal-hydraulic code validation.[9-4]

PWR IET validation tests that apply to the consolidated code are listed in Table 9-2.

No BWR IET validation tests that apply to the consolidated code are presently identified as discussed above.

9.3. Data Selection Based on Plant Type and Targeted Applications

T-H codes are specifically designed for a variety of targeted applications. Among these applications are (1) reactor safety analyses for both operating and planned reactors, (2) audits of licensee's calculations, (3) analyses of operating reactor events, (4) analyses of accident management strategies, (5) support for test planning and interpretation, (6) support for probabilistic risk assessments, (7) design analyses, and (8) nuclear plant training and instrument and control simulators.

With respect to code qualification, the list of targeted applications can be distilled to two key elements: plant type and event type.

9.3.1. Plant Type

A survey of commercial nuclear power plants was completed in 1992.[9-5] Similar plants designed by a given vendor were placed in groups characterized by coolant loop configuration (PWR only), the number of fuel bundles, and bundle design. This information is summarized in Table 9-3.

IET facilities based upon W plants have been designed and operated, e.g., Semiscale, LOFT, LSTF, LSTF-AP600, SPES, SPES-AP600, SCTF, CCTF, and UPTF. IET facilities based upon B&W plants have been designed and operated, e.g., MIST, UMCP, and once-through integral system (OTIS) have been designed and operated. The authors are unaware of any IET facilities for CE designs. The use of the W IET facility matrix as a surrogate for the CE plants may be possible.

A listing of TRAC-M input decks for PWR plants is provided in Appendix G.

IET facilities based upon GE-designed BWR plants have been designed and operated, e.g., FIST and ROSA-III. Reasonable coverage of each of the PWR and BWR designs is possible, although each facility has some atypicalities relative to the reference reactor type for which they were designed.

A listing of TRAC-M input decks for BWR plants is provided in Appendix I.

9.3.2. Event Type

It is impossible to list all the potential event scenarios (accidents, transients, and operating events) and correlate these to the accident scenarios simulated in each IET. For our purposes, a more modest goal is set, namely, to create a table of the major event scenarios and an applicable IET facility and a test to represent each scenario. This tabulation is provided for the W and B&W designs in Table 9-4.

With the exception of the SGTR and MSLB transients, TRAC-M PWR performance can be tested for the listed event scenarios for W plants using existing TRAC-P input decks.* Coverage can be provided for these two remaining transients by preparing BETHSY (SGTR) and LOBI (MSLB) facility models, but a cost-benefit assessment should be made, unless TRAC-M input models are required for these facilities for other reasons. With the exception of the LB LOCA, MSLB, loss-of-feedwater event, and ATWS, TRAC-M performance can be assessed for the listed event scenarios for B&W plants.

The companion BWR event scenarios (accidents, transients, and operating events) for which validation tests have been identified are presented in Table 9-5.

9.4. IET Selection Based on Scaling Issues

A significant amount of effort will be required to address the scaling issue. That effort is beyond the scope of the present document. However, a promising approach has been identified as part of the RELAP5 adequacy demonstration for AP600 SB LOCA analyses.[9-6] Scaling analyses are used to demonstrate the relevancy and sufficiency of the collective experimental database for representing the behavior expected of a given plant design during a selected accident scenario. With this approach, an effort is made to demonstrate that the experimental database is sufficiently diverse that the expected full-plant response is included and that the code calculations are comparable with the corresponding tests in nondimensional space. This demonstration permits conclusions relating to code capabilities, drawn from assessments comparing calculated and measured IET test data, to be extended to the prediction of the full-plant behavior. This approach appears to be generally applicable, if there are sufficient IET facilities. For the AP600 demonstration just described, there were three such IET facilities.

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* With few exceptions, existing TRAC-P input decks will require modification for the specific test, even though a TRAC-P input deck exists for the facility.

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TABLE 9-1
COMMON IET VALIDATION TESTS

PIRT Phenomenon (Appendix Table)	No.	Facility/Originator	Test Feature	Assess. Need	TRAC Input	Data	Ref: Appendix F or G; OECD/CSNI
Flow–natural circulation (Table H-26)	Ic1.1	ROSA-III/JAERI	Test NC-1 through NC-5	++	-	3	H-26=>2,3; -
	Ic1.2	FRIGG	Tests FT 36a-c	+	-	1, 4	H-26=>1; 8.3
	Ic1.3	FIST	Test 6PNCI-4	+	2	3	H-26=>4-6; -
Level (Table F-14 or G-19)	Ic2.1	Vertical Canon	Vertical tube during blowdown	+	1	1,4	F-14=>2; 3.4
	Ic2.2	Tapioca	Vertical tube–top, middle, and bottom breaks	+	-	1,4	F-14=>2; 3.6
	Ic2.3	Single Tube Level Swell	Vertical heated tube steady-state level swell tests	+	-	-	F-14=>2; 10.14
	Ic2.4	Shoukri Subcooled Boiling	Vertical annular channel	+	-	4	F-14=>4; -
	Ic2.5	Marviken	Test T-11is a level swell experiment	+	1	1	F-14=>2; 8.2
	Ic2.6	GE Level Swell	Tests 1004-3, 5801-13	++	1	3	F-14=>2; 11.44
	Ic2.7	TPTF/ROSA IV/JAERI	Core heat transfer, BWR and PWR cores	+	-	4	F-14=>2; 6.1
	Ic2.8	Creare	1/15 and 1/30 scale vessel downcomer tests	+	1	1	F-14=>2; 6.15
	Ic2.9	UPTF	1:1 German PWR core simulator	++	1	1,2	F-14=>2; 4.1
	Ic2.10	Thetis	7 x 7 test section including level swell tests	+	1	1	F-14=>2; 10.2
	Ic2.11	CCTF/JAERI	Full height 3-D 32-fuel-rod bundle core	++	1	1,2	F-14=>2; 6.15
	Ic2.12	ECN[a] Reflood and Boildown	36-rod test section, boiloff and reflood tests	+	-	-	F-14=>2; 7.1, 7.2
	Ic2.13	FRIGG	36-rod test section	+	-	1, 4	F-14=>2; 8.3
	Ic2.14	NEPTUN-1 Boiloff	33-rod test section, boil-off and reflood tests	+	2	1, 4	F-14=>2; 9.1
	Ic2.15	Pericles Cylindrical	Cylindrical 368-rod core	+	-	-	F-14=>2; 3.9
	Ic2.16	Achilles Reflood Loop	ISP-25	+	2	1, 4	F-14=>2; 10.1
	Ic2.17	FIST	Test 6DBA1B-large recirculation line break	++	2	3	G-19=>2; -

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+ = desirable.

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[a] Energieonderzoek Centrum Nederland.

TABLE 9-2
ADDITIONAL PWR IET VALIDATION TESTS

PIRT Phenomenon (Appendix Table)	No.	Facility/Originator	Test Feature	Assess Need	TRAC Input	Data	Ref: Appendix F or G; OECD/CSNI
Asymmetries (Table F-16)	Ip1.1	LOFT	Test L2-5	++	1,4	1	F-16=>1,2
Oscillations (Table F-19)	Ip2.1	FRIGG Dynamic Tests	Tests 662101, 662105, 662107, 662113, 462053, 462101	++	-	4	F-19=>2-4; 8.3
	Ip2.2	FLECHT-SEASET/W	Test 33437	+	1,4	1	F-19=>5-7; 11.23
	Ip2.3	SCTF/JAERI	Test S2-08	+	1,4	1	F-19=>8,9; 6.15

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TABLE 9-3
SUMMARY OF VENDOR AND REACTOR TYPES

Type Vendor Group	Group Description	Number of Plants	Coolant Loops	Number of Bundles	Bundle Design
PWR					
Westinghouse					
W1	High-power 4-loop	2	4	193	17 x 17
W2	Medium-power 4-loop	26	4	193	17 x 17
W3	Low-power 4-loop	5	4	193	15 x 15
W4	Unique 4-loop	1	4	157	15 x 15
W5	Unique 4-loop	1	4	76	16 x 16
W6	High-power 3-loop	8	3	157	17 x 17
W7	Medium-power 3-loop	5	3	157	15 x 15
W8	Low-power 3-loop	1	3	157	14 x 14
W9	2 loop	5	2	121	14 x 14
AP600	Advanced passive	0	2 x 4	145	17 x 17
CE					
C1	Unique	1	3	217	14 x 14
C2	High-power	4	2 x 4	241	16 x 16
C3	Medium-power	3	2 x 4	217	16 x 16
C4	Unique	1	2 x 4	217	16 x 16
C5	Low-power	4	2 x 4	217	14 x 14
C6	Unique	1	2 x 4	204	15 x 15
C7	Unique	1	2 x 4	177	16 x 16
C8	Unique	1	2 x 4	133	14 x 14
B&W					
B1	High-power, raised-loop	3	2 x 4	205	17 x 17
B2	Low-power, raised-loop	1	2 x 4	177	15 x 15
B3	Low-loop	7	2 x 4	177	15 x 15
BWR					
GE					
G1	BWR/1	1	NA	84	11 x 11
G2	BWR/2	2	NA	560, 532	8 x 8
G3	Low-power BWR/3	3	NA	484	8 x 8
G4	Medium-power BWR/3	2	NA	580	8 x 8
G5	High-power BWR/3	4	NA	724	8 x 8, 9 x 9
G6	Low-power BWR/4	2	NA	368	8 x 8
G7	Medium-power BWR/4	5	NA	560, 548	8 x 8
G8	High-power BWR/4	11	NA	764	8 x 8, 9 x 9
G9	BWR/5	4	NA	764	8 x 8, 9 x 9
G10	Low-power BWR/6	2	NA	624	8 x 8
G11	Medium-power BWR/6	2	NA	748	8 x 8
G12	High-power BWR/6	1	NA	800	

TABLE 9-4
IET VALIDATION TESTS FOR PWR PLANTS AND TARGETED APPLICATIONS

Plant Type	No.	Event	IET Facility and Test	Assess Need	TRAC Input	Data	Reference: OECD/CSNI
Westinghouse	Pw1.1	LB LOCA	LOFT L2-3 or L2-5	++	1, 3	1	9-7; 9-8
	Pw1.2	IB[a] LOCA	LOFT L5-1 or L8-2	+	1, 3	1	9-7; 9-8
	Pw1.3	SB LOCA	LOFT L3-5 or L3-6	++	1, 3	1	9-7; 9-8
	Pw1.4	SGTR	BETHSY[b] 4.3b	++	-	4	9-9; 9-8
	Pw1.5	MSLB	LOBI BT12	++	2	-	- ; 9-8
	Pw1.6	LOSP[c]	LOFT L9-4	++	1, 3	1	9-7; 9-8
	Pw1.7	Loss of feedwater	LOFT L9-1/L3-3	++	1, 3	1	9-7; 9-8
	Pw1.8	Reactor trip	LOFT L6-2	+	1, 3	1	9-7; 9-8
	Pw1.9	ATWS	LOFT L9-3 or L9-4	+	1, 3	1	9-7; 9-8
	Pw1.10	Multiple failure events	LSTF-AP600 AP-SL-01	+	1, 3	1	9-10; -
	Pw1.11	Accident management	BETHSY 9.3	+	-	4	9-11 ; 9-8
Babcock & Wilcox	Pb1.1	LB LOCA	CCTF C2-10 (vent-valve test)	++	1,3	1	9-12; 9-8
	Pb1.2	IB LOCA	MIST 4100B2	++	1	1	9-13; 9-8
	Pb1.3	SB LOCA	MIST 3109AA	++	1	1	9-13; 9-8
	Pb1.4	SGTR	MIST 3404AA	++	1	1	9-13; 9-8
	Pb1.5	MSLB	None available	-	-	-	-
	Pb1.6	LOSP	MIST 4SB011	++	1	1	9-13; 9-8
	Pb1.7	Loss of feedwater	None available	-	-	-	-
	Pb1.8	Reactor trip	MIST 4SB011	++	1	1	9-13; 9-8
	Pb1.9	ATWS	None available	-	-	-	-
	Pb1.10	Multiple failure events	MIST 410BD1 or 410 AT3	+	1	1	9-13; 9-8
	Pb1.11	Accident management	MIST 410BD1 or 410AT3	+	1	1	9-13; 9-8

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[a] Intermediate break.
[c] Loss of offsite power.
[b] Boucle d'Etudes Thermohydrauliques Système.

TABLE 9-5
IET VALIDATION TESTS FOR BWR PLANTS AND TARGETED APPLICATIONS[9-14]

Plant Type	No.	Event	IET Facility and Test or Plant	Assess Need	TRAC Input	Data	Reference; OECD/CSNI
		LOCA	**IET FACILITY**				
BWR/6	Pb1.1	Large recirculation line	FIST 6DBA1B	++	1	3	9-15; 9-8
BWR/4	Pb1.2	Large recirculation line	FIST 4DBA1	++		3	9-14 ; 9-8
BWR/general	Pb1.3	Large recirculation line	FIX-II Test 3061				9-14 ; 9-8
BWR/general	Pb1.4	Large recirculation line	ROSA-III Run 901	++		3	9-16; 9-8
BWR/general	Pb1.5	Large recirculation line	ROSA-III Run 905			3	9-16; 9-8
BWR/general	Pb1.6	Large recirculation line	ROSA-III Run 902	+		3	9-16; 9-8
BWR/general	Pb1.7	Large recirculation line	ROSA-III Run 924			3	9-16; 9-8
BWR/general	Pb1.8	Large recirculation line	ROSA-III Run 926			3	9-14 ; 9-8
BWR/general	Pb1.9	Large recirculation line	TBL[a] Test 108				9-14 ; 9-8
BWR/general	Pb1.10	Large recirculation line	TLTA 6422 Run 3			3	9-17; 9-8
BWR/general	Pb1.11	Large recirculation line	TLTA 6424 Run 1			3	9-17; 9-8
BWR/general	Pb1.12	Large recirculation line	TLTA 6423 Run 3	++	1	3	9-17; 9-8
BWR/general	Pb1.13	Large recirculation line	TLTA 6426 Run 1	+		3	9-17; 9-8
BWR/6	Pb1.14	Medium recirculation line	FIST 6IB1			3	9-14 ; 9-8
BWR/6	Pb1.15	Medium recirculation line	FIST 6LB1A			3	9-18; 9-8
BWR/general	Pb1.16	Medium recirculation line	ROSA-III Run 962				9-16; 9-8
BWR/general	Pb1.17	Refill/reflood	Piper-ONE PO-LB-1				9-14 ; 9-8
BWR/general	Pb1.18	Refill/reflood	SSTF	++		3	9-19; 9-8
BWR/6	Pb1.19	Small recirculation line	FIST 6SB1	++	2	3	9-14 ; 9-8
BWR/general	Pb1.20	Small recirculation line	Piper-ONE PO-SB-7				9-14 ; 9-8
BWR/general	Pb1.21	Small recirculation line	ROSA-III Run 912	++		3	9-14 ; 9-8
BWR/general	Pb1.22	Small recirculation line	ROSA-III Run 984	+		3	9-14 ; 9-8
BWR/general	Pb1.23	Small recirculation line	TBL Test 311				9-14 ; 9-8
BWR/general	Pb1.24	Small recirculation line	TLTA 6432 Run 1			3	9-14 ; 9-8
BWR/6	Pb1.25	Steam line break	FIST 6MSB1	++		3	9-14 ; 9-8
BWR/general	Pb1.26	Steam line break	ROSA-III Run 953	+		3	9-14 ; 9-8
BWR/general	Pb1.27	Steam line break	TBL Test 314				9-14 ; 9-8

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[a] Two-bundle loop.

TABLE 9-5 (cont)
IET VALIDATION TESTS FOR BWR PLANTS AND TARGETED APPLICATIONS[9-14]

Plant Type	No.	Event	IET Facility and Test or Plant	Assess. Need	TRAC Input	Data	Reference; OECD/CSNI
		TRANSIENT					
BWR/6	I28	ATWS MSIV[a] closure	FIST 6PMC2A	++	1	3	9-15; 9-8
	I29	Water level drop	FIST T23C	+		3	9-14 ; 9-8
BWR/6	I30	Controlled depress.	FIST 6PMC3	++		3	9-14 ; 9-8
BWR/6	I31	Natural circulation	FIST 6PNC1	+	2	3	9-15; 9-8
BWR/6	I32	Natural circulation	FIST 6PNC3			3	9-18; 9-8
	I33	Natural circulation	ROSA-III NC-1 ...NC-5	++		3	9-16; 9-8
	I34	Water level drop	FIST T1QUV			3	9-14 ; 9-8
BWR/4	I35	Turbine trip	FIST 4PTT1	++	2	3	9-14 ; 9-8
			PLANT				
BWR/4	P1	AOT: feedwater trip	Browns Ferry	+	1	3	
BWR/4	P2	Load rejection	Browns Ferry	+	1	3	
BWR/4	P3	Reactor coolant pump trip	Browns Ferry	+	1	3	
BWR/GETSCO reactor	P4	MSIV closure	Leibstadt	+	2		9-14 ; 9-8
BWR/GETSCO reactor	P5	Feedwater loss	Leibstadt	+	2		9-14 ; 9-8
BWR/4	P6	turbine trip	Peach Bottom-2	++	2	3	9-14 ; 9-8
		STABILITY					
	P7		Dodeward		1	3	9-20; -
BWR/5	P8		LaSalle-2	++	1		9-20; -
BWR/GETSCO reactor	P9		Leibstadt	+	2		9-20; -
BWR/ABB Atom reactor	P10		Ringhals-1	++	2		9-20; -
BWR/5	P11		WNP-2[b]	+			9-20; -

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[a] Main steam isolation valve.
[b] Washington Nuclear Power Unit 2.

APPENDIX A

VALIDATION SUCCESS METRICS

Validation is defined in this report as the comparison of code predictions to standards, either experimental data or other. The success metrics are the same as those used in the recently completed RELAP5 adequacy assessment effort;[A-1] they are repeated here for convenience.

"Excellent agreement" applies when the code exhibits no deficiencies in modeling a given behavior. Major and minor phenomena and trends are correctly predicted. The calculated results are judged to agree closely with the data. The calculations will, with few exceptions, lie within the specified or inferred uncertainty bands of the data. The code may be used with confidence in similar applications. The term "major phenomena" refers to phenomena that influence key parameters, such as rod cladding temperature, pressure, differential pressure, mass flow rate, and mass distribution. Predicting the major trends means that the prediction shows the significant features of the data. Significant features include the magnitude of a given parameter through the transient, slopes, and inflection points that mark significant changes in the parameter.

"Reasonable agreement" applies when the code exhibits minor deficiencies. Overall, the code provides an acceptable prediction. All major trends and phenomena are predicted correctly. Differences between calculated values and data are greater than are deemed necessary for excellent agreement. The calculation will frequently lie outside but near the specified or inferred uncertainty bands of the data. However, the correct conclusions about trends and phenomena would be reached if the code were used in similar applications. The code models and/or facility model noding should be reviewed to see if improvements can be made.

"Minimal agreement" applies when the code exhibits significant deficiencies. Overall, the code provides a prediction that is only conditionally acceptable. Some major trends or phenomena are not predicted correctly, and some calculated values lie considerably outside the specified or inferred uncertainty bands of the data. Incorrect conclusions about trends and phenomena may be reached if the code were used in similar applications; an appropriate warning must be issued to users. Selected code models and/or facility model noding must be reviewed, modified, and assessed before the code can be used with confidence in similar applications.

"Insufficient agreement" applies when the code exhibits major deficiencies. The code provides an unacceptable prediction of the test because major trends are not predicted correctly. Most calculated values lie outside the specified or inferred uncertainty bands of the data. Incorrect conclusions about trends and phenomena are probable if the code is used in similar applications; an appropriate warning must be issued to users. Selected code models and/or facility model noding must be reviewed, modified, and assessed before the code can be used with confidence in similar applications.

REFERENCES

A-1. C. D. Fletcher, P. D. Bayless, C. B. Davis, M. G. Ortiz, T. K. Larson, S. M. Sloan, R. A. Shaw, R. R. Schultz, C. E. Slater, G. W. Johnsen, L. S. Ghan, and D. E. Bessette, "Adequacy Evaluation of RELAP5/MOD3, Version 3.2.1.2 for Simulating AP600 Small-Break Loss-of-Coolant Accidents (Final Draft)," Idaho National Engineering Laboratory document INEL-96/0400 (December 1996).

APPENDIX B

ADDITIONAL PERSPECTIVES
SEPARATE EFFECT AND INTEGRAL EFFECT TESTS

Three categories of experimental data have traditionally been identified for use in T-H code validation: separate effect, component effect, and integral effect (Fig. 2-2). The three categories are generally distinguished by both the complexity of the processes/phenomena and the geometric scale of the respective facilities. Separate effect tests (SETs) generally focus on a few processes or phenomena within a single component test fixture, although some multiple component tests are classified as SETs also. Component effect tests (CETs) generally focus on a single component. Integral effect tests (IETs) generally focus on multiple, coupled processes and components in facilities that have numerous hardware components. A gray area arises at the interfaces where assignment of a particular facility or test to the SET, CET, or IET categories is arbitrary.

SET, CET, and IET data are generally applied in different ways within the code development/code qualification process. SET data are most useful for model development. SET data are also the most applicable data for validating flow field models and engineering correlation (closure) and component models.

CET and IET data are most useful for assessing performance and qualifying the integrated T-H code for its targeted applications. IET data can sometimes be used for equipment component model qualification. If sufficient instrumentation is provided in an IET facility, these facilities can assume some characteristics of SET facilities and tests. The SCTF, CCTF, and UPTF facilities have variously been categorized as either SET, CET, or IET facilities, depending upon how they are configured for a given test or test series.

A distinguishing characteristic between SET and IET data is the extent and accuracy of the instrumentation. Instrumentation for SET data can generally have very detailed spatial and temporal resolution and high accuracy. The larger physical scale of integral test facilities generally limits both the spatial and temporal resolution, primarily because of the larger number of instruments and the broader instrumentation ranges to cover the range through which the measured parameter moves during an integral test.

Generally, as experiments move from fundamental separate effect to large-scale integral effect, the situations of interest become more complex, the data become more limited in quality (spatial and temporal resolution and accuracy), interactions between components and physical processes in different components become more important, and understanding of the experimental results becomes much more difficult.

We have attempted to capture the scale and complexity relationships between various SET, CET, and IET facilities in Fig. 2-2 where we show a spectrum of SET, CET, and IET facilities in a matrix. Plant data arising from operational tests, operational transients, and accidents are also shown. The abscissa of the matrix conveys qualitative or semi-quantitative information about facility scale and the ordinate conveys qualitative information about the facility complexity. Within the SET category, separate scales are assigned to fundamental, single component, and several component tests. IET facilities are plotted relative to a volume scale; the positions are approximate.

B.1. Separate Effect Tests

Separate effect experiments are experiments in which a very limited number of physical phenomena are of interest and detailed, high-quality data are obtained. In a steady-state experiment, for example, detailed distributions of pressure, void fraction, and wall temperature will be reported along the flow direction. For the case of transient experiments, instrumentation with temporal resolution sufficient to measure all changes of interest will be employed. The fine spatial and temporal detail and high accuracy of the data make separate effect data appropriate for model development. Predictions of these kinds of experiments usually lead to nearly complete understanding of the code results and resolution of any differences between code predictions and the measured data. In Fig. 2-2, we show three different types of SET facilities: fundamental, single component, and several component.

The objective of fundamental SET facilities is to make a single physical phenomena (e. g., wall friction, momentum flux, gravity, and radiation heat transfer) or some aspect of the numerical solution methods (stability, convergence) dominant in the data. These data are the most prized, then, both for the development of engineering correlations and for evaluating the fundamental models in a T-H code. Frequently, however, it is not possible to isolate a single physical phenomenon. Thus, fundamental tests are also conducted to focus on a single parameter, such as the pressure gradient that arises from the flow process. The two-phase pressure gradient, however, is the integrated result of several fundamental phenomena, e.g., the void distribution both across the flow channel transverse to the flow direction and in the direction of flow, and fluid properties encountered in single-phase flows.

The objective of single-component SETs is broader in that more interacting phenomena and processes occur. Component tests can focus on either the detailed behaviors within the component, e.g., thermal stratification or level changes in a coolant makeup tank; the boundaries of a component, e.g., the output from a circulating pump under a full range of operating conditions; or a combination of both.

Several component tests arise not so much from the desire to combine a few components in a facility but the practical necessity of combining several components to produce the desired test characteristics. In addition, several facilities produce either SET or IET data, depending upon their configuration. Examples are CCTF, SCTF, UPTF, and FLECHT-SEASET.

We view relatively complex physical processes in larger scale facilities to be naturally located near the boundary between separate effect and integral effect experiments. Forced reflood heat transfer of full-length rod bundles is an example of complex separate effect data that generally arises in several component facilities such as FLECHT-SEASET, CCTF, and SCTF when they are operated in a SETs mode.

B.2. Component Effect Tests

CETs investigate behavior in a plant component, frequently but not always at full-scale. Component effect experiments are of several types. Some tests are designed to test the performance and characteristics of a particular component, e.g., a pump or valve. More frequently, however, component data is extracted from an integral test facility that includes several components. The IET facility can be run in an integral mode, component mode, or separate effect mode. The Flecht-Seaset facility is an example of a facility that has utilized this type of flexible design.

B.3. Integral Effect Tests

Integral effect experiments are generally designed to investigate a complete system, or a scaled model of complete nuclear reactor systems. IETs may also be designed to investigate a single phenomena in a complete system, e.g., natural circulation in a complete model of a pressurized water reactor. Finally, IETs frequently develop specific component data, an obvious overlap with some SET facilities.

Generally, the physical scale of the test rigs is such that detailed instrumentation is not possible. Additionally, the data may be difficult to understand, especially as the scale of the facility increases because both the complexity of the physical phenomena and the amount of data taken. Comparison of code predictions with data from these tests may not result in closure of differences between the data and code predictions because of the complexity of both the physical phenomena and the geometry of the region of interest.

Numerous IET facilities simulating nuclear power plants have been designed, built, and operated in the past 30 years. The PWR IETs identified as part of an OECD/CSNI effort to prepare IET data assessment matrices are displayed in Fig. 2-3. The volume scales of the facilities range from 1/1 for UPTF to 1/1705 for Semiscale (see Table 8-2). Similarly, the facility complexity various from the OTIS and GERDA facilities, which were single-loop representations of OTSG PWRs, to LOFT, the only IET facility with a nuclear core.

APPENDIX C

THE MODELS AND METHODS IN TRAC-M

An expanded view of the models and methods in the TRAC-M code is given in the following discussion. The detailed lists developed herein will be used to identify appropriate experimental data for validation of the models and methods.

C.1. Basic-Equation Models

The basic-equation models in TRAC-M were listed in Section 3.1 of the main report. The contents of these model equations are given in more detail in the following paragraphs.

C.1.1. Mass, Momentum, and Energy Equations for the Fluid Flow

The basic fluid flow model equations in TRAC-M are outlined in Sections C.1.1.1 through C.1.1.4 below.

C.1.1.1. Mass Conservation Equations. TRAC-M contains mass conservation equations for

- the liquid phase of water,
- the mixture of the vapor phase of water plus the noncondensable gas,
- noncondensable gases, and
- solids dissolved in the liquid phase.

These equations contain convection and mass exchange contributions. The verification and validation efforts will focus on the mass exchange contribution due to heat transfer, which is a function of specific-area and heat transfer coefficient models.

C.1.1.2. Equations of Motion. TRAC-M contains momentum equations, or equations of motion for

- the liquid phase of water and
- the mixture of vapor and noncondensable gas.

Any solids dissolved in the liquid phase are merely transported by the liquid. There is no feedback from the solids to the liquid equation of motion. This modeling is based on the assumption that the dissolved solids are present in trace amounts in the liquid.

The equations of motion contain accounting of

- momentum flux,
- interfacial drag,
- the pressure gradient,
- momentum exchange due to mass exchange,
- wall-to-phase drag,
- gravity,
- pressure change due to local losses, and
- an area-change contribution.

The local-losses modeling includes abrupt expansion and contraction, turning flow loss, and thin plate orifice.

The wall and interfacial drag contributions contain quantities that are functions of the two-phase flow regime. The verification and validation efforts will consider all the terms in the equations of motion and focus especially on the flow-regime dependent terms. These latter terms are primarily the quantities with the largest uncertainty.

C.1.1.3. Energy Equations. TRAC-M contains energy conservation equations for

- the vapor plus noncondensable gas mixture;
- the liquid-plus-gas vapor mixture, i.e., the entire mixture; and
- the liquid.

The vapor-plus-gas energy equation contains

- energy convection for the mixture of gases,
- a pressure-work contribution,
- wall-to-gas-mixture heat transfer,
- direct energy deposition to the gas mixture by neutrons,
- interface-to-gas-mixture heat transfer, and
- energy exchange due to mass exchange.

The energy equation for the entire mixture contains

- energy convection for the entire mixture,
- a pressure-work contribution,
- wall-to-gas-mixture heat transfer,
- wall-to-liquid heat transfer,
- direct energy deposition to the liquid by neutrons, and
- direct energy deposition to the gas mixture by neutrons.

The energy equation for the liquid contains:

- energy convection for the liquid,
- a pressure-work contribution,
- wall-to-liquid heat transfer,
- direct energy deposition to the liquid by the neutrons,
- heat transfer at the interface, and
- energy exchange due to mass exchange.

As in the case of the equations of motion, the wall-to-phase and interfacial energy exchange will be the focus of the verification and validation efforts for the fluid energy equations. Note that not all the items listed above are unique; some are repeated between the various forms of the energy equations.

The temperature of the liquid and the temperature of the gas mixture, along with the pressure, are the dependent variables for the equation of state in the code.

C.1.1.4. The 3D Vessel Model Equations. The reactor pressure vessel model in TRAC-M contains 3D versions of the fluid flow equations given in the three previous sections above.

C.1.2. Heat Conduction in Solid Structures

The heat conduction model in TRAC is applicable to conduction in rectangular slabs and cylindrical rods. The conduction model includes accounting of

- gap conductance,
- metal-water reaction, and
- temperature and space dependent material properties.

The fuel-clad gap conductance has been found to be important and highly ranked in previous PIRT studies.

There are four numerical solution methods available:

- lumped-parameter (the lumped-capacitance method);
- 1D radial conduction without axial conduction;
- 2D radial plus axial conduction, implicit in the radial direction, and explicit in the axial direction; and
- fully implicit radial and axial conduction for use in reflood modeling. Fine-mesh rezoning is also available for reflood modeling.

C.1.3. Reactor Core Power Model

Three methods are available for calculating the reactor core power in TRAC-M:

- a table as input to the code,
- a point-reactor kinetics model, and
- a 3D neutron kinetics model.

Reactivity feedback is based on changes in

- fuel temperature,
- the coolant temperature,
- coolant void fraction, and
- boron concentration.

C.1.4. Radiative Energy Exchange in the Core

The radiative energy exchange model in TRAC-M accounts for surface-to-surface radiation for solid surfaces that are attached to the same hydrodynamic node. The model also accounts for the effects of a two-phase mixture between the radiating surfaces.

C.1.5. Equations of State

TRAC-M has the following equations of state:

- For the water liquid, the density and specific internal energy are given by functions of the total pressure and the liquid temperature.
- For the water vapor, the density and specific internal energy are given by functions of the partial pressure for the vapor and the gas-mixture temperature.
- For the noncondensable gas, the density and specific internal energy are given by of the partial pressure of the noncondensable gas and the gas mixture temperature.

C.1.6. Other Fluid Properties

The viscosity and thermal conductivity for all fluids in the flow field are also needed. Various derivatives of the equation of state are needed for numerical solution and other purposes.

C.2. Flow Field Models and Engineering Correlations (Closure)

As noted in Section 3.2, closure for the fluid flow equations is based on the use of flow-regime maps plus models and correlations for wall-to-phase and interfacial mass, momentum, and energy exchange. Additional information about the closure for the fluid flow model equations is given in the following discussions.

C.2.1. Flow Regime Map(s)

The flow regime modeling in TRAC includes

- a vertical flow regime map
- a horizontal flow regime map
- modeled flow regimes, including
  single phase
  bubbly
  slug
  annular-mist
  mist
  churn
  horizontal stratified
  vertical stratified

In TRAC-M, the horizontal flow regime map is basically the same as the vertical map.

The flow regime criteria and interfacial area for the individual flow regimes are summarized in Table C-1, which is taken from Reference 3-1. Table C-1 applies to all applications except for reflood heat transfer in the core. Flow regime criteria under reflood conditions are given in Section C.4.

C.2.2. Fluid Mass Equation Closure

Closure of the fluid mass conservation equation models used in TRAC requires accounting of wall-to-phase and interfacial heat transfer and interfacial area to get the mass transfer due to heat transfer. The subcooled boiling model in TRAC-M is part of the closure of the fluid mass balance equations. The solids dissolved in liquid can plate out, and modeling this process is the closure for the dissolved-solids mass conservation equation.

Fluid mass balance equation closure in TRAC-M is summarized in Table C-2, which has been taken from Reference 3-2. Verification, validation, and qualification activities will ultimately be applied to the individual correlations given in the table.

C.2.3. Fluid Momentum Equation Closure

Closure of the fluid equations of motion requires modeling for wall-to-phase and interfacial momentum exchange. Modeling of momentum exchange is needed for both the 1D and 3D equations of motion. The terms in the momentum equations used in TRAC-M have been summarized in Section C.1.1.2. Additional information about the wall and interfacial drag models is given below.

The models and correlations that make up the wall-drag accounting for the equations of motion are summarized in Table C-3. The wall-drag models are used for applications that do and do not involve reflood heat transfer. The interfacial momentum exchange modeling for applications that do not involve reflood heat transfer is summarized in Table C-4. Both Tables have been taken from Reference 3-1. Verification, validation, and qualification activities will ultimately be applied to the individual correlations given in the tables.

C.2.4. Fluid Energy Equation Closure

Closure of the fluid energy equations requires modeling of the wall-to-phase and interfacial energy exchanges. Modeling of the energy exchange is needed for both the 1D and 3D energy equations. The terms in the energy equations used in TRAC-M have been summarized in Section C.1.1.3. Additional information about the wall and interfacial energy exchange models is given below.

The models and correlations that make up the wall-to-phase energy exchange are summarized in Table C-5 for applications that do not involve reflood. The interfacial energy exchange models and correlations for applications that do not use the reflood heat transfer modeling in TRAC are summarized in Table C-6. Verification, validation, and qualification activities will ultimately be applied to the individual correlations given in the tables.

C.3. Equipment Component Models

The system-equipment component models in TRAC-M have been listed in Section C.3. The properties of these models are best determined at present by reference to the TRAC-P Theory Manual.[3-2]

C.4. Special-Purpose Models

The special-purpose models in TRAC-M have been listed in Section 3.4. The special-purpose models that have been found to be important and highly ranked in previous PIRT studies are the (1) CCFL model, (2) critical flow model that determines the flow rate of the fluid under choked-flow conditions, (3) two-phase level-tracking model, and (4) reflood heat transfer model.

The CCFL model in TRAC-M is based on a generalized formulation from which both the Wallis and Kutaladaze forms can be recovered.

The critical flow model in TRAC-M is based on critical flow of (1) a subcooled liquid including modeling of nucleation delay under rapid pressure change conditions, (2) critical flow of a two-phase (liquid and vapor water), two-component (water and a gas) mixture based on the basic fluid flow equations in TRAC, and (3) critical flow based on isentropic expansion of a single-phase vapor.

The reflood heat transfer model in TRAC-M is quite complex and contains special versions of (1) flow-regime modeling, (2) some wall-to-phase energy exchange models, (3) interfacial momentum and energy exchange models and correlations, and (4) special modeling and numerical solution methods for conduction heat transfer. The flow-regime criteria models and correlations are summarized in Table C-7, interfacial momentum exchange models and correlations are summarized in Table C-8, and those for interfacial energy exchange are given in Table C-9. All these tables have been taken from Reference 3-1. Verification, validation, and qualification investigations will ultimately be applied to the individual correlations given in these tables.

The TEE component offtake flow model in TRAC-M includes accounting for three offtake geometries and four offtake flow patterns. The modeling allows calculation of entrainment of liquid and vapor by vapor and liquid, respectively, for example. The control system models and methods may be important for some operational transients. The control system elements in TRAC include

- component hardware actions,
- plant system trips,
- control block functions, and
- use of control system elements for steady state calculations.

The control system elements available in TRAC-M are quite general and can probably model almost any control system encountered in TRAC-M applications.

C.5. Numerical Solution Methods

All the numerical solution methods used in TRAC-M must undergo verification and validation. The solution methods for the fluid flow equations are especially important because they are the bases of almost every analysis done with TRAC. The numerical solution methods associated physical components and phenomena/ processes rated highly important in previous PIRT studies should also receive priority relative to verification and validation.

For completeness of this Section, the numerical solution methods listed in Section 3.5 are repeated here. The solution methods in TRAC-M include those for

- fluid field equations

- 1D SETS method
- 3D SETS method

- conduction in solid materials
  - 1D rectangular and cylindrical
  - 2D rectangular and cylindrical
- power generation in the fuel rods
- the trip and control system elements
- the fluid equation of state
- fluid boundary conditions
- the equipment component models
- the special-purpose models
- steady-state solution methods, and
- timestep size and control methods.

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TABLE C-1
TRAC CLOSURE RELATION SUMMARY:
FLOW-REGIME CRITERIA AND INTERFACIAL AREA
FOR NON-REFLOOD APPLICATIONS

Flow Regime	Flow-Regime Criteria	Interfacial Area (A_i)
Bubbly Flow	$a \le 0.3$; or $a \le 0.5$ and $G \ge 2700$ kg/m^2-s	based on Ishii and Mishima[C-1]
Bubbly Slug Transition	$0.3 < a \le 0.5$ and $2000 < G < 2700$ kg/m^2-s	based on Ishii and Mishima[C-1]
Bubbly Slug Flow	$0.3 < a \le 0.5$ and $G \le 2000$ kg/m^2-s	based on Ishii and Mishima[C-1]
Churn Flow	$0.5 < a \le 0.75$	weighted average of bubbly slug and annular-mist interfacial areas
Annular-Mist Flow	$a > 0.75$	superimpose film and droplet fields; droplet area based on the droplet diameter defined by Kataoka[C-2] or Kitscha and Kocamustafaogullari,[C-3] and on the entrainment fraction of Ishii and Mishima;[C-4] film area based on geometry and entrainment fraction
Transition to Stratified Flow	1D components: gas (or liquid) velocity between 1 and 10 times the critical velocity 3D components: gas velocity between 1 and 2 times the critical velocity	weighted average of stratified flow and basic flow-regime map interfacial areas

TABLE C-1 (cont)
TRAC CLOSURE RELATION SUMMARY: FLOW-REGIME CRITERIA AND INTERFACIAL AREA FOR NON-REFLOOD APPLICATIONS

Flow Regime	Flow-Regime Criteria	Interfacial Area (A_i)
Stratified Flow	1D components: critical velocity criteria 3D vessel: horizontal stratified flow uses critical relative velocity of Mishima and Ishii;[C-5] vertical stratified flow uses terminal bubble rise velocity criterion	interfacial area for horizontal stratified flow based on circular pipe geometry; interfacial area for vertical stratified flow based on average cross-sectional area
Plug Flow	liquid side under condensation mode; void fraction (over three contiguous cells) must satisfy plugging criterion	based on circular pipe geometry

TABLE C-2
TRAC CLOSURE RELATION SUMMARY: INTERFACIAL MASS TRANSFER

Model	Interfacial Mass Transfer
Total Interfacial Mass Transfer Rate (G)	sum of the mass transfer rates from interfacial heat transfer and subcooled boiling
Mass Transfer Caused by Interfacial Heat Transfer (G_i)	based on the sum of the interface-to-gas and interface-to-liquid heat-transfer rates
Mass Transfer Caused by Subcooled Boiling (G_{sub})	based on Lahey's mechanistic model[C-6] for the evaporation fraction and on the modified Saha-Zuber OSV correlation[C-7] (Note: this model is used only when the subcooled boiling heat-transfer coefficient is nonzero)
Plateout of Dissolved Solids	Later

TABLE C-3
TRAC CLOSURE RELATION SUMMARY:
WALL DRAG

Model Type	Wall-to-Liquid Drag Coefficient (c_{wl})	Wall-to-Gas Drag Coefficient (c_{wg})
Single-Phase	single-phase liquid: based on the modified friction factor correlation[C-8] single-phase vapor: zero	single-phase liquid: zero single-phase vapor: based on the modified Churchill friction factor correlation[C-8]
Two-Phase, Homogeneous	based on the modified Churchill friction factor correlation[C-8] using the two-phase mixture Reynolds number	based on the modified Churchill friction factor correlation[C-8] using the two-phase mixture Reynolds number
Two-Phase, Horizontal Stratified	laminar flow: based on fully-developed laminar friction factor relation turbulent flow: based on McAdams friction factor correlation	laminar flow: based on fully-developed laminar friction factor relation turbulent flow: based on McAdams friction factor correlation

TABLE C-4
TRAC CLOSURE RELATION SUMMARY:
INTERFACIAL DRAG FOR NON-REFLOOD APPLICATIONS

Flow Regime	Interfacial Drag Coefficient (c_i)
Bubbly Flow, Bubbly Slug Flow, Bubbly Slug Transition	defined as per Ishii and Chawla[C-9] (bubble diameter and profile slip based on Ishii;[C-10] bubble drag coefficient for three Reynolds number regimes based on Stokes drag law, the empirical relation proposed by Schiller and Nauman,[C-11] and the recommendation of Bird, Stewart, and Lightfoot[C-12])
Churn Flow	weighted average of bubbly slug and annular-mist interfacial drag coefficients
Annular-Mist Flow	based on drift velocity developed by Kataoka and Ishii[C-13] and total interfacial shear force defined as per Ishii and Mishima[C-1] (film interface friction factor obtained from Wallis;[C-14] droplet diameter based on Kataoka, Ishii, and Mishima;[C-2] droplet drag coefficient based on Ishii and Chawla;[C-9] entrainment based on Kataoka and Ishii[C-13])
Transition to Stratified Flow	weighted average of stratified and flow-regime map interfacial drag coefficients
Stratified Flow	derived from the method of Taitel and Dukler[C-15] (interfacial friction factor based on Ohnuki et al.[C-16])
Plug Flow	no specific model for interfacial drag

TABLE C-5
TRAC CLOSURE RELATION SUMMARY:
WALL-TO-FLUID HEAT TRANSFER
FOR BOTH REFLOOD AND NON-REFLOOD APPLICATIONS

Heat-Transfer Regime	Wall-to-Liquid Heat-Transfer Coefficient (h_{wl})	Wall-to-Gas Heat-Transfer Coefficient (h_{wg})
Natural Convection to Liquid	laminar and turbulent natural-convection correlations[C-17]	zero
Forced Convection to Liquid	Dittus-Boelter correlation[C-18]	zero
Nucleate Boiling	based on the total heat flux (as determined by the Chen correlation[C-19]) minus the wall-to-gas heat flux	maximum of either the natural convection[C-20] or Dougall-Rohsenow[C-21] correlations
Critical Heat Flux	Biasi correlation[C-22]	Biasi correlation[C-22]
Transition Boiling	based on the total heat flux minus the wall-to-gas heat flux (the total heat flux is a weighted average of q_{chf}, calculated via Biasi and q_{min}, which is based on natural convection,[C-20] Dougall-Rohsenow,[C-21] modified Bromley,[C-23] and radiation heat-transfer coefficients) reflood model: total heat flux based on exponential decrease from q_{chf} to q_{film}	maximum of either the natural convection[C-20] or Dougall-Rohsenow[C-21] correlations reflood model: Webb-Chen correlation[C-24]
Minimum Stable Film Boiling Temperature	based on the Fauske homogeneous nucleation temperature[C-25]	based on the Fauske homogeneous nucleation temperature[C-25]

TABLE C-5 (cont)
TRAC CLOSURE RELATION SUMMARY:
WALL-TO-FLUID HEAT TRANSFER
FOR BOTH REFLOOD AND NON-REFLOOD APPLICATIONS

Heat-Transfer Regime	Wall-to-Liquid Heat-Transfer Coefficient (h_{wl})	Wall-to-Gas Heat-Transfer Coefficient (h_{wg})
Film Boiling	based on the modified Bromley film boiling heat-transfer coefficient[C-23] and a radiation term reflood model: based on the Denham[C-26] and modified Bromley[C-23] correlations and a radiation term	maximum of either the natural convection[C-20] or Dougall-Rohsenow[C-21] correlations reflood model: based on Webb-Chen correlation[C-24]
Single-Phase Vapor	zero	maximum of the turbulent natural-convection correlation and either the Sieder-Tate[C-12] or Dittus-Boelter[C-18] correlations
Condensation	zero or the maximum of the laminar natural-convection, turbulent natural-convection, and Chen[C-19] (S = 0) correlations	based on Nusselt, turbulent natural-convection[C-27] and turbulent forced-convection[C-17] correlations
Two-Phase Forced Convection	maximum of the Rohsenow-Choi[C-28] and Dittus-Boelter[C-18] correlations	zero or the maximum of the turbulent natural-convection[C-17] and Dittus-Boelter[C-18] correlations

TABLE C-6
TRAC CLOSURE RELATION SUMMARY:
INTERFACIAL HEAT TRANSFER
FOR NON-REFLOOD APPLICATIONS

Flow Regime	Interface-to-Liquid Heat-Transfer Coefficient (h_{il})	Interface-to-Gas Heat-Transfer Coefficient (h_{ig})	Liquid-to-Gas Sensible Heat-Transfer Coefficient (h_{gl})
Bubbly Flow, Bubbly Slug Flow, Bubbly Slug Transition	condensation or evaporation: based on the Chen and Mayinger[C-29] and the Whittaker[C-30] Nusselt number correlations flashing: based on liquid superheat subcooled boiling: h_{il} is weighted to include Lahey and Moody model[C-21]	1000 W/m^2-K	1000 W/m^2-K
Churn Flow	cond/evap: based on weighted average of annular-mist and bubbly slug heat-transfer factors flashing: based on maximum of weighted heat-transfer factor and liquid superheat relation	based on weighted average of annular-mist and bubbly slug heat-transfer factors	based on weighted average of annular-mist and bubbly slug heat-transfer factors

TABLE C-6 (cont)
TRAC CLOSURE RELATION SUMMARY: INTERFACIAL HEAT TRANSFER FOR NON-REFLOOD APPLICATIONS

Flow Regime	Interface-to-Liquid Heat-Transfer Coefficient (h_{il})	Interface-to-Gas Heat-Transfer Coefficient (h_{ig})	Liquid-to-Gas Sensible Heat-Transfer Coefficient (h_{gl})
Annular-Mist Flow	cond/evap: superimpose droplet and film field droplet field: based on transient conduction solution[C-31] film field: based on Bankoff correlation for Stanton number[C-32] flashing: based on maximum of weighted heat-transfer factor and liquid superheat relation	superimpose droplet and film field droplet field: based on Ryskin correlation for Nusselt number[C-33] film field: based on Bankoff correlation for Stanton number[C-32]	superimpose droplet and film field droplet field: based on Ryskin correlation for Nusselt number[C-33] film field: based on Bankoff correlation for Stanton number[C-32]
Transition to Stratified Flow	cond/evap: weighted average of stratified and flow-regime map heat-transfer factors flashing: based on maximum of weighted heat-transfer factor and liquid superheat relation	heat-transfer factor equivalent to value calculated from basic flow-regime map	heat-transfer factor equivalent to value calculated from basic flow-regime map

TABLE C-6 (cont)
TRAC CLOSURE RELATION SUMMARY:
INTERFACIAL HEAT TRANSFER
FOR NON-REFLOOD APPLICATIONS

Flow Regime	Interface-to-Liquid Heat-Transfer Coefficient (h_{il})	Interface-to-Gas Heat-Transfer Coefficient (h_{ig})	Liquid-to-Gas Sensible Heat-Transfer Coefficient (h_{gl})
Stratified Flow	cond/evap: based on Linehan Stanton number relation[C-34] flashing: based on maximum of weighted heat-transfer factor and liquid superheat relation	heat-transfer factor equivalent to value calculated from basic flow-regime map	heat-transfer factor equivalent to value calculated from basic flow-regime map
Plug Flow	condensation: weighted average of flow-regime map, stratified, and plug-flow heat-transfer factors (plug-flow HTC is calculated from a constant Stanton number model)	heat-transfer factor equivalent to value calculated from basic flow-regime map	heat-transfer factor equivalent to value calculated from basic flow-regime map

TABLE C-7
TRAC CLOSURE RELATION SUMMARY:
FLOW-REGIME CRITERIA AND INTERFACIAL AREA
FOR REFLOOD APPLICATIONS

Flow Regime	Flow-Regime Criteria	Interfacial Area (A_i)
Reflood: Bubbly Flow	transition to IAF defined by mechanistic elevation model based on critical heat flux, film-boiling heat flux, and void fraction	defined as above
IAF	flow regime defined by mechanistic elevation models based on capillary number and limited by a range of void fractions	based on liquid core geometry
Dispersed Flow	flow regime defined by mechanistic elevation model based on capillary number and limited by a range of void fractions	superimpose droplet and film fields (similar to annular-mist flow regime); droplet area based on the droplet diameter defined by Kataoka[C-2] or Kitscha and Kocamustafaogullari;[C-3] film area based on geometry and the stable liquid film thickness
Low-Velocity, Vertical Flow	1D components; inclination ≥45 degrees; liquid temperature greater than saturated vapor temperature; gas velocity <0.1 m/s; maximum void fraction over three contiguous cells >0.50; cell void fraction <0.999	based on average cross-sectional area

TABLE C-8
TRAC CLOSURE RELATION SUMMARY: INTERFACIAL DRAG MODELS FOR REFLOOD APPLICATIONS

Flow Regime	Interfacial Drag Coefficient (c_i)
Reflood: Subcooled Boiling	composed of the drag coefficient from bubbles at the wall (based on the Colebrook turbulent friction factor) and by the drag coefficient from free-stream bubbles (based on Ishii[C-10])
Smooth IAF	based on smooth tube friction factor correlations (laminar and turbulent flow)
Rough-Wavy IAF	based on Colebrook friction factor for rough walls (relative roughness based on Ishii entrained droplet diameter[C-10])
Agitated IAF	same as rough-wavy IAF
Post-Agitated (Dispersed) Flow	weighted average of agitated IAF and highly dispersed interfacial drag coefficients
Highly Dispersed Flow	composed of separate droplet and film terms; droplet interfacial drag based on form drag of Ishii and Chawla[C-9] and on Ishii[C-10] droplet size; film interfacial drag based on modified Wallis friction factor (film thickness derived by Pasamehmetoglu[C-17])
Low Velocity, Vertical Flow	no specific model for interfacial drag

TABLE C-9
TRAC CLOSURE RELATION SUMMARY:
INTERFACIAL HEAT TRANSFER
FOR REFLOOD APPLICATIONS

Flow Regime	Interface-to-Liquid Heat-Transfer Coefficient (h_{il})	Interface-to-Gas Heat-Transfer Coefficient (h_{ig})	Liquid-to-Gas Sensible Heat-Transfer Coefficient (h_{gl})
Reflood: Bubbly Flow	cond/evap: weighted average of bubbly, IAF, and dispersed flow heat-transfer factors defined as above, this table	weighted average of bubbly, IAF, and dispersed flow heat-transfer factors defined as above, this table	weighted average of bubbly, IAF, and dispersed flow heat-transfer factors defined as above, this table
IAF	based on HTVSSL model for subcooled liquid kinetic theory of evaporation for flashing[C-35]	$3x10^3$ W/m^2-K	10^3 W/m^2-K
Dispersed Flow	heat-transfer factor equivalent to IAF value flashing: based on maximum of above evap/cond factor and liquid superheat relation	based on Unal[C-35] model	weighted average of Ryskin[C-33] and Bankoff[C-32] models

TABLE C-9 (cont)
TRAC CLOSURE RELATION SUMMARY:
INTERFACIAL HEAT TRANSFER
FOR REFLOOD APPLICATIONS

Flow Regime	Interface-to-Liquid Heat-Transfer Coefficient (h_{il})	Interface-to-Gas Heat-Transfer Coefficient (h_{ig})	Liquid-to-Gas Sensible Heat-Transfer Coefficient (h_{gl})
Low Velocity, Vertical Flow	weighted average of flow-regime map and low velocity, vertical flow heat-transfer factors (vertical flow factor based on pressurizer data assessment)	weighted average of flow-regime map and low velocity, vertical flow heat-transfer factors (vertical flow factor based on kinetic gas theory)	no modification
Effect of Noncondensables	evaporation: heat-transfer factor calculated by flow-regime-independent diffusion model condensation: heat-transfer factor adjusted using model of Sklover and Rodivilin[C-36]	no modification	no modification