LA-UR--97-3990

**TRAC-P Validation Test Matrix
(Draft)**

by

**E. D. Hughes and B. E. Boyack
Nuclear Systems Design and Analysis
Los Alamos National Laboratory
Los Alamos, NM**

**September 5, 1997
Revision 1.0**

DISTRIBUTION OF THIS DOCUMENT IS UNLIMITED

MASTER

DISCLAIMER

This report was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor any agency thereof, nor any of their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof.

DISCLAIMER

Portions of this document may be illegible electronic image products. Images are produced from the best available original document.

CONTENTS

	Page No.
Contents	iii
Acronyms	vi
Glossary	viii
Acknowledgments	x
Executive Summary	xi
Abstract	1-1
1.0. Introduction	1-1
1.1. Background	1-2
1.2. Document Objectives	1-2
1.3. Document Structure	1-2
2.0. Code Qualification Overview	2-1
2.1. Code Qualification Elements	2-1
2.2. Validation Test Matrix	2-4
2.4. Standard Test Matrix	2-4
2.5. Completeness Issues	2-5
3.0. TRAC Overview	3-1
3.1. Basic Equation Models	3-1
3.2. Flow Field Models and Engineering Correlations (Closure)	3-3
3.3. Equipment Component Models	3-4
3.4. Special-Purpose Models	3-5
3.5. Numerical Solution Methods	3-5
3.6. Current TRAC-P Qualification Status	3-6
4.0. PIRT Overview	4-1
4.1. PIRT Concepts and Utility	4-1
4.2. PIRT Library	4-2
4.3. Summary Findings	4-2
4.4. Application to TRAC Qualification	4-3
5.0. Code Qualification—Validation Using Other Standard Tests	5-1
5.1. Features Tests	5-1
5.2. Equilibrium Problems	5-2
5.3. Concept Problems	5-4
5.4. Analytical Problems	5-5
5.4.1. Basic Equation Models	5-6
5.4.2. Equipment Component and Special Purpose Models	5-8
5.5. Numerical Methods Test Problems	5-9
5.6. Validation Test Matrix - Validation Using Other Standard Tests	5-10
6.0. Code Qualification - Validation Using Separate Effect Test Data	6-1
6.1. Data Characterization	6-1
6.2. Existing TRAC-P and RELAP5 Models	6-2
6.3. Data Sources	6-2
6.4. Data Selected for the TRAC Validation Matrix	6-14
6.4.1. Selection Based On PIRT Summary	6-14
6.4.2. Selection Based On TRAC Models and Methods	6-21
6.5. Summary Observations	6-22

CONTENTS (cont)

7.0.	Code Qualification - Validation Using Integral Effect Test Data.....	7-1
7.1.	Data Characterization	7-1
7.2.	Data Sources	7-2
7.3.	Data Selected for TRAC Qualification.....	7-5
	7.3.1. IET Selection Based on PIRT Summary.....	7-5
	7.3.2.IET Selection Based on Targeted Application Coverage.....	7-6
	7.3.3.IET Selection Based on Scaling Issues.....	7-8
7.4.	Summary.....	7-9
8.0.	Summary Observations.....	8-1
Appendices		
A.	Validation Success Metrics	A-1
B.	Additional Perspectives - Separate Effect and Integral Effect Tests.....	B-1
C.	The Models and Methods in TRAC.....	C-1
D.	Additional Summary PIRT Tabulations	D-1
E.	Other Standard Test Problem Specification Examples.....	E-1
F.	Expanded Listing of TRAC-P Decks for Separate Effect Tests	F-1
G.	Expanded Listing of TRAC-P Decks for Integral Effect Tests.....	G-1
H.	Summary Description of IET Facilities	H-1

FIGURES

1-1	Components of NRC's Thermal-Hydraulic Research Plan.....	1-3
2-1	Code Qualification Overview.	2-7
2-2	Spectrum of SET and IET Facilities	2-8
2-3	Information Sources Supporting Creation of the Acceptance Test Matrix.	2-9

TABLES

3-1	TRAC Elements by Category, Subcategory, and Model.....	3-9
4-1	Summary Tabulation of Processes/Phenomena.....	4-5
4-2	PIRT Process/Phenomenon Descriptions.....	4-8
5-1	Features Test Problems.....	5-2
5-2	Equilibrium Test Problems.....	5-3
5-3	Concept Test Problems.....	5-5
5-4	Analytical and Numerical Methods Test Problems.....	5-11
5-5	Validation of TRAC-P Using Other Standards.....	5-12
6-1	TRAC-P Input Decks for Separate Effect Tests.....	6-3
6-2	Separate Effect Test Facility Summary.....	6-5
6-3	Identification of TRAC-P Validation Data Sets.....	6-15
6-4	Summary Tabulation of Local Level Processes/Phenomena.....	6-18
6-5	Validation of TRAC-P Using Separate Effect Data.....	6-33
7-1	TRAC-P Input Decks for Integral Effect Tests.....	7-2
7-2	OECD/CSNI Integral Effect Test Facility Summary.....	7-3
7-3	PIRT Identified Processes/Phenomena Requiring IET Data.....	7-7
7-4	Facilities and Tests for PIRT Identified Processes/Phenomena Requiring IET Data.....	7-8
7-5	Summary of Vendor and Reactor Types.....	7-9
7-6	Event Scenarios and Applicable IET Tests.....	7-10
7-7	Summary of IET facilities and Tests.....	7-11
C-1	TRAC Closure Relations Summary: Flow-Regime Criteria and Intefacial Area for Non-Reflood Applications.....	C-11
C-2	TRAC Closure Relations Summary: Intefacial Mass Transfer.....	C-12
C-3	TRAC Closure Relations Summary: Wall Drag.....	C-13
C-4	TRAC Closure Relations Summary: Interfacial Drag for Non-Reflood Applications.....	C-14
C-5	TRAC Closure Relations Summary: Wall-to-Fluid Heat Transfer for Both Reflood and Non-Reflood Applications.....	C-15
C-6	TRAC Closure Relations Summary: Interfacial Heat Transfer for Non-Reflood Applications.....	C-16
C-7	TRAC Closure Relations Summary: Flow-Regime Criteria and Interfacial Area for Reflood Applications.....	C-18
C-8	TRAC Closure Relations Summary: Interfacial Drag Models for Reflood Applications.....	C-19
C-9	TRAC Closure Relations Summary: Interfacial Heat Transfer for Reflood Applications.....	C-20
D-1	Phenomena/Processes for Typical High Importance in Prior PIRT Applications.....	D-3
D-2	Phenomena/Processes for Typical Moderate Importance in Prior PIRT Applications.....	D-4
D-3	Relative Importance of Components in Prior PIRT Applications.....	D-5
D-4	Comparison of High and Moderate Importance Processes/Phenomena and TRAC Models.....	D-6
F-1	TRAC-P Input Decks for Separate Effect Tests.....	F-1
F-2	RELAP5 Input Decks for Separate Effect Tests.....	F-2
G-1	TRAC-P Input Decks for Integral Effect Tests.....	G-1
H-1	IET Facility Summary.....	H-2

ACRONYMS

1D	One dimensional
2D	Two dimensional
3D	Three dimensional
ADS	Automatic depressurization system
ANO	Arkansas Nuclear One
ATWS	Anticipated transient without scram
BCL	Battelle Columbus Laboratories
B&W	Babcock & Wilcox
BEM	Basic equation models
BETHSY	Boucle d'Etudes Thermohydrauliques Système
BWR	Boiling water reactor
CCFL	Countercurrent flow limiting
CCTF	Cylindrical Core Test Facility
CE	Combustion Engineering
CHF	Critical heat flux
CISE	Centro Informazioni Studi Esperienze
CL	Component level
CLB	Cold-leg break
CMT	Core makeup tank
CSAU	Code scaling, applicability, and uncertainty
CSNI	Committee on the Safety of Nuclear Installations
CU	Columbia University
DOEL	(392 MWe PWR/Belgium)
ECCS	Emergency Core coolant system
ECM	Equipment component models
ECN	Energieonderzoek Centrum Nederland
EOS	Equation of state
EPRI	Electric Power research Institute
FFEC	Flow-field models and engineering correlations
FLECHT-	Full Length Emergency Cooling Heat Transfer-Separate Effects And
SEASET	Systems Effects Test
GDCS	Gravity-driven cooling system
GE	General Electric
GERDA	Geradrohr Dampferzeuger Anlage
IET	Integral effect test
INEL	Idaho National Engineering Laboratory
IRWST	In-containment refueling water storage tank
ISP	International Standard Problem
KWU	Kraftwerk Union
LANL	Los Alamos National Laboratory
LB	Large break
LOBI	Loop for Blowdown Investigation, or
	Loop for off-Normal Behaviour Investigations
LOCA	Loss-of-coolant-accident
LOFT	Loss-of-fluid test
LL	Local level
LSTF	Large Scale Test Facility
MIST	Multi-loop Integral System Test
MIT	Massachusetts Institute of Technology
MOD1	TRAC-PF1/MOD1

ACRONYMS (cont)

MOD2	TRAC-PF1/MOD2
MSLB	Main steam line break
NCG	Noncondensable gas
NASA	National Aeronautics and Space Administration
NEA	Nuclear Energy Agency
NRC	United States Nuclear Regulatory Commission
NSM	Numerical solution methods
ODE	Ordinary differential equation
OECD	Organization for Economic Co-operation and Development
OFI	Onset of Flow Instability
ONB	Onset of Nucleate Boiling
OSV	Onset of Significant Voiding
OTIS	Once-Through Integral Systems
OTSG	Once-through steam generator
PIRT	Phenomena identification and ranking table
PKL	Primarkreislaufe
PRHR	Passive residual heat removal
P/V	Power/volume
PWR	Pressurized water reactor
RIT	Royal Institute of Technology
ROSA	Rig of Safety Assessment
SB	Small break
SCTF	Slab Core Test Facility
SET	Separate effect test
SETS	Stability enhancing two-step method
SGTR	Steam generator tube rupture
SL	System level
SPES	Simulatore PWR per Esperienze di Sicurezza
SPM	Special-purpose models
SRL	Savannah River Laboratory
T-H	Thermal-hydraulic
THTF	Thermal Hydraulic Test Facility
TRAC	Transient reactor analysis code
TRAC-B	TRAC-boiling water reactor version
TRAC-P	TRAC-Pressurized water reactor version
UC	University of California
UCSB	University of California at Santa Barbara
UMCP	University of Maryland, College Park
UPTF	Upper Plenum Test Facility

GLOSSARY

Formal Code Release	Release of a fully-qualified code and associated documentation.
Integral Effect Tests	Integral effect tests generally investigate (1) a process that occurs in one or more physical systems or (2) behavior in a full nuclear power plant, either in a reduced-scale facility or in a full-size plant.
Interim Version	An internal development version of the code that has been tested against the Standard Test Matrix and any additional specific tests needed to test features of the interim code version not previously tested.
Qualification	Code qualification is the outcome of specific software life-cycle activities, specifically, (1) Requirements Definition, (2) Design, (3) Implementation, and (4) Qualification Testing as defined in the NRC's Software Quality Assurance Documentation (see Ref. 2-1).
Separate Effect Tests	Experiments in which a very limited number of physical phenomena are of interest 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.
Standard Test Matrix	A subset of the Validation Test Matrix which is used to demonstrate the adequacy of interim versions of the code.
Validation	The process of testing a computer program by comparing code-calculated results to reference data consisting of either experimental data standards or other standards not employing experimental data.
Validation - direct	Data can be used directly to validate a specific TRAC-P category, subcategory, or model because the effect of a single process/phenomenon to which the model applies is dominant in the data.
Validation - indirect	Data can be used to validate a specific TRAC-P category, subcategory, or model but only indirectly because the effect of a single process/phenomenon to which the model applies is not dominant in the data.
Validation Test Matrix	The set of separate effect, integral effect, and other standard tests selected to ensure that all important code features, models, and integrated calculational capabilities are tested. The code is tested using the Validation Test Matrix before a formal code release.

GLOSSARY (cont)

Verification

Verification is the process 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.

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. We also express appreciation to Gloria Mirabal for editing this document

EXECUTIVE SUMMARY

E. D. Hughes and B. E. Boyack
Nuclear Systems Design and Analysis
Los Alamos National Laboratory
Los Alamos, NM

INTRODUCTION

This document briefly describes the elements of the Nuclear Regulatory Commission's (NRC's) software quality assurance program leading to software (code) qualification and identifies a test matrix for qualifying Transient Reactor Analysis Code (TRAC)-Pressurized Water Reactor Version (-P), or TRAC-P, 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) Qualification Testing. The major objective of this document is to define the TRAC-P Qualification Testing effort.

WORKING CONCEPTS

We first present several concepts that are important to the following discussion.

Qualification Testing: The process that allows the sponsor to determine whether a software product complies with its requirements. Qualification 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. Taken together, Verification and Validation constitute Qualification Testing.

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

Validation: The process of demonstrating that as-built software satisfies its requirements; testing is the primary method of software validation. The validation portion of the qualification testing is the subject of this document.

TRAC-P Validation Test Matrix: The set of separate effect tests (SETs), integral effect tests (IETs), and other standard tests (OSTs) selected to ensure that all important code features, models, and integrated calculational capabilities are tested. To ensure completeness, we have taken three structured approaches to identify the individual tests to be included in the TRAC-P Validation Test Matrix. First, we have identified the basic equations models, flow-field models and engineering correlations, equipment component models, and special-purpose models in TRAC-P that must be

validated. Second, we have identified local, component and system level processes and phenomena that must be modeled by TRAC-P. Third, we have identified the set of targeted applications associated with plant type and event scenarios that must be modeled.

The TRAC-P Code

The TRAC-P 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 (CCFL) and critical flow (for example).

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

The contents of these basic 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 were reviewed and summarized to develop a generalized PIRT for PWR applications. The individual phenomena entries in the summary PIRT were correlated with the TRAC-P models and methods. The summary PIRT is presented in Section 4. The correlation of the summary PIRT and TRAC-P models and methods is also presented in Section 4.

CODE VALIDATION

We have subdivided the validation element into three subelements: validation tests using standards other than those that employ experimental data from OSTs,

validation tests comparing code-calculated results with data from SETs, and validation tests comparing code-calculated results with data from IETs.

Validation Using OSTs. This subelement 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-P are presented in Section 5 of this report.

Validation Using SETs. 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. 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-P are presented in Section 6 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 thermal-hydraulic code for its targeted applications. The IET data recommended for validation of TRAC-P are presented in Section 7 of this report.

TRAC-P VALIDATION TEST MATRIX

Given the three-coverage-element approach used to develop the TRAC-P Validation Test Matrix, we have not devised a single table that summarizes the entire test matrix. The test matrix is found in several tables as summarized below.

Relative to previous TRAC validation matrices, the TRAC Validation Test Matrix presented in this document places a much greater emphasis on validating individual TRAC models and methods using SET data, particularly fundamental test data.

There are TRAC-P 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.

Previous efforts to identify and select SET data for TRAC-P validation focused on test data generated through association with the nuclear industry. We have identified and included other sources of fundamental SET data in the TRAC-P Validation Test Matrix. It is likely that additional sources of such fundamental SET

data exist. These should be sought and added as the TRAC-P Validation Test Matrix is revised and updated.

TRAC-P VALIDATION TEST MATRIX SUMMARY

Coverage Element	Validation Element	Table
TRAC Models and Methods	OSTs	5-5
	SET Data	6-5
Phenomena and Processes	SET Data	6-4
	IET Data	7-4
Targeted Applications	IET Data	7-6

Sufficient IET data exist for validation of the integrated TRAC-P code.

A summary of the SET and IET facilities recommended for TRAC-P validation is provided below. Because some of the fundamental SET tests recommended may be relatively unfamiliar, we have pointed to the source of a brief description of each SET and IET test.

IET AND SET FACILITIES SUMMARY FOR TRAC VALIDATION

Facility	Type	Described In	Facility	Type	Described In
Akimoto Condensation	SET	Table 6-2	LOFT	SET	Table 6-2
Anderson-Benedetti Horizontal Entrainment	SET	Table 6-2	LOFT Valve/Wyle	SET	Table 6-2
Attou Expansion	SET	Table 6-2	LSTF (aka ROSA)	IET	Table 7-2
Azzopardi Horizontal Entrainment	SET	Table 6-2	LSTF-AP600	IET	Table 7-2
Babcock & Willcox (B&W) Condensation	SET	Table 6-2	Maciaszek Horizontal Entrainment	SET	Table 6-2
Battelle Columbus Laboratories (BCL) Emergency Core Cooling (ECC)/Core Steam Flow	SET	Table 6-2	Marviken	SET	Table 6-2
Bennett Annulus	SET	Table 6-2	MB-2 Steam Generator	SET	Table 6-2
Bennett Tube	SET	Table 6-2	Multi-loop Integral System Test (MIST)	IET	Table 7-2
BETHSY	IET	Table 7-2	Massachusetts Institute of Technology (MIT) Pressurizer	SET	Table 6-2
Bibeau Void Growth	SET	Table 6-2	Mod1 Pump Characterization	SET	Table 6-2
Carofano-McManus Critical Flow	SET	Table 6-2	Mudde Horizontal Entrainment	SET	Table 6-2

IET AND SET FACILITIES SUMMARY FOR TRAC VALIDATION (cont)

Facility	Type	Described In	Facility	Type	Described In
Celata CCFL	SET	Table 6-2	National Aeronautics and Space Administration (NASA) Condensation	SET	Table 6-2
Celata Direct Contact Condensation	SET	Table 6-2	Neussen Critical Flow	SET	Table 6-2
Celata Onset of Nucleate Boiling (ONB)	SET	Table 6-2	Northwestern Condensation	SET	Table 6-2
CISE Blowdown	SET	Table 6-2	Purdue Low Flow	SET	Table 6-2
Columbia University (CU) Rod Bundle	SET	Table 6-2	Reimann Horizontal Entrainment	SET	Table 6-2
Costigan Flow Map	SET	Table 6-2	Rinne Expansion	SET	Table 6-2
CU Low Flow Friction	SET	Table 6-2	Rogers Onset of Significant Voiding (OSV)	SET	Table 6-2
Cumulus Critical Flow	SET	Table 6-2	Rig of Safety Assessment (ROSA)	SET	Table 6-2
Dartmouth Counter-current Flow	SET	Table 6-2	Ruile Stratified Condensation	SET	Table 6-2
de Bertodano Annular Flow	SET	Table 6-2	Schmidt Local Loss	SET	Table 6-2
de Bertodano CCFL	SET	Table 6-2	Schrock-Grossman	SET	Table 6-2
Deich Critical Flow	SET	Table 6-2	Slab Core Test Facility (SCTF)	IET	Table 7-2
Delhaye Interfacial Area	SET	Table 6-2	Shilimkan Interfacial Area	SET	Table 6-2
Dukler-Smith CCFL	SET	Table 6-2	Shippingport Pressurizer	SET	Table 6-2
Energieonderzoek Centrum Nederland (ECN) Reflood and Boildown	SET	Table 6-2	Shoukri Subcooled Boiling	SET	Table 6-2
Electric Power Research Institute (EPRI) Air-Water Pressure Drop	SET	Table 6-2	Siddique Condensation	SET	Table 6-2
Ferrell-McGee Local Loss	SET	Table 6-2	Sjoberg Dryout	SET	Table 6-2
Fincke-Collins Critical Flow	SET	Table 6-2	Smoglie Horizontal Entrainment	SET	Table 6-2
FLECHT-SEASET	SET	Table 6-2	Sozzi-Sutherland	SET	Table 6-2
FRIGG Void	SET	Table 6-2	Savannah River Laboratory (SRL) C-reactor	SET	Table 6-2
General Electric (GE) Level Swell	SET	Table 6-2	SRL Local Loss	SET	Table 6-2
GE Separator/Dryer	SET	Table 6-2	SRL Low Flow Friction	SET	Table 6-2
Hein Condensation	SET	Table 6-2	Super Moby Dick	SET	Table 6-2

IET and SET Facilities Summary for TRAC Validation (cont)

Facility	Type	Described In	Facility	Type	Described In
Idaho National Engineering Laboratory (INEL) Tube	SET	Table 6-2	THETIS Boiloff	SET	Table 6-2
Iwamura Cross Flow	SET	Table 6-2	Thermal Hydraulic Test Facility (THTF) Boiloff	SET	Table 6-2
Kalkachnavarro Interfacial Area	SET	Table 6-2	University of California (UC)-Berkeley Reflood	SET	Table 6-2
Lehigh Post-Critical Heat Flux Bundle	SET	Table 6-2	UC at Santa Barbara (UCSB) Condensation	SET	Table 6-2
Leung Interfacial Area	SET	Table 6-2	Upper Plenum Test Facility (UPTF)	IET	Table 7-2
Liu-Winterton	SET	Table 6-2	VAPORE Critical Flow	SET	Table 6-2
Loop for Blowdown Investigation (LOBI)	IET	Table 7-2	Zeitoun Interfacial Area	SET	Table 6-2
Loss-of-Fluid Test (LOFT)	IET	Table 7-2			

TRAC-P VALIDATION TEST MATRIX

E. D. Hughes and B. E. Boyack
Nuclear Systems Design and Analysis
Los Alamos National Laboratory
Los Alamos, NM

ABSTRACT

This document briefly describes the elements of the Nuclear Regulatory Commission's (NRC's) software quality assurance program leading to code qualification, describes the current status of Transient Reactor Analysis Code (TRAC)-Pressurized Water Reactor Version (-P), or TRAC-P, qualification for the current release version, and identifies and proposes specific tests for TRAC-P qualification to satisfy the requirements of the NRC's software quality assurance program. Qualification Testing is the set of activities associated with formally testing, reviewing, and analyzing software performance. Taken together, verification and validation constitute Qualification Testing.

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 validation element into three subelements: validation tests using standards other than those that employ experimental data (other standard tests), validation tests comparing code-calculated results with data from Separate Effect Tests, and validation tests comparing code-calculated results with data from Integral Effect Tests. The set of tests identified above constitute the TRAC-P Validation Test Matrix.

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, both envisioned and realized, for T-H codes, it is important that they be qualified for their intended applications. Qualification 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.¹⁻¹

1.2. Document Objectives

The objectives for this document are as follows:

- Briefly describe the elements of the NRC's software quality assurance program¹⁻² leading to code qualification,
- Describe the status of TRAC-P code qualification for the current release version (TRAC-PF1/MOD2, version 5.4.28), and
- Identify and propose specific tests for TRAC-P qualification that satisfy the requirements of the NRC's software quality assurance program.* The set of tests thus identified constitute the TRAC-P Validation Test Matrix.

1.3. Document Structure

The report contains eight 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.

* The NRC's development plan described in Ref. 1-1 and shown in Fig. 1-1 of this document begins with work in the Code Architecture component by restructuring (modernizing) the TRAC-P database. The specific tests proposed in the initial release of this document will qualify the code for PWR targeted applications. However, the structure of this report facilitates a later extension of the document to include test problems for boiling water reactor (BWR) targeted applications.

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 of TRAC-P, including the current status of TRAC-P relative to the code qualification process. Section 4 provides a summary Phenomena Identification and Ranking Table (PIRT) for the processes/phenomena expected to occur during a spectrum of pressurized water reactor (PWR) accidents. Each process/phenomenon is cross-correlated to the appropriate TRAC-P model previously defined in Section 3. Sections 5-7 identify the tests selected for the TRAC-P Validation Test Matrix. Section 5 contains tests using standards other than those that employ experimental data. Section 6 identifies the separate effect test (SET) data selected for the TRAC-P Validation Test Matrix. Section 7 identifies the integral effect test (IET) data selected for the TRAC-P Validation Test Matrix. Summary observations are provided in Section 8.

REFERENCES

- 1-1. F. Eltawila, J. Kelly, and D. Bessette, "Thermal-Hydraulics Research Plan," US Nuclear Regulatory Commission presentation to the Advisory Committee on Reactor Safeguards, Rockville, Maryland (October 11, 1996).
- 1-2. 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

2.0. CODE QUALIFICATION OVERVIEW

Qualification testing is the process that allows the sponsor to determine whether a software product complies with its requirements.²⁻¹ Qualification testing demonstrates and assures 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 Elements

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

The life-cycle activities covered in Ref. 2-1 and shown in Fig. 2-1 assume creation and qualification of an entirely new code. Clearly, that is not the case for TRAC-P. Nevertheless, all the life-cycle activities leading to code qualification will be described briefly here. The current status of TRAC-P within its software life-cycle is discussed in Section 3.6.

Requirements Definition, Design, and Implementation. The life-cycle activities that proceed Qualification Testing for a new code are Requirements Definition, Design, and Implementation.

- *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 correct, complete, verifiable, consistent, and technically feasible
- *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.

The documentation that accompanies these three software life-cycle activities is shown in Fig. 2-1 and is described further in Ref. 2-1.

Qualification Testing is the set of activities associated with formally testing, reviewing, and analyzing software performance. Taken together, Verification and Validation constitute Qualification Testing.²⁻¹ The software is formally tested using test cases identified in the verification and validation documentation relative to the requirements defined in the software requirements document. The verification efforts are not detailed in this report, although a brief description of verification activities follows for completeness. The remainder of this document focuses on the validation effort.

- *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. Testing is the primary method of software validation. The objectives of validation are to ensure that²⁻¹
 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 element into three subelements: validation tests using standards other than those that employ experimental data [other standard tests (OSTs)], validation tests comparing code-calculated results with data from Separate Effect Tests (SETs), and validation tests comparing code-calculated results with data from Integral Effect Tests (IETs). The major portion of this document is dedicated to the validation subset of the Qualification Testing effort. Specifically, this document provides a detailed description of the OSTs, SETs, and IETs that comprise the Validation Test Matrix.

Validation Using OSTs. This subelement 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. 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.²⁻²

Validation Using SETs. This subelement 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 (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.* The Organization for Economic Co-operation and Development (OECD), Nuclear Energy Agency (NEA), Committee on the Safety of Nuclear Installations (CSNI) has produced the most comprehensive review of SETs facilities.²⁻³ The primary use of data from SETs is to assess the adequacy of the closure relationships used in the code. These data are also 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) loss-of-coolant-accident (LOCA) analyses.²⁻⁴ 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 IETs. This subelement of validation contributes to code qualification by comparing code-calculated results with data from IETs, including transients measured in real plants. Integral Effect Tests 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 code qualification efforts. First, comparisons to IET data are necessary to assess the capability of T-H codes to predict system-

* The boundary between SETs and IETs is subject to interpretation. The same facility, for example, may in different configurations be reasonably characterized as a SET facility for one configuration and an IET for another. The FLECHT-SEASET facility configured for forced reflood is an example of the former, whereas the same facility configured for gravity reflood is an example of the latter. Whereas such distinctions are made in this report, the key objective is to ensure that all applicable SETs and IETs facilities are considered and accurately evaluated to determine whether they should be included in the TRAC-P Validation Test Matrix.

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.²⁻⁵

Deficiencies exist in the current TRAC-P code.²⁻⁶ Some 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 qualification 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 SBLOCA analyses.²⁻⁴ 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 Qualification 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-P Validation Test Matrix, as shown in Fig. 2-3. These include information about the TRAC-P models and information about processes and phenomena occurring during plant events and accidents. The former are discussed in Section 3 and the latter are discussed in Section 4. The various test problems and experimental data needed to complete the Validation Test Matrix are discussed in Sections 5 through 7.

A Formal Release Version of the code, i.e., release of a fully-qualified code and associated documentation, should always 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 two years between formal releases is probably the minimum with the norm approaching three years.

2.3. 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-P Validation Test Matrix optimized in some manner (see Section 2.4) 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.

2.4. Completeness Issues

An important goal to be attained in developing the TRAC-P 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-P Validation Test Matrix contains problems that represent all 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 4.

A second ideal of completeness is that the TRAC-P 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 both individual problems within either the TRAC-P 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 only be obtained by exercising (running) the code for each of the specific tests within the Validation Test Matrix.

REFERENCES

- 2-1. *Software Quality Assurance Program and Guidelines*, US Nuclear Regulatory Commission Document NUREG/BR-0167 (February 1993).

* 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 tested and what parts were not tested.

- 2-2. P. F. Peterson, "A Method for Predicting and Minimizing Numerical Diffusion," *Numerical Heat Transfer*, Part B, V. 21, pp. 343-366 (1992).
- 2-3. 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).
- 2-4. 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).
- 2-5. CSNI Integral Test Facility Validation Matrix for the Assessment of Thermal-Hydraulic Codes for LWR LOCA and Transients, Committee on the Safety of Nuclear Installations OECD Nuclear Energy Agency report CSNI 132, Rev. 6, restricted working draft (June 1995).
- 2-6. B. E. Boyack, "TRAC-PF1/MOD2 Adequacy Assessment—Closure and Special Models," Los Alamos National Laboratory draft document LA-UR-97-232 (February 21, 1997).

DRAFT

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

Fig. 2-1. Code Qualification Overview*

DRAFT

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

DRAFT

Fig. 2-3. Information sources supporting creation of the Validation Test Matrix.

3.0. TRAC OVERVIEW

TRAC-P³⁻¹ 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-P is used by government and industry for design and safety analysis, phenomenological studies, operational transient analysis, evaluating emergency operating procedures, simulator support and operator training, and for assessing data involving basic experiments, separate-effects tests, and plant operations. TRAC-P will calculate fluid flow involving gas, liquid, and mixture states in one-dimensional (1D) and three-dimensional (3D) rectilinear and cylindrical coordinates.

The TRAC-P computer code can be viewed as being based on two major theoretical parts. The first part 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 part is the numerical solution methods applied to the mathematical models. All aspects of both parts of TRAC-P 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 (BEM),
2. flow-field models and engineering correlations (FFEC),
3. equipment-component models (ECM), and
4. special-purpose models (SPM).

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

3.1. Basic Equation Models

The BEM category in TRAC-P 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
 Fluid thermophysical and transport properties.

Several of the subcategories are further subdivided 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 PIRT processes/phenomena to TRAC-P models. This format is also used in Sections 5 and 7 to cross-correlate experimental data and other standards with the models and methods.

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-P Fill component is used to apply a specified fluid velocity or flow at a boundary link, and a TRAC-P Break component is used to specify the pressure at a boundary.

The heat conduction model includes both 1D and two-dimensional (2D) formulations for both rectangular and cylindrical solid structures. The 2D form is generally 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 as follows: (1) the power can be specified by the user, (2) the power can be modeled as point-kinetics decay heat, or (3) the power can be modeled by 3D neutron kinetics. The latter modeling capability is available in an non-NRC-sponsored TRAC-P version. 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-P 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-P 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; 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-P code.

The FFEC category in TRAC-P 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 further subdivided 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 processes/phenomena to TRAC-P models. This format is also used in Sections 5 and 7 to cross-correlate experimental data and other standards with the models and methods.

In numerous cases there are additional sublevels for the FFEC models listed in Table 3-1. For completeness, these lower level models are tabulated in Table C-1 through Table C-6 in Appendix C. The information in Table 3-1 and Appendix C are

extracted from Ref. 3-2. Verification and validation of TRAC-P will ultimately 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-P.

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

Centrifugal pumps (Pump 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-P models.

3.4. Special-Purpose Models

The SPM category in TRAC-P 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
 Fuel-cladding gap conductance

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

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

3.5. Numerical Solution Methods

All the mathematical models in the TRAC-P 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-P includes the following subcategories:

Fluid field equations including
 1D stability enhancing two-step (SETS) method,
 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
 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 further subdivided 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-P models.

3.6. Current Qualification Status

The TRAC-P code has been under development at Los Alamos National Laboratory (LANL) 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-P 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-P 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-P 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,^{3-1, 3-2, 3-3, 3-4, 3-5} but several of the key documents have remained in draft form for several years.^{3-1, 3-5}

Qualification Testing—Verification. Some verification has occurred during the years of TRAC-P development as documents such as the theory manual³⁻¹ and adequacy assessment document³⁻² 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-P by the Advisory Committee on Reactor Safeguards, Reactor Safeguards Subcommittee on Thermal Hydraulic Phenomena occurred January 20–21, 1988.

Qualification Testing—Validation Using Other Tests. This type of validation of TRAC-P 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. The SET data used as part of the developmental assessment of TRAC-PF1/MOD2, version 5.4, which dated from 1993 are as follows:³⁻⁵ 1D radial and 2D radial and axial steady-state conduction problems, 1D drain and fill problems, and a U-tube problem. The set of such problems currently used in TRAC-P validation efforts are contained in the present 42-problem Standard Test Set.³⁻⁶ Code calculations of several analytical problems are also reported in the developmental assessment manual for TRAC-P³⁻⁵ (TRAC-PF1/MOD2, version 5.4). The number of validation-using-other-tests test problems will be expanded as new problems are identified for the Validation Test Matrix.

Qualification Testing—Validation Using Separate Effect Tests. Various SET data have been used throughout the TRAC-P development history. However, these constitute, at best, a sparse subset of the SET validation (fundamental, component, and several components) needed to fully qualify TRAC-P for its targeted applications. The SET data used as part of the developmental validation of TRAC-PF1/MOD2, version 5.4, which dated from 1993 are as follows:³⁻⁵ CCFL using Bankoff data, condensation model using Akimoto's data, critical flow model using Marviken data, core reflood model using Lehigh and Berkeley tube data, multiple models using Upper Plenum Test Facility (UPTF) Tests 6 and 8, and Cylindrical Core Test Facility (CCTF) Run 14.

For the last two decades, the majority of validation testing performed for TRAC-P has used IET data. While this extensive body of IET validation has shown that TRAC-P 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.

Qualification Testing—Validation Using Integral Effect Tests. As stated in the previous paragraph, numerous validations of various versions of TRAC-P 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,³⁻⁷ extrapolation of MOD1 assessments to the MOD2 code is problematic. The IET tests used as part of the developmental assessment of TRAC-PF1/MOD2, version 5.4, which dated from 1993 are as follows:³⁻⁵ Loss-of-Fluid Tests (LOFT) L2-6 and L6-1, CCTF Run 54, and Slab Core Test Facility (SCTF) Run 719.

In summary, qualification efforts for the present TRAC-P code constitute a modest fraction of the qualification testing envisioned by NRC's current software quality assurance program and guidelines.³⁻⁸ The Validation Test Matrix, which is defined in subsequent sections of this report, is designed to fulfill the requirements of the NRC guidelines

REFERENCES

- 3-1. 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 draft document (July 21, 1993).
- 3-2. B. E. Boyack, "TRAC-PF1/MOD2 Adequacy Assessment: Closure and Special Models," Los Alamos National Laboratory document LA-UR-97-232 (February 21, 1997).
- 3-3. N. M. Schnurr, R. G. Steinke, V. Martinez, and J. W. Spore, "TRAC-PF1/MOD2 Code Manual: User's Guide," Los Alamos National Laboratory document NUREG/CR-5673, Volume 2 (July 1992).
- 3-4. L. A. Guffee, S. B. Woodruff, R. G. Steinke, and J. W. Spore, "TRAC-PF1/MOD2 Programmer's Guide," Los Alamos National Laboratory NUREG/CR-5673, Volume 3 (July 1992).
- 3-5. J. C. Lin, V. Martinez, and J. W. Spore, "TRAC-PF1/MOD2 Developmental Assessment Manual," Los Alamos National Laboratory draft report (August 1993).
- 3-6. R. G. Steinke, "A Description of the Test Problems in the TRAC-P Standard Test Matrix," Los Alamos National Laboratory document LA-UR-96-1465 (May 1996).
- 3-7. P. Giguere, "Comparison of the TRAC-PF1/MOD1 and MOD2 Computer Programs," Los Alamos National Laboratory document LA-UR-96-2220 (1996).
- 3-8. *Software Quality Assurance Program and Guidelines*, US Nuclear Regulatory Commission document NUREG/BR-0167 (February 1993).

DRAFT

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

Category	Subcategory		Model
	No.	Description	
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	As in the Fluid Mass, Fluid Momentum, Fluid Energy and Noncondensable Gas and Liquid Solute models.

DRAFT

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

Category	Subcategory		Model
	No.	Description	
BEM (continued)	6	Heat conduction equation	Lumped-capacitance model 1D radial 2D radial plus axial Reflood implicit Fuel-clad gap Metal-water reaction Material properties
	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

DRAFT

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

Category	Subcategory		Model
	No.	Description	
FFEC	1	Regime maps (Also see Appendix A, Table A-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 A, Table A-2)	Referenced at subcategory level
	2b	Interfacial mass exchange (Also see Appendix A, Table A-2)	Referenced at subcategory level
	2c	Solute mass exchange (Also see Appendix A, Table A-2)	Referenced at subcategory level
	3	Fluid momentum equation closure (momentum exchange)	
	3a	Wall-to-phase momentum exchange (Also see Appendix A, Table A-3)	Single phase Two phase, homogeneous Two phase, horizontal stratified

DRAFT

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

Category	Subcategory		Model
	No.	Description	
FFEC (continued)	3b	Interfacial momentum exchange (Also see Appendix A, Table A-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 A, Table A-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

DRAFT

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

Category	Subcategory		Model
	No.	Description	
FFEC (continued)	4b	Interfacial energy exchange (Also see Appendix A, Table A-6)	Bubbly flow Bubbly slug transition Bubbly slug flow Churn flow Annular-mist flow Transition to stratified flow Stratified flow Plug flow Effect of noncondensibles
	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

DRAFT

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

Category	Subcategory		Model
	No.	Description	
SPM (continued)	4	Reflood heat transfer models	
	4a	Flow regime modeling (Also see Appendix A, Table A-3)	Bubbly flow Inverted annular flow Dispersed flow
	4b	Wall-to-phase fluid drag (Also see Appendix A, Table A-3)	Single phase Two phase Homogeneous
	4c	Interfacial fluid drag (Also see Appendix A, Table A-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 A, Table A-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

DRAFT

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

Category	Subcategory		Model
	No.	Description	
SPM (continued)	4	Reflood heat transfer models (continued)	
	4e	Interfacial fluid heat transfer (Also see Appendix A, Table A-9)	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	
		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

DRAFT

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

Category	Subcategory		Model
	No.	Description	
NSM (continued)		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

Process 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 thermal-hydraulic 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 processes/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 convenient 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 processes/phenomena that influence the course of the scenario. Second, there is a presumption that all such components and processes/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 processes/phenomena more strongly affect the course of the scenario than others. In fact, some components and processes/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 process/phenomenon. The same can be said, therefore, 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 processes/phenomena occurring at three

levels: local, component, and system. Processes/phenomena occurring at the local level are naturally associated with SET data sets (Fig. 2-1), whereas processes/phenomena occurring at the system level are naturally associated with IET data sets. Processes/phenomena occurring at the component level are associated with either SET or IET data sets on a case-by-case basis.

4.2. PIRT Library

The first PIRT was completed in 1989.⁴⁻¹ Since that time, a number of additional PIRTs have been completed for PWRs and boiling water reactors (BWRs); these constitute the applicable PIRT library for this report. The contents of the PWR and BWR PIRT library are identified in the following tabulation. PIRTs have also been developed for other reactor types;⁴⁻² however, these are not included in the PWR and BWR PIRT library nor are they discussed further in this report.

Plant	Scenario	Citation
Westinghouse 4-Loop PWR	Large-Break LOCA	4-1
Westinghouse AP600	Large-Break LOCA	4-3
Westinghouse AP600	Small-Break LOCA, Main Steam Line Break (MSLB), and Steam Generator Tube Rupture (SGTR)	4-4
Babcock & Wilcox PWR	Small-Break LOCA	4-5
General Electric Simplified BWR	LOCA Scenarios	4-6

Because we are presently developing the Adequacy Assessment Matrix for TRAC-P, we will restrict our attention to the three most recent PWR PIRTs completed.^{4-3, 4-4, 4-5}

4.3. Summary Findings

Our summary PWR PIRT is presented as Table 4-1. This table summarizes the processes/phenomena for the source PIRTs, identifies the highest importance rank found in the collection of PIRTs, identifies whether the process/phenomenon is evident at the local level (LL), component level (CL), system level (SL), or in multiple levels. The occurrence or nonoccurrence of each process/phenomenon in a specific PIRT is communicated via citations to the appropriate individual PIRT.

In preparing our summary PIRT, we encountered and addressed several issues. First, different identifiers were used in the individual PIRTs to describe identical processes/phenomena. For our summary tabulation, we have selected unique summary identifiers and mapped the results of the individual PIRTs into our summary identifiers. Our definitions for the PIRT process/phenomenon identifiers in Table 4-1 are provided in Table 4-2. Second, an essential feature of the PIRT process is breaking the accident scenario into phases and identifying and ranking the processes/phenomena within each phase. However, as we are seeking a single list of PWR processes/phenomena to be used for preparation of the TRAC-P

Assessment Test Matrix, we have only tabulated information at the scenario level in Table 4-1.

Another more exclusive or restrictive PIRT screening activity was reported in Ref. 4-2. Fifty-six processes/phenomena are identified in Table 4-1; twenty-five processes/phenomena were identified in Ref. 4-2, which restricted its focus to high- and moderate-rank processes/phenomena appearing in two or more of the PIRT database used for the summary. Although fewer processes/phenomena are identified following this approach, the detailed summary tables of processes/phenomena of typical high and moderate importance in prior PIRT applications provided useful additional insights by summarizing the frequency with which the process/phenomena appeared in the PIRT database. Included in this database were PIRTs prepared for the original CSAU effort, simplified boiling water reactor LOCA, and production reactor doubled-ended guillotine break. The summary tables from Ref. 4-2 are presented in Appendix D.

4.4. Application to TRAC Qualification

Table 4-1 lists all the phenomena/processes identified in prior PWR PIRT applications.* TRAC must model these phenomena/processes. The processes/phenomena identified in Table 4-1 occur at different levels within a plant or facility. Most occur at the local level. There is a natural association between LL processes/phenomena and the flow field models and engineering correlations FFEC described in Section 3.2, and associated Section 3 tables and the SPM and associated tables described in Section 3.4. The appropriate cross-correlation or linkage between processes/phenomena identified in the summary PIRT tabulation and the associated TRAC-P models is provided in Table 4-1. There are two possible associations between CL processes/phenomena and TRAC models. For some CL processes/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 processes/phenomena, specific TRAC component models do exist, e.g., the Pump. When such models exist, they are treated as described in the next paragraph.

Some of the processes/phenomena listed in Table 4-1, are SL processes/phenomena. These processes/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 models at all levels with the summary PIRT phenomena/process and component lists serve to identify the associated TRAC models that must be provided and qualified.

* Table 4-1 lists all the phenomena/processes identified in prior PWR PIRT applications to the extent that they were "all" identified in the source PIRTs.

REFERENCES

- 4-1. Technical Program Group, *Quantifying Reactor Safety Margins: Application of CSAU to a LBLOCA*, Nuclear Engineering and Design 119 (1990): B. E. Boyack et al.; *Part 1: An overview of the CSAU Evaluation Methodology*, G. E. Wilson et al.; *Part 2: Characterization of Important Contributors to Uncertainty*, W. Wulff et al.; *Part 3: Assessment and Ranging of Parameters*, G. S. Lellouche et al.; *PART 4: Uncertainty Evaluation of LBLOCA Analysis Based on TRAC-PF1/MOD1*, N. Zuber et al.; *Part 5: Evaluation of Scale-Up Capabilities of Best Estimate Codes*, I. Catton et al.; *Part 6: A Physically Based Method of Estimating PWR LBLOCA PCT*.
- 4-2. G. E. Wilson and B. E. Boyack, "The Role of the PIRT Process in Identifying Code Improvements and Executing Code Development," Proceedings of the OECD/CSNI Workshop on Transient Thermal-Hydraulic and Neutronic Codes Requirements," Annapolis, Maryland (November 5-8, 1996).
- 4-3. B. E. Boyack, "AP600 LBLOCA Phenomena Identification and Ranking Tabulation," Los Alamos National Laboratory document LA-UR-95-2718 (1995).
- 4-4. J. D. Burtt, C. D. Fletcher, G. E. Wilson, C. B. Davis, and T. J. Boucher, "Phenomena Identification and Ranking Tables for Westinghouse AP600 Small Break Loss-of-Coolant Accident, Main Steam Line Break, and Steam Generator Tube Rupture Scenarios," Idaho National Engineering Laboratory document INEL-94/0061, Rev. 2 (November 1996).
- 4-5. M. G. Ortiz, L. S. Ghan, and G. E. Wilson, "Development of a Phenomena Identification and Ranking Table (PIRT) of Thermal-Hydraulic Phenomena During a PW Small-Break LOCA," Idaho National Engineering Laboratory draft document (June 1, 1990). [See M. G. Ortiz, "Transmittal of SBLOCA CSAU PIRT Draft Report," Idaho National Engineering Laboratory letter MGO-10-90 to D. Bessette (June 1, 1990)]
- 4-6. 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).

DRAFT

Table 4-1
Summary Tabulation of Processes/Phenomena

Process/Phenomenon	Rank ^a	Level ^b	Ref.	TRAC Models ^c (category: subcategory: model)
Asymmetries	M	SL,CL	4-3, 4	BEM:all:fluid flow equations FFEC:3:all flow regimes FFEC:4:all flow regimes
Boiling	M	LL	4-4	FFEC:4a:all flow regimes
Boiling—film	H	LL	4-3	FFEC:4a: film boiling
Boiling—nucleate	M	LL	4-3	FFEC:4a:nucleate boiling
Boiling—transition	H	LL	4-3	FFEC:4a:transition boiling
Condensation—interphasic	M	LL	4-4	FFEC:4b:all flow regimes
Condensation—wall	H	LL	4-3, 4, 5	FFEC:4a:condensation
Conduction	H	LL	4-3, 4, 5	BEM:6:heat conduction in solids
Convection—natural/forced (all phases)	L	LL	4-3, 5	FFEC:4a:all flow regimes
Countercurrent flow limit (CCFL)	M	LL	4-4	SPM:1:CCFL model
Critical heat flux (CHF)	M	LL	4-4	FFEC:4a:critical heat flux
Decay heat	H	LL	4-3, 4, 5	BEM:7:power generation in fuel
Distribution—liquid/void	M	SL	4-4	BEM:all:fluid flow equations FFEC:3:all flow regimes
Draining	H	LL	4-3, 4	BEM:all:fluid flow equations FFEC:3:all flow regimes
Dryout	M	LL	4-4	FFEC:4a:critical heat flux
Entrainment/deentrainment	H	LL	4-3, 4	FFEC:3b:all flow regimes

^a High = High, M= Moderate, L=Low.

^b Most of the listed processes/phenomena occur at a LL but several occur at the CL and SL.

^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.

NSM is Numerical Special Model.

DRAFT

Table 4-1 (cont)
Summary Tabulation of Processes/Phenomena

Process/Phenomenon	Rank	Level	Ref.	TRAC Models (category: subcategory: model)
Evaporation	H	LL	4-3, 4	FFEC:4a:all flow regimes
Flashing	H	LL	4-3, 4, 5	FFEC:4b:all flow regimes
Flow	H	SL, CL	4-4	BEM:all:fluid flow equations FFEC:3:all flow regimes
Flow—channeling	H	CL	4-4	BEM:5:3D vessel model FFEC:3:all flow regimes
Flow—countercurrent	M	CL	4-3, 4	FFEC:3b:all flow regimes
Flow—critical	H	LL	4-3, 4, 5	SPM:2:critical flow model
Flow—discharge	H	LL	4-3,4	BEM:all:fluid flow equations FFEC:3:all flow regimes
Flow—mixing fluid streams	L	LL	4-3, 4, 5	BEM:all:fluid flow equations
Flow—multidimensional	H	SL,CL	4-3, 5	BEM:5:3D vessel model
Flow—natural circulation	H	SL,CL	4-3, 4, 5	BEM:all:fluid flow equations FFEC:3:all:4:all
Flow—safety class coolant	M	SL	4-5	BEM:all:fluid flow equations FFEC:3:all flow regimes
Flow—stagnation	M	LL	4-3	BEM:all:fluid flow equations
Flow—subcritical	H	LL	4-5	BEM:all:fluid flow equations FFEC:3:all flow regimes
Form loss	H	LL	4-3, 4	BEM:2:local losses
Gap conductance	H	LL	4-3	BEM:6:fuel-clad gap model
Interfacial drag	H	LL	4-3	FFEC:3b:all flow regimes
Level	H	LL	4-3, 4, 5	SPM:5:level-tracking model
Level—swell	H	LL	4-4	BEM:all:fluid flow equations FFEC:4:all flow regimes
Noncondensable effects	M	LL	4-3, 4	FFEC:4b:effect of noncondensibles

DRAFT

Table 4-1 (cont)
Summary Tabulation of Processes/Phenomena

Process/Phenomenon	Rank	Level	Ref.	TRAC Models (category: subcategory: model)
Oscillations	L	SL,CL	4-3	BEM:all:fluid flow equations FFEC:3: all flow regimes FFEC:4: all flow regimes
Pressurization	M	SL,CL	4-3	BEM: all: fluid flow equations
Pump—coastdown	H	CL	4-3, 4	ECM:1:centrifugal pump component
Pump—performance, inc. degradation	H	CL	4-3, 5	ECM:1:centrifugal pump component
Reactivity—boron	M	LL	4-3, 4	BEM:7:power generation, reactivity feedback
Reactivity—fuel temperature (Doppler)	L	LL	4-3	BEM:7:power generation, reactivity feedback
Reactivity—moderator temperature	M	LL	4-3, 4	BEM:7:power generation, reactivity feedback
Reactivity—void	H	LL	4-3	BEM:7:power generation, reactivity feedback
Stored energy release	M	LL	4-3, 4, 5	BEM:6:conduction equation, fuel-clad gap
Stratification—phase separation	H	LL,CL	4-3, 4, 5	FFEC:3b:all flow regimes
Stratification—thermal	M	LL,CL	4-3, 4	Convective transport only ^d
Subcooling margin	H	LL	4-4	BEM:all:fluid flow equations BEM:9:fluid equation of state
Transport—energy	H	LL	4-4	BEM:3:energy convection
Valve—performance	M	CL	4-5	ECM:4:valve component
Vapor—expansion, compression	H	LL	4-4	BEM:10:thermophysical properties
Voiding	M	LL	4-4, 5	BEM:all:fluid flow equations FFEC:3a:two-phase, homogeneous FFEC:3b:all flow regimes
Wall friction	H	LL	4-3, 4	FFEC:3a:all flow regimes
Wetting—surface	M	LL	4-4	FFEC:4a:all flow regimes

^d Fluid conduction and turbulent mixing are not modeled; there is no thermal front tracking method in code.

DRAFT

Table 4-2
PIRT Process/Phenomenon Descriptions^a

PIRT Term	Description
Asymmetries	A difference in thermal-hydraulic behavior that can be attributed to the geometrically asymmetric arrangement of hardware.
Boiling	The process whereby fluid changes from the liquid state to the vapor state due to heat addition at a fluid-wall interface.
Boiling—film	Boiling regime in which vapor blankets all or an appreciable portion of the heating surface.
Boiling—nucleate	Boiling regime in which bubble formation is at the liquid-solid interface rather than from external or mechanical devices.
Boiling—transition	A boiling regime which spans the boiling surface between critical heat flux and minimum film boiling.
Condensation—interphasic	The process where 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.
Condensation—wall	The process where steam is cooled due to contact with a colder wall, resulting in a change of phase from vapor to liquid.
Conduction	Process by which heat flows from a region of higher temperature to a region of lower temperature within a medium (solid, liquid, gaseous) or between different mediums in direct physical contact.
Convection—natural/forced (all phases)	Process of energy transport by the combined action of heat conduction, energy storage, and mixing motion.
Countercurrent flow limit (CCFL)	The process by which interfacial drag and/or entrainment prevents or limits liquid flow opposite (counter) to the gas flow direction.
Critical heat flux (CHF)	A departure from nucleate boiling that causes a sudden deterioration in heat transfer and results in a temperature excursion of a heated surface.
Decay heat	Heat produced by the decay of radioactive nuclides.
Distribution—liquid/void	The quantity and location of liquid and vapor throughout a physical system.

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

DRAFT

Table 4-2 (cont)
PIRT Process/Phenomenon Descriptions

PIRT Term	Description
Draining	The downward flow of fluid on a surface under the influence of gravity.
Dryout	A temperature excursion of the heated surface to do starvation of liquid.
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	The process whereby a fluid changes from the liquid state to the vapor state by the addition of energy.
Flashing	The process whereby fluid changes from the liquid state to the vapor state due to a reduction in the fluid pressure (that lowers the saturation temperature).
Flow	The forward continuous movement of a fluid into, within, or out of a component or system.
Flow—channeling	Cocurrent, non-uniform flow of fluids with different properties (e.g., temperature, density, boron concentration).
Flow—countercurrent	The process whereby liquid flows opposite (counter) to the gas flow direction.
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—mixing fluid streams	The joining of two or more fluid streams with the resultant loss of identity of the entering fluid streams.
Flow—multidimensional	Flow that is characterized by two or more velocity vectors.
Flow—natural circulation	Flow induced by fluid density gradients, usually associated with thermal gradients that arise when a fluid is heated.
Flow—safety class coolant	Flow and transport of fluids introduced into the system for purposes of protecting equipment from exceeding thermal safety limits.
Flow—subcritical	Flow at less than the maximum possible flow (e.g., critical flow).
Flow—stagnation	The state in which there is no fluid motion.
Form loss	The hydraulic resistance to flow associated with geometry.

DRAFT

Table 4-2 (cont)
PIRT Process/Phenomenon Descriptions

PIRT Term	Description
Gap conductance	The overall thermal resistance to the flow of heat between the fuel pellets and cladding in a nuclear fuel rod.
Interfacial drag	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.
Level—swell	The process whereby the two-phase fluid level increases as the fluid density decreases. The phenomenon can be caused by flashing, boiling, or convection of vapor into a component.
Noncondensible effects	The impact of the presence of noncondensible 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.
Pressurization	An increase in component (e.g., containment) or system (primary coolant) pressure
Pump - coastdown	The decrease in pump rotational speed following a pump trip.
Pump—performance, including degradation	The behavior of a pump under all operating conditions
Reactivity—boron	The change in core reactivity due to an increase or decrease in the amount of boron in the moderating fluid.
Reactivity—fuel temperature (Doppler)	The change in core reactivity due to an increase or decrease in the temperature of the fuel.
Reactivity—moderator temperature	The change in core reactivity due to an increase or decrease in the temperature of the moderating fluid.
Reactivity—void	The change in core reactivity due to an increase or decrease in the amount of void in the moderating fluid.

DRAFT

Table 4-2 (cont)
PIRT Process/Phenomenon Descriptions

PIRT Term	Description
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.
Stratification—phase separation	The separation of liquid and vapor in a two-phase mixture, with the vapor on top and the fluid below.
Stratification—thermal	A state in which vertical temperature and density gradients exist in a fluid.
Subcooling margin	The difference between the fluid saturation temperature (function of the fluid pressure) and the subcooled fluid temperature. This quantity provides a measure of the relative proximity to saturation conditions and the associated heat transfer regimes.
Transport—energy	The transfer of energy associated with the flow of fluid mass.
Valve—performance	The behavior of a valve under all operating conditions.
Vapor—expansion, compression	The process whereby a vapor space volume expands or compresses as the liquid inventory changes below the vapor space, resulting in pressure reduction or increase in the vapor space.
Voiding	The process whereby gas and/or vapor is transported through or accumulates in a component.
Wall friction	The friction caused by the movement of a fluid over a solid surface.
Wetting—surface	The extent and pattern of liquid coverage on a surface.

5.0. CODE QUALIFICATION - VALIDATION USING OTHER STANDARD TESTS

As discussed in Section 2.1, this subelement 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 subelement of the TRAC-P Validation Test Matrix is limited in the sense that it does not now, nor will it ever, constitute a complete test of the TRAC-P code. For example, exact solutions, while setting the highest standard for code validation, exist for only a subset of the physical processes and conditions modeled in TRAC-P. Equilibrium, concept problems, and numerical methods also have limitations, as discussed in subsequent subsections.

The tests selected for the TRAC-P Validation Test Matrix for this subelement are given in this section. The objective of these tests is to provide increased assurance that TRAC-P code features, algorithms, and equations are correctly programmed. Test problems that focus on specific code features, algorithms, and equations in TRAC-P 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-P development continues under the multiple-team, multiple-site development format envisioned by the NRC. These should be added to the Validation Test Matrix in a timely manner.

The categories of problems used in this subelement 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.

5.1. Features Tests

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

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

The input file error checking code feature is largely untested. TRAC-P checks input files (decks) for errors. When input file errors are detected, warnings are provided in a message file. However, problems to test the input file error checking feature do not exist. Such problems are easy to create and will be added to the Validation Test Matrix problem set. A test problem(s) will be created to test this feature. No formal test problems have been created to test outfile (graphics) processing. In some measure, each user tests this feature each time the graphics file is created and used with an associated postprocessor graphical user interface. However, no formal test is routinely completed as part of the code qualification process. A test problem(s) will be created to test this feature. Test problems exist to check the English units input/output feature. The initial set of Features Tests, including development status, is presented in Table 5-1.

5.2. 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 there is no power generation. A transient is run and the outcome examined. The success is that the problem should maintain its initial state

TABLE 5-1
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

(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.

An example Equilibrium Problem specification is provided in Appendix E, Section E.1. The format for specification of the test problems given in Appendix E will be used for all problems developed for the Validation Test Matrix.

The initial set of Equilibrium Problems, including development status, is presented in Table 5-2.

5.3. 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. For example, a symmetric perturbation introduced in a symmetric

TABLE 5-2
EQUILIBRIUM TEST PROBLEMS

ID	Test	Status
EP1	Horizontal pipe hydro equilibrium	Input decks to be developed
EP2	Displaced vertical fluid column	Input decks to be developed
EP3	Static vessel	Input deck exists
EP4	TRAC-P MS#& Standard Test Matrix Problem ⁵⁻¹	Existing decks to be modified
EP5	TRAC-P Conduction Developmental Assessment Problems ⁵⁻⁹	Existing decks to be modified
EP6	Air/water hydro equilibrium	Input decks to be developed
EP7	Liquid/solute hydro equilibrium	Input decks to be developed
EP8	Radiative energy exchange	Existing decks to be modified

hardware configuration should be preserved, although the precise propagation and attenuation of the perturbation is not known.

Concept problems can be devised for most of the basic-equation models in TRAC-P, 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.⁵⁻¹ One series of problems is an isothermal, abrupt flow-area change, vertical coolant-flow channel. This test series uses six different TRAC-P-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-P-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. Example Concept Problem specifications are provided in Appendix E, Sections E.2 and E.3.

The problems already available in the Standard Test Matrix⁵⁻¹ will 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 5-2 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-P models and methods tested.

The initial set of Concept Problems, including development status, is presented in Table 5-3.

5.4. 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 5-3
CONCEPT TEST PROBLEMS

ID	Test	Status
CP1	TRAC-P MS#& Standard Test Matrix Problem ⁵⁻¹	Existing decks
CP2	Symmetric perturbations in the MS#& Standard Test Problems ⁵⁻¹	Existing decks to be modified
CP3	HCOND# Standard Test Matrix Problem ⁵⁻¹	Existing decks
CP4	DRAIN Standard Test Matrix Problem ⁵⁻¹	Existing deck
CP5	ROD2 Standard Test Matrix Problem ⁵⁻¹	Existing deck
CP6	Bubble rise problems in Appendix C	Existing decks
CP7	Falling drop problems in Appendix C	Existing decks
CP8	Boron transport problem in Appendix C	Existing decks
CP9	Restart validation for 1D SET	Existing deck to be modified
CP10	Restart validation for 3D SET	Input decks to be developed
CP11	Restart validation for conduction	Input decks to be developed
CP12	Restart validation for control system	Input decks to be developed
CP13	Restart validation for equipment component models and methods	Input decks to be developed
CP14	Restart validation for special purpose models and methods	Input decks to be developed
CP15	Mass and energy conservation validation	Input decks to be developed

5.4.1. Basic Equation Models

5.4.1.1. 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:

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

These problems will 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 will be used to develop the problem specification, as shown in Appendix C and the TRAC-P model for the problem. The success metric will be that the TRAC-P 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. 5-8, pp. 21-28).
- Draining of liquid from a tank (Ref. 5-2, p. 237).
- The U-tube manometer problem (Ref. 5-2, pp. 229-230).
- The TRAC-P drain and fill test problem⁵⁻⁹
- Problems that eliminate the momentum balance from consideration.

The last analytical solutions listed refer to the noncondensable gas capabilities in TRAC-P. 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 will be used to develop the problem specification and TRAC-P model. The success metric will be that the TRAC-P 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-P numerical solution to the analytical solution.

5.4.1.2. Heat Conduction in Solids. There are numerous analytical solutions available for the heat conduction equation. The TRAC-P Standard Test Matrix report,⁵⁻¹ TRAC-P Theory Manual,⁵⁻¹⁰ and the TRAC Developmental Assessment Manual⁵⁻⁹ 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-P validation, including the fuel-clad gap model. These and other conduction problems will be used for TRAC-P 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 C will be developed; the success metric is that the TRAC-P calculated results agree with the analytical results. User guidance is the requirement to demonstrate temporal and spatial convergence.

5.4.1.3. Other Basic Equation Models. Analytical solutions for the radiative energy exchange models have been given by Lam,⁵⁻¹¹ and these will be part of the TRAC-P 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 ORIGEN2⁵⁻¹² isotope buildup and depletion computer code.

The NESTLE code⁵⁻¹³ is the basis of the multidimensional neutron-kinetics capabilities in TRAC. An extensive benchmarking program has been associated with reactor kinetics mathematical models and numerical solution methods for many years. 2D and 3D benchmark problems are available, and predictions of the NESTLE code have been compared with other calculations of these benchmarks.⁵⁻¹⁴ NESTLE predictions have also been compared with experimental data from operating PWRs.⁵⁻¹⁴

We are not aware of benchmark problems that isolate a single reactivity feedback mechanism. Such problems may be developed as validation of the TRAC code proceeds.

5.4.1.4. 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.

5.4.2 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-P 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-P 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. Steinke⁵⁻¹⁵ has used ordinary differential equations (ODEs) with known analytical solutions to validate some elements of the TRAC-P control system. These same problems will be selected for the Validation Test Matrix. The success metric is that the TRAC-P 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 5-4.

5.5 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 5.4.1 above. The objective is to demonstrate that the numerical solution methods in TRAC-P 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.

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 5.4.1 above. The success metric is that the TRAC-P results agree with the analytical results. User guidance is provided by the requirement that convergence be demonstrated.

An example Numerical Solution Method Problem specification is provided in Appendix E, Section E.4.

The initial set of Analytical and Numerical Methods Test Problems, including development status, is presented in Table 5-4.

5.6. Validation Test Matrix—Validation Using Other Standard Tests

The contributions to the TRAC-P Validation Test Matrix by the Other Standard Tests subelement are summarized in Table 5-5. 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 5-5, the parts of the TRAC-P coded tested by these validation tests consist mainly of the BEM and numerical solution methods (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-P are discussed in the next section of this report.

TABLE 5-4
ANALYTICAL AND NUMERICAL METHODS TEST PROBLEMS

ID	Test	Status
AS1	Pressure gradient in unheated channel	Input decks to be developed
AS2	Temperature gradient in heated channel	Input decks to be developed
AS3	Flow in variable-area channel	Input decks to be developed
AS4	Flow with local pressure loss	Input decks to be developed
AS5	Flow in natural circulation loops	Input decks to be developed
AS6	Flow in distribution manifold	Input decks to be developed
AS7	Transport of a scalar	Input decks to be developed
AS8	Void "wave" in noncondensable	Input decks to be developed
AS9	Liquid enthalpy "wave" in two-phase flow	Input decks to be developed
AS10	Nusselt condensation	Input decks to be developed
AS11	Solute transport with liquid	Input decks to be developed
AS12	Incompressible flow startup	Input decks to be developed
AS13	Tank draining	Input decks to be developed
AS14	U-tube manometer problem	Existing deck
AS15	TRAC-P drain and fill problem	Existing deck
AS16	Transient noncondensable gas problems	Input decks to be developed
AS17	1D radial conduction solution	Existing decks
AS18	2D radial plus axial conduction	Existing decks
AS19	Radiative exchange	Existing decks
AS20	Equilibrium critical flow	Input decks to be developed
AS21	Control system solutions	Existing decks
AS22	Validate Tabular Power Input	Existing decks
AS23	Validate Point Kinetics Model	Input deck to be developed
AS24	3D Neutron Kinetics Benchmarks	Input decks to be developed
AS25	Numerical methods stability and convergence	Input decks to be developed

DRAFT

TABLE 5-5
VALIDATION OF TRAC-P USING OTHER STANDARDS

Category	Subcategory		Model	Validation by Other Standards Tests	
	No.	Description		Best	Candidates
BEM	1	Fluid mass equation	Mass convection	√ AS1	EP1, EP2, EP4, EP6, EP7, CP1, CP2, CP4, CP8, AS1-AS16, AS20, AS24
			Mass exchange due to phase change		
	2	Momentum equation	Momentum flux	√ AS3	EP1, EP2, EP4, EP6, EP7, CP1, CP2, CP4, CP8, AS1-AS16, AS20, AS24
			Area change	√ AS3	AS3, AS4, AS6, AS13
			Pressure gradient	√ AS1	EP1, EP2, EP4, EP6, EP7, CP1, CP2, CP4, CP8, AS1-AS16, AS20, AS24
			Wall-to-phase momentum exchange	√ AS1	EP1, EP2, EP4, EP6, EP7, CP1, CP2, CP4, CP8, AS1-AS16, AS20, AS24
			Interfacial momentum exchange		
			Momentum exchange due to mass exchange		
			Local losses	√ AS4	EP1, AS4, AS6
			Gravity	√ AS5	EP1, EP2, EP4, EP6, EP7, CP1, CP2, CP4, CP8, AS5, AS13, AS14
	3	Fluid energy equation	Energy convection	√ AS2	EP1, EP2, EP4, EP6, EP7, CP1, CP2, CP4, CP8, AS1-AS16, AS20, AS24
			Pressure-work term	√ AS16	EP1, EP2, EP4, EP6, EP7, CP1, CP2, CP4, CP8, AS1-AS16, AS20, AS24
			Wall-to-phase energy exchange	√ AS2	AS2, AS5, AS10
			Interfacial energy exchange		
			Direct energy deposition		
			Energy exchange due to mass exchange		
	4	Noncondensable gas and liquid solute	Mass convection	√ AS8	EP7, AS8
			Solute mass exchange	√ AS11	EP6, CP8, AS11
	5	3D Vessel model	As in BEM Subcategories 1-4		EP3, EP4
	6	Heat conduction equation	Lumped-capacitance model		
			1D radial	√ AS17	EP5, CP3, CP5, AS17
			2D radial plus axial	√ AS18	EP5, CP3, CP5, AS18
			Reflood implicit		
			Fuel-clad gap		
			Metal-water reaction		

DRAFT

Category	Subcategory		Model	Validation by Other Standards Tests	
	No.	Description		Best	Candidates
FFEC	7	Power generation in fuel	Material properties Tabular power input Point kinetics 3D kinetics Reactivity feedback Fuel temperature Coolant temperature Void fraction Boron concentration	√ Any √ AS22 √ AS23 √ AS24	EP5, CP3, CP5, AS17, AS18 AS22 AS23 AS24
	8	Radiative energy exchange in the core	Referenced at subcategory level	√ AS19	EP8, AS19
	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
	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		
	3	Fluid momentum equation closure (momentum exchange)			

DRAFT

Category	Subcategory		Model	Validation by Other Standards Tests	
	No.	Description		Best	Candidates
	3a	Wall-to-phase momentum exchange	Single phase	√ AS1	EP1-EP4, EP6, EP7, CP1, CP2, CP4, CP8, AS1, AS2, AS5, AS6, AS12 CP1
			Two-phase, homogeneous		
			Two-phase, horizontal stratified		
	3b	Interfacial momentum exchange	Bubbly flow		CP6
			Bubbly slug transition		
			Bubbly slug flow		
			Churn flow		
			Annular-mist flow		CP7
			Transition to stratified flow		
			Stratified flow		
			Plug flow		
	3c	Local pressure losses	Abrupt expansion	√ AS4	EP1, CP1, CP2, AS4
			Abrupt contraction	√ AS4	EP1, CP1, CP2, AS4
			Orifice plate	√ AS4	EP1, AS4
			User supplied	√ AS4	EP1, AS4
	4	Fluid energy equation closure (energy exchange)			
	4a	Wall-to-phase energy exchange	Natural convection to liquid	√ AS2	AS2
			Forced convection to liquid		
			Nucleate boiling		
			Critical heat flux		
			Transition boiling		
			Minimum stable film boiling temperature		
			Film boiling		
			Single-phase vapor		
			Condensation	√ AS10	AS10
			Two-phase forced convection		
	4b	Interfacial energy exchange	Bubbly flow		
			Bubbly slug transition		
			Bubbly slug flow		
			Churn Flow		
			Annular-mist flow		
			Transition to stratified flow		

DRAFT

Category	Subcategory		Model	Validation by Other Standards Tests	
	No.	Description		Best	Candidates
			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	√ AS20	AS20
	3	Trip and control elements	Referenced at subcategory level	√ AS21	AS21
	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		
	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		

DRAFT

Category	Subcategory		Model	Validation by Other Standards Tests	
	No.	Description		Best	Candidates
			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	√ AS25	EP1, EP2, EP4, EP6, EP7, CP1, CP2, CP4, CP8, CP9, CP15, AS1-AS16, AS20, AS25
		3D SETs	Referenced at subcategory level		EP3, EP4, CP6, CP7, CP10
		Conduction in solid materials			
		1D rectangular and cylindrical	Referenced at subcategory level	√ AS17	EP5, CP3, CP5, CP11, AS17
		2D rectangular and cylindrical	Referenced at subcategory level	√ AS18	EP5, CP3, CP5, CP11, AS18
		Power generation in fuel rods		-	-
			Tabular power input	√ AS22	AS22
			Point kinetics	√ AS23	AS23
			3D kinetics	√ AS24	AS24
			Reactivity feedback		
		Radiative energy	Referenced at subcategory level		

DRAFT

Category	Subcategory		Model	Validation by Other Standards Tests	
	No.	Description		Best	Candidates
		exchange		√ AS19	EP8, AS19
		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		-	-
		Centrifugal pumps (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	√ AS20	AS20
		Trip and control elements	Referenced at subcategory level	√ AS21	AS21
		Reflood heat transfer models	Referenced at subcategory level		
		Steady-state methods	Referenced at subcategory level	√	All Steady-State Problems
		Timestep size and control methods	Referenced at subcategory level	√	All

REFERENCES

- 5-1. R. G. Steinke, "A Description of the Test Problems in the TRAC-P Standard Test Matrix," Los Alamos National Laboratory document LA-UR-96-1475 (May 1996).
- 5-2. R. B. Bird, W. E. Stewart, and E. N. Lightfoot, *Transport Phenomena*, John Wiley & Sons, Inc., New York, New York (1960).
- 5-3. N. E. Todreas and M. S. Kazimi, *Nuclear Systems II: Elements of Thermal Hydraulic Design* (Hemisphere Publishing Corporation, New York, New York, 1990).
- 5-4. R. A. Bajura, "A Model for Flow Distribution in Manifolds," *Transactions of the ASME Journal of Engineering for Power* (1971), pp. 7-12.
- 5-5. R. A. Bajura, "Flow Distribution Manifolds," *Transactions of the ASME Journal of Fluids Engineering* (1976), pp. 7-12.
- 5-6. J. H. Mahaffy, "Numerics of Codes: Stability, Diffusion, and Convergence," *Nuclear Engineering and Design* **145**, 131-145 (1993).
- 5-7. M. P. Paulsen, J. G. Shatford, J. L. Westacott, and L. J. Agee, "A Nondiffusive Solution Method For RETRAN-03 Boiling Water-Reactor Stability Analysis," *Nuclear Technology* **100**, No. 2, 162-173 (1992).
- 5-8. F. J. Moody, *Introduction to Transient Thermofluid Mechanics* (John Wiley & Sons, New York, New York, 1990).
- 5-9. J. C. Lin, V. Martinez, and J. W. Spore, "TRAC-PF1/MOD2 Developmental Assessment Manual," Los Alamos National Laboratory draft report (1993).
- 5-10. J. W. Spore et al., "TRAC-PF1/MOD2 Volume I. Theory Manual," LA-12031-M, Vol. I (1993).
- 5-11. Kin L. Lam, "Implementation of Radiation Heat-transfer Model into the TRAC-P Code," Los Alamos National Laboratory report LA-UR-96-0174 (October 1995).
- 5-12. A. G. Croff, "ORIGEN2 - Revised and Updated Version of the Oak Ridge Isotope Generation and Depletion Code," Oak Ridge National Laboratory report ORNL-5621 (July 1980).
- 5-13. P. J. Turinsky, R. M. K. Alchalabi, P. Engrand, H. N. Sarour, F. X. Faure, and W. Guo, "NESTLE," *Nuclear Science and Engineering* **120**, No. 1, 72-73 (1995).

- 5-14. Russel D. Mosteller, "Static Benchmarks of the NESTLE Advanced Nodal Code," to be Presented at the Joint International Conference on Mathematical Methods and Supercomputing for Nuclear Applications, Saratoga Springs, New York, October 6-10, 1997.
- 5-15. R. G. Steinke, "TRAC Upgrade for Evaluating Laplace-Transform Ordinary Differential Equation and PI/PID-Controller Control Blocks," Los Alamos National Laboratory report TSA8-LA-4 (August 1994).

6.0. CODE QUALIFICATION — VALIDATION USING SEPARATE EFFECTS TEST DATA

The data from separate effects experiments to be used for validation of TRAC-P are discussed in this section. The characteristics of separate effects data, and the role of the various kinds of separate effects data in validation, have been discussed in Section 2 and Appendix B. The SET data sets specified in this section are selected to fulfill that role.

Whereas some specific SET data sets and experimental runs have been chosen, we still need to identify additional data sets and specific experimental runs within given data sets. We will define the specific runs for the remaining data sets as the Validation Test Matrix is refined and validation of TRAC proceeds.

6.1. Data Characterization

An essential element of data selection is data characterization. For SET data, 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 4-1). This factor addresses whether the data can be used directly to validate a particular model or whether it can only be used in an indirect manner. 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; it is a go/no-go factor. The fourth factor, quality of data, is evident; high-quality data are required if the validation part of code qualification is to accurately reflect code capabilities and adequacy. 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 a 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 are covered in one, we would select the facility with the broader range and variety of data because overall program costs are reduced.

6.2. Existing TRAC-P and RELAP5 Models

For some specific model validation efforts, there are several candidate facilities that qualify 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-P input decks exist are given priority.
- Facilities for which TRAC-P 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-P input deck are assigned the next highest priority.

A list of TRAC-P SET input decks is provided in Table 6-1. Not all input decks have been updated for use with the latest TRAC-P version, namely TRAC-PF1/MOD2 (MOD2). The latest TRAC-P version for which a TRAC-P facility deck exists is also provided in Table 6-1. Decks last used with TRAC-PF1/MOD1 (MOD1) must be updated before they can be used for TRAC-P code qualification. Several MOD1 input decks have been archived for specific facility tests. A more extensive tabulation of both facility- and test-specific input decks is provided in Appendix F. A tabulation of RELAP5 SET input decks is also provided in Appendix F.

6.3. Data Sources

Various sources of information have been used to identify potential SET validation tests including:

- The OECD/CSNI compilation of 185 SET facilities (Ref. 6-1).
- Reports on validation of TRAC-P and other computer codes (Ref. 6-2 through 6-9).
- Electronic bibliographies of publications associated with the TRAC-P, RELAP5, and RETRAN computer codes.

TABLE 6-1
TRAC-P INPUT DECKS FOR SEPARATE EFFECT TESTS

Facility^a	Code Version
Akimoto	MOD2 ^b
Bankoff (Northwestern Condensation)	MOD2
Batelle Columbus Laboratories (BCL)	MOD1
Bennett	MOD1
Berkeley [University of California (UC)-Berkeley Reflood)	MOD2 ^b
Centro Informazioni Studi Esperienze (CISE)	MOD1
Dartmouth	MOD1
Edwards	MOD1
Full Length Emergency Cooling Heat Transfer (FLECHT)	MOD1
Full Length Emergency Cooling Heat Transfer-Separate Effects and Systems Effects Test (FLECHT- SEASET)	MOD2
Idaho National Engineering Laboratory (INEL)	MOD2
Lehigh	MOD2
Marviken	MOD1; MOD2 for Test 4
THETIS	MOD2
Thermal-Hydraulic Test Facility (THTF)	MOD1
Winfrith	MOD2

^a Acronyms for all facilities are provided in the acronym list at the front of this report.

^b Early MOD2 input deck; some modification required to make current.

- Searches and reviews of the current literature for reports and papers about validation of TRAC-P, RELAP5, and RETRAN.
- Searches and review of the current literature for small-scale, fundamental experiments.

The CSNI compilation, published in 1993/1994 and compiled before that time, focused on nuclear-safety related facilities around the world. The latter four sources of information listed above supplement and update the facility information given in the CSNI compilation.

Searches and reviews of the current literature for publications about validation of the TRAC-P, RELAP5, and RETRAN codes provide information about the availability and quality of experimental data and the existence of input files for these codes. Literature searches and reviews are ongoing processes, and results from these have not yet been factored into the TRAC-P Validation Test Matrix.

Reports on small-scale experiments regularly appear in the literature and many of these are of a more fundamental nature than the facilities and experiments that were the primary focus of the CSNI compilation. Small-scale fundamental experiments generally allow for direct validation of a single process/phenomena and associated model or method in TRAC-P. Some fundamental data have been identified for inclusion in the validation matrix.

The SET test facilities selected for use in the TRAC Validation Test Matrix are summarized in Table 6-2. Facilities identified in the OECD/CSNI SET matrix for thermal-hydraulic code validation,⁶⁻¹ are identified in the Key Features column of Table 6-2. Facilities not having a commonly recognized facility name are identified by the last name of the first author of the associated citation (Table 6-3 and Reference list). Fully current TRAC-P input decks exist for facilities with names appearing in bold type. Facilities for which TRAC-P input decks exist but require updating are underlined.

The test facilities listed in Table 6-2 have been assigned to categories of phenomena and further assigned a facility number for use in the remainder of this section. These assignments are given in Table 6-3. Many of the phenomena listed in Table 6-3 correspond to those given in the summary PIRT, Table 4-1, in Section 4.0. Other phenomena are unique to the models in the TRAC-P code and are generally used in TRAC to construct models of the phenomena listed in the summary PIRT.

TABLE 6-2
SEPARATE EFFECT TEST FACILITY SUMMARY

Facility	Key Features
<u>Akimoto Condensation</u>	Studied condensation of steam on subcooled water in a horizontal test section of rectangular cross section.
Anderson-Benedetti Horizontal Entrainment	Compilation and analysis of steam-water data and development of correlation for entrainment under horizontal stratified conditions at pressures from 3.4 to 6.2 MPa. Horizontal and downward directed offtakes were investigated.
Attou Expansion	Studied two-phase air-water bubbly flow through a horizontal sudden enlargement at atmospheric pressure. Detailed pressure distribution data are available.
Azzopardi Horizontal Entrainment	Source of extensive information on experimental and theoretical study of entrainment under horizontal stratification conditions.
Babcock & Willcox (B&W) Condensation	Studied condensation in the presence of noncondensable gas for downflow in a 3.04 m long vertical tube of 14.07 mm diameter at 13.43 MPa pressure.
<u>BCL emergency core cooling (ECC)/Core Steam Flow</u>	Studied countercurrent core-steam/ECC fluid flow in a 1/15th scale PWR downcomer during a PWR cold-leg break (OECD/CSNI facility 11.4).
Bennett Annulus	Studied wall-to-fluid heat transfer and the pressure gradient for vertical upflow of boiling water in an annulus.
<u>Bennett Tube</u>	Studied heat transfer to steam-water mixtures flowing in uniformly heated tubes in the region beyond the dryout point for various coolant flow rates, wall heat fluxes, and coolant inlet subcoolings (OECD/CSNI facility 10.4).

TABLE 6-2 (cont)
SEPARATE EFFECT TEST FACILITY SUMMARY

Facility	Key Features
Bibeau Void Growth	Studied void growth and wall temperature for vertical upflow of boiling water in annular channels under forced convective subcooled nucleate boiling conditions at low flow and pressures (about 1.0, 2.0, and 3.0 MPa).
Carofano-McManus Critical Flow	Studied critical flow of two-phase water at about 0.16 MPa.
Celata Countercurrent Flow Limiting (CCFL)	Presents compilation of CCFL data for round tube test sections.
Celata Direct Contact Condensation	Experimental study and modeling of direct-contact condensation of steam onto subcooled water at about atmospheric pressure.
Celata Onset of Nucleate Boiling (ONB)	Studied the onset of nucleate boiling and the pressure gradient for water flowing at high speeds in a horizontal 0.10 m long round tube of 8 mm diameter.
<u>CISE Blowdown</u>	A vertical-pipe blowdown experiment studied depressurization and heat-transfer phenomena of initially flowing subcooled water.
Columbia University (CU) Rod Bundle	Rod bundle (5x5 square array of 3.81 m heated length) blowdown heat transfer test facility in which transient critical heat flux (CHF) and post-CHF heat transfer phenomena expected to occur in PWR cores during large-break (LB) LOCA conditions was studied (OECD/CSNI facility 11.10).

TABLE 6-2 (cont)
SEPARATE EFFECT TEST FACILITY SUMMARY

Facility	Key Features
Costigan Flow Map	Studied the flow regime map, from the bubbly to annular regimes, for vertical air-water flows in a 2 m long round tube of 32 mm diameter at atmospheric pressure.
Creare Downcomer	Examined downcomer countercurrent flow, ECC water by-pass and delivery, annulus ECC flow oscillations, hot wall effects in 1/30, 1/15, and 1/5 scale models of a reactor vessel (OECD/CSNI facility 11.13).
CU Low Flow Friction	Studied pressure gradient and onset of flow instability (OFI) in vertical upflow of single-phase water in 96 in long heated round tube of 0.612 in diameter at 34.7 and 64.7 psia pressure with inlet temperatures of 25 and 50°C.
Cumulus Critical Flow	Critical flow of superheated vapor and subcooled liquid through the pressurizer relief valves of a French PWR.
Dartmouth Countercurrent Flow	Studied countercurrent annular flow regimes for steam and subcooled water in vertical tubes as a function of inlet water temperature and test section geometry (OECD/CSNI facility 11.16).
de Bertodano Annular Flow	Studied upward flow of two-phase water in the annular flow regime in a 4.18 m long tube of 9.5 mm diameter at 0.14 to 0.66 MPa pressure. Superficial gas speeds ranged from 25 to 126 m/s. Pressure gradient and entrainment data are given.
de Bertodano CCFL	Studied CCFL in a model of the hot leg of a PWR.
Deich Critical Flow	Studied two-phase critical flow at 0.12 MPa.
Delhaye Interfacial Area	Studied the interfacial area for upward bubbly flow in a vertical round pipe under forced and natural circulation.

TABLE 6-2 (cont)
SEPARATE EFFECT TEST FACILITY SUMMARY

Facility	Key Features
Dukler-Smith CCFL	Studied CCFL for vertical air-water annular flow in a 3.96 m long, 50 mm diameter round pipe at atmospheric pressure (OECD/CSNI facility 11.45 but no data sheet).
Energieonderzoek Centrum Nederland (ECN) Reflood and Boildown	Studied reflood and boildown in an electrically-heated 6 x 6-rod bundle under the influence of non-uniform temperature and power profiles (OECD/CSNI facility 7.1/7.2).
Electric Power Research Institute (EPRI) Air-Water Pressure Drop Ferrell-McGee Local Loss	Air-water flow through a rectangular flow channel containing a blockage. Studied two-phase water flow through expansions and contractions in vertical round tubes with various flow-area ratios.
Fincke-Collins Critical Flow	Studied critical flow of subcooled water at pressure from 0.09 to 0.30 MPa.
FLECHT-SEASET	Forced reflood experiments conducted for a 17 x 17 bundle in the unblocked configurations (OECD/CSNI facility 11.23).
FRIGG Void	Studied flow and heat transfer in a highly-instrumented 36-rod bundle with rods in a circular layout (OECD/CSNI facility 8.3).
GE Level Swell	Studied the governing phenomena that controls two-phase mixture level swell and void fraction distribution during vessel blowdown experiments (OECD/CSNI facility 11.44).
General Electric (GE) Separator/Dryer	The data used by GE to develop the GE separator/dryer model. The description of the test section is given in two ASME reprints that we have not yet obtained.

TABLE 6-2 (cont)
SEPARATE EFFECT TEST FACILITY SUMMARY

Facility	Key Features
Hein Condensation	Studied condensation in the presence of noncondensable gas in a 2.035 m long stainless steel U-tube of 19 mm inside diameter at 0.494 MPa pressure.
INEL Tube	Studied post-CHF and reflood heat transfer in a vertical round tube (OECD/CSNI facility 11.3).
Iwamura Cross Flow	Studied two-dimensional distribution of two-phase air-water flow in a tube bundle at atmospheric pressure.
Janssen Local Loss	Flow of subcooled water through a rectangular channel containing expansions and contractions in the flow area.
Kalkachnavarro Interfacial Area	Studied the interfacial area for bubbly two-phase flow.
Lehigh Post-CHF Bundle	Studied post-CHF heat transfer in a vertical tube containing a 3 x 3 rod bundle with heated shroud (OECD/CSNI facility 11.42).
Leung Interfacial Area	Studied the interfacial area for air-water vertical upflow in a 3.75 m long round tube of 50.8 mm diameter at atmospheric pressure.
Liu-Winterton	A extensive compilation of data sources for subcooled and saturated boiling water heat transfer data in round tubes and annuli in upflow, downflow, and horizontal flow.
LOFT	1:60 P/V scaled; reduced height with atypicalities; 2-loop; full pressure; nuclear core; spectrum of tests were performed, including some in the separate effect test mode.

TABLE 6-2 (cont)
SEPARATE EFFECT TEST FACILITY SUMMARY

Facility	Key Features
LOFT Valve/Wyle	Studied small-break blowdown from a horizontal round pipe through a 16.0 mm diameter nozzle (may be OECD/CSNI facility 11.5 or 11.34 but no data sheet for either).
Maciaszek Horizontal Entrainment	Experimental study of steam-water flow from a horizontal pipe into an offtake with horizontal, upward, and downward orientation at about 2 MPa.
Marviken	Studied critical two-phase flow with large orifice diameters (OECD/CSNI facility 8.2).
MB-2 Steam Generator	Studied the thermal-hydraulic behavior of the steam generator under transient conditions in a facility that simulated loss-of-feedwater transients, steam generator tube ruptures, and steam line breaks (OECD/CSNI facility 11.52).
Massachusetts Institute of Technology (MIT) Pressurizer Mod1 Pump Characterization	Simulated a PWR pressurizer (OECD/CSNI facility 11.43). Characterization of INEL Semiscale Mod1 centrifugal pump via single- and two-phase steady-state flow tests in a closed-loop recirculation circuit, forward and reverse flow directions (OECD/CSNI facility 11.39).
Mudde Horizontal Entrainment	Experimental air-water study of flow split from horizontal header pipe into upward-directed smaller pipe at atmospheric pressure.
National Aeronautics and Space Administration (NASA) Condensation	Studied condensation at high flow rates in the presence of noncondensable gas for downflow in a vertical copper tube 2.128 m long and 7.44 mm inside diameter at 0.180 MPa pressure.
Neussen Critical Flow	Studied critical flow of two-phase water at pressure from 0.84 to 6.5 MPa.

TABLE 6-2 (cont)
SEPARATE EFFECT TEST FACILITY SUMMARY

Facility	Key Features
Northwestern Condensation	Studied interface condensation heat transfer coefficient in co- and counter-current stratified flow (OECD/CSNI facility 11.53).
Purdue Low Flow	Studied wall-to-fluid friction and heat transfer at low flow conditions near atmospheric pressure.
Reimann Horizontal Entrainment	Experimental study of air-water flow split at a Tee-junction from a horizontal pipe into offtakes of various diameter and orientations at pressures from 0.2 to 0.5 2 MPa.
Rinne Expansion	Studied air-water bubbly flow through a sudden expansion a vertical round pipe at atmospheric pressure.
Rogers Onset of Significant Voiding (OSV)	Studied the onset of significant void for vertical upflow of water in 0.48 and 0.60 m long annulus test sections of various diameters at 0.15 MPa pressure and low speed (< 0.5 m/s).
Rig of Safety Assessment (ROSA)	1:30 volume scaled for AP600; 1:1 height; 2 loops; full pressure; electrically heated core; includes core makeup tanks, pressure balance lines, passive residual heat removal system, in-containment refueling water storage tank, accumulator injection system, and automatic depressurization system. Some tests run in separate effect mode.
Ruile Stratified Condensation	Studied interfacial heat and mass transfer for horizontal flow of steam over liquid water in a 1.0 m long rectangular channel at up to 6 MPa pressure.
Schmidt Local Loss	Studied two-phase air-water flows in sudden contractions in vertical round tubes with various area ratios. Detailed pressure distribution data are available.

TABLE 6-2 (cont)
SEPARATE EFFECT TEST FACILITY SUMMARY

Facility	Key Features
Schrock Horizontal Entrainment	Experimental study and analysis of air-water and steam-water flow from a horizontal pipe under stratified conditions at about atmospheric pressure. Horizontal, upward, and downward orientation of the offtake were investigated.
Schrock-Grossman	Studied wall-to-fluid heat transfer and pressure gradient for vertical upflow of boiling water in a round tube.
Shilimkan Interfacial Area	Studied the interfacial area for vertical upflow of air-water in a 1.524 m long round tubes of 10, 15, and 20 mm diameter. The pressure gradient and void fraction are also reported.
Shippingport Pressurizer	Studied transient response of the Shippingport reactor pressurizer.
Shoukri Subcooled Boiling	Studied subcooled boiling in a vertical 30.6 cm long stainless steel annulus with 12.7 mm inside diameter and 25.0 mm outside diameter in the pressure range 0.15 to 0.17 MPa. A recondensation section downstream of the heated section provides interfacial mass exchange information.
Siddique Condensation	Studied condensation in the presence of noncondensable gas for downflow in a 2.54 m long vertical stainless steel round tube of 46.0 mm inside diameter in the pressure range 0.11 to 0.48 MPa.
Sjoberg Dryout	Studied heat transfer and pressure gradient for vertical upflow of boiling water in a 7.0 m long, 15.0 mm diameter round tube at a pressure of about 7.0 MPa.
Smoglie Horizontal Entrainment	Experimental study of air-water flow split at a Tee-junction from a horizontal pipe into smaller offtakes about atmospheric pressure.

TABLE 6-2 (cont)
SEPARATE EFFECT TEST FACILITY SUMMARY

Facility	Key Features
Sozzi-Sutherland	Studied critical flow of subcooled and saturated water from initially high pressure.
Savannah River Laboratory (SRL) C-reactor	An experiment in the Savannah River C-reactor operating at 60% of full power. Ink concentration was used to simulate the transport of boron.
SRL Local Loss	Studied the local-loss coefficient under natural circulation conditions for single-phase liquid water at 1.17 MPa and 25 and 50°C inlet temperature.
SRL Low Flow Friction	Studied pressure gradient and OFI in vertical upflow of single-phase water in 3.81 m long heated annulus test section at about atmospheric pressure with inlet temperature of 25°C.
Super Moby Dick	Studied steady state critical flow for vertical upflow of water in test sections with three different nozzles. Both subcooled liquid and saturated steam-liquid mixtures to 100% quality were investigated in the pressure range of 2.0 to 12.0 MPa (OECD/CSNI facility 3.2).
THETIS Boiloff	Studied reflood heat transfer in a 7 x 7 rod bundle in a square array (OECD/CSNI facility 10.2).
<u>THTF Boiloff</u>	Studied transient heat transfer within a 8 x 8 electrically heated rod bundle (OECD/CSNI facility 11.38 but no data sheet).
<u>UC-Berkeley Reflood</u>	Studied reflood behavior in an inconnel 600 alloy tube of 14.4 mm inside diameter and 3.66 m length (OECD/CSNI facility 11.8).
UC Santa Barbara (SB) Condensation	Studied reflux condensation in a 16.0 mm diameter U-tube at atmospheric pressure (OECD/CSNI facility 11.26 but no data sheet).
VAPORE Critical Flow	Two-phase critical flow through the full-scale automatic depressurization system (ADS) valve trains for the AP600.

TABLE 6-2 (cont)
SEPARATE EFFECT TEST FACILITY SUMMARY

Facility	Key Features
Winfrith Tube	Studied post-CHF heat transfer in a single vertical tube (OECD/CSNI facility 10.7).
Zeitoun Interfacial Area	Studied the interfacial area for vertical upflow of condensing water-steam flows in a 0.306 m long annulus test section at low flow and pressure.

6.4. Data Selected for the TRAC-P Validation Test Matrix

6.4.1. Selection Based on PIRT Summary

A summary tabulation of processes/phenomena based upon three contemporary PWR PIRTs was presented in Section 4.0 (Table 4-1). Most of the processes/phenomena listed in the summary occur at a location; these are associated the level identifier LL (Local Level) in Table 4-1. These local processes/phenomena identify the models in TRAC that must be validated with SET data. The LL entries have been extracted from Table 4-1 and are presented as Table 6-4 here.

The SET data from Table 6-3 that will be used to validate the TRAC models and methods for the processes listed in Table 6-4 are given in the third column of the table. The SET data are identified by the P-SET number assigned in Table 6-3 above.

The TRAC models associated with the local-level phenomena are given in the last column of the table. As shown in the table, almost all of the TRAC models are in the FFEC, SPM, and ECM categories. These are appropriately validated via SET experiments.

Our validation matrix structure was constructed to ensure completeness. We have identified validation tests needed to ensure phenomena coverage and validation tests needed to ensure code model coverage. Our coverage of components from the PIRT standpoint is presented in Section 7, Table 7-4.

TABLE 6-3
IDENTIFICATION OF TRAC-P VALIDATION DATA SETS

P-SET No.	Process/ Phenomena	Facility No.	Facility	Reference
1	Critical Flow			
		1.01	CISE Blowdown	6-10
		1.02	LOFT Valve/Wyle	6-11
		1.03	Marviken	6-12, 6-13
		1.04	ROSA SET (APCL - 03)	6-14
		1.05	Sozzi-Sutherland	6-15
		1.06	Super Moby Dick	6-16
		1.07	Carofano-McManus	6-17
		1.08	Cumulus Critical Flow	6-17
		1.10	Deich Critical Flow	6-17
		1.10	Fincke-Collins Critical Flow	6-17
		1.11	Neussen Critical Flow	6-17
		1.12	VAPORE	6-18
2	Void/Level			
		2.01	ECN Reflood and Boildown	6-19
		2.02	FRIGG Void	6-20, 6-21
		2.03	GE Level Swell	6-22, 6-23
		2.04	Shoukri Subcooled Boiling	6-24
		2.05	THETIS Boiloff	6-25
		2.06	THTF Boiloff	6-26-6.29
3		CCFL		
		3.01	Celata CCFL	6-30
		3.02	de Bertodano Annular Flow	6-31
		3.03	Dukler-Smith CCFL	6-32
4	Heat Transfer/CHF			
		4.01	Columbia University Rod Bundle	6-33
		4.02	Bennett Annulus	6-34
		4.03	Bennett Tube	6-35
		4.04	Celata Onset of Nucleate Boiling	6-36
		4.05	Liu-Winterton	6-37, 6-38
		4.06	MB-2 Steam Generator	6-39, 6-40
		4.07	Sjoberg Dryout	6-41
		4.08	Rogers Onset of Significant Void	6-42
		4.09	Schrock-Grossman	6-43

Table 6-3 (cont)
Identification of TRAC-P Validation Data Sets

P-SET No.	Process/ Phenomena	Facility No.	Facility	Reference
5	Reflood Heat Transfer			
		5.01	FLECHT-SEASET	6-44, 6-45
		5.02	INEL Tube	6-46
		5.03	Lehigh Post-CHF Bundle	6-47
		5.04	UC-Berkeley Reflood	6-48, 6-49
		5.05	Winfrith Tube	6-50
6	Condensation/ Noncondensables			
		6.01	B&W Condensation	6-51-6-53
		6.02	Hein Condensation	6-54
		6.03	Siddique Condensation	6-55, 6-56
		6.04	NASA Condensation	6-57
		6.05	UC Berkeley Condensation	6-58, 6-59
		6.05	UCSB Condensation	6-60
7	Interfacial Condensation			
		7.01	Akimoto Condensation	6-61, 6-62
		7.02	Bibeau Void Growth	6-63
8	Wall Friction/Local Loss			
		8.01	Attou Expansion	6-64
		8.02	CU Low Flow Friction	6-65, 6-66
		8.03	de Bertodano Annular Flow	6-67
		8.04	Ferrell-McGee Local Loss	6-68
		8.05	Iwamura Cross Flow	6-69
		8.06	Purdue Low Flow	6-70-6-72
		8.07	Rinne Expansion	6-73
		8.08	Schmidt Local Loss	6-74, 6-75
		8.09	SRL Local Loss	6-76
		8.10	SRL Low Flow Friction	6-76
		8.11	Janssen Local Loss	6-77
		8.12	EPRI Air-Water Pressure Drop	6-78-6-81
9	Interfacial Area			
		9.01	Delhaye Interfacial Area	6-82
		9.02	Kalkachnavarro Interfacial Area	6-83
		9.03	Leung Interfacial Area	6-84
		9.04	Shilimkan Interfacial Area	6-85
		9.05	Zeitoun Interfacial Area	6-86

Table 6-3 (cont)
Identification of TRAC-P Validation Data Sets

P-SET No.	Process/ Phenomena	Facility No.	Facility	Reference
10	Flow Regime Map			
		10.01	Costigan Flow Map	6-87
11	Stratified Condensation			
		11.01	Celata Direct Contact Condensation.	6-88
		11.02	Northwestern Condensation	6-89-6-91
		11.03	Ruile Stratified Condensation	6-92
12	Countercurrent Flow			
		12.01	BCL ECC/Core Steam Flow	6-93
		12.02	Creare Downcomer	6-94
		12.03	Dartmouth Countercurrent Flow	6-95
13	Boron Transport			
		13.01	LOFT L6-6	6-96
		13.02	SRL C-reactor	6-97
14	Components			
		14.01	LOFT L3-1 Accumulator	6-98
		14.02	MIT Pressurizer Component	6-99-6-101
		14.03	Shippingport Pressurizer	6-102
		14.04	GE Separator/Dryer	6-103-6-105
		14.05	Mod1 Pump Characterization	6-106
15	Thermal Stratification			
	15.01		ROSA/APCL	6-107
16	Horizontal Entrainment			
	16.01		Schrock	6-108
	16.02		Anderson-Benedetti	6-109
	16.03		Azzopardi	6-110, 6-111
	16.04		Mudde et al.	6-112
	16.05		Reimann	6-113
	16.06		Smoglie	6-114
	16.07		Maciaszek	6-115

TABLE 6-4
SUMMARY TABULATION OF LOCAL LEVEL PROCESSES/PHENOMENA

Process/Phenomenon	Rank ^a	P_SET No. from Table 6-3	TRAC Models ^b (category: subcategory: model)
Boiling	M	4, 5	FFEC: 4a: all flow regimes
Boiling—film	H	4, 5	FFEC: 4a: film boiling
Boiling—nucleate	M	4, 5	FFEC: 4a: nucleate boiling
Boiling—transition	H	4, 5	FFEC: 4a: transition boiling
Condensation— interphasic	M	7, 11	FFEC: 4b: all flow regimes
Condensation—wall	H	6	FFEC: 4a: condensation
Conduction	H	See Table 5-5	BEM: 6: heat conduction in solids
Convection—natural/ forced (all phases)	L	4, 5	FFEC: 4a: all flow regimes
Countercurrent flow limit (CCFL)	M	3	SPM: 1: CCFL model
Critical heat flux (CHF)	M	4	FFEC: 4a: critical heat flux
Decay heat	H	See Table 5-5	BEM: 7: power generation in fuel
<u>Draining</u>	<u>H</u>	<u>See Table 5-5</u> 8	<u>BEM: all: fluid flow equations</u> <u>FFEC: 3: all flow regimes</u>

a H=High, M=Moderate, L=Low

b Per Section 3, there are five model categories. Each category has subentries.

BEM is the Basic Equation Models

FFEC is the Flow Field Model and Engineering Correlation

ECM is Equipment Component Model

SPM is Special Purpose Model

NSM is Numerical Solution Model

c Fluid conduction and turbulent mixing are not modeled; there is no thermal-front tracking method in the code.

TABLE 6-4 (cont)
SUMMARY TABULATION OF LOCAL LEVEL PROCESSES/PHENOMENA

Process/Phenomenon	Rank	P_SET No. from Table 6-3	TRAC Models (category: subcategory: model)
Dryout	M	4	FFEC: 4a: critical heat flux
Entrainment/ deentrainment	H	16	FFEC: 3b: all flow regimes
Evaporation	H	4, 5	FFEC: 4a: all flow regimes
Flashing	H	1	FFEC: 4b: all flow regimes
Flow—countercurrent	M	12	FFEC: 3b: all flow regimes
Flow—critical	H	1	SPM: 2: critical flow model
Flow—discharge	H	See Table 5-5 8	BEM: all: fluid flow equations FFEC: 3: all flow regimes
Flow—mixing fluid streams	L	See Table 5-5	BEM: all: fluid flow equations
Flow—natural circulation	H	See Table 5-5 8 4, 5	BEM: all: fluid flow equations FFEC: 3: all: FFEC: 4: all
Flow—stagnation	M	See Table 5-5	BEM: all: fluid flow equations
Flow—subcritical	H	See Table 5-5 8	BEM: all: fluid flow equations FFEC: 3: all flow regimes
Form loss	H	8	BEM: 2: local losses
Gap conductance	H	See Table 5-5	BEM: 6: fuel-clad gap model
Interfacial drag	H	2, 12	FFEC: 3b: all flow regimes
Level	H	2	SPM: 5: level-tracking model
Level—swell	H	See Table 5-5 2	BEM: all: fluid flow equations FFEC: 3b: all flow regimes

TABLE 6-4 (cont)
SUMMARY TABULATION OF LOCAL LEVEL PROCESSES/PHENOMENA

Process/Phenomenon	Rank	P_SET No. from Table 6-3	TRAC Models (category: subcategory: model)
Noncondensible effects	M	6, 11	FFEC: 4b: effect of noncondensibles
Pump—coastdown	H	14	ECM: 1: centrifugal pump component
Pump—performance, including degradation	H	14	ECM: 1: centrifugal pump component
Reactivity—boron	M	See Table 5-5	BEM: 7: power generation, reactivity feedback
Reactivity—fuel temperature (Doppler)	L	See Table 5-5	BEM: 7: power generation, reactivity feedback
Reactivity—moderator temperature	M	See Table 5-5	BEM: 7: power generation, reactivity feedback
Reactivity—void	H	See Table 5-5	BEM: 7: power generation, reactivity feedback
Stored energy release	M	See Table 5-5	BEM: 6: conduction equation, fuel-clad gap
Stratification—phase separation	H		FFEC: 3b: all flow regimes
Stratification—thermal	M	15, 11	Convective transport only ^c Not modeled in TRAC
Subcooling margin	H	See Table 5-5 See Table 5-5	BEM: all: fluid flow equations BEM: 9: fluid equation of state
Transport—energy	H	See Table 5-5	BEM: 3: energy convection
Valve—performance	M	14	ECM: 4: valve component
Vapor—expansion, compression	H	See Table 5-5	BEM: 10: thermophysical properties

6-4 (cont)

SUMMARY TABULATION OF LOCAL LEVEL PROCESSES/PHENOMENA

Process/Phenomenon	Rank	P_SET No. from Table 6-3	TRAC Models (category: subcategory: model)
Voiding	M	See Table 5-5 8 2, 12	BEM: all: fluid flow equations FFEC: 3a: two-phase, homogeneous FFEC: 3b: all flow regimes
Wall friction	H	8	FFEC: 3a: all flow regimes
Wetting—surface	M	Not explicitly treated in TRAC-P	FFEC: 4a: all flow regimes

6.4.2. Selection Based on TRAC Models and Methods

The SET data sets chosen for validation of TRAC-P models and methods are summarized in Table 6-5. The TRAC-P models and methods are further described in Appendix C. The table uses the same format previously used in Table 5-5 in Section 5, i.e., TRAC elements by category (column 1), subcategory (columns 2 and 3), and model (column 4).

Columns 5 and 6 in Table 6-5 show the data set as providing either direct or indirect validation, and identifies the applicable facility number from the P-SET data set given in Table 6-3 above. Although we have not performed sufficient detailed review of each facility and test (e.g., availability of facility description and data), we have identified and recommended the initial facility to be used for validation of each model; the facility number for these facilities is entered in bold type in column 6. For completeness, reference is made to validation by "Other Standards" as documented in Section 5, if applicable.

Within Table 6-5, column 5, the following symbols are used to characterize the type of validation.

- A "✓" signifies that the process/phenomena was dominant in the experiment, and the data provide direct validation of the model or method.
- A "x" signifies that process/phenomena was present in the experiment but not sufficiently dominant; therefore, the data can only be used indirectly to validate a model or method. Additionally, especially for interfacial phenomena and wall-to-fluid phenomena, existing measurement methods are usually not sufficient to resolve the phenomena.

A blank means that the process/phenomena does not play a part in the validation.

6.5. Summary Observations

The SET facilities listed in Table 6-3 have been identified for use in the validation of TRAC-P. The rationale for these selections are (1) coverage of the LL and CL PIRT-listed processes and phenomena, and (2) coverage of the TRAC-P models and methods. The coverage of the PIRT validation requirements are summarized in Table 6-4, and coverage of the TRAC models and methods validation requirements are summarized in Table 6-5.

REFERENCES

Other Validation Reports

- 6-1. "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).
- 6-2. R. G. Steinke, "A Description of the Test Problems in the TRAC-P Standard Test Matrix," Los Alamos National Laboratory report LA-UR-1475 (1996).
- 6-3. J. C. Lin, V. Martinez, and J. W. Spore, "TRAC-PF1/MOD2 Developmental Assessment Manual," Los Alamos National Laboratory draft report (1993).
- 6-4. T. D. Knight, "AP600 Large-Break Loss-of-Coolant-Accident Developmental Assessment Plan for TRAC-PF1/MOD2," Los Alamos National Laboratory report LA-UR-96-2700 (1996).
- 6-5. M. P. Paulsen et al., "RETRAN-3D - A program for Transient Thermal-Hydraulic Analysis of Complex Fluid Flow Systems Volume 4: Verification and Validation," Electric Power Research Institute report EPRI NP-7450 (1996).
- 6-6. R. W. Shumway et al., "RELAP5 MOD3.2 Developmental Assessment Reports," Idaho National Engineering Laboratory draft report (1995).
- 6-7. K. Carlson, R. Riemke, S. Rouhani, R. Shumway, W. Weaver, "RELAP5/MOD3 Code Manual Volume III: Developmental Assessment Problems (DRAFT)," C. Allison, C. Miller, N. Wade, Eds., EG&G Idaho, Inc. document EGG-2596, NUREG/CR-5535 (June 1990).

- 6-9. Fax from the United States Nuclear Regulatory Commission to Brent Boyack (February 26, 1997).
- 6-10. A. Premoli and W. T. Hancox, "An Experimental Investigation of Subcooled Blowdown with Heat Addition," Specialists Meeting on Transient Two-Phase Flow, S. Banerjee and K. R. Weaver, Eds., Atomic Energy of Canada, Ltd., Mississauga, Ontario (1978).
- 6-11. J. E. Lin, G. E. Gruen, and W. J. Quapp, "Critical Flow in Small Nozzles for Saturated and Subcooled Water at High Pressure," in *Basic Mechanisms in Two-Phase Flow and Heat Transfer*, presented at a Symposium of the American Society of Mechanical Engineers, Chicago, November 16-21, pp. 9-17 (1980).
- 6-12. L. Ericksen et al., "The Marviken Full-Scale Critical Flow Tests Interim Report: Results from Test 22," MXC-222 (1979).
- 6-13. L. Ericksen et al., "The Marviken Full-Scale Critical Flow Tests Interim Report: Results from Test 24," MXC-224 (1979).
- 6-14. C. D. Fletcher et al., "Adequacy Evaluation of RELAP5/MOD3, Version 3.2.1.2 for Simulating AP600 Small Break Loss-of-Coolant Accidents: Appendices A, B, and C (Final Draft)," Idaho National Engineering Laboratory document INEL-96/0400 (December 1996).
- 6-15. G. L. Sozzi and W. A. Sutherland, "Critical Flow of Saturated and Subcooled Water at High Pressure," General Electric Report NEDO-13418 (May 1975).
- 6-16. J. C. Rousseau, "Flashing Flow," *Multiphase Science and Technology* 3, (Hemisphere Publishing, 1987), pp. 378-389.
- 6-17. J. M. Kelly, ALWR Model Development, Nuclear Regulatory Commission presentation to the Advisory Committee on Reactor Safeguards Thermal-Hydraulic Subcommittee Meeting (February 22-23, 1996).
- 6-18. L. S. Ghan, J. P. Adams, and S. M. Sloan, "Assessment of RELAP5/MOD3 using Data from the Westinghouse VAPORE ADS-123 Test Facility" (Proprietary), attachment to INEL letter from S. M. Sloan to T. M. Lee, SMS-06-96 (September 27, 1996).
- 6-19. T. C. de Boer, S. B. van der Molen, J. R. C. Maareveld, and H. Hogeland, "Final Report on ECN 36-Rod Boildown and Reflood Experiments. Data and Evaluations," Netherlands Energy Research Foundation document ECN-84-25, (1984).

- 6-20. O. Nylund et al., "Hydrodynamic and Heat Transfer Measurements on a Full Scale Simulated 36-Rod Marviken Fuel Element with Uniform Heat Flux Distribution," ASEA and ABB Atomenergi, FRIGG-2 (1968).
- 6-21. O. Nylund et al., "Hydrodynamic and Heat Transfer Measurements on a Full-Scale Simulated 36-Rod Marviken Fuel Element with Uniform Heat Flux Distribution," ASEA and AB Atomenergi Report, FRIGG-4, R4-502/RTL-1253 (1970).
- 6-22. L. S. Lee, S. A. Allison, G. L. Sozzi, "BWR Large-Break Simulation Tests—BWR Blowdown/Emergency Core Cooling Program," General Electric, Electric Power Research Institute, and United States Nuclear Regulatory Commission document GEAP-24962-1, EPRI NP-1783, NUREG/CR-2229 (April 1982).
- 6-23. J. A. Findlay, "BWR Refill-Reflood Program Task 4.8—Model Qualification Task Plan," United States Nuclear Regulatory Commission, Electric Power Research Institute, and General Electric document NUREG/CR-1899, EPRI NP-1527, GEAP-24898 (1981).
- 6-24. M. Shoukri, B. Donevski, R. L. Judd, and G. R. Dimmick, "Experiments on Subcooled Flow Boiling and Condensation in Annular Channels," in Proceedings of the International Seminar on Phase Interface Phenomena in Multiphase Systems (Hemisphere Publishing, 1991), pp. 413-422.
- 6-25. M. G. Croxford and P. C. Hall, "Analysis of the THETIS Boildown Experiments Using RELAP5/MOD2," United States Nuclear Regulatory Commission document NUREG/IA-0014 (1989).
- 6-26. C. B. Mullins, C. R. Hyman, W. G. Craddick, T. M. Anklam, and R. A. Hedrick, "PWR Blowdown Heat-Transfer Separate-Effects Program Data Evaluation Report-THTF Test Series II," Oak Ridge National Laboratory document ORNL/NUREG-53, NUREG/CR-0539 (April 1979).
- 6-27. D. K. Fields et al., "Facility Description—Thermal Hydraulic Test Facility (THTF) Mod3—ORNL PWR Blowdown Heat Transfer Separate Effects Program," Oak Ridge National Laboratory document ORNL/TM-7842, NUREG/CR-2640 (1982).
- 6-28. T. M. Anklam et al., "Experimental Investigations of Uncovered-Bundle Heat Transfer and Two-Phase Mixture-Level Swell Under High-Pressure Low Heat-Flux Conditions," Oak Ridge National Laboratory document NUREG/CR-2456, ORNL-5848 (1982).

- 6-30. G. P. Celata, M. Cumo, and T. Setaro, "A Data Set of Flooding in Circular Tubes," *Experimental Thermal and Fluid Science* 5, No. 4, 437-447 (1992).
- 6-31. Martin Lopez de Bertodano, "Countercurrent Gas-Liquid Flow in a Pressurized Water Reactor Hot Leg," *Nuclear Science and Engineering* 117, 126-133 (1994).
- 6-32. A. E. Duckler and L. Smith, "Two Phase Interactions in Counter-Current Flow: Studies of the Flooding Mechanism," United States Nuclear Regulatory Commission document NUREG/CR-0617 (1979).
- 6-33. Columbia Rod Bundle Report, Electric Power Research Institute document EPRI NP-112 (1977) and EPRI NP-113 (1977).
- 6-34. J. A. R. Bennett, J. G. Collier, H. R. C. Pratt, and J. D. T. Thornton, "Heat Transfer to Two-Phase Gas-Liquid Systems, Part I: Steam Water mixtures in the Liquid Dispersed Region in an Annulus," Atomic Energy Research Establishment document AERE-R 3159 (1959).
- 6-35. A. W. Bennett, G. F. Hewitt, H. A. Kearsy, and R. K. F. Keeys, "Heat Transfer to Steam-Water Mixtures Flowing in Uniformly Heated Tubes in which the Critical heat Flux has been Exceeded," Atomic Energy Research Establishment document AERE-R 5373 (1967).
- 6-36. Gian Piero Celata, Maurizio Cumo, and Andrea Mariani, "Experimental Evaluation of the Onset of Subcooled Flow Boiling at high Liquid Velocity and Subcooling," *International Journal of Heat and Mass Transfer* 40, No. 3, 2879-2885 (1997).
- 6-37. Z. Liu and R. H. S. Winterton, "A General Correlation for Saturated and Subcooled Flow Boiling in Tubes and Annuli, Based on a Nucleate Pool Boiling Equation," *International Journal of heat and Mass transfer* 34, No. 11, 2759-2766 (1991).
- 6-38. K. E. Gungor and R. H. S. Winterton, "Simplified General Correlation for Saturated Flow Boiling and Comparisons of Correlations with Data," *Chemical Engineering Research and Design* 65, 148-156 (1987).
- 6-39. M. Y. Young, K. Takeuchi, O. J. Mendler, and G. W. Hopkins, "Prototypical Steam Generator (MB-2) Transient Testing Program," United States Nuclear Regulatory Commission document NUREG/CR-3661 (1984).

- 6-40. O. J. Mendler, K. Takeuchi, and M. Y. Young, "Loss-of-Feedwater, Steam Generator Rupture, and Steam Line Break Experiments: Steam generator Transient Response Test Program," United States Nuclear Regulatory Commission document NUREG/CR-4751, EPRI NP-4786, WCAP-11206 (1987).
- 6-41. A. Sjoberg and D. Caraher, "Assessment of RELAP5/MOD2 Against 25 Dryout Experiments Conducted at the Royal Institute of Technology," United States Nuclear Regulatory Commission document NUREG/IA-0009 (1986).
- 6-42. J. T. Rogers, M. Salcudean, Z. Abdullah, D. McLeod, and D. Poirier, "The Onset of Significant Void in Up-Flow Boiling of Water at Low Pressure and Velocities," *International Journal of Heat and Mass Transfer* 30, No. 11, 2247-2260 (1987).
- 6-43. V. E. Schrock and L. M. Grossman, "Forced Convection Boiling Studies," TID-14632 (1959).
- 6-44. M. J. Loftus et. al, "PWR FLECHT-SEASET Unblocked Bundle, Forced and Gravity Reflood Task: Data Report," United States Nuclear Regulatory Commission document NUREG/CR-1532, Volumes 1-2 (June 1980)
- 6-45. N. Lee et. al, "PWR FLECHT-SEASET Unblocked Bundle Forced and Gravity Reflood Task: Data Evaluation and Analysis Report," United States Nuclear Regulatory Commission document NUREG/CR-2256 (February 1982).
- 6-46. R. C. Gottula, K. G. Condie, R. K. Sundaram, S. Neti, J. C. Chen, and R. A. Nelson, "Forced Convective, Non-Equilibrium, Post-CHF Heat Transfer. Experiment Data and Correlation Comparison Report," United States Nuclear Regulatory Commission document NUREG/CR-3193 (March 1985).
- 6-47. K. Tuzla, C. Unal, O. Badr, S. Neti, and J. C. Chen, "Thermodynamic Nonequilibrium in Post-Critical-Heat-Flux Boiling in a Rod Bundle," United States Nuclear Regulatory Commission document NUREG/CR-5095 (1987). See also NUREG/CR-3849 (1984).
- 6-48. R. Seban et. al, UC-B Reflood Program: Experimental Data Report," Electric Power Research Institute document EPRI-NP-743 (April 1978).
- 6-49. R. Seban, "Reflooding of a Vertical Tube at 1, 2, and 3 Atmospheres," Electric Power Research Institute document EPRI-NP-3191 (July 1983).
- 6-50. D. Swinnerton, M. L. Hood, and K. G. Pearson, "Steady-State Post-Dryout at Low Quality and Medium Pressure Data Report," Winfrith United Kingdom Atomic Energy Authority document AEEW-R 2267 (June 1988).

- 6-51. C. K. Nithianandan, C. D. Morgan, N. H. Shah, and F. R. Miller, "RELAP5/MOD2 Model for Surface Condensation in the Presence of Noncondensable Gases," Proceedings of 8th International Heat Transfer Conference (San Francisco, August 17-22, 1986) Vol. 4, pp. 1627-1633.
- 6-52. C. D. Morgan, "An Analysis of Condensation Heat Transfer with Noncondensable Gases Present in a Vertical Tube at high Pressure," Proceedings of the 21st National Heat Transfer Conference, Seattle, Washington, ASME-HTD, Vol. 27, pp. 83-89 (1983).
- 6-53. C. D. Morgan and G. C. Rush, "Experimental Measurements of Condensation Heat Transfer with Noncondensable Gases Present in a Vertical Tube at high Pressure," Proceedings of the 21st National Heat Transfer Conference, Seattle, Washington, ASME-HTD, Vol. 27, pp. 91-98 (1983).
- 6-54. D. Hein, R. Rippel, and P. Weiss, "The Distribution of Gas in a U-Tube heat Exchanger and Its Influence on the Condensation Process," Proceedings of the 7th International Heat Transfer Conference, Kraftwerk Union Ag, NR12, Vol. 5, pp. 467-474 (1982).
- 6-55. M. Siddique, "The Effects of Noncondensable Gases on Steam Condensation Under Forced Convection Conditions," Ph.D. Thesis, MIT (1992).
- 6-56. M. Siddique, M. W. Golay, and M. S. Kazimi, "Theoretical Modeling of Forced Convection Condensation of Steam in a Vertical Tube in the Presence of a Noncondensable Gas," *Nuclear Technology* 106, 202-215 (1994).
- 6-57. J. H. Goodykoontz and R. G. Dorsch, "Local Heat Transfer Coefficient and Static Pressures for Condensation of High-Velocity Steam Within a Tube," National Aeronautics and Space Administration document NASA TN D-3953 (1967).
- 6-58. S. Z. Kuhn, V. E. Schrock, and P. F. Peterson, "Final Report on U. C. Berkeley Single Tube Condensation Studies," University of California Berkeley report UCB-NE-4201, Rev. 2 (1994).
- 6-59. E. Vial and V. E. Schrock, "A Correlation Based on the Combined UCB and MIT Data Sets for Condensation Inside Tubes with Noncondensable Gas," University of California Berkeley report UCB-NE-4193 (1993).
- 6-60. Q. Nguyen and S. Banerjee, "Experimental Data Report on Condensation in a Single Inverted U-Tube," Electric Power Research Institute document EPRI NP-3471 (1984).

- 6-61. H. Akimoto, Y. Tanaka, T. Kozwa, A. Inoue, and S. Aoki, "Oscillatory Flows Induced by Direct-Contact Condensation of Flowing Steam with Injected Water," *Journal of Nuclear Science and Technology* 22, No. 4, 269-283 (1985).
- 6-62. H. Akimoto, T. Kozwa, A. Inoue, and S. Aoki, "Analysis of Direct-Contact Condensation of Flowing Steam onto Injected Water with Multifluid Model of Two-Phase Flow," *Journal of Nuclear Science and Technology* 22, No. 12, 1006-1022 (1983).
- 6-63. E. L. Bibeau and M. Salcudean, "Subcooled Void Growth Mechanisms and Prediction at Low Pressure and Low Velocity," *International Journal of Multiphase Flow* 20, No. 5, 837-863 (1994).
- 6-64. A. Attou, M. Gito, and J. M. Seynhaeve, "Modeling of Steady-State Two-Phase Bubbly Flow Through a Sudden Enlargement," *International Journal of Heat and Mass Transfer* 40, No. 14, 3375-3385 (1997).
- 6-65. Columbia University, "Flow Excursion Experimental Program: Single Tube Uniformly Heated Tests," CU-HTRF-T4, CU-90-01 (1990).
- 6-66. Columbia University, "Flow Excursion Experimental Program: Parallel Flow Tests," CU-HTRF-T6, CU-90-04 (1990).
- 6-67. Martin A. Lopez de Bertodano, Jian-Feng Shi, and Stephen G. Beus, "Air-Water Experiment for Annular Flow Pressure Drop in a Small Pipe," *Nuclear Science and Engineering* 126, 108-114 (1997).
- 6-68. J. K. Ferrell and J. W. McGee, "Two-Phase Flow Through Abrupt Expansions and Contractions," TID-23394 (1966).
- 6-69. T. Iwamura, H. Adachi, and M. Sobajima, "Cross Flow Resistance in Air-Water Two-Phase Flow in Rod Bundle," Japan Atomic Energy Research Institute document JAERI-M 86-184 (January 1987).
- 6-70. R. Viskanta and M. J. Gruszczynsky, "Heat Transfer to Water from a Vertical Tube Bundle Under Natural Circulation Conditions," United States Nuclear Regulatory Commission document NUREG/CR-3167, ANL-83-7 (1983).
- 6-71. K. P. Hallinan and R. Viskanta, "Dynamics of a Natural Circulation Loop: Analysis and Experiments," *Heat Transfer Engineering* 7, 43-51 (1986).
- 6-72. K. P. Hallinan and R. Viskanta, "Heat Transfer from a Vertical Tube Bundle under Natural Circulation Conditions," *International Journal of Heat and Fluid Flow* 6, No. 4, 256-264 (1986).

- 6-73. A. Rinne and R. Loth, "Development of Local Two-Phase Flow Parameters for Vertical Bubbly Flow in a Pipe with Sudden Expansion," *Experimental Thermal and Fluid Science* 13, No. 2, 152-166 (1996).
- 6-74. J. Schmidt and L. Friedel, "Two-Phase Pressure Drop Across Sudden Contractions in Duct Areas," *International Journal of Multiphase Flow* 23, No. 2, 283-299 (1997).
- 6-75. J. Schmidt and L. Friedel, "Two-Phase Flow Pressure Change Across Sudden Expansions in Duct Areas," *Chemical Engineering Communications* 141, 175-190 (1996).
- 6-76. Z. H. Qureshi, "Preliminary Assessment of RELAP5/MOD3," New Production Reactor Program, Westinghouse Savannah River Company document NPR-DEC-91-0373, Rev. 0 (1991).
- 6-77. E. Janssen, "Two-Phase Pressure Drop Across Contractions and Expansions," GEAP-4622 (June 1964).
- 6-78. A. Tapucu et al., "Experimental Study of the Diversion Cross-Flow Caused by Subchannel Blockages," Electric Power Research Institute document EPRI NP-3459, Volume 1 (April 1984).
- 6-79. Tapucu A, Teyssedou A, Geckinli M, Merilo, "Axial Pressure Distribution In Two Laterally Interconnected Channels with Blockages," *International Journal of Multiphase Flow* 16, No. 3, 461-479 (1990).
- 6-80. A. Tapucu, A. Teyssedou, N. Troche, and M. Merilo, "Pressure Losses Caused by Area Changes in a Single-Channel Flow under Two-Phase Flow Conditions," *International Journal of Multiphase Flow* 15, No. 1, 51-64 (1989).
- 6-81. A. Teyssedou, A. Tapucu, M. Geckinli, and M. Merilo, "Axial Void Distribution in Two Laterally Interconnected Channels with Blockages," *International Journal of Multiphase Flow* 15, No. 1, 65-79 (1989).
- 6-82. J. M. Delhay and P. Bricard, "Interfacial Area in Bubbly Flow: Experimental-Data and Correlations," *Nuclear Engineering and Design* 151, No. 1, 65-77 (1994).
- 6-83. S. Kalkachnavarro, R. T. Lahey, D. A. Drew, and R. Meyder, "Interfacial Area Density, Mean radius and Number Density-Measurements in Bubbly 2-Phase Flow," *Nuclear Engineering and Design* 142, 341-351 (1993).
- 6-84. W. H. Leung, S. T. Revankar, Y. Ishii, and M. Ishii, "Axial Development of Interfacial Area and Void Concentration Profiles Measured by Double-Sensor

- Probe Method," *International Journal of Heat and Mass Transfer* 38, No. 3, 445-453 (1995).
- 6-85. R. V. Shilimkan and J. B. Stepanek, "Interfacial Area in Cocurrent Gas-Liquid Upward Flow in Tubes of Various Size," *Chemical Engineering Science* 32, 149-154 (1977).
 - 6-86. O. Zeitoun, M. Shoukri, and V. Chatoorgoon, "Measurement of Interfacial Area Concentration in Subcooled Liquid-Vapor Flow," *Nuclear Engineering and Design* 152, 243-255 (1994).
 - 6-87. G. Costigan And P. B. Whalley, "Slug Flow Regime Identification From Dynamic Void Fraction Measurements In Vertical Air-Water Flows," *International Journal of Multiphase Flow* 23, No. 2, 263-282 (1997).
 - 6-88. G. P. Celata, M. Cumo, G. E. Farello, and G. Focardi, "Direct Contact Condensation of Superheated Steam on Water," *International Journal of Heat and Mass Transfer* 30, No. 3, 449-458 (1987).
 - 6-89. I. S. Lim, S. G. Bankoff, R. S. Tankin, and M. C. Yuen, "Cocurrent Steam/Water Flow in a Horizontal Channel," United States Nuclear Regulatory Commission document NUREG/CR-2289 (1981).
 - 6-90. S. G. Bankoff, H. J. Kim, R. S. Tankin, and M. C. Yuen, "Counter-Current Steam-Water Flow in a Flat Plate Geometry," United States Nuclear Regulatory Commission document NUREG/CR-2783 (1982).
 - 6-91. H. J. Kim, S. C. Lee, S. G. Bankoff, "Heat Transfer and Interfacial Drag in Countercurrent Steam-Water Stratified Flow," *International Journal of Multiphase Flow* 11, No. 5, 593-606 (1985).
 - 6-92. Herbert Ruile, "Influence of Turbulence Intensity on heat transfer by Direct Contact Condensation in Stratified Steam Water Flows," American Society of Mechanical Engineers document ASME FED-Vol. 180 (1994), pp. 129-136.
 - 6-93. R. P. Collier, L. J. Flanigan, and J. A. Dworak, "Data Report on ECC Bypass Tests for TRAC Assessment," Batelle Columbus Laboratories report (July 1980) and "Compendium of ECCS Research for Realistic LOCA Analysis," United States Nuclear Regulatory Commission document NUREG-1230 (December 1988).
 - 6-94. C. J. Crowley, P. H. Rothe, and R. G. Sam, "1/5 Scale Countercurrent Flow Data Presentation and Discussion," Creare, Inc. document NUREG/CR-2106 (November 1981).

- 6-95. G. B. Wallis, P. C. DeSicyes, P. J. Roselli and J. Lacombe, "Countercurrent Annular Flow Regimes for Steam and Subcooled Water in a Vertical Tube," Electric Power Research Institute document NP-1336 (January 1980).
- 6-96. J. P. Adams and V. T. Berta, "Quick-Look Report on LOFT Boron Dilution Experiment L6-6." EG&G Idaho Inc. document EGG-LOFT-5867 (1982).
- 6-97. C. E. Ahlfeld, "SSS Test Results," Savannah River Laboratory document DPST-75-341 (1975).
- 6-98. P. D. Bayless et al., "Experiment Data Report for LOFT Nuclear Small Break Experiment L3-1," United States Nuclear Regulatory Commission document NUREG/CR-1145, EGG-2007 (January 1980).
- 6-99. H. R. Saedi and P. Griffith, "The Pressure Response of a PWR Pressurizer During an Insurge Transient," Transactions of the American Nuclear Society 1983 Annual Meeting, Detroit, Michigan, June 12-16 (1983) pp. 606-607.
- 6-100. H. R. Saedi and P. Griffith, "The Pressure Response of a PWR Pressurizer During an Insurge Transient," Transactions of the American Nuclear Society 1983 Annual Meeting, Detroit, Michigan, June 12-16 (1983).
- 6-101. H. R. Saedi, "Insurge Pressure Response and Heat Transfer for a PWR Pressurizer," Massachusetts Institute of Technology Thesis (1982).
- 6-102. J. A. Redfield, V. Pressop, and S. G. Margolis, "Pressurizer Performance During Loss-of-Load tests at Shippingport: Analysis and Test," *Nuclear Applications* (1968).
- 6-103. R. H. Moen et al., "Advances in Boiling Water Reactor System Separator Systems," American Society of Mechanical Engineers document ASME 69-WA/NE-5 (November 1969).
- 6-104. E. L. Burley "Performance of Internal Steam Separator System in Boiling Water Reactors," American Society of Mechanical Engineers document ASME 69-WA/NE-24 (November 1969).
- 6-105. S. Wolf and R. H. Moen, "Advances in Boiling Water Reactor System Separator Systems," American Society of Mechanical Engineers document ASME 73-WA/PWR-4 (November 1973).
- 6-106. D. J. Olson, "Experiment Data Report for Single and Two-Phase Steady State Tests of the 1-1/2 Loop Mod1-1 Semiscale System Pump," Westinghouse Canada, Ltd., document ANCR-1150 (May 1974).

- 6-107. C. D. Fletcher et al., "Adequacy Evaluation of RELAP5/MOD3, Version 3.2.1.2 for Simulating AP600 Small Break Loss-of-Coolant Accidents: Appendices A, B, and C (Final Draft)," Idaho National Engineering Laboratory document INEL-96/0400 (December 1996).
- 6-108. V. E. Schrock et al., "Small Break Critical Discharge-The Role of Vapor and Liquid Entrainment in a Stratified Two-Phase Region Upstream of the Break," United States Nuclear Regulatory Commission document NUREG/CR-4761 (December 1986).
- 6-109. J. L. Anderson and R. L. Benedetti, "Critical Flow Through Small Breaks," Electric Power Research Institute document EPRI NP-4532 (May 1986).
- 6-110. B. J. Azzopardi and E. Hervieu, "Two-Phase Flow Split at T-Junctions," Department of Chemical Engineering, University of Nottingham, United Kingdom (1991).
- 6-111. B. J. Azzopardi and A. P. Smith, "Two-Phase Flow Split at T-Junctions: Effect of Side Arm Orientation and Downstream Geometry," *International Journal of Multiphase Flow* 18, No. 6, 861-875 (1992).
- 6-112. R. F. Mudde, J. S. Groen, and H. E. A. VanDen Akker, "Two-Phase Flow Redistribution Phenomena in a Large T-Junction," *International Journal of Multiphase Flow* 19, No. 4, 563-573 (1993).
- 6-113. J. Reimann, H. J. Brinkmann, and R. Domanski, "Gas-Liquid Flow in Dividing Tee-Junction with Horizontal Inlet and Different Branch Orientations and Diameters," Kernforschungszentrum Karlsruhe, Institute fur Reaktorbauelemente document KfK 4399 (1988).
- 6-114. C. Smoglie, "Two-Phase Flow Through Small Branches in a Horizontal Pipe with Stratified Flow," Kernforschungszentrum Karlsruhe, Institute fur Reaktorbauelemente document KfK 3861 (December 1984).
- 6-115. T. Maciaszek and A. Menponteil, "Experimental Study on Phase Separation in a Tee-Junction for Steam-Water Stratified Inlet Flow," Paper C2, European Two-Phase Flow Working Group Meeting, Federal Republic of Germany (June 10-13, 1986).

DRAFT

TABLE 6-5
VALIDATION OF TRAC-P USING SEPARATE EFFECT DATA

Category	Subcategory		Model	Validation by Separate Effect Tests Data	
	No.	Description			P-SET Facility Number from Table 6-XX
BEM	1	Fluid mass equation	Mass convection	✓	See Table 5-5, Other Standards
			Mass exchange due to phase change		Validated by Other Standards - TBD
	2	Momentum equation	Momentum flux	✓	See Table 5-5, Other Standards
			Area change	✓	See Table 5-5, Other Standards
			Pressure gradient	✓	See Table 5-5, Other Standards
			Wall-to-phase momentum exchange	✓	See Table 5-5, Other Standards
			Interfacial momentum exchange		Validated by Other Standards - TBD
			Momentum exchange due to mass exchange		Validated by Other Standards - TBD
			Local losses	✓	See Table 5-5, Other Standards
			Gravity	✓	See Table 5-5, Other Standards
	3	Fluid energy equation	Energy convection	✓	See Table 5-5, Other Standards
			Pressure-work term	✓	See Table 5-5, Other Standards
			Wall-to-phase energy exchange	✓	See Table 5-5, Other Standards
			Interfacial energy exchange		Validated by Other Standards - TBD
			Direct energy deposition		Validated by Other Standards - TBD
			Energy exchange due to mass exchange		Validated by Other Standards - TBD
	4	Noncondensable gas and liquid solute	Mass convection	✓	See Table 5-5, Other Standards
			Solute mass exchange	✓	See Table 5-5, Other Standards
	5	3D Vessel model	As in BEM Subcategories 1-4		Validated by Other Standards - TBD
	6	Heat conduction equation	Lumped-capacitance model	✓	See Table 5-5, Other Standards
			1D radial or rectangular	✓	See Table 5-5, Other Standards
			2D radial plus axial	✓	See Table 5-5, Other Standards
			Reflood implicit		Validated by Other Standards - TBD
			Fuel-clad gap		Validated by Other Standards - TBD
			Metal-water reaction		Validated by Other Standards - TBD
			Material properties	✓	See Table 5-5, Other Standards

DRAFT

TABLE 6-5 (Cont.)
VALIDATION OF TRAC-P USING SEPARATE EFFECT DATA

Category	Subcategory		Model	Validation by Separate Effect Tests Data	
	No.	Description			P-SET Facility Number from Table 6-XX
FFEC	7	Power generation in fuel	Tabular power input Point kinetics 3D kinetics Reactivity feedback Fuel temperature Coolant temperature Void fraction Boron concentration	√ √ √ 	See Table 5-5, Other Standards See Table 5-5, Other Standards See Table 5-5, Other Standards Validated by Other Standards - TBD Validated by Other Standards - TBD Validated by Other Standards - TBD Validated by Other Standards - TBD Validated by Other Standards - TBD
	8	Radiative energy exchange in the core	Referenced at subcategory level	√	See Table 5-5, Other Standards
	9	Equation of state for fluids	Referenced at subcategory level	√	See Table 5-5, Other Standards
	10	Fluid thermophysical and transport properties	Referenced at subcategory level	√	See Table 5-5, Other Standards
	1	Regime maps	Bubbly flow Bubbly slug transition Bubbly slug flow Churn flow Annular-mist flow Transition to stratified flow Stratified flow Plug flow	√ √ √ √ x √ √	9.01 - 9.05, 10.01 10.01 10.01 10.01 4.02, 4.03, 4.07, 4.09, 8.03 None Identified at Present 11.01 - 11.03, 15.01 None Identified at Present
	2	Fluid mass equation closure (mass exchange)		-	-
	2a	Subcooled boiling	Referenced at subcategory level	√	2.02, 4.04, 4.08
	2b	Interfacial mass exchange	Referenced at subcategory level	√	6.01 - 6.05, 7.01, 7.02, 11.01, 11.02, 11.03
	2c	Plateout of dissolved solids	Referenced at subcategory level	√	13.01, 13.02

DRAFT

**TABLE 6-5 (Cont.)
VALIDATION OF TRAC-P USING SEPARATE EFFECT DATA**

Category	Subcategory		Model	Validation by Separate Effect Tests Data	
	No.	Description			P-SET Facility Number from Table 6-XX
	3	Fluid momentum equation closure (momentum exchange)		-	-
	3a	Wall-to-phase momentum exchange	Single phase	√	8.02, 8.06, 8.09, 8.10, 8.12
			Two-phase, homogeneous	x	4.02, 4.03, 4.07, 4.09, 8.03, 8.05
			Two-phase, horizontal stratified	x	11.01, 11.02, 11.03
	3b	Interfacial momentum exchange	Bubbly flow	x	2.02, 2.03, 2.04, 4.08, 7.02, 9.01 - 9.05, 10.01
			Bubbly slug transition	x	2.02, 2.03, 2.04, 4.08, 4.09, 7.02, 10.01
			Bubbly slug flow	x	2.02, 2.03, 7.02, 10.01, 12.01 - 12.03
			Churn flow	x	2.01, 2.05, 2.06, 4.03, 4.07, 4.09, 12.01 - 12.03
			Annular-mist flow	x	2.01, 2.05, 2.06, 4.03, 4.07, 4.09, 8.03, 12.01 - 12.03
			Transition to stratified flow		None Identified at Present
			Stratified flow	x	11.01, 11.02, 11.03
			Plug flow		None Identified at Present
	3c	Local pressure losses	Abrupt expansion	√	8.01, 8.04, 8.07 - 8.09, 8.11
			Abrupt contraction	√	8.04, 8.08, 8.11, 8.12
			Orifice plate		None Identified at Present
			User supplied	√	8.01, 8.04, 8.07 - 8.09, 8.11, 8.12
	4	Fluid energy equation closure (energy exchange)		-	-
	4a	Wall-to-phase energy exchange	Natural convection to liquid		None Identified at Present
			Forced convection to liquid	√	4.01, 4.03, 4.04, 4.05, 4.06, 4.07, 4.08, 4.09
			Nucleate boiling	x	4.01, 4.03, 4.04, 4.05, 4.06, 4.07, 4.08, 4.09
			Critical heat flux	√	2.01, 2.05, 2.06, 4.01, 4.02, 4.07
			Transition boiling		None Identified at Present
			Minimum stable film boiling temperature		None Identified at Present

DRAFT

**TABLE 6-5 (Cont.)
VALIDATION OF TRAC-P USING SEPARATE EFFECT DATA**

Category	Subcategory		Model	Validation by Separate Effect Tests Data	
	No.	Description			P-SET Facility Number from Table 6-XX
			Film boiling	x	2.01, 2.05, 2.06, 4.01, 4.02, 4.07, 5.01 - 5.05
			Single-phase vapor	√	2.01, 2.05, 2.06, 5.01 - 5.05
			Condensation	√	6.01 - 6.05
			Two-phase forced convection	√	4.02, 4.03, 4.05, 4.06, 4.07, 4.09
	4b	Interfacial energy exchange	Bubbly flow	x	2.04, 4.04, 4.08, 7.02
			Bubbly slug transition		None Identified at Present
			Bubbly slug flow		None Identified at Present
			Churn Flow		None Identified at Present
			Annular-mist flow	√	6.01 - 6.05
			Transition to stratified flow		None Identified at Present
			Stratified flow	√	11.01, 11.02, 11.03
			Plug flow		None Identified at Present
			Effect of noncondensables	√	6.01 - 6.05
ECM	1	Centrifugal pumps (Pump component)	Referenced at subcategory level	√	14.05
	2	Steam-water separator	Referenced at subcategory level	√	14.04
	3	Plenum component	Referenced at subcategory level		None Identified at Present
	4	Valve component	Referenced at subcategory level	√	1.12
	5	Turbine	Referenced at subcategory level		None Identified at Present
	6	Pressurizer	Referenced at subcategory level	√	14.02, 14.03, 11.01
SPM	1	Model for CCFL	Referenced at subcategory level	√	3.01 - 3.03
	2	Critical flow model	Referenced at subcategory level	√	1.01 - 1.12
	3	Trip and control elements	Referenced at subcategory level	√	See Table 5-5, Other Standards

DRAFT

TABLE 6-5 (Cont.)
VALIDATION OF TRAC-P USING SEPARATE EFFECT DATA

Category	Subcategory		Model	Validation by Separate Effect Tests Data	
	No.	Description		P-SET Facility Number from Table 6-XX	
	4	Reflood heat transfer models		-	-
	4a	Flow regime modeling	Bubbly flow	x	5.01 - 5.05
			Inverted annular flow	x	5.01 - 5.05
			Dispersed flow	x	5.01 - 5.05
	4b	Wall-to-phase fluid drag	Single phase	x	5.01 - 5.05
			Two-phase homogeneous	x	5.01 - 5.05
	4c	Interfacial fluid drag	Subcooled boiling	x	5.01 - 5.05
			Smooth inverted annular flow	x	5.01 - 5.05
			Rough-wavy inverted annular flow	x	5.01 - 5.05
			Agitated inverted annular flow	x	5.01 - 5.05
			Post-agitated (dispersed) flow	x	5.01 - 5.05
			Highly dispersed flow	x	5.01 - 5.05
	4d	Wall-to-phase fluid heat transfer	Forced convection to a single-phase liquid	x	5.01 - 5.05
			Nucleate boiling	x	5.01 - 5.05
			Critical heat flux	x	5.01 - 5.05
			Transition boiling	x	5.01 - 5.05
			Min. stable film boiling temperature	x	5.01 - 5.05
			Film boiling	x	5.01 - 5.05
			Convection to a single-phase vapor	x	5.01 - 5.05
			Convection to a two-phase mixture	x	5.01 - 5.05
			Condensation		None Identified at Present
			Natural convection to a single-phase liquid		None Identified at Present
	4e	Interfacial fluid heat transfer	Bubbly flow	x	5.01 - 5.05
			Inverted annular flow	x	5.01 - 5.05
			Dispersed flow	x	5.01 - 5.05
	4f	Conduction heat transfer	Referenced at subcategory level	x	5.01 - 5.05

DRAFT

**TABLE 6-5 (Cont.)
VALIDATION OF TRAC-P USING SEPARATE EFFECT DATA**

Category	Subcategory		Model	Validation by Separate Effect Tests Data	
	No.	Description			P-SET Facility Number from Table 6-XX
NSM	5	Two-phase level-tracking model	Referenced at subcategory level	x	2.01, 2.05, 2.06
	6	Offtake model for Tee component	Referenced at subcategory level	√	16.01 - 16.07
		Fluid field equations		-	-
		1D stability enhancing two-step (SETs) method	Referenced at subcategory level	√	See Table 5-5, Other Standards
		3D SETs	Referenced at subcategory level		Validated by Other Standards - TBD
		Conduction in solid materials		-	-
		Lumped capacitance	Referenced at subcategory level	√	See Table 5-5, Other Standards
		1D rectangular and cylindrical	Referenced at subcategory level	√	See Table 5-5, Other Standards
		2D rectangular and cylindrical	Referenced at subcategory level	√	See Table 5-5, Other Standards
		Power generation in fuel rods	Referenced at subcategory level	√	See Table 5-5, Other Standards
		Trip and control system elements	Referenced at subcategory level	√	All
		Fluid equation of state	Referenced at subcategory level	√	See Table 5-5, Other Standards
		Fluid boundary conditions	Referenced at subcategory level	√	All
		Equipment component models		-	-
	1	Centrifugal pumps (Pump component)	Referenced at subcategory level		Validated by Other Standards - TBD
	2	Steam-water separator	Referenced at subcategory level		Validated by Other Standards - TBD
	3	Plenum component	Referenced at subcategory level		Validated by Other Standards - TBD

DRAFT

TABLE 6-5 (Cont.)
VALIDATION OF TRAC-P USING SEPARATE EFFECT DATA

Category	Subcategory		Model	Validation by Separate Effect Tests Data	
	No.	Description			P-SET Facility Number from Table 6-XX
	4	Valve component	Referenced at subcategory level		Validated by Other Standards - TBD
	5	Turbine	Referenced at subcategory level		Validated by Other Standards - TBD
	6	Pressurizer	Referenced at subcategory level		Validated by Other Standards - TBD
		Special-purpose models		-	-
	1	Model for CCFL	Referenced at subcategory level		Validated by Other Standards - TBD
	2	Critical flow model	Referenced at subcategory level	√	See Table 5-5, Other Standards
	3	Trip and control elements	Referenced at subcategory level	√	See Table 5-5, Other Standards
	4	Reflood heat transfer models	Referenced at subcategory level		Validated by Other Standards - TBD
		Steady-state methods	Referenced at subcategory level	√	All Steady State Tests
		Timestep size and control methods	Referenced at subcategory level	√	All

7.0. CODE QUALIFICATION—VALIDATION USING INTEGRAL EFFECT TEST DATA

The data from integral effect experiments to be used for validation of TRAC-P are discussed in this section. The characteristics of IET data and the role of IET data in validation have been discussed previously in Section 2 and Appendix B.

7.1. Data Characterization

An essential element of data selection is data characterization. For SET data the important characterizing factors are

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

The first factor, experiment characteristics, focuses on the simulated plant type, facility 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 4-1). The third factor, data availability addresses whether the data can be acquired; it is a go/no-go factor. The fourth factor, quality of data, is evident; high-quality data are required if the validation part of code qualification is to accurately reflect code capabilities and adequacy. 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 a the pragmatic issue of the cost of preparing facility input decks. Given two IET facilities, equal in all aspects except that a broader range of conditions are covered in one, we would select the facility with the broader range and variety of data because overall program costs are reduced.

For some specific model validation efforts, there are several potential facilities and data sets for TRAC-P qualification from which to choose. For example, numerous facilities have simulated SBLOCAs. 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-P input decks exist are given priority.
- Facilities for which TRAC-P input decks for earlier code versions exist are assigned the next highest priority; the input decks will need to 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-P input deck are assigned the next highest priority.

A list of TRAC-P facility input decks is provided in Table 7-1. Not all input decks have been updated for use with the latest TRAC-P version, namely TRAC-PF1/MOD2 (MOD2). The latest TRAC-P version for which a TRAC-P facility deck exists is also provided in Table 7-1. Decks last used with TRAC-PF1/MOD1 (MOD1) must be updated before they can be used for TRAC-P code qualification. Numerous MOD1 input decks have been archived for specific facility tests. A more extensive tabulation of both facility- and test-specific input decks is provided in Appendix G.

7.2. Data Sources

Recently, the OECD/CSNI prepared a companion IET validation matrix document⁷⁻¹ to complement the previously issued SET validation matrix document.⁷⁻² The OECD/CSNI validation matrix is a valuable resource because it represents the culmination of over a decade of effort. Separate IET assessment matrices are

TABLE 7-1
TRAC-P INPUT DECKS FOR INTEGRAL EFFECT TESTS

Facility ^a	Code Version
CCTF	MOD2
LOFT	MOD2
Large-Scale Test Facility (LSTF) (aka ROSA-IV)	MOD1 ^b
Multi-Loop Integral System Test (MIST)	MOD1
Primarkreislaufe (PKL)	MOD1
SCTF	MOD2 ^c
Semiscale Mod-1	MOD21
Semiscale Mod-2a	MOD1
Semiscale Mod-3	MOD1
UPTF Semiscale Mod-3	MOD2
	MOD1

^a Acronyms for all facilities are provided in the acronym list at the front of this report.

^b The NRC has a MOD2 version of the LSTF-AP600 configuration.

^c Updating is in progress.

provided for both PWR and BWR reduced-scale IET facilities. For PWR reduced-scale facilities, the matrices are further focused on the following scenarios: LBLOCA, intermediate-break (IB)LOCA, SBLOCA, operating power, shutdown power, and accident management. Further differentiation is made for PWRs with U-tube steam generators and OTSGs.

For the purposes of this document, creation of a TRAC-P Validation Test Matrix, the OECD/CSNI IET document has an important drawback: data were selected solely according to their technical quality for the purposes of code assessment, irrespective of the availability of their data.

The CSNI list of PWR IET facilities and key facility characteristics is provided in Table 7-2. Fully current TRAC-P input decks exist for facilities whose names appear in bold type. A single facility deck may not be applicable to all tests in the facility. Facilities for which TRAC-P input decks exist but require updating are underlined. A more extensive summary of the IET facility characteristics is presented in Appendix H.

TABLE 7-2
OECD/CSNI INTEGRAL EFFECT TEST FACILITY SUMMARY

Facility ^a	Key Features
Boucle d'Etudes Thermohydrauliques Système (BETHSY)	~1:100 power/volume (P/V) scaled; 1:1 height; 3 loop; full pressure; electrically heated core; 10% of nominal power; spectrum of tests (LOCAs, transients, and transients at shutdown)
CCTF	1:25 P/V scaled; 1:1 height; 4 loops; x pressure; electrically heated core; multiple tests of refill and reflood phases of LBLOCA.
Loop for Blowdown Investigation or Loop for Off-Normal Behavior Investigations (LOBI)	1:712 P/V scaled; 1:1 height; x loop; full pressure; electrically heated core; 28 LBLOCA tests in Mod-1 configuration and 42 tests in Mod-2 configuration for SBLOCA and special transients.
LOFT	1:60 P/V scaled; reduced height with atypicalities; 2-loop; full pressure; nuclear core; spectrum of tests (LOCA's, anticipated and transients, and multiple failure transients).

^a Acronyms for all facilities are provided in the acronym list at the front of this report.

TABLE 7-2 (cont)
OECD/CSNI INTEGRAL EFFECT TEST FACILITY SUMMARY

Facility	Key Features
<u>LSTF (aka ROSA)</u>	1:48 P/V scaled; 1:1 height; 2 loops; full pressure; electrically heated core; 14% of nominal power; more than 100 SBLOCAs, transients, and transients at shutdown.
LSTF-AP600	1:30 volume scaled for AP600; 1:1 height; 2 loops; full pressure; electrically heated core; includes core makeup tanks, pressure balance lines, passive residual heat removal system, in-containment refueling water storage tank, accumulator injection system, and automatic depressurization system.
<u>PKL</u>	1:134 to 1:145 P/V scaled; 1:1 height, 3 configurations changed from 3-loop to 4-loop; reduced pressure; electrically heated core; LBLOCA end of blowdown, refill and reflood, and other events.
SCTF	1:21 P/V scaled; 1:1 height; 3 core configurations; intact and broken loops; x pressure; electrically heated core; refill and reflood phases of LBLOCA including multiple coolant injection configurations. Note: Appears in Ref. 7-2 as SET facility but not listed in Ref. 7-1 as a IET facility.
SEMISCALE	1:1705 P/V scaled; 1:1 height; 2 loops but several configurations; full pressure; electrically heated core; simulated LOCAs and operational transients.
Simulatore PWR per Esperienze de Sicurezza (SPES)	1:427 P/V scaled; 1:1 height, 3 loops; full pressure; electrically heated core; simulated SBLOCAs, single and two-phase natural circulation, and transients.
SPES-AP600	1:395 P/V scaled; 1: 1 height with exception of pressurizer; 2 x 4 loop AP600 loop configuration; hardware to simulate passive core cooling system; full pressure; electrically heated core; scaled full power; simulated SBLOCAs and other transients.

TABLE 7-2 (cont)
OECD/CSNI INTEGRAL EFFECT TEST FACILITY SUMMARY

Facility	Key Features
UPTF	1:1 volume scaled; 1:1 height; 4 loops; reduced pressure; unheated (core simulators); simulated features of LBLOCA and separate effects. Note: Appears in both Ref. 2-1 as IET facility and in Ref. 2-2 as a SET facility.
Geradorohr Dempferzeuger Anlage (GERDA)	1:1686 P/V scaled; 1:1 height; single loop; full pressure; electrically heated core; less than full nominal power; OTSG; over 100 SETs and IETs performed covering a wide range of SBLOCA and natural circulation conditions.
<u>MIST</u>	1:817 P/V scaled; 1:1 height; 2 x 4 configuration; full pressure; electrically heated core; 10% of scaled power; OTSGs; 41 experiments simulating SBLOCA, SGTR, feed and bleed, pump operation, effect of noncondensibles, and natural circulation.
Once-Through Integral Systems (OTIS)	1:1686 P/V scaled; 1:1 height; single loop; full pressure; electrically heated core; 10% of scaled power; OTSG; no primary pump; and 13 SBLOCA tests.
University of Maryland, College Park (UMCP)	1:500 P/V scaled; reduced height; 2 x 4 loop configuration; reduced pressure; electrically heated core; 24.7% of scaled power; simulated SBLOCA, and natural circulation behavior.

7.3. Data Selected for TRAC Qualification

The selected IETs are to satisfy multiple needs. Each of these needs will be addressed in the following subsections. However, while addressing these needs separately, care must be taken to maximize the benefit from a given IET facility. Otherwise, addressing these needs independently of one another will increase the number of proposed IET tests to unreasonable levels.

7.3.1. IET Selection Based on PIRT Summary

A summary tabulation of processes/phenomena based upon three contemporary PWR PIRTs was presented in Section 4.0 (Table 4-1). Most of the

processes/phenomena listed occur at a location; these are associated with the level identifier LL in Table 4-1. However, other processes/phenomena clearly are not local; they occur at either the CL or the SL. Multidimensional flow within the core is an example of the former and distribution of liquid and void throughout the primary system of a PWR is an example of latter. The CL and SL entries have been extracted from Table 4-1 and are presented as Table 7-3.

Following the selection criteria presented in Section 7.1, our primary focus is on data from the following IET facilities: CCTF, LOFT, LSTF-AP600, SCTF, and UPTF. If IET validation needs remain that cannot be satisfied with data from these facilities, we then consider data from the LSTF-ROSA IV, MIST, PKL, and Semiscale facilities. Our recommendations are presented in Table 7-4. Continuing the flags used in Table 7-1, updated TRAC-P input decks exist for facilities with names appearing in bold type. Facilities for which TRAC-P input decks exist but require updating are underlined.

7.3.2. IET Selection Based on Targeted Application Coverage

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.

Plant Type

A survey of commercial nuclear power plants was completed in 1992.⁷⁻³ 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 7-5.

The authors are unaware of any IET facilities for combustion engineering (CE) designs. IET facilities based upon Westinghouse (Semiscale, LOFT, LSTF, LSTF-AP600, SPES, SPES-AP600, SCTF, CCTF, and UPTF) and B&W designs (MIST, UMCP, OTIS) have been designed and operated. Therefore, reasonable coverage of these designs is possible, although each facility has some atypicalities relative to the reference reactor type for which they were designed.

TABLE 7-3
PIRT IDENTIFIED PROCESSES/PHENOMENA REQUIRING IET DATA

Process/Phenomena	PIRT Rank	Level
Asymmetries	M	CL, SL
Distribution—liquid/void	M	SL
Flow	HL	CL, SL
Flow—channeling	H	CL
Flow—countercurrent	M	CL
Flow—multidimensional	H	CL, SL
Flow—natural circulation	H	CL, SL
Flow—safety class coolant	M	SL
Oscillations	L	CL, SL
Pressurization	M	CL, SL
Pump—coastdown	H	CL
Pump—performance, including degradation	H	CL
Stratification—phase separation	H	CL
Stratification—thermal	M	CL
Valve performance	M	CL

In Section 7.3.1, LOFT and SCTF were selected based upon the need to simulate system-level phenomena identified in the summary PIRT (Table 7-4). These same two facilities also seem adequate for representing the currently operating Westinghouse designs. The LSTF-AP600 facility is adequate for representing the Westinghouse advanced passive reactor, AP600. If more prototypical representations of the loops are required, the LSTF facility (pre-AP600) appears to be the best choice. MIST is the best choice for simulating B&W designs. No direct approach for simulating CE designs is evident.

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 Westinghouse and B&W designs in Table 7-6.

With the exception of the SGTR and MSLB transients, TRAC-P performance can be tested for the listed event scenarios for Westinghouse plants using existing TRAC-P

TABLE 7-4
FACILITIES AND TESTS FOR PIRT IDENTIFIED PROCESSES/PHENOMENA
REQUIRING IET DATA

Process/Phenomena	Facility	Test
Asymmetries	<u>MIST</u>	3109AA ⁷⁻⁴
Distribution—liquid/void	<u>MIST</u>	3109AA ⁷⁻⁴
Flow	All Facilities	
Flow—channeling	SCTF	Runs 719, 720 ⁷⁻⁵
Flow—countercurrent	SCTF	Runs 719, 720 ⁷⁻⁵
	UPTF	Runs 5, 6, 21 ⁷⁻⁶
Flow—multidimensional	SCTF	Runs 719, 720 ⁷⁻⁵
	UPTF	Runs 5, 6, 21 ⁷⁻⁶
Flow—natural circulation	<u>LSTF</u>	ST-NC-02 ⁷⁻⁷
Flow—safety class coolant	LOFT	L2-3 or L2-5 ⁷⁻⁸
	UPTF	Tests 8, 28 ⁷⁻⁶
Oscillations	SCTF	Runs 719, 720 ⁷⁻⁵
Pressurization	LOFT	L9-1 ⁷⁻⁸
Pump—coastdown	LOFT	L6-2 ⁷⁻⁹
Pump—performance, including degradation	LOFT	L3-5, L3-6 ⁷⁻⁸
Stratification—phase separation	LSTF-AP600	1-in CLB ⁷⁻¹⁰
Stratification—thermal	LSTF-AP600	1-in CLB ⁷⁻¹⁰
Valve performance	VAPORE	Phase B1 Tests ⁷⁻¹¹

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-P input models are required for these facilities for other reasons. With the exception of the LBLOCA, MSLB, loss-of-feedwater event, and anticipated transient without scram (ATWS), TRAC-P performance can be assessed for the listed event scenarios for B&W plants.

7.3.3. 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.⁷⁻¹² 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

* 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.

TABLE 7-5
SUMMARY OF VENDOR AND REACTOR TYPES

<u>Vendor Group</u>	<u>Group Description</u>	<u>Coolant Loops</u>	<u>Number of Bundles</u>	<u>Bundle Design</u>
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

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.

7.4. Summary

The IET facilities and data listed in Table 7-7 have been identified for TRAC-P validation. The rationale for these selections are (1) coverage of system-level PIRT-listed processes/phenomena, and (2) coverage of the targeted applications, specifically addressed via plant type and event type. IET selection based on scaling

TABLE 7-6
EVENT SCENARIOS AND APPLICABLE IET TESTS

Designer	Event	IET facility and Test
Westinghouse	LBLOCA IBLOCA SBLOCA SGTR MSLB Loss-of-offsite power Loss of feedwater Reactor trip Anticipated transient w/o scram Multiple-failure events Accident management scenarios	LOFT L2-3 or L2-5 ⁷⁻⁸ LOFT L5-1 or L8-2 ⁷⁻¹³ LOFT L3-5 and L3-6 ⁷⁻⁸ BETHSY 4.3b LOBI BT12 LOFT L9-4 ⁷⁻¹⁴ LOFT L9-1/L3-3 ⁷⁻¹³ LOFT L6-2 ⁷⁻⁹ LOFT L9-3 or L9-4 ⁷⁻¹⁴ LSTF-AP600 LSTF-AP600
B&W	LBLOCA IBLOCA SBLOCA SGTR MSTL Loss-of-offsite power Loss of feedwater Reactor trip Anticipated transient w/o scram Multiple-failure events Accident management scenarios	None MIST 4100B2 ⁷⁻¹⁵ MIST 3109AA ⁷⁻⁴ MIST 3404AA ⁷⁻¹⁶ None MIST 4SB011 ⁷⁻¹⁵ None MIST 4SB011 ⁷⁻¹⁵ None MIST 410BD1 or 410AT3 ⁷⁻¹⁵ MIST 410BD1 or 410AT3 ⁷⁻¹⁵

issues was discussed, but insufficient information exists at present to determine whether more IET facilities should be added to the Validation Test Matrix to address scaling issues. IET selection based on overall TRAC-P adequacy demonstration is treated as a confirmatory effort, wherein the validation results defined per (1) and (2) above are sufficient to demonstrate code adequacy.

TABLE 7-7
SUMMARY OF IET FACILITIES AND TESTS

Vendor	Integral Test Facility	Tests
Westinghouse	BETHSY LOBI LOFT	4.3b BT12 L2-3 or L2-5 ⁷⁻⁸ L5-1 or L8-2 ⁷⁻¹³ L3-5 and L3-6 ⁷⁻⁸ L9-4 ⁷⁻¹⁴ L9-1/L3-3 ⁷⁻¹³ L6-2 ⁷⁻⁹ L9-3 or L9-4 ⁷⁻¹⁴ ST-NC-02 ⁷⁻⁷
	LSTF LSTF-AP00 SCTF UPTF	Multiple-failure event Accident management 1-inch cold-leg break Runs 719 and 720 ⁷⁻⁵ Tests 5a,b; 6; 8, 21a,b; 28 ⁷⁻⁶
B&W	MIST	3109AA ⁷⁻⁴ 3404AA ⁷⁻¹⁶ 4100B2 ⁷⁻¹⁵ 410BD1 or 410AT3 ⁷⁻¹⁵ 4SB011 ⁷⁻¹⁵

REFERENCES

- 7-1. "CSNI Integral Test Facility Validation Matrix for the Assessment of Thermal-Hydraulic Codes for LWR LOCA and Transients," Committee on the Safety of Nuclear Installations, OECD Nuclear Energy Agency report CSNI 132, Revision 6, restricted working draft (June 1995).
- 7-2. "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).
- 7-3. 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).
- 7-4. J. L. Steiner, D. A. Siebe, and B. E. Boyack, "Posttest Analysis of MIST Test 3109AA Using TRAC-PF1/MOD1," Los Alamos National Laboratory document NUREG/CR-5887 (September 1992).

- 7-5. B. E. Boyack, P. R. Shire, and S. C. Harmony, "TRAC-PF1/MOD1 Code Assessment Summary Report for SCTF Core-III," Los Alamos National Laboratory document LA-CP-90-71 (February 8, 1990).
- 7-6. P. S. Damerell and J. W. Simons, Eds., "2D/3D Program Work Summary Report," US Nuclear Regulatory Commission document NUREG/IA-0126 (June 1993).
- 7-7. H. J. Stumpf and F. M. Motley, "Results of TRAC Analysis of Run ST-NC-02 from the Large-Scale Test Facility," Los Alamos National Laboratory document LA-CP-87-131 (1987).
- 7-8. T. D. Knight, Ed., "TRAC-PD2 Independent Assessment," Los Alamos National Laboratory document NUREG/CR-3866 (December 1984).
- 7-9. M. S. Sahota and F. L. Addessio, "TRAC-PF1/MOD1 Developmental Assessment," Los Alamos National Laboratory document NUREG/CR-4278 (August 1985).
- 7-10. 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, and L. S. Ghan, "Adequacy Evaluation of RELAP5/MOD3, Version 3.2.1.2 for Simulating AP600 Small-Break Loss-of-Coolant Accidents: Appendices A, B, and C (Final Draft)," Idaho National Engineering Laboratory document INEL-96-0400, proprietary information (December 1996).
- 7-11. L. S. Ghan, J. P. Adams and S. M. Sloan, "Assessment of RELAP5/MOD3 Using Data From the Westinghouse VAPORE ADS-123 Test Facility," Idaho National Engineering Laboratory Proprietary document, transmitted by letter DGH-02-96 (November 15, 1996).
- 7-12. 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).
- 7-13. T. D. Knight and V. B. Metzger (compilers), "TRAC-PF1 Independent Assessment," Los Alamos National Laboratory document NUREG/CR-3646 (October 1985).
- 7-14. C. L. Nalezny, "Summary of Nuclear Regulatory Commission's LOFT Program Experiments," EG&G Idaho, Inc. document NUREG/CR-3214 (July 1983).

- 7-15. J. R. Gloudemans, "Multiloop Integral System Test (MIST): Final Report," Babcock & Wilcox Nuclear Power Division document NUREG/CR-5395 (April 1991).
- 7-16. D. A. Siebe, J. L. Steiner, and B. E. Boyack, "Posttest Analysis of MIST Test 3404AA Using TRAC-PF1/MOD1," Los Alamos National Laboratory document LA-UR-92-2699 (August 1992).

8.0. SUMMARY OBSERVATIONS

The NRC has selected TRAC-P as the base code for its future code development activities. Given the important role assigned to TRAC-P, qualification of the code for its targeted applications is essential.

For new codes being developed under the NRC's software quality assurance program and guidelines, the software life-cycle activities that proceed Qualification Testing are Requirements Definition, Design, and Implementation. Qualification Testing is the set of activities associated with formally testing, reviewing, and analyzing software performance. Taken together, verification and validation constitute Qualification Testing. The former is a process of ensuring that the products of each major software development activity meet the standards set for that activity. Verification activities include formal reviews and audits, formal peer reviews, and informal testing. Validation is the process of demonstrating that the as-built software meets its requirements. Testing is the primary method of software validation. The set of tests thus identified constitute the TRAC-P Validation Test Matrix.

The TRAC-P Validation Test Matrix encompasses separate effect tests (Section 6), integral effect tests (Section 7), and other standard tests (Section 5) selected to ensure that all code features, models, integrated calculational capabilities, and applications are tested. To ensure completeness, we have taken three structured approaches to identifying the individual tests to be included in the validation matrix.

First, we have identified the basic equations models, flow-field models and engineering correlations, equipment component models, and special-purpose models in TRAC-P that must be validated. Elements of the TRAC-P Validation Test Matrix providing coverage of TRAC models and methods using standard tests employing other than experimental data are summarized in Table 5-5. Elements of the TRAC-P Validation Test Matrix providing coverage of TRAC models and methods using SET data are summarized in Table 6-5.

Second, we have identified local, component, and system level processes and phenomena that must be modeled by TRAC for its targeted applications as described in Section 1. Elements of the TRAC-P Validation Test Matrix providing coverage of the PIRT processes and phenomena identified in Section 4 are summarized in Table 6-4 (SET tests) and Table 7-4 (IET tests).

Third, we have identified the set of targeted applications associated with plant type and event scenarios that must be modeled. The event scenarios and applicable IET facility and test are summarized in Table 7-6.

Before each formal code release, the TRAC-P code should be tested for adequacy by exercising the code on the test problems in the TRAC-P Validation Test Matrix and confirming code adequacy for those test problems.

In the numbered comments that follow, we provide additional specific observations that relate to the TRAC-P Validation Test Matrix provided herein.

1. Relative to previous TRAC validation matrices, the TRAC-P Validation Test Matrix presented in this document places a much greater emphasis on validating individual TRAC models and methods using SET data, particularly fundamental test data.
2. There are TRAC-P 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. The potential for introducing compensating errors is greater when indirect data sets are used because the code developer must inevitably make conclusions about the underlying physics.
3. A number of SET facilities and tests are identified. Having identified the desired data, Los Alamos will work with the NRC to request data sets not presently residing in the NRC databank. Equally important, we must acquire sufficient test facility description information to permit development of an accurate TRAC-P input model description for each test facility.
4. Previous efforts to identify and select SET data frequently focused on test data generated through association with the nuclear industry. We have identified and included other sources of fundamental SET data in the TRAC-P Validation Test Matrix. It is likely that additional sources of such fundamental SET data exist. These should be sought and added as the TRAC-P Validation Test Matrix is revised and updated.
5. Tests are proposed for the "Other Standards" element of the Validation Test Matrix. Additional test problems will be added by Los Alamos as they are identified. Because the NRC is implementing a multiparty TRAC-P development effort, other participants should also contribute test problems as they evolve.
6. Sufficient IET data exist for validation of the integrated TRAC-P code.

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

Two categories of experimental data have traditionally been identified for use in T-H code validation: separate effect and integral effect. The two 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. 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 interface where assignment of a particular facility or test to either the SET or IET category is arbitrary.

SET 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.

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 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 and IET facilities in Fig. 2-2 where we show a spectrum of SET 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 semiquantitative 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 radiative 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. 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 varies 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-P

An expanded view of the models and methods in the TRAC-P 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-P 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-P are outlined in Sections C.1.1.1. through C.1.1.4. below.

C.1.1.1. Mass Conservation Equations. TRAC-P 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-P 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-P 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-P 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-P:

- 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-P 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-P 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-P, 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-P 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-P 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-P 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-P 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-P have been listed in Section C.3. The properties of these models are best determined by reference to the TRAC-P Theory Manual.³⁻²

C.4. Special-Purpose Models

The special-purpose models in TRAC-P 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-P is based on a generalized formulation from which both the Wallis and Kutaladaze forms can be recovered.

The critical flow model in TRAC-P 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-P 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-P 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-P are quite general and can probably model almost any control system encountered in TRAC-P applications.

C.5. Numerical Solution Methods

All the numerical solution methods used in TRAC-P 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-P 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.

REFERENCES

- C-1. M. Ishii and K. Mishima, "Study of Two-Fluid Model and Interfacial Area," Argonne National Laboratory report ANL-80-111 (NUREG/CR-1873) (1980).
- C-2. I. Kataoka, M. Ishii, and K. Mishima, "Generation and Size Distribution of Droplet in Annular Two-Phase Flow," *Trans. ASME, J. Fluid Engineering* **105**, 230-238 (1983).
- C-3. J. Kitscha and G. Kocamustafaogullari, "Breakup Criteria for Fluid Particles," *Int. J. Multiphase Flow* **15**, 573-588 (1989).
- C-4. M. Ishii and K. Mishima, "Droplet Entrainment Correlation in Annular Two-Phase Flow," *Int. J. Heat Mass Transfer* **32**, 1835-1846 (1989).
- C-5. K. Mishima and M. Ishii, "Theoretical Prediction of Onset of Horizontal Slug Flow," *Trans. ASME, J. Fluids Engineering* **102**, 441-445 (1980).
- C-6. R. T. Lahey, "A Mechanistic Subcooled Boiling Model," *Proc. 6th Int. Heat Transfer Conf.* (Toronto, Canada, 1978), Vol. 1, pp. 293-297.
- C-7. P. Saha and N. Zuber, "Point of Net Vapor Generation and Vapor Void Fraction in Subcooled Boiling," *Proc. 5th Int. Heat Transfer Conf.* (Tokyo, Japan, 1974), Paper B4.7.
- C-8. S. W. Churchill, "Friction-Factor Equation Spans All Fluid-Flow Regimes," *Chemical Engineering*, pp. 91-92 (Nov. 7, 1977).
- C-9. M. Ishii and T. C. Chawla, "Local Drag Laws in Dispersed Two-Phase Flow," Argonne National Laboratory report ANL-79-105 (NUREG/CR-1230) (December 1979).
- C-10. M. Ishii, Argonne National Laboratory, personal communication to R. Nelson, Los Alamos National Laboratory July 1987.
- C-11. L. Shiller and A. Z. Nauman, *Ver. Deut. Ing.* **77**, 318-320 (1933).
- C-12. R. B. Bird, W. E. Stewart, and E. N. Lightfoot, *Transport Phenomena* (John Wiley and Sons, New York, 1960).
- C-13. I. Kataoka and M. Ishii, "Mechanism and Correlation of Droplet Entrainment and Deposition in Annular Two-Phase Flow," Argonne National Laboratory report ANL-82-44 (NUREG/CR-2885) (1982).

- C-14. G. B. Wallis, *One Dimensional Two Phase Flow* (McGraw-Hill Book Company, New York, 1969).
- C-15. Y. Taitel and A. E. Dukler, "A Model for Predicting Flow Regime Transitions in Horizontal and Near Horizontal Gas-Liquid Flow," *AIChE J.* **22** (1), 47-55 (1976).
- C-16. A. Ohnuki, H. Adachi, and Y. Murao, "Scale Effects on Countercurrent Gas-Liquid Flow in Horizontal Tube Connected to Inclined Riser," proceedings of 1987 National Heat Transfer Conference, Pittsburgh, Pennsylvania (August 9-12, 1987). pp. 40-49.
- C-17. J. P. Holman, *Heat Transfer*, 5th ed. (McGraw-Hill Book Co., New York, 1981).
- C-18. F. E. Incropera and D. P. DeWitt, *Fundamentals of Heat Transfer* (John Wiley & Sons, New York, 1981).
- C-19. J. M. Delhay, M. Giot, and M. L. Riethmuller, *Thermohydraulics of Two-Phase Systems for Industrial Design and Nuclear Engineering* (Hemisphere Publishing Corporation, New York, 1981).
- C-20. W. M. McAdams, *Heat Transmission*, 3rd ed. (McGraw-Hill Book Co., New York, 1954).
- C-21. R. T. Lahey and F. J. Moody, *The Thermal-Hydraulics of a Boiling Water Nuclear Reactor* (American Nuclear Society, La Grange Park, Illinois, 1977).
- C-22. L. Biasi, G. C. Clerici, S. Garribba, R. Sala, and A. Tozzi, "Studies on Burnout, Part 3: A New Correlation for Round Ducts and Uniform Heating and Its Comparison with World Data," *Energia Nucleare* **14**, 530-536 (1967).
- C-23. L. A. Bromley, "Heat Transfer in Stable Film Boiling," *Chem. Eng. Prog.* **46** (5), 221-227 (May 1950).
- C-24. S. Webb and J. C. Chen, "A Two-Region Vapor Generation Rate Model for Convective Film Boiling," Int. Workshop of Fundamental Aspects of Post-Dryout Heat Transfer, Salt Lake City, Utah, April 1-4, 1984.
- C-25. R. E. Henry, "A Correlation for the Minimum Film Boiling Temperature," *AIChE Symposium Series* **138**, 81-90 (1974).
- C-26. M. K. Denham, "Inverted Annular Film Boiling and the Bromley Model," Atomic Energy Establishment Winfrith report AEEW-R 1590 (January 1983).

- C-27. F. Kreith, *Principles of Heat Transfer*, 3rd. ed., (Harper and Row, New York, 1973).
- C-28. W. M. Rohsenow and H. Choi, *Heat, Mass, and Momentum Transfer* (Prentice-Hall, Englewood Cliffs, New Jersey, 1961).
- C-29. Y. M. Chen and F. Mayinger, "Measurement of Heat Transfer at the Phase Interface of Condensing Bubbles," *ANS Proc. 1989 National Heat Transfer Conf.*, (Philadelphia, Pennsylvania, August 6-9, 1989) HTC-Vol. 4, pp. 147-152.
- C-30. S. Whittaker, "Forced Convection Heat Transfer Correlations for Flows in Pipes, Past Flat Plates, Single Cylinder, Single Sphere, and Flows in Packed Beds and Tube Bundles," *AIChE J.* 18, 361-372 (1972).
- C-31. K. Pasamehmetoglu and R. Nelson, "Transient Direct-Contact Condensation on Liquid Droplets," *Nonequilibrium Transport Phenomena* (American Society of Mechanical Engineers, New York, 1987), HTD-Vol. 77, pp. 47-56.
- C-32. S. G. Bankoff, "Some Condensation Studies Pertinent to Light Water Safety," *Int. J. Multiphase Flow* 6, 51-67 (1980).
- C-33. G. Ryskin, "Heat and Mass Transfer from a Moving Drop—Some Approximate Relations for the Nusselt Number," *Int. Comm. Heat Mass Transfer* 14, 741-749 (1987).
- C-34. J. H. Linehan, M. Petrick, and M. M. El-Wakil, "The Condensation of Saturated Vapor on a Subcooled Film During Stratified Flow," *Chem. Eng. Symp. Series* 66 (102), 11-20 (1972).
- C-35. C. Unal, K. Tuzla, C. A. Tuzla, and J. C. Chen, "Vapor Generation Model for Dispersed Drop Flow," *ANS Proc. 1989 National Heat Transfer Conf.* (August 1989), HTC-Vol. 4.
- C-36. G. G. Sklover and M. D. Rodivilin, "Condensation on Water Jets with a Cross Flow of Steam," *Teploenergetika* 23, 48-51 (1976).

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	$a \leq 0.3$; or $a \leq 0.5$ and $G \geq 2700 \text{ kg/m}^2\text{-s}$	based on Ishii and Mishima ^{C-1}
Bubbly Slug Transition	$0.3 < a \leq 0.5$ and $2000 < G < 2700 \text{ kg/m}^2\text{-s}$	based on Ishii and Mishima ^{C-1}
Bubbly Slug Flow	$0.3 < a \leq 0.5$ and $G \leq 2000 \text{ kg/m}^2\text{-s}$	based on Ishii and Mishima ^{C-1}
Churn Flow	$0.5 < a \leq 0.75$	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 SahC-a-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 (cwl)	Wall-to-Gas Drag Coefficient (cwg)
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	<p>based on the modified Bromley film boiling heat-transfer coefficient^{C-23} and a radiation term</p> <p>reflood model: based on the Denham^{C-26} and modified Bromley^{C-23} correlations and a radiation term</p>	<p>maximum of either the natural convection^{C-20} or Dougall-Rohsenow^{C-21} correlations</p> <p>reflood model: based on Webb-Chen correlation^{C-24}</p>
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	<p>cond/evap: superimpose droplet and film field</p> <p>droplet field: based on transient conduction solution^{C-31}</p> <p>film field: based on Bankoff correlation for Stanton number^{C-32}</p> <p>flashing: based on maximum of weighted heat- transfer factor and liquid superheat relation</p>	<p>superimpose droplet and film field</p> <p>droplet field: based on Ryskin correlation for Nusselt number^{C-33}</p> <p>film field: based on Bankoff correlation for Stanton number^{C-32}</p>	<p>superimpose droplet and film field</p> <p>droplet field: based on Ryskin correlation for Nusselt number^{C-33}</p> <p>film field: based on Bankoff correlation for Stanton number^{C-32}</p>
Transition to Stratified Flow	<p>cond/evap: weighted average of stratified and flow-regime map heat-transfer factors</p> <p>flashing: based on maximum of weighted heat- transfer factor and liquid superheat relation</p>	<p>heat-transfer factor equivalent to value calculated from basic flow-regime map</p>	<p>heat-transfer factor equivalent to value calculated from basic flow-regime map</p>

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 ³⁻¹⁷)
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:	cond/evap: weighted average of bubbly, IAF, and dispersed flow heat-transfer factors	weighted average of bubbly, IAF, and dispersed flow heat-transfer factors	weighted average of bubbly, IAF, and dispersed flow heat-transfer factors
Bubbly Flow	defined as above, this table	defined as above, this table	defined as above, this table
IAF	based on HTVSSL model for subcooled liquid kinetic theory of evaporation for flashing ^{C-35}	$3 \times 10^3 \text{ W/m}^2\text{-K}$	$10^3 \text{ W/m}^2\text{-K}$
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

APPENDIX D

ADDITIONAL SUMMARY PIRT TABULATIONS

The information in a broadened PIRT database^{D-1-D-7} has been examined within the context of two limited objectives.^{D-8} The first limited objective was the identification of highly and moderately ranked phenomena that have been common to several of the PIRTs in the PIRT library. The second was the identification of the relative importance of components in previous PIRTs using a normalization scheme based on the frequency of the occurrence of low, moderate, and high phenomena ranks, and weighted by ranking importance.^{D-8}

Table D-1 summarizes phenomena/processes that have typically been found to be of high importance during one or more phases of the scenarios being examined. Similarly, Table D-2 summarizes the phenomena/processes that are typically of moderate importance. The processed results in Tables B-1 and D-2 are felt by the authors to be appropriate to the limited objectives stated in the previous paragraph. However, the processing assumptions should be understood. First, phenomena/processes that appeared in only one plant design or one scenario were not included. Second, cells that are shaded indicate that the time phase of interest either does not exist, is combined into another time phase shown in the table, or that a PIRT does not exist for the indicated time phase. Thus, a caution is issued. Additional important components and processes/phenomena may exist for a given plant and scenario. In fact, they almost surely do.

Table D-3 summarizes the importance of components in the previous PIRT applications forming the database for Ref. B-8. Table D-4 repeats the summary tabulation process of Section 4 of the main text. The unique process/phenomena are tabulated, as well as their importance rank, level, and associated TRAC models.

Several previously undefined acronyms are used in Tables D-2 and D-3. They are defined here for the readers convenience.

<u>Acronym</u>	<u>Definition</u>
ADS	Automatic depressurization system
CCFL	Countercurrent flow limiting
CHF	Critical heat flux
CMT	Core makeup tank
ECCS	Emergency Core coolant system
GDSC	Gravity-driven cooling system
IRWST	In-containment refueling water storage tank
PRHR	Passive residual heat removal

REFERENCES

- D-1. R. A. Shaw, T. K. Larson and R. K. Dimenna, "Development of a Phenomena Identification and Ranking Table (PIRT) for Thermal-Hydraulic Phenomena During a PWR LBLOCA," EG&G Idaho, Inc. document NUREG/CR-5074 (1988).
- D-2. M. G. Ortiz and L. S. Ghan, "Uncertainty Analysis of Minimum Vessel Liquid Inventory During a SBLOCA in a Babcock and Wilcox Plant," EG&G Idaho, Inc. document NUREG/CR-5818 (1992).
- D-3. R. G. Hanson, G. E. Wilson, M. G. Ortiz, and D. P. Griggs, "Development of a Phenomena Identification and Ranking Table (PIRT) for a Postulated Double-Ended Guillotine Break in a Production Reactor," *Nuclear Engineering and Design* 136, pp. 335-346 (1992).
- D-4. J. D. Burtt, C. D. Fletcher, G. E. Wilson, C. B. Davis, and T. J. Boucher "Phenomena Identification and Ranking Tables for Westinghouse AP600 Small-Break Loss-of-Coolant Accident, Main Steam Line Break, and Steam Generator Tube Rupture Scenarios," Lockheed Martin report INEL-94/0061-Rev. 2 (1996) (distribution controlled by the USNRC).
- D-5. G. E. Wilson, C. D. Fletcher, and F. Eltawila, "Use of PIRT Process in Research Related to Design Certification of the AP600 Advance Passive LWR," Proceedings of the International Conference on Nuclear Engineering, Vol. 2 ASME (1996).
- D-6. B. E. Boyack, "AP600 LBLOCA Phenomena Identification and Ranking Tabulation," Los Alamos National Laboratory document LA-UR-95-2718, (1995) (distribution controlled by the USNRC).
- D-7. P. G. Kroeger, U. S. Rohatgi, J. H. Jo, and G. C. Slovik, "Preliminary Phenomena Identification and Ranking Tables for SBWR LOCA Scenarios," Brookhaven National Laboratory technical letter report W-6092-5 (June 1995) (distribution controlled by the USNRC).
- D-8. G. E. Wilson and B. E. Boyack, "The Role of the PIRT Process in Identifying Code Improvements and Executing Code Development," Proceedings of the OECD/CSNI Workshop on Transient Thermal-Hydraulic and Neutronic Codes Requirements," Annapolis, Maryland (November 5-8, 1996).

TABLE D-1
PHENOMENA/PROCESSES OF TYPICAL HIGH IMPORTANCE IN PRIOR PIRT APPLICATIONS^{D-8}

General reactor behavior	Phenomenon	Frequency of high rank throughout the plant systems of interest										
		Total data base	WEC 4-loop LBLOCA	AP600 LBLOCA	B&W SBLOCA	AP600 SBLOCA	AP600 MSLB	SBWR MSLB	SBWR bottom drain line LOCA	SBWR GDSCS line LOCA	AP600 SGTR	Production reactor DEGB
Rapid blowdown from high pressure through large breaks and/or ADS	Critical flow	17	1	1		1	1	2	5	5		1
	Flashing	15				1	1	4	4	4		1
	Subcritical flow	12				2		2	4	4		
	Voiding & distribution	10						3	4	3		
	Condensation	10						2	4	4		
	Entrainment/de-entrainment	10					1	1	4	4		
	Convective heat transfer	8	2				1	2	1	1		1
	Inventory/level	8				3	1		1	2		1
	Conduction heat transfer	6	2				1		1	1		1
	Decay heat	6				1	1	1	1	1		1
	Phase separation	5				2		1	1	1		
	Natural/intenal circulation	4						2	1	1		
	Evaporation	3						1	1	1		
	Stored energy	3	1					1				1
	Parallel channel flow	2						1				1
	Energy transport by liquid	2					1	1				
Noncondensible effects	2							1	1			
Core inventory recovery, including refill and reflood	Decay heat	7	1	1			1	1	1	1	1	
	Convective heat transfer	7	3	1			1				2	
	Two-phase flow/delta-p	5	2					1	1	1		
	Inventory/level	4	2	2								
	Critical flow	4	1	1							2	
	Conduction heat transfer	4	1				1				2	
	Flow resistance/friction/form loss	3						1	1	1		
	Subcritical flow	2		1							1	
Slow depressuriztion from high pressure through small breaks	Critical flow	2			1						1	
	Decay heat	2			1						1	
Long-term recovery	Subcritical flow	13		4	2	1		2	2	2		
	Noncondensible effects	9						3	3	3		
	Inventory/level	7				5		1	1			
	Convective heat transfer	5		1	1			1	1	1		
	Flow resistance/friction/form loss	4				1		1	1	1		
	Condensation	4		1				1	1	1		
	Conduction heat transfer	4			1			1	1	1		
	Decay heat	4				1		1	1	1		
	Natural/intenal circulation	3						1	1	1		

TABLE D-2
PHENOMENA/PROCESSES OF TYPICAL MODERATE IMPORTANCE IN PRIOR PIRT APPLICATIONS^D

General reactor behavior	Phenomenon	Frequency of moderate rank throughout the plant systems of interest										
		Total data base	WEC 4-loop LBLOCA	AP600 LBLOCA	B&W SBLOCA	AP600 SBLOCA	AP600 MSLB	SBWR MSLB	SBWR bottom drain line LOCA	SBWR GDCS line LOCA	AP600 SGTR	Production reactor DEGB
Rapid blowdown from high pressure through large breaks and/or ADS	Condensation	24				2	1	7	7	7		
	Flashing	23		4		4	4	2	4	4		1
	Voiding & distribution	19	1			1	6	2	4	4		1
	Stored energy	19				2		5	6	6		
	Subcritical flow	17		5		2		2	4	3		1
	Conduction heat transfer	16		1		2	2	3	3	3		2
	Convective heat transfer	15				2	2	2	3	3		3
	Noncondensable effects	11				2	2	3	2	2		
	Inventory/level	9		1		4	1	1	1	1		
	Entrainment/de-entrainment	7		1		2			2	2		
	Thermal stratification	6				3		1	1	1		
	Natural/intenal circulation	5						1	2	2		
	Critical flow	4				1			2	1		
	Flow resistance/friction/form loss	4				2			1	1		
	Two-phase flow/delta-p	3						1	1	1		
	Parallel channel flow	3						1	1	1		
	CHF/dryout	3				1	2					
	Phase separation	2		1				1				
Boiling	2	1			1							
Core inventory recovery, including refill and reflood	Subcritical flow	14	1	3			1	2	3	2	2	
	Convective heat transfer	9	3	3			1				2	
	Voiding & distribution	8	2				5				1	
	Conduction heat transfer	8	2	4			1				1	
	Noncondensable effects	7		2			4				1	
	Inventory/level	6		1			3		1	1		
	Condensation	5	1	2			1				1	
	Countercurrent flow/CCFL	4	1	3								
	Natural/intenal circulation	3	1					1			1	
	Flashing	3	1				1				1	
	Flow resistance/friction/form loss	2					1				1	
	Entrainment/de-entrainment	2	1	1								
	Stored energy	2		1				1				
Long-term recovery	Condensation	8				2		2	2	2		
	Subcritical flow	5		2		2			1			
	Noncondensable effects	5		1		1		1	1	1		
	Inventory/level	3		2		1						

TABLE D-3
RELATIVE IMPORTANCE OF COMPONENTS IN PRIOR PIRT APPLICATIONS*

Component	Normalized relative component importance	Total number at indicated rank																													
		WEC 4-loop LBLOCA			AP600 LBLOCA			B&W SBLOCA			AP600 SBLOCA			AP600 MSLB			SBWR MSLB			SBWR bottom drain line LOCA			SBWR GDCS line LOCA			AP600 SGTR			Production reactor DEGB		
		L	M	H	L	M	H	L	M	H	L	M	H	L	M	H	L	M	H	L	M	H	L	M	H	L	M	H	L	M	H
ECCS including CMT, IRWST PRHR, Sump, Suppression pool, GDCS, etc.	10	1	1	6	11	1	5		2	1	15	11	8	10	14	1	31	6	4	31	6	4	31	6	4	3	11	1	4	1	
Downcomer	8	16	2	5	24	9	3		1		7	3	1	2	1		16	7	7	13	9	8	13	9	8	2					
Break (including ADS)	7	6	1	2	4	1	2		1	3	4	9	5	1		2	8	2	8	13	12	14	1	4	6		3	5	5	3	1
Core	7	8	8	4	12	9	7	9	5	2	4	7	5	4	4	1	24	10	14							2	1				
Containment interior	7				3	10					2	4		9	12	1	21	7	7	28		7	28		7		10	1			
Cold legs	6	4	1	2	2	3		1			8	2	1	1	1					28	12	10	28	12	10	1					
Fuel rods	5	7	1	3	30	9	13				1	2	2	2	1	2												2	3	3	3
Lower plenum	4	2	1		9	3					5	2		2	1		14	3	3	12	4	3	12	4	3	2					
PWR Steam generator	3	4		1		1		4		2	4	1		3	7	6										1	6	4			
Upper plenum	3	12	2	2	13	12		1	2	1	9	3	1	1	7											1	2				
Hot legs	2	9	1	1	2	1					11	3	1	2	6											1	3		2	2	1
Pressurizer	2	2		3	5	2		3			3	4	1	1	7											3	2	4			
Pumps	2	2	1	2	1		1		1		3			2		1										2			2	2	1
Containment exterior	2				5	1	2							1	9	1											9	1			
Accumulators	1					1	2				1	1	1																		

TABLE D-4
CORRELATION OF HIGH AND MODERATE IMPORTANCE
PROCESSES/PHENOMENA AND TRAC MODELS

Process/Phenomenon	Rank ^a	Level ^b	TRAC Models ^c (category:subcategory:specific model)
Boiling	M	LL	FFEC:4a:all flow regimes
CHF/dryout	M	LL	FFEC:4a:critical heat flux
Condensation	H	LL	FFEC:4a:condensation
Conduction heat transfer	H	LL	BEM:6:heat conduction in solids
Convective heat transfer	H	LL	FFEC:4a:all flow regimes
Cou:tercurrent flow/CCFL	M	LL	SPM:1:CCFL model
Critical flow	H	LL	SPM:2:critical flow model
Decay heat	H	LL	BEM:7:power generation in fuel rods
Energy transport by liquid	H	LL	BEM:3:energy convection
Entrainment/de-entrainment	H	LL	FFEC:3b:annular,stratified regimes
Evaporation	H	LL	FFEC:4a:all flow regimes
Flashing	H	LL	FFEC:4b:all flow regimes
Flow resistance	H	LL	FFEC:3:all flow regimes
friction			FFEC:3a:all flow regimes
form loss			FFEC:3c:local pressure losses
Inventory/level	H	SL	SPM:5:level tracking
Natural/internal circulation	H	SL	BEM:all:fluid flow equations:5:3D vessel
			FFEC:3:all:4:all
Noncondensible effects	H	LL	FFEC:4b:effect of noncondensibles
Parallel channel flow	H	SL	BEM:all:fluid flow equations
			FFEC:3:all
Phase separation	H	LL	FFEC:3a:two-phase horizontal stratified
			FFEC:3b:transition to stratified flow
Stored energy	H	LL	BEM:6:fuel-clad gap
Subcritical flow	H	LL	BEM:all:fluid flow equations
Thermal stratification	M	LL	Convective transport only ^d
Two-phase flow and ΔP	H	LL	FFEC:3a:two-phase homogeneous
Voiding & Distribution	H	SL	BEM:all:fluid flow equations
			FFEC:3:all flow regimes

^a Highest rank in Tables 4-1 and 4-2. High = High, M= Moderate.

^b Most of the listed processes/phenomena occur at a local level (LL) but several occur at the component level (CL) and system level (SL)

^c Per Section 3, there are five model categories. Each model category has subcategories.

BEM is Basic Equation Model (See Section 3.1 for subcategories)

FFEC is Flow Field Model and Engineering Correlation (See Section 3.2 for subcategories)

ECM is Equipment Component Model (See Section 3.3 for subcategories)

SPM is Special Purpose Model (See Section 3.4 for subcategories)

NSM is Numerical Solution Methods (See Section 3.5 for subcategories)

^d Fluid conduction and turbulence are not modeled; no thermal front tracking method in code.

APPENDIX E

OTHER STANDARD TEST PROBLEM SPECIFICATION EXAMPLES

Test problems developed by J. Mahaffy of Pennsylvania State University are summarized in this appendix. These problems illustrate several aspects of validation using standards other than those that employ experimental data as discussed in Section 2 of the main report.

E.1. Static Vessel Test Problem

Purpose: The purpose of this problem is to test for anomalies in the 3D momentum transport terms that can result in spurious circulation patterns. It is an important test to qualify the code for use on passive reactors.

Success Metric: Fluid velocities should be observed at all positions in the final large edit and compared with the expected zero flow. In addition, the void fraction in level 11 should be compared with the expected value of 0.50.

Problem Description: This problem consists of a PWR vessel connected via short, single-cell pipes to zero flow boundary conditions on the cold legs, and constant atmospheric pressure conditions on the hot legs. All temperatures in the system are set to 300 K. All pressures are initialized to 0.1 MPa. The hot- and cold-leg pipes are initially full of air, and the vessel contains water up through the midpoint of the second level below the cold (or hot) legs. The upper vessel is filled with air.

Under ideal conditions this problem undergoes a brief transient to adjust the pressures to appropriate hydrostatic values, and then settles into a steady configuration with no flow and level water surface.

The vessel model used was obtained from the standard USPWR test problem. It has 4 radial zones with boundaries at 1.0919, 1.6855, 1.9376, and 2.1971 meters and 8 evenly spaced azimuth zones. There are 17 axial zones with upper faces at the following meters:

1.3672	1.9389	2.4469	3.0882	3.6400	4.2800
5.0100	5.9200	6.7458	7.1395	7.5523	7.9650
8.7015	9.2655	1.0137	10.926	12.575	

Void fraction in the vessel is set to 0 for levels 1 through 10; to 0.5 for level 11; and to 1.0 for levels 12 through 17. The air partial pressure is initially set equal to the total pressure (0.1 MPa) in all cells.

Connections to the vessel are through simple, single-cell PIPE components representing the nozzle sections of the hot and cold legs. The hot legs have a cell length of 0.825 m, cell volume of 0.408 m^3 , cell face adjacent to the vessel with 0.8 m^2 area, and cell face adjacent to the BREAK of 0.427 m^2 . The cold legs have a cell length of 1.163 m, a cell volume of 0.445 m^3 , a cell face adjacent to the vessel of 0.6297 m^2 , and a cell face adjacent to the FILL of 0.383 m^2 .

The type 3 FILLs connected to the cold-leg PIPEs have geometries (DX and VOL) matching the adjacent PIPE cell. Both inlet velocities are set to 0. The type 0 BREAKs are also given geometries matching the adjacent PIPE cell.

E.2. Bubble Rise Test Problems

Purpose: The primary purpose of these problems is to check the logic for an initial increase above zero void fraction when the gas entering a cell is primarily non-condensable. As the run approaches steady state and timestep size increases, the problem also provides a valuable test of stability associated with interfacial drag.

Additionally these tests provide a simple assessment of the low void interfacial drag and can be used as a check for changes in the low void evaporation model or in numerical diffusion.

Success Metrics: The output of Control block -100 at the end of the second timestep should be compared with the total mass of air that has flowed in from the FILL during the first two timesteps. This is a good flag for problems in the transition from single phase liquid to bubbly flow.

Time history plots should be compared for timestep size, as should those of the void fraction, air partial, and vapor velocity midway up the tank. This information will permit detection of instabilities. When stable results are obtained, the information can be compared with data on bubble rise velocities, and can be used to indicate changes in the evaporation model at low void.

Problem Description: These problems follow bubbles injected into the bottom of a tank of water. The tank is 2 m high, and 2 m in diameter, and is initially full of water. At time zero, air bubbles are injected at the bottom at velocity of 0.132 m/s from a source that has a void fraction of 0.03. Only the air enters from this source. The air-bubble velocity has been set to match the bubble rise velocity obtained from the present 1D interfacial drag correlation in TRAC for a void fraction of 0.03. It should be changed if the interfacial drag correlation is changed. The liquid velocity at this boundary is set to zero. The top of the tank is bounded by a pressure boundary condition of 0.1001 MPa. All temperatures in the tank and boundary conditions are 300 K. After ~15 s, the bubbles have spread uniformly through the tank, and a steady state should follow.

In all decks the air is supplied by a type 3 FILL. The FILL's total pressure and air partial pressure are set to 0.1001 MPa. Its liquid and vapor temperatures are set to 300 K, and its void fraction set to 0.03. The volume of the fill is 0.3145926 m^3 and the length 0.1 m. The liquid fill velocity is zero and the vapor velocity 0.132 m/s. All decks also share the same upper pressure boundary condition. This is provided with a type 0 BREAK, which has the same pressure, temperatures, void fraction, and geometry as the FILL.

The 1D versions of the test problems model the tank with a 20 cell PIPE. Each cell is 0.1 m long, with cell volume and cell edge flow areas calculated automatically from the 2-m, hydraulic diameter and the assumption of a uniform, circular cross section (FA and VOL set to -1.0 in the input). Two 1D problems have been created that differ only in the final maximum timestep size. One input deck runs to steady state, while the second develops a bounded instability due to a higher requested maximum timestep. As the code is improved, the final maximum timestep should be increased to maintain one stable problem and one with instability.

The 3D versions of the problem replace the central 18 cells of the pipe with an equivalent vessel configured with 1 radial ring, 1 theta zone, and 18 axial levels, each 0.1 m high. One pair of problems results in stable and unstable runs analogous to those for the pure 1D. A final problem was created with the new reflood model activated (the rod temperatures are all 300 K).

E.3. Falling Droplet Test Problems

Purpose: The two primary purposes of this test series are to check logic for initial decrease from a void fraction of one- to two-phase dispersed flow, and to test for stability problems associated with interfacial drag. Additionally, this test provides a simple assessment of the low void interfacial drag and can be used as a check for changes in the low void evaporation model or in numerical diffusion.

Success Metrics: Computed total system mass should be compared for all large edits in the calculation, with particular attention paid to the first three edits. This is used as a flag for problems in the transition from single-phase gas to dispersed flow.

Time history plots should be compared for timestep size, as should those of the void fraction, air partial and vapor velocity midway up the standpipe. This information will permit detection of instabilities. When stable results are obtained, the information can be compared with data droplet velocities and can be used to indicate changes in the evaporation model at high void.

Problem Description. This problem follows drops injected at the top of an air-filled standpipe. The standpipe is 2 m high, and 2 m in diameter, and initially contains only air. At time zero, water is injected into the top of the pipe at velocity of 0.2287 m/s from a source that has a void fraction of 0.99. Only the liquid enters from

this source. This velocity has been set to match the droplet terminal velocity obtained from the current 1D interfacial drag correlation in TRAC for a void fraction of 0.99. This injection velocity should be changed if the interfacial drag correlation is changed. The gas velocity at this upper boundary is set to zero. The bottom of the standpipe is connected to a pressure boundary condition of 0.100 MPa. All temperatures in the standpipe and boundary conditions are 300 K. After ~10 s, the droplets have spread uniformly through the system and a steady state should follow.

In all decks the liquid is supplied by a type 3 FILL. The FILL's total pressure and air partial pressure are set to 0.100 MPa. Its liquid and vapor temperatures are set to 300 K, and its void fraction set to 0.03. The volume of the fill is 0.3145926 m^3 and the length 0.1 m. The gas fill velocity is 0, and the liquid velocity is 0.2287 m/s. All decks also share the same lower pressure boundary condition. This is provided with a type 0 BREAK, which has the same pressure, temperatures, void fraction, and geometry as the FILL.

The 1D version of these test problems models the standpipe with a 20-cell PIPE. Each cell is 0.1 m long, with cell volume and cell edge flow areas calculated automatically from the 2-m hydraulic diameter and the assumption of a uniform circular cross section (FA and VOL set to -1.0 in the input). Only a single 1D problem has been created, because the code is stable for all timestep sizes currently permitted. As the code timestep control is improved, a second 1D test may be needed to mark a threshold of instability.

The 3D versions of the problem replace the central 18 cells of the pipe with an equivalent vessel configured with 1 radial ring, 1 theta zone, and 18 axial levels, each 0.1 m high. One pair of problems results in stable and unstable runs analogous to those for the pure 1D. A final problem pair was created with the new reflood model activated (although the rod temperature is 300 K).

E.4. Boron Transport

Purpose: The primary purpose of this test set is to provide a quantitative measure of the numerical diffusion associated with the code's boron transport equations. It has as a secondary purpose the introduction of a method by which the numerical diffusion of any of the mass or energy equations may be measured.

Success Metrics: The key output variable is the value of control block -120. The numerical value should be that predicted by the C-curve method for the conditions used in the calculation. The final value is of prime interest; however, a time history plot of this variable should be examined to be certain that it has ceased to change.

Problem Description: This problem models the propagation of a 1-s-long square pulse of boron with a peak concentration of 0.002 and a base concentration of 0. Flow is through a pipe 10 m in length and 1 m in diameter. Velocity of the pure

liquid flow is maintained at 2.0 m/s. Temperature of the liquid is 577.6 K, and pressure at the outlet is fixed at 15.51 MPa.

Flow is driven by a type 10 FILL. Input is set to only take boron concentration from a control block, other variables are taken as constants. The FILL void fraction is fixed at 0, the liquid velocity is at 2.0 m/s, the liquid temperature is at 577.6 K, and pressure is at 15.51 MPa. The volume associated with the FILL is 0.785398 m^3 and the length is 1.0 m. The control block supplying boron concentration (CB -5) is simply a table with entries of 0.002 at 0 and 1 s, and 0 at 1.001 and 10000.0 s.

The PIPE component has 20 cells each 0.5 m long with cell volumes and face areas computed internally from the 1.0 m hydraulic diameter. Initial conditions in the pipe are set to give velocity of 2 m/s at all faces, and temperature of 577.6 K, pressure of 15.51 MPa, and void fraction of 0 in all cells.

Conditions at the PIPE outlet are provided by a type 0 BREAK component. Fluid conditions and geometry of the BREAK match those of the FILL, except that boron concentration is fixed at 0.

A key feature of the test problem is a set of control blocks (-1, -2, and -10 through -120) that implement the C-curve method to provide a quantitative measure of the numerical diffusion associated with the propagation of the boron. The method was originally developed for analysis of experimental data on turbulent mixing (Levenspiel, "Chemical Reaction Engineering," Second Edition, Wiley, 1972) and has been adapted for quantifying numerical diffusion.

APPENDIX F

EXPANDED LISTING OF TRAC-P DECKS FOR SEPARATE EFFECT TESTS

Table F-1 lists the available TRAC-P SET input decks for each facility input deck by briefly describing the test type, test number, and report reference in addition to the latest code version on which the input deck was exercised.

TABLE F-1
TRAC-P INPUT DECKS FOR SEPARATE EFFECT TESTS

Facility	Type of Test	Test ID	References	Decks
Akimoto	Condensation		MOD2-5.4 Dev. Assessment	Early MOD2
Bankoff	CCFL	Air-water steam-water	MOD2-5.4 Dev. Assessment	Current MOD2
BCL	Downcomer counter-current flow	26204, 26502, 29111	NUREG/CR-3866	MOD1
Bennett	Heated-tube CHF	5336, 5431, and 5442	NUREG/CR-3208	MOD1
Berkeley	Reflood heat transfer		MOD2-5.4 Dev. Assessment	Early MOD2
CISE	Critical Flow	4	NUREG/CR-3208	MOD1
Creare	Downcomer counter-current flow		NUREG/CR-3208	No decks
Dartmouth	Air-water counter-current flow	2-in pipe and 6-in. pipe	NUREG/CR-3280	MOD1
Edwards	Critical Flow		NUREG/CR-3208	MOD1
Flecht	Reflood heat transfer	4831 17201	NUREG/CR-3208	MOD1 for 4831 only
Flecht-Seaset	Reflood heat transfer	31504	NUREG/CR-3866	MOD1
Lehigh	Reflood heat transfer		MOD2-5.4 Dev. Assessment	Current MOD2
Marviken	Critical Flow	4, 13, 20, 22, and 24	NUREG/CR-3866	MOD1, Current MOD2 for Test 4
Thetis	Boil-down level-swell test		MOD2-5.0 Dev. Assessment	Current MOD2
THTF	Rod-bundle blowdown heat transfer	177	NUREG/CR-3208	MOD1
Winfrith	Heated tube CHF		MOD2-5.0 Dev. Assessment	Current MOD2

Table F-2 lists the available RELAP5 SET input decks for each facility input deck by briefly describing the test type, test number, and report reference, in addition to the latest code version on which the input deck was exercised. The information in the table is taken from References 6-6 through 6-9. The latter reference is an informal transmittal of information from the NRC to LANL. Tests of a similar type are grouped together.

TABLE F-2
RELAP5 INPUT DECKS FOR SEPARATE EFFECT TESTS

Facility	Type of Test	Test ID	References	Version/ Comment
ACHILLES	Void/Level	Not Identified	6-9	Not Identified
B&W	Condensation	Transient Test	6-6, 6-8	MOD3
Bennett Heated Tube	CHF, Heat Transfer	5358, 5294, 5394	6-7	MOD3
Columbia OFI	Low Flow Wall Friction	8 Test Series	6-8	MOD3
Cumulus	Critical Flow	Not Identified	6-9	Not Identified
Deich	Critical Flow	Not Identified	6-9	Not Identified
Dukler -Smith Air/Water	CCFL	Not Identified	6-7	MOD3
ECN	Void/Lvel	3230, 3231	6-6, 6-8	MOD3
EPRI Air/Water	Pressure Drop	Not Identified	6-9	Not Identified
Finke & Collins	Critical Flow	Not Identified	6-9	Not Identified
Flech-Seaset Forced Reflood	Reflood Heat Transfer	31504, 31701	6-7	MOD3
Flecht-Seaset	Void/Level	Not Identified	6-9	Not Identified
FRIGG	Void	27 tests used	6-6, 6-8	MOD3
FRIGG	Subcooled Boiling	06,07,15,20	6-8	MOD3
GE Large Level Swell	Void/Level	5702-16, 5801- 13, 5801-15, 5801-19	6-6, 6-7, 6-8	MOD3
GE Small Level Swell	Void/Level	1004-2, 1004-3	6-6, 6-7, 6-8	MOD3
Hein (KWU)	Condensation	1 and 9	6-6, 6-8	MOD3
Hsieh/North- western Plate	CCFL	Not Identified	6-9	Not Identified
JAERI	Crossflow Pressure Drop	2 Tests Run	6-8	MOD3
Jensen	Pressure Drop	Not Identified	6-9	Not Identified
LOFT L3-1	Accumulator	L3-1	6-7	MOD3
LOFT L6-6	Boron Dilution	L6-6A, L6-6B	6-7	MOD3
LOFT Wyle	Critical Flow	WSB03R	6-7	MOD3
Marviken	Critical Flow	22, 24	6-7	MOD3
MB-2	SG Secondary Side Boiling Heat Transfer	Test 1712		MOD3
McMaster	Subcooled Boiling	A, B, C	6-8	MOD3
MIT Pressurizer	Thermal Stratification	ST4	6-7, 6-8	MOD3
MIT-Siddique	Condensation	18 tests used	6-6, 6-8	MOD3
NASA	Condensation	171-174	6-6, 6-8	MOD3
Nuessen	Critical Flow	Not Identified	6-9	Not Identified

TABLE F-2 (cont)
RELAP5 INPUT DECKS FOR SEPARATE EFFECT TESTS

Facility	Type of Test	Test ID	References	Version/ Comment
Oakridge National Laboratory (ORNL) Bundle CHF	CHF, Heat Transfer, Void	3.07.9B, 3.07.9N, 3.07.9W, 3.09.10i	6-6, 6-7, 6-8	MOD3
Pericles	Void/Level	Not Identified	6-9	Not Identified
Royal Institute of Technology (RIT) Tube Test	CHF, Heat Transfer	261	6-7	MOD3
ROSA AP- CL-03	Critical Flow	Not Identified	6-9	Not Identified
ROSA-IV/ TPTF	Horizontal Stratification	4 Tests	6-8	MOD3
ROSA/APCL 03 (as SET)	Thermal Stratification	SB-CL-03	6-8	MOD3
ROSA/CMT (as SET)	Thermal Stratification		6-8	MOD3
Sozzi & Sutherland	Critical Flow	Not Identified	6-9	Not Identified
SRL C- Reactor	Boron Transport	Operating Plant	6-7	MOD3
SRL NC	Local Loss at Low Flow	8 Test Series	6-8	MOD3
Super Moby Dick	Critical Flow	Not Identified	6-9	Not Identified
THETIS	Void/Level	5 pressures	6-6, 6-8	MOD3
THTF/ORNL	Void/Level	12 tests used	6-6, 6-7, 6-8	MOD3
TRAC-B Case	Separator/Dryer	Two Tests Run	6-8	MOD3
UC-Berkeley	Condensation	27 tests used	6-6, 6-8	MOD3
UCSB	Reflux Condensation	101, 309	6-7	MOD3
UPTF	Countercurrent Flow	6	6-7	MOD3

APPENDIX G

EXPANDED LISTING OF TRAC-P DECKS FOR INTEGRAL EFFECT TESTS

A condensed listing of existing TRAC-P input decks for IET facilities was previously presented in Table 7-1. Table G-1 provides a more detailed listing of the available input decks for each facility input deck by briefly describing the test type, test number, and report reference in addition to the latest code version on which the input deck was exercised.

TABLE G-1
TRAC-P INPUT DECKS FOR INTEGRAL EFFECT TESTS

Facility	Type of test	Test Nos.	References	Decks
PKL	Natural circulation	ID1-4	NUREG/CR-3280	MOD1
	Natural circulation	ID1-9	NUREG/CR-3280	MOD1
	Reflux cooling	ID1-14	NUREG/CR-3280	MOD1
	Gravity reflood	K9	NUREG/CR-3866	MOD1
	Gravity reflood	K5.4A	NUREG/CR-3866	MOD1
Semiscale Mod-1	200% cold-leg break without ECCS	S-02-8	NUREG/CR-3208	MOD1
	200% cold-leg break with ECCS	S-06-3	NUREG/CR-3208	MOD2
Semiscale Mod-3	2.5% cold-leg break, early pump trip	S-SB-P1	NUREG/CR-3280	MOD1
	2.5% cold-leg break, delayed pump trip	S-SB-P2	NUREG/CR-3280	MOD1
	2.5% cold-leg break, late pump trip	S-SB-P7	NUREG/CR-3280	MOD1
	10% cold-leg break with delayed ECCS and secondary blowdown	S-07-10D	NUREG/CR-3280	MOD1
	2.5% hot-leg break, pumps off	S-SB-P3	NUREG/CR-3866	MOD1
	2.5% hot-leg break, pumps on	S-SB-P4	NUREG/CR-3866	MOD1
	Natural circulation	S-NC-2B	NUREG/CR-3646	MOD1
	Natural circulation	S-NC-5	NUREG/CR-3646	MOD1
	Natural circulation	S-NC-6	NUREG/CR-3646	MOD1
	Natural circulation	S-NC-7C		MOD1
Semiscale Mod-2a	10% cold-leg break with upper-head injection (UHI)	S-UT-2	NUREG/CR-3646	MOD1
	5% cold-leg break without UHI	S-UT-6	NUREG/CR-3646	MOD1
	5% cold-leg break with UHI	S-UT-7	NUREG/CR-3646	MOD1
LOFT	Isothermal DEGB blowdown	L1-4	NUREG/CR-3208	MOD1
	50% power, DEGB cold-leg break	L2-2	NUREG/CR-3280	MOD1
	2.5% cold-leg break in broken cold leg	L3-1	NUREG/CR-3866	MOD1

TABLE G-1 (cont)
TRAC-P INPUT DECKS FOR INTEGRAL EFFECT TESTS

Facility	Type of test	Test Nos.	References	Decks
	15% cold-leg break in broken cold leg	L3-7	NUREG/CR-3280	MOD1
	2.5% cold-leg break in intact cold leg, early pump trip	L3-5	NUREG/CR-3866	MOD1
	2.5% cold-leg break in intact cold leg, late pump trip	L3-6	NUREG/CR-3866	MOD1
	20.7% cold-leg break in broken cold leg	L5-1	NUREG/CR-3866	MOD1
	20.7% cold-leg break in broken cold leg with delayed ECCS	L8-2	NUREG/CR-3866	MOD1
	200% cold-leg break, pumps on	L2-3	NUREG/CR-3866	MOD1
	200% cold-leg break, early pump trip	L2-5	NUREG/CR-3866	MOD1
	200% cold-leg break, higher power	L2-6 (LP-02-6)	MOD2 5.4 Dev. Assessment	MOD2
	Loss of feedwater transient	L9-1/L3-3	NUREG/CR-3646	MOD1
	Cooldown transient	L6-7/L9-2	NUREG/CR-3646	MOD1
	Loss of steam load	L6-1	MOD2 5.4 Dev. Assessment	Early MOD2
	Pump trip	L6-2	NUREG/CR-4278	MOD1
	Excessive-load increase	L6-3	NUREG/CR-4278	MOD1
Crystal River Transient	Anticipated transients—non-nuclear instrumentation failure		NUREG/CR-3646	MOD1
CCTF	Core-I reflood base case	14		MOD1
	Core-II reflood low power	54		Early MOD2
	Core-II reflood base case	62		MOD1
	Core-II upper plenum injection	57	TN-86-16	MOD1
	Core-II upper plenum injection	59	TN-86-16	MOD1
	Core-II upper plenum injection	72	TN-86-16	MOD1
	Refill/reflood with asymmetric injection	76	TN-86-16	MOD1
	Refill/reflood with UPI	78	TN-86-16	MOD1
	Downcomer injection/vent valves closed	58	TN-86-19	MOD1
	Cold- and hot-leg injection	79	TN-86-20	MOD1
	Best-estimate	71	TN-86-8	MOD1
MIST	Delayed HPI/PORV feed-and-bleed cooling	330302	NUREG/CR-5889	MOD1
	50-cm ² SBLOCA	320201	NUREG/CR-5888	MOD1

TABLE G-1 (cont)
TRAC-P INPUT DECKS FOR INTEGRAL EFFECT TESTS

Facility	Type of test	Test Nos.	References	Decks
	10-cm ² SBLOCA	3109AA	NUREG/CR-5887	MOD1
	STGR	3404AA	LA-UR-92-2699	MOD1
	SBLOCA	320604	LA-CP-87-50	MOD1
ROSA-IV LSTF	Single- and two-phase natural circulation	ST-NC-02	LA-CP-87-131	MOD1
SCTF	refill/reflood	S2-SH2 (Run 605)	LA-CP-87-103	MOD1
			LA-CP-87-112	MOD1
		S3-9 (Run 713)	LA-CP-87-11	MOD1
			LA-CP-88-131	MOD1
			LA-CP-88-234	MOD1
		(no input decks)	LA-CP-89-113	
			LA-TN-85-13	MOD1
			LA-TN-85-15	MOD1
			LA-TN-85-2	MOD1
			LA-TN-85-4	MOD1
			LA-TN-85-6	MOD1
			LA-TN-86-13	MOD1
			LA-TN-86-15	MOD1
			LA-TN-86-9	MOD1
		S3-15 (Run 719)	MOD2 5.4 Dev. Assessment	Early MOD2
UPTF		17	LA-CP-92-79	Early MOD2
		21	LA-CP-92-188	MOD2
		27	LA-CP-92-408	MOD2

APPENDIX H

SUMMARY DESCRIPTION OF IET FACILITIES

An expanded description of IET facilities is provided in this Appendix. The information in the table was extracted from several sources.^{H-1-H-4}

REFERENCES

- H-1. "CSNI Integral Test Facility Validation Matrix for the Assessment of Thermal-Hydraulic Codes for LWR LOCA and Transients," Committee on the Safety of Nuclear Installations, OECD Nuclear Energy Agency report CSNI 132, Revision 6, restricted working draft (June 1995).
- H-2. P. S. Damerell and J. W. Simons, Eds., "2D/3D Program Work Summary Report," U. S. Nuclear Regulatory Commission report NUREG/IA-0126 (June 1993).
- H-3. C. L. Nalezny, "Summary of Nuclear Regulatory Commission's LOFT Program Experiments," EG&G Idaho, Inc. document NUREG/CR-3214 (July 1983).
- H-4. J. R. Gloudemans, "Multiloop Integral System Test (MIST): Final Report," Babcock & Wilcox Nuclear Power Division document NUREG/CR-5395 (April 1991).

DRAFT

Table H-1
IET Facility Summary

Plant Type	Facility	Scaling Information	Other Information
U-Tube PWR	Boucle d'Etudes Thermo-hydrauliques Système (BETHSY) ^{H-1}	Power scaling ~1:100; 1:1 height	<p>Full pressure, 3 identical loops modeling 900 MWe Framatome PWR. Core power limited to 10% of scaled nominal, i.e., 3 MW, electrically heated core. All major safety systems simulated.</p> <p>Covered a spectrum of test types: LBLOCA (reflood phase), SB- and IBLOCA, transients, and transients at shutdown. Used to assess accident management procedures.</p>
	CCTF ^{H-2}	Power scaling 1:25; 1:1 height	<p>Primary coolant system of a 1300 MWe 4-loop PWR, with 4 loops, 2 steam generators, 4 pump simulators, and 2 tanks attached to broken ends of cold leg to simulate containment. Electrically heated core. ECC injection nozzles in cold legs, hot legs, upper plenum, downcomer, and lower plenum. Vent valves for tests simulating B&W reactors.</p> <p>Overall system response, as well as core behavior, during refill and reflood phases of a LBLOCA.</p>
	LOBI ^{H-1}	Power scaling 1:712; 1:1 height	<p>Full pressure, full height model of a German PWR. Electrically heated core.</p> <p>Twenty-eight LBLOCA experiments in MOD-1 configuration. Additional 42 experiments in MOD-2 configuration for SBLOCA and special transients.</p>
	LOFT ^{H-3}	Power scaling 1:60; reduced height with atypicalities	<p>Simulated 4-loop Westinghouse PWR. Nuclear heated core.</p> <p>Three LBLOCA tests; twenty-five additional tests over wide range of conditions; eight experiments by OECD/LOFT consortium</p>

DRAFT

Table H-1 (cont)
IET Facility Summary

Plant Type	Facility	Scaling Information	Other Information
	LSTF ^{H-1} (aka ROSA)	Volume scale 1: 48: 1:1 height; horizontal legs sized to scale two-phase flow regime transitions.	Full pressure model of Westinghouse 3420 MWt 4-loop PWR. The 4 plant loops simulated with 2 equal-volume loops. Full pressure. Core power is limited to 14% of nominal power (10 MW). Electrically heated core. All major safety systems simulated.
	LSTF-AP600 (aka ROSA)		
	Primarkreislaufe (PKL) I ^{H-1}	Power scaling 1:134; 1:1 height	One single loop, one double loop, and one broken loop simulated. Electrically heated core. LBLOCA refill and reflood simulated as well as SBLOCA. International Standard Problem (ISP) No. 10. Pressure range 0.4 to 0.45 MPa.
	PKL II ^{H-1}	Power scaling 1:145 for German Siemens/Kraftwerk Union (KWU) PWR	Same configuration as PKL I but maximum pressure increased to 4.0 Mpa to cover end of blowdown.
	PKL III ^{H-1}	Power scaling 1:145	Four identical loops with active coolant pumps. Secondary side feedwater and steam systems represented. Investigated primary system cooldown after incidents and accidents, and accident measurement procedures after multiple failures.
	SEMISCALE ^{H-1}	Volume scale 1:1705; 1:1 height	Simulated 4-loop reference PWR; 2 primary loops with one loop simulating 3 full-size loops. Electrically heated core. External downcomer. Simulated LOCAs and operational transients.

DRAFT

Table H -1 (cont)
IET Facility Summary

Plant Type	Facility	Scaling Information	Other Information
	Simulatore PWR per Esperienze di Sicurezza (SPES) ^{H-1}	Volume scale 1:427; 1:1 height	Simulated 3-loop PWR at 2775 MWth. Electrically heated core. Simulated SBLOCA and transients. ISP No. 22 data from SPES.
	SPES-2 ^{H-1} AP600		
	UPTF ^{H-2}	Volume scale 1:1	Simulated 4-loop 1300 MWe PWR including reactor vessel with downcomer, lower plenum, core simulators (not heated), upper plenum and four loops with pump simulators and steam generator simulators. Maximum pressure is 2 MPa. Vent valves are installed to permit simulation of B&W plants. Facility can be used for either IETs or SETs.
	GERDA ^{H-1}	Volume scale 1:1686; 1:1 height	Raised loop Brown Boveri Reactors plant. Over 100 SETs and IETs performed covering a wide range of SBLOCA and natural circulation conditions.
	MIST ^{H-4}	Volume scale of 1:817; 1:1 height. Hot- and cold-leg piping sized to preserve two-phase phenomena.	A 2 x 4 loop simulation of B&W lowered loop plant. Electrically heated core delivers 10% scaled power based on a 2584 MWth PWR. All active components are simulated, including primary coolant pumps. Uses two 19-tube OTSGs. Highly instrumented. Forty-one experiments to study SBLOCA, SGTR, feed and bleed, pump operation, noncondensibles, and natural circulation.

DRAFT

Table H -1 (cont)
IET Facility Summary

Plant Type	Facility	Scaling Information	Other Information
	OTIS ^{H-1}	Volume scale 1:1686; 1:1 height.	Single loop (1 hot leg and 1 cold leg) with 19 tube prototypical OTSG. Electrically heated core delivers 10% of scaled power based on a 2584 MWth plant. Operates at full PWR system pressure. No primary pump. Thirteen SBLOCA tests conducted.
OTSG PWR	UMCP ^{H-1}	Volume scale 1:500; reduced-height scale	A 2 x 4 loop simulation of the B&W TMI Unit 2 lowered-loop reactor. Electrically heated core delivers 24.7% of full power for a 2800 MWth reactor. Maximum facility pressure is 300 psi (20.7 bar). Loop designed to simulate SBLOCA and natural circulation behavior.
OTSG PWR	Crystal River		
U-Tube PWR	Ginna		
X PWR	DOEL-2		
X PWR	Arkansas Nuclear One (ANO-2)		