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VALIDATION TEST MATRIX FOR THE CONSOLIDATED TRAC (TRAC-M) CODE

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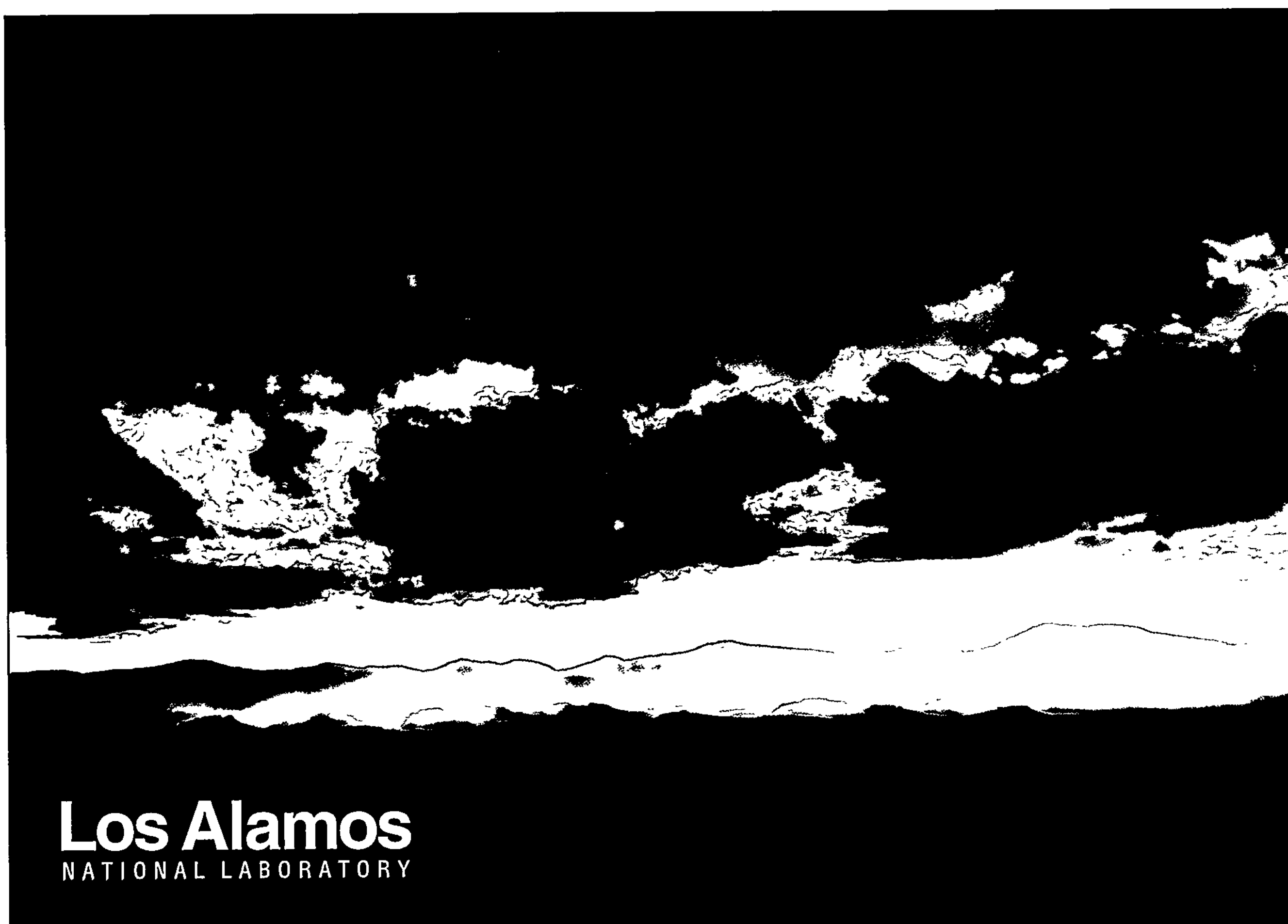

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Validation Test Matrix for the Consolidated TRAC (TRAC-M) Code[1]

Part I: Overview

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ABSTRACT

The United States Nuclear Regulatory Commission is consolidating the capabilities of four of its thermal-hydraulic neutronics codes, i.e., TRAC-P, TRAC-B, RELAP-5, and RAMONA, into a single state-of-the-art analysis code, TRAC-M. Qualification testing will be conducted to ensure that TRAC-M achieves its design requirements. Code validation is an essential element of qualification testing; it is the process whereby satisfaction of the design requirements is demonstrated. A comprehensive validation test matrix is required to qualify TRAC-M for its intended applications. In this three-part paper, the validation test matrix for the consolidated TRAC-M code is presented. Part I provides an overview of the principles guiding development of the validation test matrix and lays the foundation for presentation of the tests selected for the validation test matrix in Parts II and III.

1. INTRODUCTION

The United States (US) Nuclear Regulatory Commission (NRC) is consolidating the capabilities of four of its thermal-hydraulic neutronics codes, i.e., TRAC-P,[1] TRAC-B,[2] RELAP-5,[3] and RAMONA,[4] into a single state-of-the-art analysis code, TRAC-M. This code will be used to address emerging issues, such as risk-informed decision making, potential burden reductions, and resolution of technical issues. Qualification testing will be conducted to ensure that TRAC-M achieves its design requirements. Qualification testing demonstrates and ensures that the code and its models and methods satisfy the code's design objectives and are both applicable and adequate for the specified targeted applications.

Code validation is an essential element of qualification testing. Validation is the process of demonstrating that the as-built software meets its requirements. Testing is the primary method of software validation. Because TRAC-M is to be applied broadly, i.e., to a broad spectrum of events from accidents to anticipated transients in both pressurized-water reactors (PWRs) and boiling-water reactors (BWRs), a comprehensive validation test matrix is required to qualify TRAC-M for its intended applications.

Information, insights, and data are collected from several sources and are used to support development of a comprehensive TRAC-M validation test matrix. Formulation of the TRAC-M validation test matrix is based on the categorization and description of each

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TRAC-M model, tabulations of important processes and phenomena occurring during plant events and accidents in PWR and BWR nuclear power plants, and the applicability and availability of experimental data and other test problems needed to validate the code.

The TRAC-M validation matrix consists of four elements: (1) validation tests using standards other than those that employ experimental data, i.e., other standard tests (OSTs) and validation tests comparing code-calculated results with data from (2) separate effect tests (SETs), (3) component effect tests (CETs), and (4) integral effect tests (IETs).

Part I of the paper provides an overview of the philosophy that guided construction of the comprehensive TRAC-M validation test matrix. The categorization of TRAC-M models is discussed. The use of PWR and BWR phenomena identification and ranking tables (PIRTs) to guide the selection of validation tests also is discussed. Part 2 of the paper presents the OSTs and SETs selected for the TRAC-M validation test matrix. Part 3 of the paper presents CETs and IETs selected for the TRAC-M validation test matrix.

2. MODERNIZED TRAC (TRAC-M) CODE

For many years, the NRC has maintained four thermal-hydraulic codes of similar, but not identical, capability.[5] For PWRs, the RELAP5 code[3] provides a primarily one-dimensional (1D) representation of the flow field and includes both point and 1D reactor kinetics models. RELAP5 is used primarily for small-break loss-of-coolant accident (LOCA) and plant transient analyses; however, the NRC-sponsored RELAP5 code lacks the models needed for the analysis of large-break (LB) LOCA transients. Analyses requiring the modeling of multidimensional flows, and in particular LBLOCAs, use the TRAC-P [1] code. In principle, RELAP5 was intended to be a fast-running, "simple" code for long-term transients, whereas TRAC-P was designed to provide a more detailed description of the flow field and to be suitable for transients of shorter duration. TRAC-P also was to be used for benchmarking RELAP5. Over the years, this distinction has been blurred, and today, many of these two codes' capabilities overlap.

For analyzing BWRs, a similar situation exists. The RAMONA [4] code provides a very simple 1D representation of the flow field but contains a three-dimensional (3D) reactor kinetics model. The TRAC-B [2] code, which was developed from the TRAC-P code, was developed to provide a more detailed representation of the flow field. In addition to adding BWR-specific models, e.g., jet pumps, the TRAC-B code implemented a different constitutive package and numerical scheme from TRAC-P; since their separation, each of the two codes has followed its own independent development path.

The costs of maintaining four thermal-hydraulic system analysis codes are high. In addition, each of the codes can be considered a "legacy" code in that the initial development of each was begun decades ago. Each of the four codes is a large code. The architecture of each was designed for the computers of decades ago, i.e., computers with small computational engines. Computer architectures and capabilities have advanced rapidly in the last decade. Each of the four codes now can be run on desktop workstations and personal computers. However, many of the deficiencies of the legacy codes remain and hinder the performance of the codes.

Given the above history, the NRC decided to modify its overall thermal-hydraulic code strategy to match today's and future needs better. The NRC concluded that advances in software engineering, data distribution, expert systems and graphical user interfaces, machine intelligence, and knowledge of thermal-hydraulic phenomena permit consolidation of the capabilities of TRAC-P, RELAP5, TRAC-B, and RAMONA into a single code while retaining and improving the existing capabilities.

The consolidated code currently is designated the TRAC-M code. The NRC selected the TRAC-P code as the base code. The first step in the consolidation process was to modernize the TRAC-P database structure. The modernization consisted primarily of translating custom and difficult-to-extend Fortran-77 code syntax into modern, standard, extensible, and maintainable Fortran 90.[6] The next step of the consolidation process, adding the BWR modeling capability within the base TRAC-P code, is nearing completion, as is the incorporation of a 3D reactor kinetics model to recover the RAMONA capability in TRAC-M. Also nearing completion is a significant improvement in the numerical solution method to improve code speed and robustness.

3. CODE QUALIFICATION

Qualification testing is the process that allows the sponsor to determine whether a software product complies with its requirements.[7] This testing demonstrates and ensures that the code and its models and methods satisfy the code's design objectives and are both applicable and adequate for the specified targeted applications.

Code qualification is the outcome of specific software life-cycle activities. The subset of software life-cycle activities culminating in code qualification is illustrated in Fig. 1. The life-cycle activities leading to code qualification are requirements definition, design, implementation, and qualification testing. These activities assume the creation and qualification of an entirely new code. Clearly, that is not the case for TRAC-M. Nevertheless, all of the life-cycle activities leading to code qualification will be described briefly here.

Requirements Definition, Design, and Implementation. The life-cycle activities that precede 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. 1 and is described further in the NRC's software quality assurance guidelines.[7]

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 software is tested formally 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 paper, although a brief description of verification activities follows for completeness. The remainder of this paper 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.

- *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 that

  1. the as-built software performs correctly and adequately 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

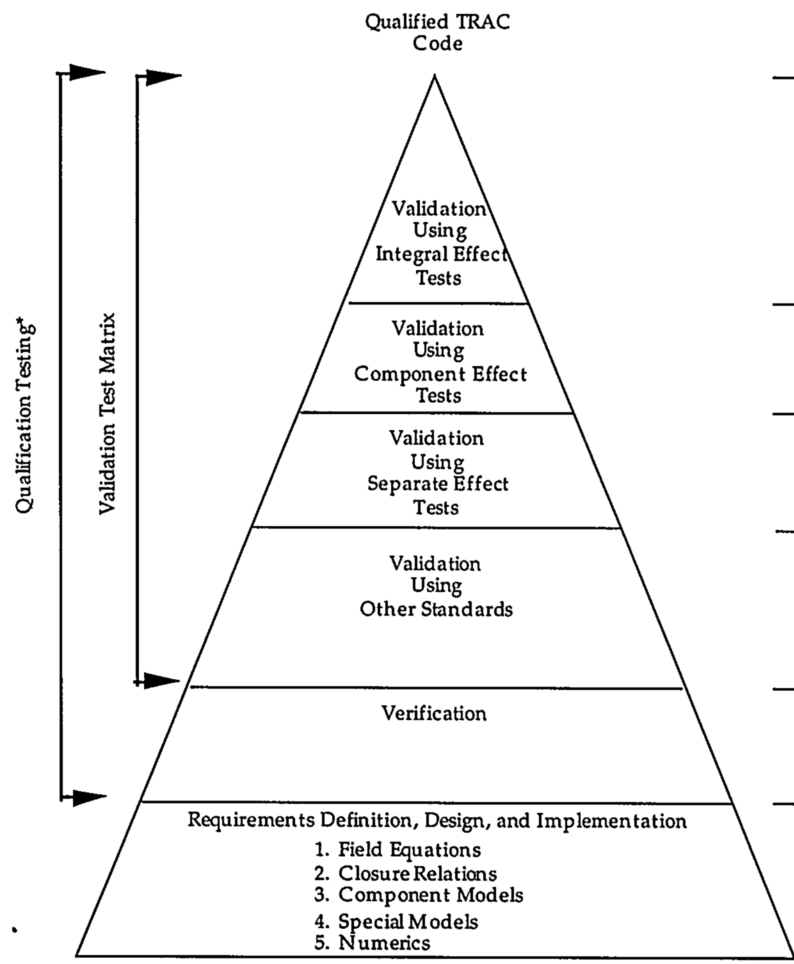
  3. all nonfunctional requirements, e.g., performance, design constraints, attributes, and external interfaces, are met.

The basic principles underlying the creation of the TRAC-M validation test matrix and the outcomes of applying those principles are discussed in the next section.

4. TRAC-M VALIDATION MATRIX PRINCIPLES AND ELEMENTS

The TRAC-M computer code consists of two major functional elements. One element consists of the individual, fundamental building blocks for the code. Examples of these building blocks are mathematical models of specific physical processes, such as heat conduction in a pipe wall or the friction between a moving fluid and the wall as fluid moves through a pipe. The former is a complete theoretical model, whereas the latter requires experimental data to effect an engineering solution. The experimental insights are embodied in closure models, also called constitutive models. TRAC-M contains more than 100 of these individual theoretical and closure models.

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



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

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

Fig. 1. Code Qualification Overview.*

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

Clearly, if the TRAC-M code is to fulfill its design objectives, it must model the important phenomena and processes occurring at the LLs, CLs, and SLs.

However, all phenomena and processes occurring within a nuclear power plant, whether at the LL, CL, or SL, do not have the same impact on the path and outcome of the accident or transient. Some phenomena and processes are more important than others in this regard. It is from this reality that the value of PIRTs is derived. The essence of a PIRT is captured in its name—it first identifies all of the processes and phenomena occurring in a specified nuclear power plant undergoing a specific accident or transient. It next ranks the identified processes and phenomena for importance relative to one or more primary evaluation criteria. The TRAC-M validation matrix uses all available PWR and BWR PIRTs to construct a consolidated list of highly important processes and phenomena for which the adequacy of the TRAC-M code must be validated, including all LL, CL, and SL processes appearing in the consolidated PWR and BWR PIRT. PIRTs play an important role in defining the TRAC-M validation test matrix.

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

The several information sources that have been considered in formulating the TRAC-M validation test matrix are illustrated in Fig. 2. These sources are the code itself; the library of existing, applicable PIRTs; and candidate experimental and other test problems. The consideration of TRAC models and correlations in developing the validation matrix is discussed in Section 4.1. The consideration of available PIRTs in developing the validation test matrix is discussed in Section 4.2. The consideration of test data and other test problems for the validation test matrix is discussed in Section 4.3.

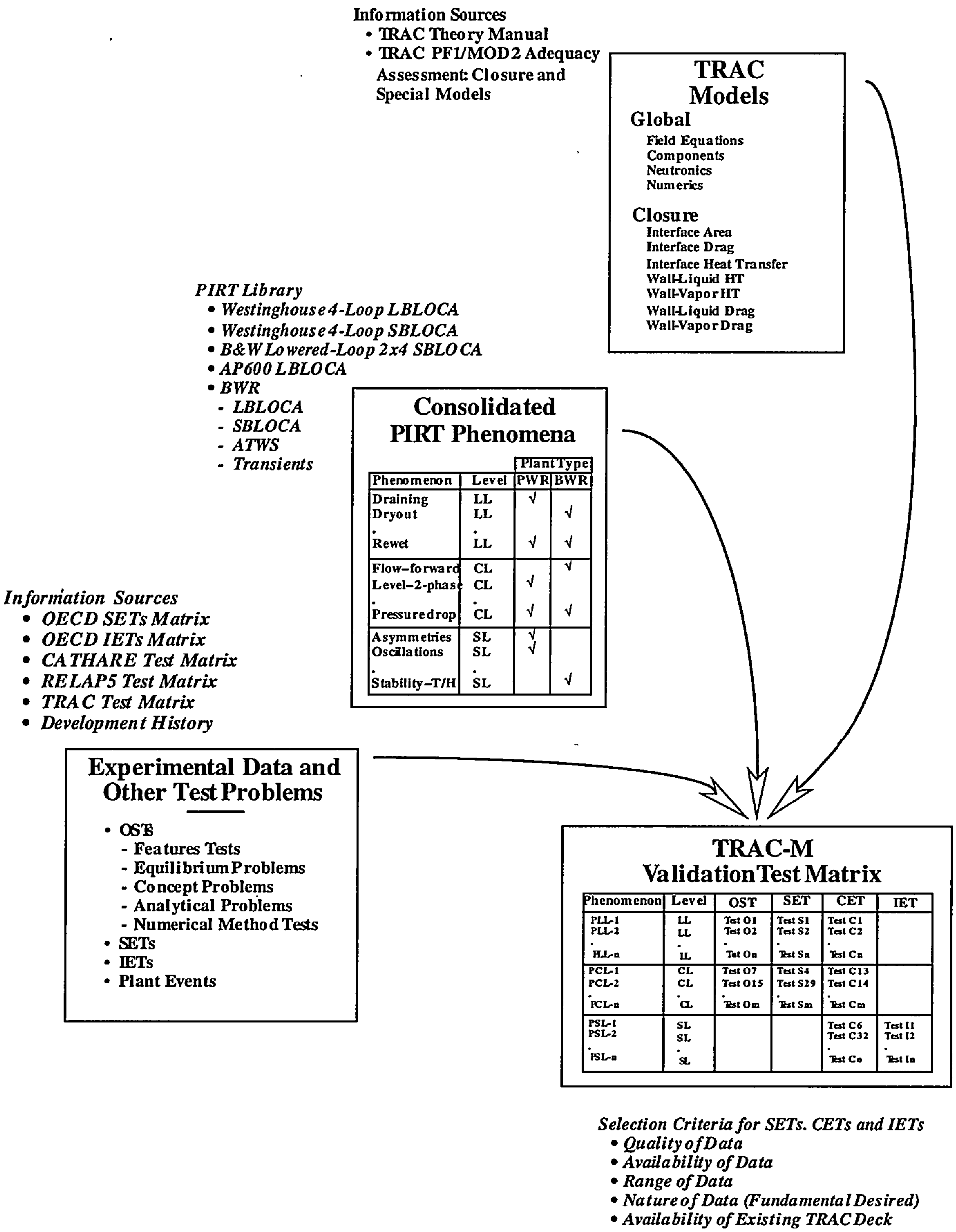


Fig. 2. Information sources supporting creation of the TRAC-M validation test matrix.

4.1. TRAC-M Models and Correlations

The TRAC-M computer code includes mathematical models that describe the physical processes/phenomena needed for the targeted applications areas and the numerical solution methods applied to the mathematical models. Each of these aspects of TRAC-M must be tested by elements of the TRAC-M validation test matrix. A high-level tabulation of the TRAC-M mathematical and numerical models follows. The mathematical models are divided into categories and subcategories. Several of the subcategories are subdivided further into models. In this paper, only model categories and subcategories are presented. Full details are presented in the source report.[8]

The mathematical models can be assigned to one of the following categories. The subcategories for each category are listed in Table 1.

- Basic-equations models
- Flow-field models and engineering correlations
- Equipment-component models
- Special-purpose models

The basic fluid-flow equations require various models to account for mass, momentum, and energy exchange among (1) the flow-channel walls; (2) each phase in the flow field; and (3) the liquid and vapor phases. The models for these processes generally comprise correlations for heat, mass, and momentum exchange taken from the literature. These correlations account for the majority of the empirical correlations in the TRAC-M code. These models are correlations that are catalogued in the flow-field models and engineering correlations category.

Models for equipment components usually are developed and used when the equipment, and the phenomena that occur in the equipment, are (1) so complex or too-little understood that a reliable mathematical description of the equipment and processes at a fundamental level is not possible or (2) 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.

All of the mathematical models in the TRAC-M code must be integrated into the overall solution methods used to advance the model equations over a timestep. Generally, finite-difference approximations to the continuous equations are used to implement the solution methods. The resulting systems of algebraic equations then are solved to advance the time. The subcategories for the numerical solution methods category are listed in Table 1.

4.2. PIRT Library

PIRTs first were developed during the pioneering code-scaling, applicability, and uncertainty study.[9] They since have provided useful support for many code-related activities. For the purposes of this paper, we focus on the utility of PIRTs in identifying needed code improvements and supporting code development decisions.

Table 1 TRAC-M elements by category and subcategory

Category	Subcategory
Basic-equations models	Fluid mass Fluid momentum Fluid energy Noncondensable gas mass Dissolved solute in the liquid 3D Vessel component Heat conduction Power generation in fuel Radiative energy exchange in the core Equation of state for fluids Fluid thermophysical and transport properties

Flow-field models and engineering correlations	Regime maps
	Fluid mass equation closure
	  Subcooled boiling,
	  Interfacial mass exchange, and
	  Solute mass exchange
	Fluid momentum equation closure
	  Wall-to-phase momentum exchange,
	  Interfacial momentum exchange, and
	  Local pressure losses
	Fluid energy equation closure
	  Wall-to-phase energy exchange and
	  Interfacial energy exchange

Equipment-component models	Centrifugal pumps Steam-water separator Plenum component Valve component Turbine Pressurizer

Special-purpose models	Countercurrent flow limitation model
	Critical flow model for fluid boundary conditions
	Trip and control system elements
	Reflood heat-transfer models
	  Flow regime modeling
	  Wall-to-phase and interfacial fluid drag
	  Wall-to-phase and interfacial fluid heat transfer
	  Conduction heat transfer
	Two-phase mixture level tracking model
	Offtake model for Tee component
	Fuel-cladding gap conductance

Numerical solution methods	Fluid field equations
	  1D stability enhancing two-step method
	  3D stability enhancing two-step method
	Conduction in solid materials
	  1D rectangular and cylindrical
	  2D rectangular and cylindrical
	  Lumped capacitance method
	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

A PIRT identifies 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, e.g., either high, medium, or low. The information obtained through the application of the PIRT process supports the identification of requirements to be imposed on transient thermal-hydraulic codes used to simulate given scenarios.

PIRT development proceeds through the following steps:[10] (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 characteristic time phases; (7) partitioning the plant design into components; (8) identification of plausible phenomena by phase and component; and (9) ranking component and phenomena importance.

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 of 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 thermal-hydraulic code used to simulate the scenario so that this information identifies a portion of the code design requirements. Third, some components and processes/phenomena affect the course of the scenario more strongly 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. Therefore, the same can be said about related requirements imposed on the code. The PIRT provides the needed ranking information. Fourth, the ranking information found in a PIRT also can be used as the basis for programmatic decisions made about the sequencing of development activities.

An ideal library would contain PIRTs for each plant type of each US vendor and selected scenarios for each plant type. Such an extensive PIRT library is not available at this time. However, enough PIRTs have been developed to lay a sufficient, if not entirely complete, basis for developing the TRAC-M validation test matrix. The PIRT library used in developing the TRAC-M validation matrix is summarized in Table 2.

PWR and BWR phenomena derived from the PIRTs identified in Table 2 have been compiled and consolidated into a single table of highly ranked light-water-reactor (LWR) processes and phenomena (Table 3). The source of each phenomenon (PWR, BWR, or both) is indicated. The phenomena are grouped by the level at which they occur, i.e., LL, CL, or SL. Although PIRTs do not exist for all PWR and BWR plant types and accident sequences, the list in Table 3 is believed to represent the majority of highly important thermal-hydraulic processes occurring in LWRs. The list can be updated easily as additional PIRTs are generated for other PWR and BWR accident sequences.

TRAC-M must model the phenomena appearing in Table 3 accurately. The phenomena occur at different levels within a plant or facility. Most PIRT-identified phenomena occur at the LLs and CLs. A natural association between LL phenomena and (1) the flow field models and engineering correlations and (2) special purpose models is described in Section 4.1. The appropriate cross correlation or linkage between phenomena identified in Table 3 and the associated TRAC-M models, although beyond the scope of this paper, is found in the TRAC-M validation test matrix report.[8]

Two possible associations exist between component-level phenomena and TRAC models. For some CL phenomena, there is no unique TRAC component model. Thus, the modeling capability is founded in more fundamental TRAC components and the underlying flow field models and engineering correlations. For other CL phenomena, specific TRAC component models do exist, e.g., the Pump. When such models exist, they are treated as described in the next paragraph. Although not the primary source of SL requirements, these being derived from the need to model various plant types and transients, several SL phenomena were identified in the various PIRT efforts. These phenomena can invoke the entire hierarchy of TRAC models: basic equation models, flow field models and engineering correlations, equipment component models, and special-purpose models.

Table 2 PWR and BWR PIRT library

<table>
<tr><th></th><th colspan="3">PWR</th><th colspan="3">BWR[a]</th></tr>
<tr><th>Category</th><th><u>W</u>[b]</th><th>B&W[c]</th><th>CE[d]</th><th>2</th><th>3,4</th><th>5,6</th></tr>
<tr><td>Accidents</td><td></td><td></td><td></td><td></td><td></td><td></td></tr>
<tr><td>LBLOCA</td><td>X[11]</td><td></td><td></td><td>X[14]</td><td>X[14]</td><td>X[14]</td></tr>
<tr><td>SBLOCA</td><td>X[12]</td><td>X[13]</td><td></td><td>X[14]</td><td>X[14]]</td><td>X[14]</td></tr>
<tr><td>SGTR[e]</td><td></td><td></td><td></td><td></td><td></td><td></td></tr>
<tr><td>MSLB[f]</td><td></td><td></td><td></td><td></td><td></td><td></td></tr>
<tr><td>ATWS[g]</td><td></td><td></td><td></td><td colspan="3">X[14]</td></tr>
<tr><td>Transients</td><td></td><td></td><td></td><td></td><td></td><td></td></tr>
<tr><td>Pressurization</td><td></td><td></td><td></td><td colspan="3">X[14]</td></tr>
<tr><td>Depressurization</td><td></td><td></td><td></td><td colspan="3">X[14]</td></tr>
<tr><td>Rapid reactivity increase</td><td></td><td></td><td></td><td colspan="3">X[14]]</td></tr>
<tr><td>Coolant temperature decrease</td><td></td><td></td><td></td><td colspan="3">X[14]</td></tr>
<tr><td>Instability</td><td></td><td></td><td></td><td colspan="3">X[14]</td></tr>
</table>

[a]Individual PIRTs have been produced for BWR/2, BWR/3,4, and BWR/5,6 designs for some accidents as noted. General BWR PIRTs have been prepared for the ATWS and all transients.
[b]W plants are differentiated further as two-loop, three-loop, and four-loop plants. Additional variations include bundle design (14 x 14, 15 x 15, 16 x 16, or 17 x 17), number of fuel assemblies, and power level (high, medium, or low).
[c]B&W plants are differentiated further as lowered loop or raised loop. Additional variations include bundle design (15 x 15 or 17 x 17), number of fuel assemblies, and power level (high or low).
[d]CE plants are differentiated further on bundle design (14 x 14, 15 x 15, or 16 x 16) and power level (high, low, or unique).
[e]SGTR=steam-generator tube rupture.
[f]MSLB=main steam-line break.
[g]ATWS=anticipated transient without scram.

Table 3 Summary of highly ranked PWR and BWR PIRT phenomena

Phenomena	Level	W-P[a] LBLOCA	W-P SBLOCA	B&W-P SBLOCA	GE-BWR LBLOCA	GE-BWR SBLOCA	GE-BWR TRANSIENT
Boiling—film	LL	X			X	X	X
Boiling—nucleate	LL				X	X	
Boiling—subcooled	LL						X
Boiling—transition	LL	X					
Condensation—fluid to surface	LL		X				
Condensation—interfacial	LL	X	X		X	X	X
Draining	LL	X					
Dryout	LL				X	X	X
Entrainment/deentrainment	LL	X	X				
Evaporation—interfacial	LL	X					
Flashing—interfacial	LL	X	X		X	X	
Flow—critical	LL	X	X	X	X	X	X
Flow—discharge	LL	X					
Flow—high-pressure injection	LL			X			
Heat conductance—fuel pellet	LL						X
Heat conductance—fuel-clad gap	LL	X					X
Heat transfer—forced convection to vapor	LL	X					
Heat transfer—post-CHF	LL		X		X	X	
Heat transfer—primary to secondary	LL			X			
Heat transfer—radiation	LL				X		
Heat transfer—stored energy release	LL	X					
Heat—stored	LL				X	X	
Interfacial shear	LL	X	X		X	X	X
Noncondensable effects	LL	X					
Oxidation	LL		X				
Rewet	LL		X		X	X	
Flow—channel-bypass leakage	CL				X	X	
Flow—countercurrent	CL	X	X		X	X	
Flow—distribution	CL				X	X	
Flow—forward	CL				X	X	X

[a]P=pressurized.
[b]GE=General Electric.

Table 3 Summary of highly ranked PWR and BWR PIRT phenomena (cont)

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

[a]T/H=thermal hydraulic.

4.3. Selection of Test Data and Other Test Problems

The validation matrix is divided into four elements. The first element is validation of code-calculated results using OSTs. The second element is validation tests comparing code-calculated results with data from SETs. The third element is validation tests comparing code-calculated results with data from CETs. The fourth element is validation tests comparing code-calculated results with data from IETs.

Validation Using OSTs. This element of the validation matrix 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 verifies that 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.

Validation Using SETs. This element of the validation matrix contributes to code qualification by comparing code-calculated results with SET data. SETs are experiments in which a limited number of physical phenomena of interest occur and detailed, high-quality data are obtained under closely controlled conditions. SETs cover a spectrum of tests from the most fundamental to those investigating interactions between phenomena and components or equipment in a specific region of the physical system.* The Organization for Economic Co-operation and Development, Nuclear Energy Agency, Committee on the Safety of Nuclear Installations has produced the most comprehensive review of SETs facilities.[15] The primary use of data from SETs is to assess the adequacy of the closure relationships used in the code. These data also are used to address scaling issues. The selected SETs become part of the TRAC-M validation test matrix.

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

* The boundary between SETs, CETs, and IETs is subject to interpretation. For example, the same facility in different configurations may be reasonably characterized as a SET or CET facility for one configuration and an IET for another. Regardless of the characterization, the key objective is to ensure that all applicable SET, CET, and IET facilities are considered and evaluated accurately to determine whether they should be included in the TRAC-M validation test matrix.

Validation Using IETs. This element of the validation matrix contributes to code qualification by comparing code-calculated results with data from IETs, including transients measured in real plants. IETs investigate behavior in a full nuclear power plant, usually in a reduced-scale facility. 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 thermal-hydraulic codes to predict SL processes identified in PWR PIRTs. In this manner, IET data are used to determine if the behaviors 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 Organization for Economic Co-operation and Development, Nuclear Energy Agency, Committee on the Safety of Nuclear Installations also has produced a comprehensive review of IETs facilities.[16]

Nomenclature

ATWS	Anticipated Transient without Scram
B&W	Babcock & Wilcox
BWR	Boiling Water Reactor
CE	Combustion Engineering
CET	Component Effect Test
CL	Component Level
GE	General Electric
IET	Integral Effect Test
LL	Local Level
LOCA	Loss-of-Coolant Accident
MSLB	Main Steam-Line Break
NRC	(United States) Nuclear Regulatory Commission
OST	Other Standard Test
P	Pressurized
PIRT	Phenomena Identification and Ranking Table
PWR	Pressurized Water Reactor
SET	Separate Effect Test
SGTR	Steam-Generator Tube Rupture
SL	System Level
W	Westinghouse

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REFERENCES

[1] TRAC-PF1/MOD2 Theory Manual, Los Alamos National Laboratory, US Nuclear Regulatory Commission report NUREG/CR-5673, Vol. 1, Draft, July 21, 1993.

[2] TRAC-BF1/MOD1: An Advanced Best-Estimate Computer Program for BWR Accident Analysis, Idaho National Engineering Laboratory, US Nuclear Regulatory Commission report NUREG/CR-4356, Vol. 1, August 1992.

[3] K. E. Carlson et al., RELAP5/MOD3, Code Manual, Idaho National Engineering Laboratory, US Nuclear Regulatory Commission report NUREG/CR-5535, 1994.

[4] U. S. Rohatgi et al., RAMONA-4B: A Computer Code with Three-Dimensional Neutron Kinetics for BWR and SBWR System Transients, Brookhaven National Laboratory, US Nuclear Regulatory Commission report NUREG/CR-6359, November 1996.

[5] J. M. Taylor, Thermal-Hydraulic Five Year Research Plan, US Nuclear Regulatory Commssion memorandum to Commissioners, September 6, 1996.

[6] J. Dearing, TRAC Modernization Completion Report, Los Alamos National Laboratory document LA-UR-99-1801, April 1999.

[7] USNRC, Software Quality Assurance Program and Guidelines, US Nuclear Regulatory Commission report NUREG/BR-0167, February 1993.

[8] B. E. Boyack and L. W. Ward, TRAC-M Validation Test Matrix, Los Alamos National Laboratory document LA-UR-99-6158, Rev. 0, December 1999.

[9] Technical Program Group, Quantifying Reactor Safety Margins: Application of CSAU to a LBLOCA, EG&G Idaho, Inc., US Nuclear Regulatory Commission report NUREG/CR-5249, 1989.

[10] 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).

[11] B. E. Boyack, AP600 Large-Break Loss-of-Coolant Accident Phenomena Identification and Ranking Tabulation, Los Alamos National Laboratory document LA-UR-95-2718 (August 1995).

[12] S. M. Bajorek et al., Small Break Loss of Coolant Accident Phenomena Identification and Ranking Table (PIRT) for Westinghouse Pressurized Water Reactors, Proceedings of the Ninth International Topical Meeting on Nuclear Reactor Thermal Hydraulics (NURETH-9), San Francisco, California, October 3–8, 1999.

[13] M. G. Ortiz, Uncertainty Analysis of Minimum Vessel Liquid Inventory during a Small Break LOCA in a B&W Plant: An Application of the CSAU Methodology, Idaho National Engineering Laboratory, US Nuclear Regulatory Commission report NUREG/CR-5818, December, 1992).

[14] M. Straka and L. W. Ward, BWR PIRT and Assessment Matrices for BWR LOCA and Non-LOCA Events, Scientech, Inc., SCIE-NRC-393-99, 1999.

[15] 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, NEA/CSNI/R(93)14/Part 1, Part 2/Rev., September 1993.

[16] 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.

among these methods.

We have obtained very high quality of images for the 2D sections of the SEG/EAGE salt model using the GOFFD method.

Conclusions

We have used a rational approximation of the square-root operator in the one-way wave equation to develop a globally optimized Fourier finite-difference method for imaging complex structures with strong lateral velocity variations and steep dips. The two optimized coefficients in the rational approximation are fixed for a given model, therefore, our optimized method does not need a table of coefficients, which is required by Ristow-Rühl's locally optimized Fourier finite-difference scheme. The formal error analysis of different Fourier finite-difference methods and impulse response migrations using these methods demonstrate that our optimized method is superior to the other Fourier finite-difference methods. The computational cost of our method is the same as other Fourier finite-difference methods. Our method can handle approximately 26° larger dip angles than the Padé-based Fourier finite-difference method, 15°–20° larger dip angles than Ristow-Rühl's unoptimized scheme, while Ristow-Rühl's optimized scheme can handle approximately 16° larger dip angles than their unoptimized scheme. For large lateral velocity contrasts, the maximum dip angle for our method is gradually larger than Ristow-Rühl's optimized scheme.

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References

Claerbout, J. F., 1985, Imaging the earth's interior: Blackwell Scientific Publications, Oxford.

Gazdag, J., 1978, Wave equation migration with the phase-shift method: Geophysics, 43, 1342–1351.

Huang, L.-J., and Fehler, M. C., 1998, Accuracy analysis of the split-step Fourier propagator: implications for seismic modeling and migration: Bull. Seis. Soc. Am., 88, 18–29.

Huang, L.-J., and Fehler, M. C., 2000, Quasi-Born Fourier migration: Geophys. J. Intern., 140, 521–534.

Huang, L.-J., Fehler, M. C., Roberts, P. M., and Burch, C. C., 1999a, Extended local Rytov Fourier migration method: Geophysics, 64, 1535–1545.

Huang, L.-J., Fehler, M. C., and Wu, R.-S., 1999b, Extended local Born Fourier migration method: Geophysics, 64, 1524–1534.

Ristow, D., and Rühl, T., 1994, Fourier finite-difference migration: Geophysics, 59, 1882–1893.

Stoffa, P. L., Fokkema, J. T., de Luna Freire, R. M., and Kessinger, W. P., 1990, Split-step Fourier migration: Geophysics, 55, 410–421.

Xie, X.-B., and Wu, R.-S., 1998, Improve the wide angle accuracy of screen method under large contrast: 68th Ann. Internat. Mtg., Soc. Expl. Geophys., Expanded Abstracts, 1811–1814.

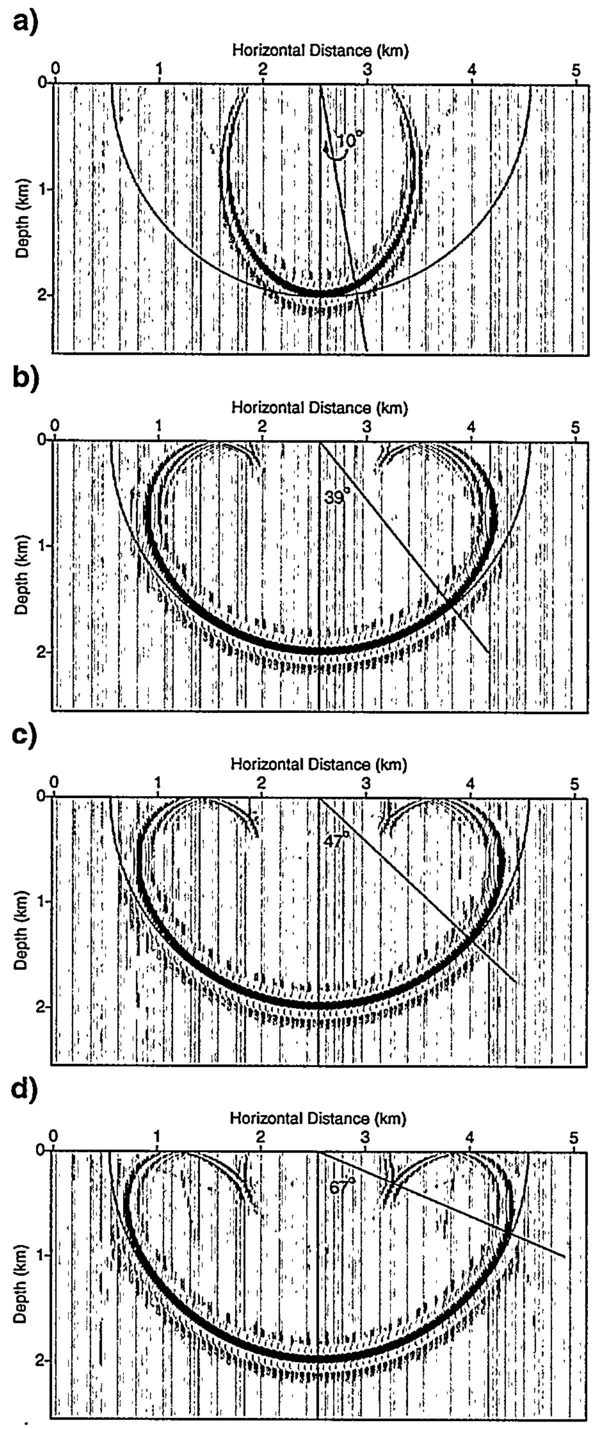

Fig. 3: Migration images of an impulse response in a medium with $v = 4500$m/s. Migrations were done using $v_0 = 1500$m/s. In each panel, the red-solid-line semicircle is the ideal image position and the angle is the maximum dip angle predicted by the formal error analysis. (a) SSF migration; (b) PFFD migration; (c) FFD migration; (d) GOFFD migration.