RELAP-7 Software Verification and Validation Plan

Requirements Traceability Matrix (RTM) Update and Code Verification Strategy

Junsoo Yoo
Yong-Joon Choi

September 2017

DOE Office of Nuclear Energy

NOTICE

RELAP-7 Software Verification and Validation Plan

Requirements Traceability Matrix (RTM) Update and Code Verification Strategy

Junsoo Yoo
Yong-Joon Choi

September 2017

Idaho National Laboratory
Idaho Falls, Idaho 83415

ABSTRACT

This document describes the recent progress of the RELAP-7 Software Verification and Validation Plan (SVVP). The RELAP-7 RTM has been updated by adding the validation requirement items, rearranging the requirement items, and introducing the classifier to better describe the RELAP-7 V&V status at a specified point in time. Also, from the perspective of nuclear system code validation, six items from the list of LWR safety-relevant phenomena were identified as validation data gaps. Lastly, motivated by the needs revealed from the previous RELAP-7 IV&V activities, the independent verification plan for RELAP-7 has been established. The verification method, procedure, and verification test coverage suite discussed in this document will be applied to the future work for the RELAP-7 independent verification.

PREFACE

Document Version

This document is released as Revision 0.

It is the reader's responsibility to ensure he/she has the latest version of this document. Direct Questions may be directed to the owner of the document and project manager:

Project Manager: Curtis L. Smith, RISMC Pathway Lead

Idaho National Laboratory

Phone: (208) 526-9804.

E-mail: Curtis.Smith@inl.gov .

CONTENTS

FIGURES

Tables

ACRONYMS

CT	Component Test
DOE	Department of Energy
EOS	Equation of State
FT	Fundamental Test
IET	Integral Effect Test
INL	Idaho National Laboratory
IV&V	Independent Verification and Validation
LWR	Light Water Reactor
LWRS	Light Water Reactor Sustainability
MOOSE	Multi-Physics Object Oriented Simulation Environment
RTM	Requirements Traceability Matrix
SET	Separate Effect Test
SVVP	Software Verification and Validation Plan
V&V	Verification and Validation

RELAP-7 Software Verification and Validation Plan: Requirements Traceability Matrix (RTM) Update and Code Verification Strategy

ix

Idaho National Laboratory

RELAP-7 Software Verification and Validation Plan

Requirements Traceability Matrix (RTM) Update and Code Verification Strategy

1. INTRODUCTION

RELAP-7 is a next generation nuclear reactor system analysis code that has been developed by Idaho National Laboratory (INL). The RELAP-7 development has been supported by the LWRS program of DOE, which aims to provide an advanced analysis tool that can be applied to the Risk-Informed Safety Margins Characterization (RISMC) methodology and to support the nuclear power plant safety analysis. The development of system safety analysis code, such as RELAP-7, generally involves four sequential phases: (i) Phase I – prototype code, (ii) Phase II – demonstration code, (iii) Phase III – production code, and (iv) Phase IV – licensing code. As of FY-17, the development status of RELAP-7 is in Phase II [1].

Besides the development effort for RELAP-7, INL has also launched a "RELAP-7 Software Verification and Validation Plan (SVVP)." The primary goal of RELAP-7 SVVP is to identify all the requirements for RELAP-7, such as software design requirements, V&V test matrix, and measureable metric matrix that can quantify the code assessment activities (i.e., RTM), etc., and to establish the RELAP-7 assessment plan. If needed, the RELAP-7 development status can also be assessed with the test problems designated by the code assessment team [2]. The RELAP-7 IV&V activities, a major part of RELAP-7 assessment [3], should be in principle independent of the code development activities to ensure the quality of code [3]. Nonetheless, since the RELAP-7 features are still evolving, a certain level of communication between the code developers and code assessment team is inevitable, but must be done within the prescribed procedure. Furthermore, the RELAP-7 assessment plan and work scope should be set considering the RELAP-7 development status. Table 1 summarizes the work scope of RELAP-7 assessment corresponding to each stage of RELAP-7 development. The second column of Table 1, describing the RELAP-7 development status/plan, is given based on Ref. [1].

This document describes the continuing effort of RELAP-7 assessment plan and RELAP-7 IV&V activities since FY-15. The specific contents include (i) RELAP-7 RTM update (section 3), (ii) a design of RELAP-7 RTM evaluation matrix and validation data gap identification (section 4), and (iii) RELAP-7 verification strategy and procedure (section 5). Also, a summary of previous RELAP-7 assessment activities are provided in section 2 to help readers understand the current work in a larger framework.

In the following subsections, we reiterate the work scope and objectives of RELAP-7 SVVP described in previous documents [3, 4] while incorporating the recent updates due to the RELAP-7 activities since 2016. This document is a "living" document because it will be updated as new or revised information is achieved through the future activities of RELAP-7 development and assessment.

Table 1. RELAP-7 assessment work scope/plan according to the progress of RELAP-7 development

	RELAP-7 development [1]	**RELAP-7 assessment (including IV&V activity)**
Phase 1 (Prototype code)	- Develop a pilot code and demonstrate the proof of concept - Demonstrate the robustness of numerical methods and physical models - Numerical verification - Validation with classical phenomenological problems (e.g., water-faucet, fill-drain, etc.)	- Establish RTM - Review on the availability and accessibility of experimental data that can be used for RELAP-7 code validation - Validation data review
Phase 2 (Demonstration code)	- Implement real water/steam (IAPWS95 package) and other material properties - Implement/test major closure models - Implement/test major components (e.g., pipe, branch, valve, etc.) - Some validation work with SET	- Update RTM - Validation data gap identification - Establish verification coverage test suite - Code verification for the basic governing equations with available options of boundary conditions, stabilization schemes, and EOS, etc. - Code verification for the major components (e.g., pipe, branch, etc.). - Simple V&V work with FT and SET problems listed in RELAP-7 RTM - Documentation of (i) test results and (ii) maturity level of independent V&V
Phase 3 (Production code)	- Fully develop/test all the desired features (e.g., input/output generation and checking, error diagnostics) - Implement/test all the closure models/components/control systems necessary for LWR simulation - Full implementation of runtime diagnostics - Validate the code capabilities (e.g., LOCA/reflood analyses) with SET/IET - Define the code's applicability range - Documentation (e.g., theory manual, user' guide)	- Validation work with a set of constitutive models (e.g., wall/interfacial momentum transfer, wall/interfacial energy transfer, etc.) - Validation work (CT and SET) with PWR/BWR components (e.g., pressurizer, centrifugal/jet pump, valve, U-tube steam generator, steam separator/dryer, 1D downcomer, etc.) - Further validation work (SET) with closure models such as CCFL, CHF, non-condensable gas model and solute transport model -- - Full validation work with CT, SET, and IET listed in RELAP-7 RTM - Solution verification work for some important safety analysis problems (e.g., LOCA, reflood, SBO) - Documentation of (i) test results and (ii) maturity level of independent V&V
Phase 4 (Licensing code)	- Transfer to end users of production code - Incorporating proprietary models - Extensive validation work - Quality assurance process to obtain approval from NRC	-

* Validation test type described in RELAP-7 Requirement Traceability Matrix (RTM):
FT: fundamental tests; **CT**: component tests; **SET**: separate effect tests; **IET**: integral effect tests

Idaho National Laboratory

1.1   System Description

The RELAP-7 (Reactor Excursion and Leak Analysis Program) code is a nuclear reactor system safety analysis code being developed at Idaho National Laboratory (INL). The code is based on the INL's modern scientific software development framework – MOOSE (Multi-Physics Object-Oriented Simulation Environment). The overall design goal of RELAP-7 is to take advantage of the previous thirty years of advancements in computer architecture, software design, numerical integration methods, and physical models. The end result will be a reactor systems analysis capability that retains and improves upon RELAP5's capability and extends the analysis capability for a variety of reactor system simulation scenarios.

1.2   Plan Objectives

The objective of this plan is to document the verification and validation activities for the software development process for RELAP-7. Additional information provided in this plan includes the Requirement Traceability Matrix which is the set of General Requirements, Specific Requirements and Code V&V Requirements.

For the INL, Software Quality Assurance (SQA) requirements are contract driven and interpreted from DOE Order 414.1D, "Quality Assurance", 10 CFR 830 "Nuclear Safety Management", Subpart A, "Quality Assurance Requirements", and ASME NQA-1-2008 with the NQA-1a-2009 addenda, "Quality Assurance Requirements for Nuclear Facility Applications." The INL internal document, PDD-13610 (Revision 13, 4/1/2015), "Software Quality Assurance Program" describes the SQA Program at the INL:

- PDD-13610 describes the Software Quality Assurance Program, which INL applies, to confirm that software used at INL is consistent with applicable requirements and is directed towards preventing software errors from occurring. The SQA Program includes a systematic set of standards, conventions, and methodologies implementing a standardized approach to the life cycle for all software at INL.

Per PDD-13610, INL SQA Program applies to all organizations, facilities, programs, projects, and subcontractors. The extent to which the program establishes required SQA activities is determined by the risk or quality level associated with failure of the software to meet established requirements. This graded approach consists of activities and sub-activities that can be implemented at varying levels of rigor based upon the potential impact on safety and the type of software. The more critical the software, the more formal and detailed the SQA activities must be performed and documented. Implementation of the SQA Program focuses on a life cycle management approach for Information Technology (IT) assets. This approach is described in LWP-13620, ″Managing Information Technology Assets." The INL technology developed and/or used within RISMC pathway (*e.g.*, RELAP-7) also follows the LWP-13620.

PDD-13610 defines "Software" as *Computer programs and associated documentation and data pertaining to the operation of a computer system and includes application software and support software* [ASME NQA-1-2008 with the NQA-1a-2009 addenda edited]. Other softwares are defined as:

- Application software - A type of software designed to help users perform particular tasks or handle particular types of problems, as distinct from software tools (e.g., compilers) and system software (see def.) that controls the computer itself. Examples include timesheet, payroll, Electronic Document Management System (EDMS), Microsoft Excel spreadsheets, computer models, or process control applications. [ISO/IEC/IEEE Std. 24765-2010 edited]

- Support Software - Software that includes software tools (e.g., compilers) and system software. [ASME NQA-1-2008 with the NQA-1a-2009 addenda]

Note that within the INL SQA process, software that does not fall within the scope of the SQA Program includes any software covered by a contractual agreement, such as Work for Others, which includes references or requires a specific documented SQA process.

Applicable documents that apply to RELAP-7 development include:

- Software Quality Assurance Plan for RELAP-7, PLN-4212, 5/31/2012.

- Software Configuration Management Plant for the RELAP-7 Project, PLN-4214, 6/28/2012.

- Software Verification and Validation Plan for RELAP-7, PLN-4215, 6/28/2012.

- RELAP-7 Development Plan, INL/MIS-13-28183, 1/2013.

It is the responsibility of the **Software Owner** to make the determination as to whether a particular software can be classified as "Safety Software." Safety Software includes the following type of softwares:

- **Safety System Software**. Software for a nuclear facility that performs a safety function as part of a structure, system, or component *and* is cited in either (a) a DOE approved documented safety analysis or (b) an approved hazard analysis per DOE P 450.4, "Safety Management System Policy", dated 10-15-96, (or latest version) and 48 CFR 970-5223.1.

- **Safety Analysis and Design Software**. Software that is used to classify, design, or analyze nuclear facilities. This software is not part of a structure, system, or component (SSC) but helps to ensure that the proper accident or hazards analysis of nuclear facilities or an SSC that performs a safety function.

- **Safety Management and Administrative Controls Software**. Software that performs a hazard control function in support of nuclear facility or radiological safety management programs or technical safety requirements or other software that performs a control function necessary to provide adequate protection from nuclear facility or radiological hazards. This software supports eliminating, limiting or mitigating nuclear hazards to worker, the public, or the environment as addressed in 10 CFR Parts 830 and 835, the DEAR Integrated Safety Management System clause, and 48 CFR 970-5223.1. [DOE O 414.1D]

For all software that falls within the scope of the SQA Program, a **quality level** must be assigned by a qualified Quality Level Analyst with review and concurrence by a Quality Level Reviewer (i.e., a second Quality Level Analyst) per LWP-13014 (4/25/2013), "Determining Quality Levels." The Quality Level Analyst should then communicate to the Software Owner the determined quality level.

There is no consistent definition for the term Quality Level (QL). QLs only serve as a designator to identify the unmitigated risk or potential consequence level associated with the failure of an item or activity and to facilitate communication for a common understanding of the rigor to be applied through the appropriate implementation procedures:

Quality Level 1   High unmitigated risk or high potential consequence level of failure

Quality Level 2   Medium unmitigated risk or medium potential consequence level of failure

4

Quality Level 3 Low unmitigated risk

Quality Level 4 No risk item or service

The risk analysis used to designate QLs must be performed by personnel designated, trained, and qualified as QL Analysts. This initial training and every 3-year requalification of QL Analysts, also established by this procedure, is necessary to implement the graded approach effectively.

All documentation that furnishes evidence of the software quality is considered a QA record and should be handled as a quality record according to the organization, program, or project's "Records Management" as required by LWP-1202. QA records generated during the software development life cycle could include project plans, requirement specifications, configuration management plans, software quality assurance plans, security plans, and verification and validation documentation (e.g., test plans, test cases, and design review documents). Per LWP-1202, "Records Management," the INL Records Schedule Matrix, and associated record types list(s) provide current information on the retention, quality assurance, and/or destruction moratorium requirements for these records. Contact a Records Coordinator for assistance if needed.

It is the responsibility of the contractor to ensure that these quality criteria are adequately addressed throughout the course of the research that is performed.

1.2.1   Software Quality Assurance

Software assurance is the planned and systematic set of activities that ensures that software processes and products conform to requirements, standards, and procedures. These processes are followed in order to enhance the robustness of the development process. Having formal documented development procedures and requirements helps to streamline the development cycle and focus on customer-driven needs.

In an attempt to improve the quality of the RELAP-7 tool set, effort has been made to establish criteria to which the development and control processes adhere. The recording of coding standards and the creation of the Requirements Traceability Matrix (RTM) will be added to improve code use and to establish traceability.

The roles and responsibilities of each team member are described below:

- Project Manager – Executes, maintains, and updates this plan. Monitors SV&V activities for the RELAP-7 Project. Coordinates formal user acceptance testing, when required. Performs as an alternate for technical team members.

- Software Developer – Performs design reviews, test case identification, design, construction, and functional unit testing during software development; reports anomalies and deviations to the Project Manager.

- Quality Assurance – Supports SV&V activities including RELAP-7 reviews. Is independent of the development and testing work

1.3   Supporting Activities

1.3.1   Development of MOOSE Application

RELAP-7 is a MOOSE (Multiphysics Object-Oriented Simulation Environment) based application which uses open source software packages, such as PETSC (a nonlinear solver developed at Argonne National Laboratory) and LibMesh (a Finite Element Analysis package developed at University of Texas). MOOSE provides numerical integration methods and mesh management for parallel computation. Therefore RELAP-7 code developers only need to focus upon the physics and user interface capability. By using the MOOSE development environment, RELAP-7 code is developed by following the same modern software design paradigms used for other MOOSE development efforts.

There are currently over 20 different MOOSE based applications ranging from 3-D transient neutron transport, detailed 3-D transient fuel performance analysis, to long-term material aging. Multi-physics and multiple dimensional analyses capabilities, such as radiation transport, can be obtained by coupling RELAP-7 and other MOOSE-based applications through MOOSE. This allows restricting the focus of RELAP-7 to systems analysis-type simulations.

The RISMC Toolkit is being built using the INL's MOOSE framework. MOOSE has been designed to solve multi-physics systems that involve multiple physical models or multiple simultaneous physical phenomena. Inside MOOSE, the Jacobian-Free Newton Krylov (JFNK) method is implemented as a parallel nonlinear solver that naturally supports effective coupling between physics equation systems (or Kernels). This capability allows for a tightly-coupled set of tools that work together, as shown in Figure 1.
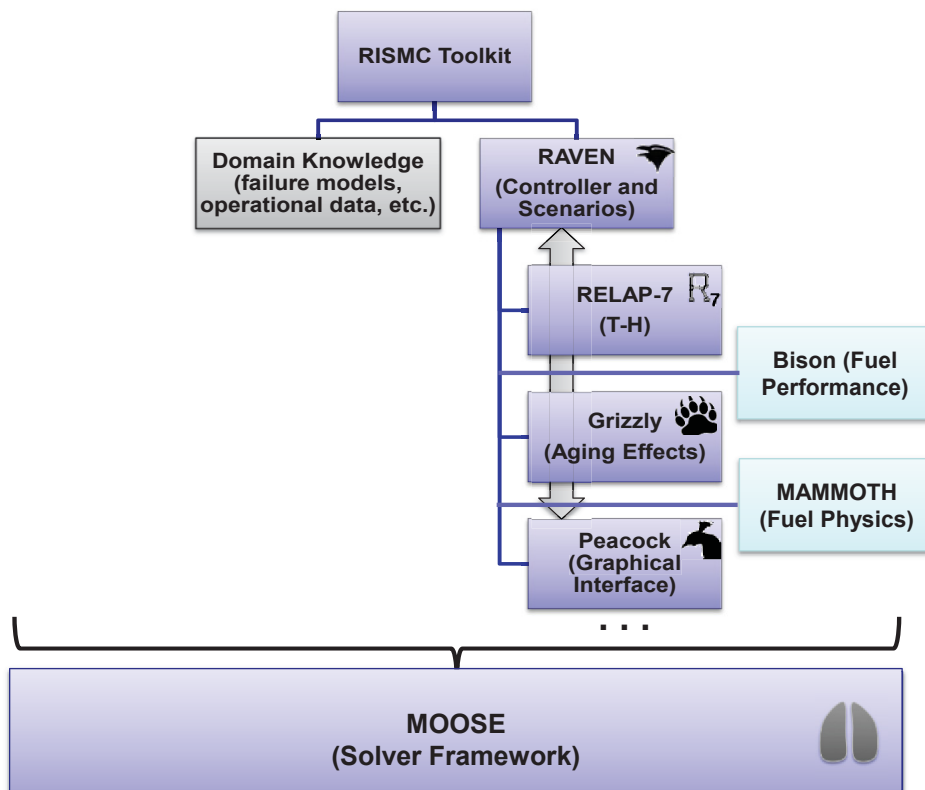
Figure 1. MOOSE-based applications

1.3.2 Technology Transfer

Development of RELAP-7 is to support US nuclear power industry and technical stewardship is envisaged. To realize this long-term vision, several items are considered.

The RELAP-7 quality assurance (QA) process includes the specific activities of verification, validation, assessment, and related documentation to facilitate reviews of these activities. To support these QA activities, a various results from facility operation, integral effects test, separate effect tests, and fundamental tests including experiments on individual components have been collected. The INL has started the QA process by implementing modern software management processes (including the use of tools such as source code version control) as a part of the RELAP-7 development, conducting NQA-1 audits, and creating a software verification and validation plan (SVVP).

The type of software license for RELAP-7 is still to be determined. RELAP-7 is subject to U.S. Export Control laws, including a complete embargo against any person from a T5 country (currently: Cuba, Iran, North Korea, Syria and Sudan). The software license for the supporting MOOSE framework is the open source license "Lesser GNU Public License (LGPL) version 2.1."

1.4 RELAP-7 Features

In general RELAP-7 provides computational simulation of thermal-hydraulic behavior in a nuclear power plant and its components. Representative thermal hydraulic models are used to depict the major physical components and describe major physical processes. RELAP-7 has five main types of components/capabilities:

- Three-dimensional (3D) analysis coupled with other physics applications
- Two dimensional (2D)
- One-dimensional (1D) components (e.g., pipe)
- Zero-dimensional (0D) components for setting boundary conditions for the 1D components (e.g., Pressure boundary condition of pump)
- 0D components for connecting 1D components

RELAP-7 could be coupled to 3D core modeling MOOSE-based codes to enable detailed resolution.

The RELAP-7 code development started in 2012 based upon development input from the Electric Power Research Institute. During the first year of the code development, the software framework was created to establish the basic reactor system simulation capability with a number of components developed for single-phase thermal fluid flow. Later, two-phase flow modeling capability was implemented in the RELAP-7 code. These early capabilities have been demonstrated via application to a boiling water reactor simulation with representative components under extended Station Black Out (SBO) transient conditions.

The RELAP-7 α-0.1 was released in May 2012, and followed by α-0.2 versions in August 2013 and α-0.6 versions in September 2014. Since 2015, the code developers are using GitLab project which is the web base open community for code developers. The GitLab will automatically provide code version number when the code has been updated.

The RELAP-7 application is the next generation nuclear reactor system safety analysis code. The code is based upon the MOOSE (Multi-Physics Object-Oriented Simulation Environment). The goal of RELAP-7 development is to leverage of advancements in software design, numerical integration methods, and physical models.

The Homogeneous Equilibrium two-phase flow Model (HEM) has been archived.

Table 2. Component-related attributes for the RELAP-7 (as of 2017)

RELAP-7 Component	Dimensionality			Hydrodynamic Model		3D Linkage
	0D	1D	2D	Single Phase	Two Phase 7-Eq.	Application
Inlet	■	n/a	n/a	■	■	n/a
Outlet	■	n/a	n/a	■	■	n/a
SolidWall	■	n/a	n/a	■	■	n/a
Pipe	n/a	■	n/a	■	■	BISON
PipeWithHeatStructure	n/a	■	■	■	■	n/a
HeatStructure	n/a	n/a	■	n/a	n/a	n/a
HeatGeneration	n/a	n/a	■	n/a	n/a	n/a
CoreChannel	n/a	■	■	■	■	n/a
VolumeBranch	■	n/a	n/a	■	□	n/a
Branch	■	n/a	n/a	■	□	n/a
Valve	■	n/a	n/a	■	□	n/a
CompressibleValve	■	n/a	n/a	■	□	n/a
CompressibleBranch	Δ	n/a	n/a	Δ	□	n/a
CheckValve	■	n/a	n/a	■	□	n/a
IdealPump	■	n/a	n/a	■	n/a	n/a
Pump	■	n/a	n/a	■	□	n/a
PointKinetics	■	n/a	n/a	n/a	n/a	n/a
SeparatorDryer	■	n/a	n/a	n/a	□	n/a
Downcomer	■	n/a	□	n/a	□	n/a
WetWell	■	□	n/a	■	□	n/a
PrescribedReactorPower	■	n/a	n/a	n/a	n/a	n/a
Turbine	■	n/a	n/a	■	□	n/a
Pressurizer	Δ	□	n/a	n/a	□	n/a
Accumulator	Δ	□	n/a	n/a	□	n/a
Steam Generator	n/a	□	n/a	n/a	□	n/a
Jet Pump	n/a	□	n/a	n/a	□	n/a

* ■: Available, Δ: Under review (developed, but not merged yet), □: Planned, n/a: Not applicable

In summary the RELAP-7 design is based upon:

- Modern Software Design:
  - o Object-oriented C++ construction provided by the MOOSE framework
  - o Designed to significantly reduce the expense and time of RELAP-7 development
  - o Designed to be easily extended and maintain
  - o Meets NQA-1 requirements
- Advanced Numerical Integration Methods:
  - o Multi-scale time integration, PCICE (operator split), JFNK (implicit nonlinear Newton method), and a point implicit method (long duration transients)
  - o New pipe network algorithm based upon Mortar FEM (Lagrange multipliers)
  - o Ability to couple to multi-dimensional reactor simulators
- State-of-the-Art Physical Models:
  - o All-speed, all-fluid (vapor-liquid, gas, liquid metal) flow
  - o Well-posed 7-equation two-phase flow model
  - o New reactor heat transfer model based upon fuels performance

Table 2 summarizes the development status of major components for RELAP-7 (as of 2017).

1.4.1   Software Framework

The RELAP-7 (Reactor Excursion and Leak Analysis Program) code is based on INL developed framework software MOOSE (Multi-Physics Object Oriented Simulation Environment) which may model fully coupled nonlinear partial differential equations. The Graphical User Interface (GUI) of RELAP-7 can be provided by other MOOSE based softwares.

1.4.2   Governing Theory

Fundamentally, the RELAP-7 code is designed to simulate all-speed and all-fluid for both single and two-phase flow. However, current status RELAP-7 development focuses on simulation of the light water reactors (LWR), thus, two-phase flow model is described here.

The main governing theories of RELAP-7 are: 7-equation two-phase flow; reactor core heat transfer; and reactor kinetics models.

The 7-equation two-phase flow model consists of mass, momentum and energy (or pressure) equation for both liquid and vapor phases and a topological equation which explains the state of the two-phase mixture. This model may solve compressible fluid at all-speed multiphase flow which allows analyzing various transient phenomena and accident scenarios in LWR. In the RELAP-7, the 7-equation model is implemented in the MOOSE finite element framework.

 Both convective and conduction heat transfer is simulated for fuel, fluid, and structures. The reactor core heat source is modeled by point kinetic method considering hydraulic reactivity feedback. The three-dimensional reactor kinetics may simulate through coupling with RattleSNake which is a reactor kinetics code with both diffusion and transport capabilities based on MOOSE framework.

1.4.3   Computational Approach

The RELAP-7 uses MOOSE-based applications with a multitude of mathematical and numerical libraries: LibMesh for the second-order accurate spatial discretization by employing linear basis, one-dimensional finite elements; Message Passing Interface (MPI) for distributed parallel processing; Intel Threading Building Blocks (Intel TBB) for parallel C++ programs to take full advantage of multi-core architecture found in most large-scale machines; and PETSc, Trilinos and Hypre for the mathematical libraries and nonlinear solver capabilities for Jacobian-Free Newton Krylov (JFNK).

To cover various time scale range of reactor transient and accident scenarios, the RELAP-7 pursues three-level time integration approaches: Pressure-Corrected Implicit Continuous-fluid Eulerian (PCICE) computational fluid dynamics (CFD) scheme for highly compressible and/or contain significant energy deposition, chemical reactions, or phase change problems; JFNK method for multi-physics problems during the transients; Point Implicit time Integration method for long duration and slow transient scenarios.

2. RELAP-7 INDEPENDANT VERIFICATION AND VALIDATION PLAN

The work described in this document, such as RELAP-7 RTM update (section 3), RTM evaluation matrix (section 4), and code verification plan/strategy (section 5) is based on the framework that has been established since 2015. This section summarizes the previous activity of RELAP-7 IV&V to help readers to understand the present work in the context of such a big frame.

2.1 RELAP-7 Code Assessment Plan and RTM Establishment [3]

The RELAP-7 code assessment strategy was established and efforts were made to identify the RELAP-7 test requirements. Then, the code assessment plan was proposed in the form of Requirement Traceability Matrix (RTM), the activity of which was first started in 2015 [4]. The RELAP-7 RTMs have been created by assembling all the necessary information, i.e., RELAP-7 test requirements, into the condensed form of matrices. Consequently, this allows us to effectively trace the progress of code development as well as the code V&V (or assessment). As of 2017, the RELAP-7 RTM consists of three elements, (i) *general RTM*, (ii) *specific RTM*, and (iii) *code V&V RTM*, as shown in Figure 2. The *general RTM* involves a set of general requirements in order for RELAP-7 to play a role as a next-generation nuclear system analysis code; the *specific RTM* contains a set of technical aspects of requirements. In particular, rhea requirements related to the legacy issues of existing nuclear system codes are included in this *specific RTM*; the *code V&V RTM* provides a detailed list of V&V test problems for RELAP-7.
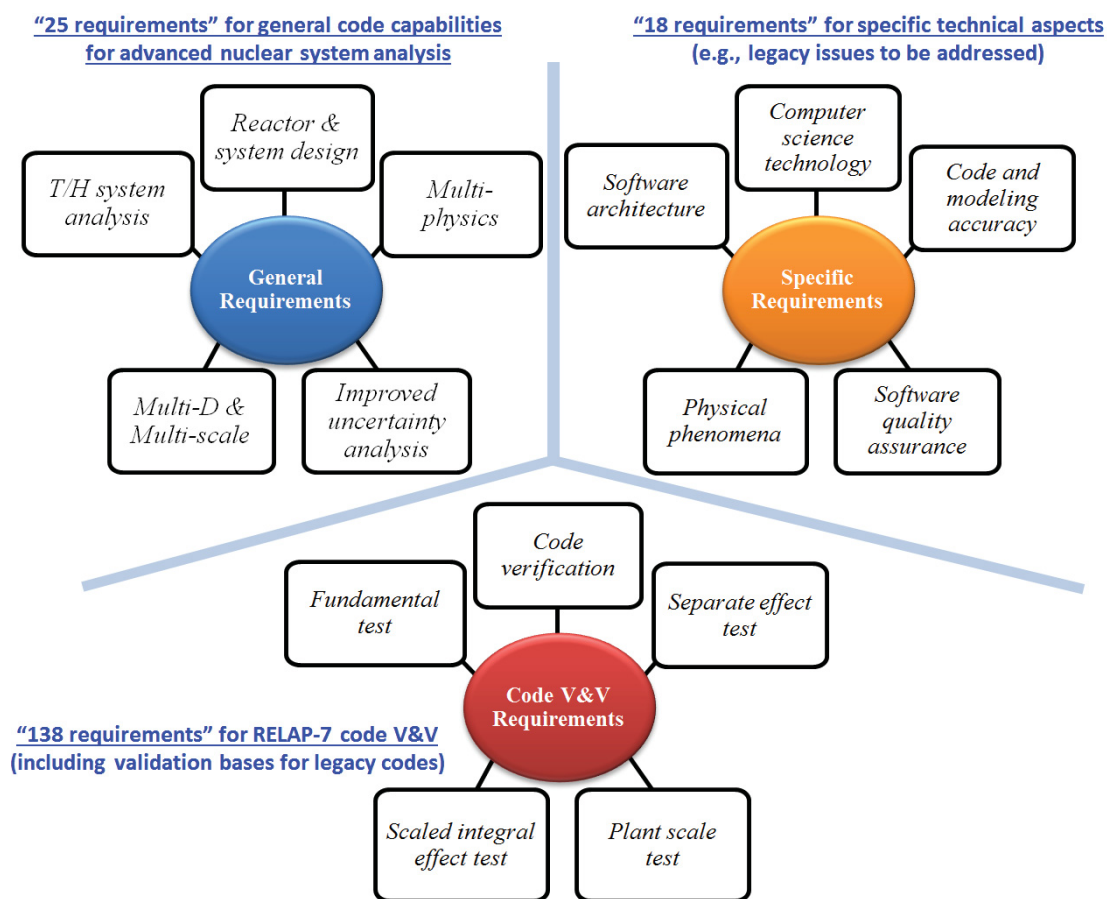
Figure 2. Characterization of requirements for RELAP-7 RTM (as of 2017)

2.2 Code Verification and Validation Activity [2]

Among the list of V&V test problems in RELAP-7 *code V&V RTM*, five test problems were selected and used to assess the RELAP-7 simulation capability (as of 2016). The three tests were performed for code verification while the other two tests were performed for code validation. The two verification tests were conducted at hydrostatic condition that did not account for gravity. The test results verified that the hydrostatic equilibrium was well maintained during the simulation. However, the vapor velocity was observed to fluctuate significantly by introducing a gravity term. The other verification test was to investigate the advection of void fraction through a horizontal channel, which is schematically illustrated in Figure 3 (top side). The RELAP-7 simulation result shown in Figure 3 (bottom side) indicates that the profile of initially-given void fraction is deformed significantly due to the numerical errors such as numerical dissipation and dispersion. In particular, it was found that the code often failed when the void fraction values became negative during the simulation as a result of the numerical dispersion. Also, one of the validation tests with 'water-faucet test problem' revealed that mixted boundary condition needs to be better addressed in RELAP-7. The other validation test was performed with 'phase-separation test problem' as shown in Figure 4. This test problem assumed that the vertical pipe was initially filled with the two-phase mixture of uniform void fraction (see the top of Figure 4). Then, the two different phases, i.e., liquid and vapor, were expected to be separated over time due to the effect of gravity. The RELAP-7 simulation results for this test were largely reasonable as shown on the

bottom of Figure 4, but it was concluded that more attention still needs be paid to the fluctuating behavior of void fraction observed during the simulation.

The above V&V tests were good confidence-building excercises for RELAP-7, but at the same time several issues were found while running the code as noted above. As a result, we reached a conclusion that more strict code verification work is required. This motivated the establishment of RELAP-7 code verification plan and strategy detailed in section 5.
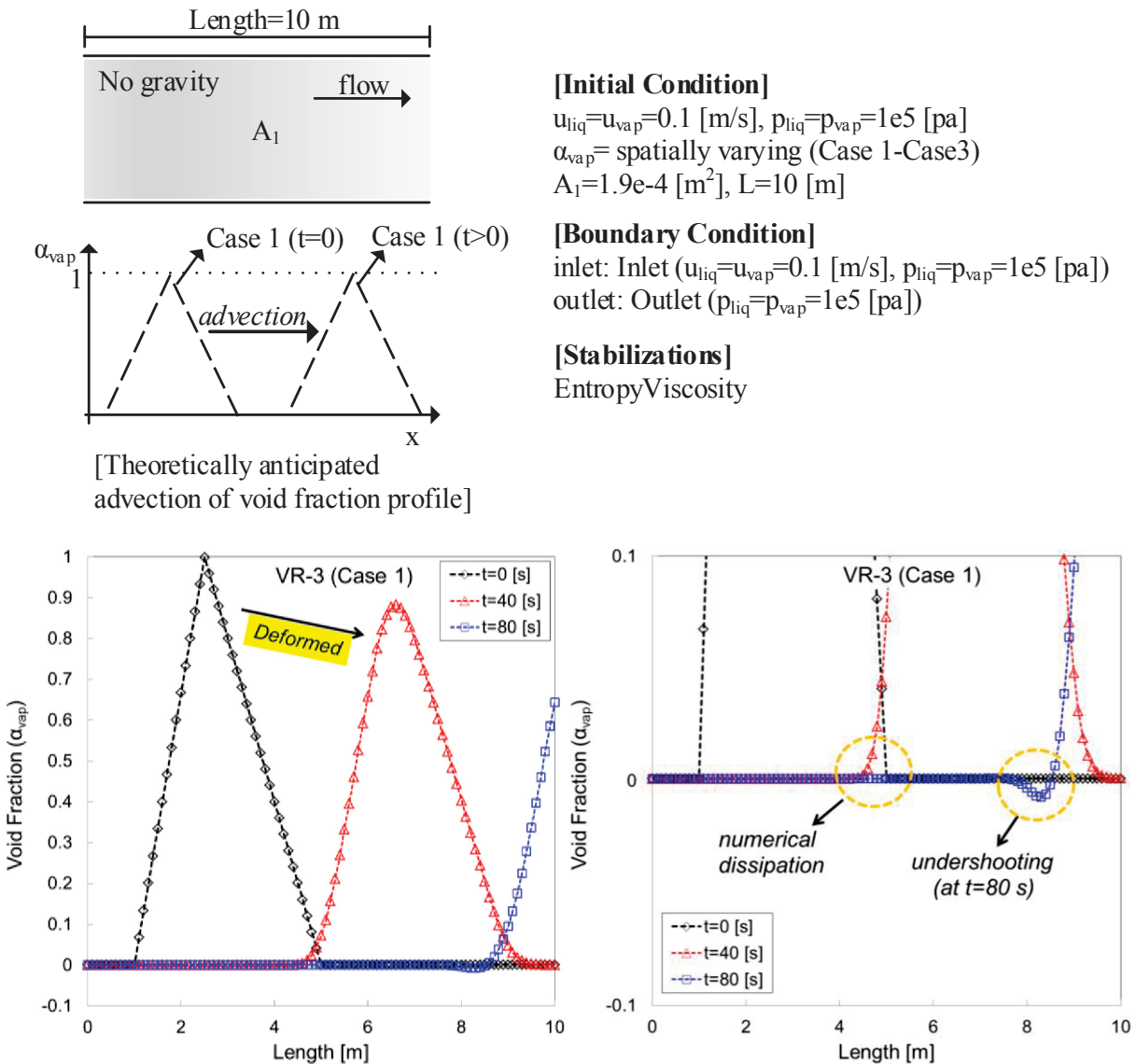
Figure 3. RELAP-7 test setup for void fraction advection problem (top) and test result (bottom) [2]

[Initial Condition]
$u_{liq}=u_{vap}=0$ [m/s], $p_{liq}=p_{vap}=7e6$ [pa]
$\alpha_{vap}=\alpha_{liq}=0.5$
$A_1=1.9e-4$ [m^2], L=10 [m]
No interfacial & wall friction

[Boundary Condition]
SolidWall (both inlet and outlet)

[Stabilizations]
EntropyViscosity
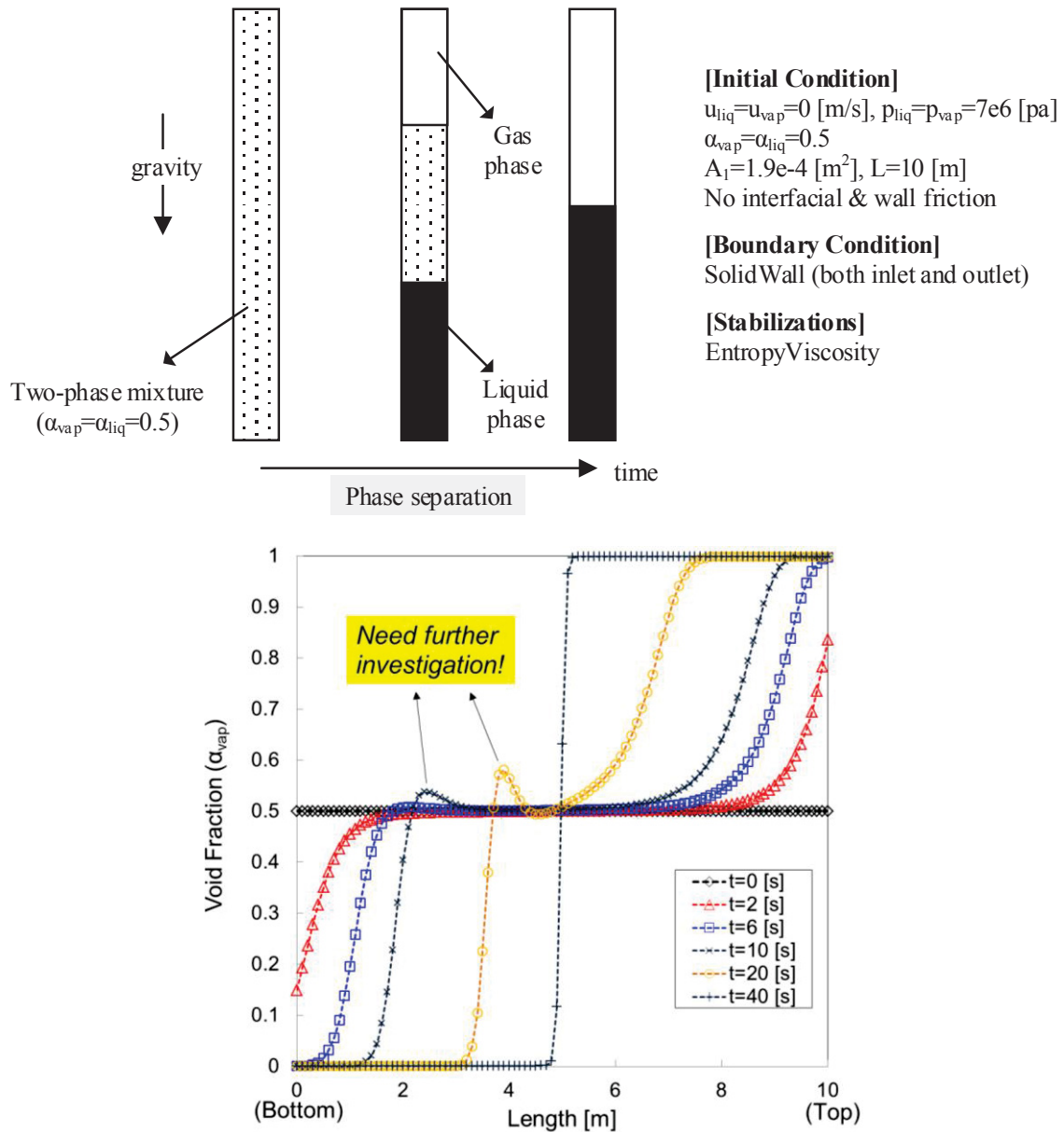
Figure 4. RELAP-7 test setup for phase-separation problem (top) and test result (bottom) [2]

3.   RELAP-7 RTM UPDATE

As noted in section 2, the current RELAP-7 RTM consists of three elements (i) *general RTM*, (ii) *specific RTM*, and (iii) *code V&V RTM*, the framework of which has been constructed and modified since 2015 [3, 4]. In this fiscal year, three major updates have been made while maintaining this framework:

First, a set of V&V test problems used for SPACE code validation [5] were reviewed and some of the test items were added to the RELAP-7 *code V&V RTM*. According to No et al. (2012) [5], the SPACE code V&V has been performed in two separate stages, Phase I (model verification test, integration test, and conceptual problem test) and Phase II (integral effect test). Some of the validation test items have been found to be useful for reducing the validation data gap identified during the establishment of RELAP-7 RTM evaluation matrix (see section 4 for details). For example, as of 2017, the RELAP-7 *code V&V RTM* needs more validation data for "flow split" phenomenon (see section 4 for details), while the related validation tests were already done for the SPACE code, i.e., "branch reentrant tee/cross-flow tee/cross tank problems." (see TABLE II in No et al. (2012)). This information seems to be very useful and would be great if it could be included into the RELAP-7 validation plan. The detailed information on the validation tests, however, will become available after the SPACE code manual is released.

Second, several requirement items in the RELAP-7 RTM were rearranged so that they fall into the proper categories. Two items in the previous *code V&V RTM* have been moved to the sub-category of software quality assurance in the *specific RTM* (see Figure 2). Also, two test items were newly added to the sub-category of fundamental test in the *code V&V RTM*; one is for the entrainment/de-entrainment in horizontal flow and the other is for offtake test. Some requirement descriptions and references in the *code V&V RTM* have also been improved to clarify the test objective.

Third, the 'RELAP-7 Test Status' in the *code V&V RTM* has been updated. Specifically, new classifiers of six level (i.e., tested, partly tested, testable, in progress, not ready, need to check) have been introduced. These classifiers were applied by considering the development and IV&V status of RELAP-7 as of 2017. Consequently, this will continue to be updated as the RELAP-7 development and IV&V work progresses. For the future IV&V activity of RELAP-7, a priority will be given to the tasks that have been classified as "testable", "in progress" and "partly tested" in this updated *code V&V RTM*.

The detailed updates for RELAP-7 RTM are summarized in Table 3. The full version of RELAP-7 RTM reflecting these updates are given in Appendix.

Table 3. Details of the RELAP-7 RTM update

	Existing ID	Updated ID	Requirement specification (updated)
General RTM	GR-6	Deleted	
Specific RTM	-	SR-17	Check consistency of code results depending on computer hardware and software environment (e.g., compiler, libraries, etc.)
	-	SR-18	Regression test and code coverage test after any updates in the source code
Code V&V RTM	VR-8	Deleted	Iterative scheme convergence tests (e.g., JFNK)
	VR-11	VR-10	Conservation tests in 0-D & 1-D components (e.g., Branches/Junctions, LWR components like steam generator or pressurizer, pipe)
	VR-13	Deleted	-
	VR-15	Deleted	-
	VR-18	Deleted	-
	VR-33	VR-29	Convective heat transfer (single-phase)
	VR-19	VR-13	Gravitational head effect & Countercurrent flow development
	VR-20	VR-14	Heat conduction (1D/Multi-D)
	VR-21	VR-15	Decay heat model test with various decay options
	VR-22	VR-16	Reactor kinetics model
	VR-23	VR-17	Metal-water reaction model (e.g., Zr-cladding oxidation)
	VR-24	VR-18	Wall-to-fluid friction (single phase)
	VR-25	VR-19	Single-phase shock problem
	-	VR-37	Entrainment/de-entrainment in horizontal flow
	-	VR-54	Offtake test

Idaho National Laboratory

4. EVALUATION MATRIX FOR RELAP-7 RTM AND VALIDATION DATA GAP

This section describes the evaluation matrices for the RELAP-7 *code V&V RTM*. The purpose of creating the evaluation matrix is to check the overall suitability of the test requirements included in the RELAP-7 *code V&V RTM*. The examples are shown in Tables 4 and 5, which are the evaluation matrices for the fundamental tests (FT) and the separate effect tests (SET) included in the RELAP-7 *code V&V RTM*, respectively. These matrices provide an efficient way to check how well the test problems (or test requirements) in the *code V&V RTM* are organized to demonstrate the RELAP-7 simulation capability. The RELAP-7, as an advanced nuclear system safety analysis code, must be proven to have the simulation capability on the phenomena considered important for the LWR safety. The left column of Tables 4 and 5 lists the generic single-phase and two-phase phenomena considered important in the safety analysis of LWR system. The list of these phenomena has been created based on the collaborative effort with EPRI [6], reviewing the OECD/NEA report [7], and considering the demand for the future nuclear system analysis codes as described in Ref. [8, 9] and in our previous report [3].

The first row of Tables 4 and 5 lists the requirement ID (e.g., VR-xx) used in the RELAP-7 *code V&V RTM*. The check mark (√) in the matrices indicates that the phenomena listed in the left column can be addressed by the validation test problems provided in the *code V&V RTM*. Note that this check mark is used only when we have the specific data to compare with the simulation results. If there is no validation data available for a given task (or phenomenon), despite mentioning the need in the RELAP-7 *code V&V RTM*, the entire row is shaded in red and an asterisk (*) is added to the place of corresponding requirement ID as shown in Tables 4 and 5.

The RELAP-7 RTM evaluation matrix provides several benefits. First, the matrices effectively present how well the RELAP-7 V&V plan has been designed in view of addressing the wide range of safely phenomena relevant for the analysis of LWR system. Second, the validation data gap can be clarified at a glance, allowing us to focus on the areas where further research (e.g., experiment) is needed. Lastly, the V&V status of RELAP-7 at a specific point in time can be easily checked at the management level with these tables. To do this, the identifiers should be improved to better specify the code V&V status (e.g., O: completed, Δ: in progress, ×: not started).

Given the present RELAP-7 RTM evaluation matrices (Tables 4 and 5), the validation data gaps are identified as follows:

- **Flow split (single-phase)**

- Single-phase convective heat transfer (especially, forced laminar and natural convective heat transfer for vertical bundles)

- Boiling heat transfer under forced or free convection within geometries other than tube (e.g., vertical bundle, annulus)

- Condensation heat transfer

- **Phase separation at branches**

- **Boron mixing and transport**

In particular, the validation data are found to be significantly lacking for the three test items marked in bold in the six items above, i.e., 'Flow split', 'Phase separation at branches', and 'Boron mixing and transport'. No validation data for these test problems exist in the current *code V&V RTM*. As for the

single-phase convective heat transfer, there is no correlation for the forced laminar and natural convective heat transfer for vertical bundles and hence further research is required [10]. More validation data for 'Boiling heat transfer' are also required in view of the fact that the validation data in the current RELAP-7 *code V&V RTM* are available only for the tube geometry. Lastly, although there are some validation data for 'Condensation heat transfer', it is still judged to be insufficient.

In the context of RELAP-7 IV&V plan and validation data gap described above, INL is collaborating with the University partner, University of Illinois at Urbana-Champaign (UIUC), under Nuclear Energy University Program (NEUP Project 16-10630). It is noted that the experimental effort made by UIUC is in line with the effort for reducing the validation data gap especially for the items 'Single-phase convective heat transfer' and 'Boiling heat transfer'. The general description on the experiment is given as follows:

Natural circulation experiments are to be performed at University of Illinois at Urbana-Champaign in the Multiphase Thermo-fluid Dynamics Laboratory. The closed loop facility fitted with a condenser, 18 kW preheater, high-temperature pump, test section with 54 kW custom immersion heater, and pressurizing tank can acquire detailed measurements in single-phase and two-phase natural and forced convection flows. The 5 meter test section geometry is an annulus with 3 meters of vertical heated length, followed by 2 meters of unheated length. Five measurement ports along the test section measure pressure, liquid temperature, and two-phase properties such as void fraction, gas velocity, and interfacial area concentration. Pressure and temperature is measured at many location around the facility, flow rate is measured upstream of the test section using a magnetic flowmeter, and the custom heater has five imbedded thermocouples for wall temperature measurement along the heated length. The natural circulation tests will span pressures up to 1 MPa, heat fluxes up to 300 kW/m^2, and a wide range of flow rates through manipulation of the test section inlet loss coefficient

The experimental design and conditions described above are likely to address some important aspects of the validation data gap we have identified. For instance, boiling heat transfer data for forced or free convection in a test section geometry of annulus directly match the needs discussed above. Also, this experiment has advantage for code validation in view of the fact that more detailed measurements and a more one-to-one comparison with system codes can be done at much lower cost, compared to the experiment using a rod bundle.

Idaho National Laboratory

RELAP-7 Software Verification and Validation Plan: Requirements Traceability Matrix (RTM) Update and Code Verification Strategy

Table 4. Evaluation matrix for fundamental tests (FT, VR-18~VR-54) in RELAP-7 code V&V RTM

	VR-18	VR-19	VR-20	VR-21	VR-22	VR-23	VR-24	VR-25	VR-26	VR-27	VR-28	VR-29	VR-30	VR-31	VR-32	VR-33	VR-34	VR-35	VR-36	VR-37	VR-38	VR-39	VR-40	VR-41	VR-42	VR-43	VR-44	VR-45	VR-46	VR-47	VR-48	VR-49	VR-50	VR-51	VR-52	VR-53	VR-54
Subcooled Single-Phase Phenomena																																					
Wall to fluid friction	v																																				
Pressure drop at geometric discontinuities						v	v																														
Pressure wave propagation								v																													
Flow split									*																												
Convection heat transfer (Forced and natural)											*																										
Natural circulation																																			v		
Two-Phase Phenomena																																					
Wall to fluid friction					v		v									v																	v				
Pressure drop at geometric discontinuities							v																														
Interphase friction in vertical flow							v						v																								
Phase separation in vertical flow													v	v		v			v						v												
Two-phase mixture level swell (or level tracking)														v			v	v							v												
Phase separation in horizontal flow														v					v		v											v					
Phase separation at branches															*																						
Entrainment/de-entrainment																v			v	v																	
Pressure wave propagation										v																											
Flashing														v		v						v											v				
Counter-current flow																							v	v													
Counter-current flow limitation																							v	v													
Boiling heat transfer																									v	v											
Critical heat flux/dryout																									v	v											
Re-wetting heat transfer																											v										
Film boiling/superheating heat transfer																												v									
Superheating due to compression																													v								
Radiation heat transfer																														v							
Interphase heat transfer																															v						
Condensation heat transfer on surfaces																																v					
Non-condensable gas effects																																		v			
Critical flow, blowdown																																	v				
Other relevant phenomena																																					
Boron mixing and transport																																				*	
Multi-D effect tests																																					
Two-Phase Rod Bundle Phenomena																																					
1. Fluid mixing																																					
2. Spacer grid effects																																					
3. Parallel channel instability (BWR)																																					

Idaho National Laboratory

Table 5. Evaluation matrix for separate effect tests (SET, VR-55~VR-77) in RELAP-7 code V&V RTM

	VR-55	VR-56	VR-57	VR-58	VR-59	VR-60	VR-61	VR-62	VR-63	VR-64	VR-65	VR-66	VR-67	VR-68	VR-69	VR-70	VR-71	VR-77
Subcooled Single-Phase Phenomena																		
Wall to fluid friction																		
Pressure drop at geometric discontinuities																		
Pressure wave propagation																		
Flow split																		
Convection heat transfer (Forced and natural)																		
Natural circulation																		
Two-Phase Phenomena																		
Wall to fluid friction						√												
Pressure drop at geometric discontinuities						√												
Interphase friction in vertical flow	√	√	√			√		√	√	√	√							
Phase separation in vertical flow		√	√	√		√	√	√	√	√	√							
Two-phase mixture level swell (or level tracking)	√	√		√		√		√		√								
Phase separation in horizontal flow																		
Phase separation at branches																		
Entrainment/de-entrainment				√				√			√							
Pressure wave propagation																		
Flashing				√														
Counter-current flow					√		√						√					
Counter-current flow limitation					√		√						√					
Boiling heat transfer	√	√	√				√	√		√								
Critical heat flux/dryout	√	√	√					√		√		√	√	√				
Re-wetting heat transfer			√				√	√		√		√	√	√				
Film boiling/superheating heat transfer	√	√	√					√	√	√								
Superheating due to compression																		√
Radiation heat transfer																		
Interphase heat transfer																		√
Condensation heat transfer on surfaces																		
Non-condensable gas effects																		
Critical flow, blowdown			√	√														
Other relevant phenomena																		
Boron mixing and transport																		
Multi-D effect tests												√	√	√	√	√	√	
Two-Phase Rod Bundle Phenomena																		
1. Fluid mixing																√		
2. Spacer grid effects								√										
3. Parallel channel instability (BWR)						√												

Idaho National Laboratory

5. RELAP-7 VERIFICATION STRATEGY, PROCEDURE, AND VERIFICATION TEST COVERAGE SUITE

Motivated by the RELAP-7 IV&V activity in 2016 [2] and the development progress of RELAP-7 (i.e., Phase II, see Table 1), RELAP-7 V&V team has recently begun the work for RELAP-7 (independent) verification. The main goal of this independent verification is to find any coding mistakes or subtle errors that may have been overlooked by code developers through the RELAP-7 development. This is an essential procedure to ensure that the source code is free of error, while the validation aims to assess how accurately the "verified" code predicts the real world (see Figure 5). Therefore, the verification must be done in principle prior to any validation tasks for RELAP-7 as well as before the code is distributed for real applications. Another important point is that, as suggested by IEEE Std.1012-2004 [11], the code verification should be performed by personnel who are not involved in the code development activity to maintain the technical independence.
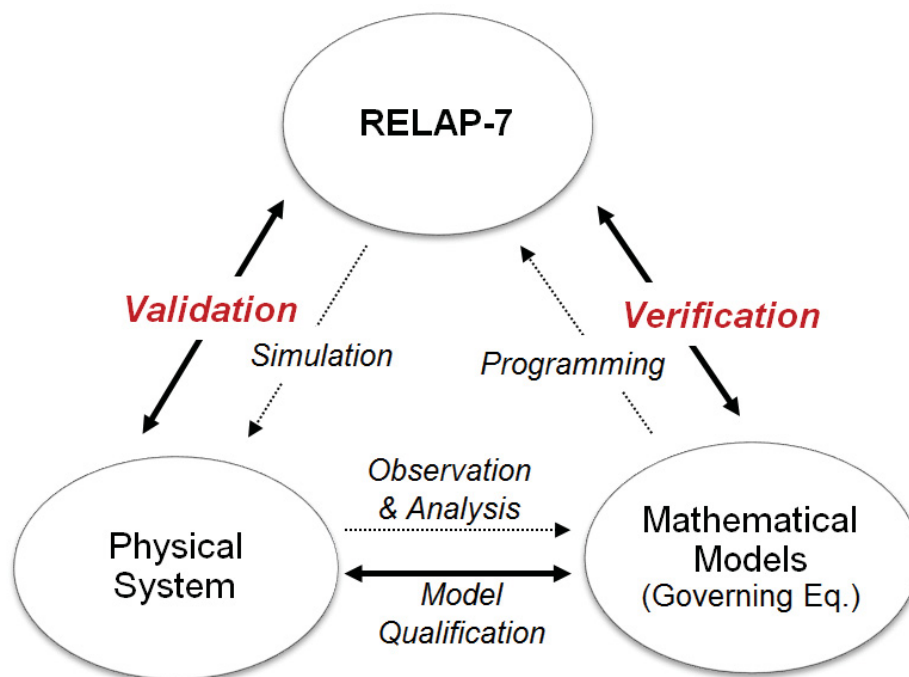
Figure 5. Conceptual schematic for RELAP-7 code verification and validation

In general, there are three different ways of code verification to ensure the correctness of a code that deals with the partial differential equations such as RELAP-7: (i) static code testing, (ii) dynamic code testing, and (iii) formal code testing [12]. Static code testing refers to a test to check the coding consistency in the use of computer language without running the code. General coding mistakes such as variable initialization, function/subroutine naming error or calling statement errors are subject to the static test. Once the static code testing is complete, the next step is dynamic code testing. The dynamic code testing is performed to find coding errors/mistakes via running the code and analyzing the results. Many different kinds of code testing methods fall into this category, e.g., trend test, symmetry test, comparison test, benchmark test, and order-of-accuracy verification test (hereafter, order-verification test). Of them, the most rigorous way of detecting coding errors is using order-verification test. As the last step of code verification, there is formal code testing. The formal code testing is performed in a manner reviewing the source code line-by-line, aiming to search for additional coding mistakes that cannot be detected through either static or dynamic code testing.

For RELAP-7 independent verification, the static code test is assumed complete, and the dynamic code test is underway by RELAP-7 V&V team. Specifically, RELAP-7 will be verified via the method of order-of-accuracy verification test (or simply order-verification test). The overall procedure for RELAP-7 order-verification is as follows: First, the theoretical order-of-accuracy of the discretization schemes applied to RELAP-7 is identified. Then, a set of test problems (i.e., verification test coverage suite) is designed in which reference solutions (e.g., exact solution) are provided together to eventually compare them with the numerical solutions calculated by the code. Next, for a given test problem a series of code runs is performed while systematically refining the mesh or time step size. The global discretization error is then calculated for each code run by comparing the result with reference solution. Then, the global discretization errors are used to determine the observed order-of-accuracy for a given test problem.

If there is no error in the source code, the theoretical order-of-accuracy for RELAP-7 will match the observed order-of-accuracy. If this is not the case, one must suspect either a coding mistake in the source code or any errors in the test input used for the order-verification test. In any case, if an error is suspected, we have to go through the process to fix it and repeat the above-mentioned procedure until the results of theoretical and observed orders-of-accuracy match. In case that any error is suspected in the source code, the result should be reported to the RELAP-7 developers for trouble shooting. This implies that, during the work for RELAP-7 IV&V, although the technical independence is required [11], significant level of communication is necessary with RELAP-7 developers because the code is still evolving at the moment. However, the communication should be made within the prescribed procedure and scope. The overall procedure that has been established for the RELAP-7 independent verification is shown in Figure 6.

As for the mesh (or time step) refinement for code verification, three different ways can be applied, i.e., (i) direct approach, (ii) decoupled approach, and (iii) iterated Richardson extrapolation [13]. These concepts are especially important for the verification of a code that conducts transient calculations like RELAP-7. In principle, the mesh and time step refinement should be performed such that the spatial and temporal discretization errors are decreased at the same factor (direct approach). Otherwise, the correct convergence rate of the discretization error cannot be computed. Each refinement method is illustrated in Figure 7. To easily isolate the coding mistake or to avoid the high computational cost, decoupled approach [14] or iterated Richarson extrapolation [13] has been preferred by the previous researchers. Note that the exact solution is not required for the use of iterated Richardson extrapolation.

23

RELAP-7 Verification Procedure   **Specific Task**

```
┌─────────────────────────────┐      ┌─ - Identify the governing equations & ─┐
( 1. Define Verification Scope )      │   RELAP-7 code options                │
└─────────────────────────────┘      └───────────────────────────────────────┘
              │
              ▼
┌─────────────────────────────┐      ┌─ - Designed to fully test code functions and ─┐
│ 2. Establish Verification   │      │   code options (e.g., boundary conditions,   │
│    Test Coverage Suite      │      │   adaptive time step solver, etc.)           │
└─────────────────────────────┘      │ - Designed to test all the requirements      │
              │                       │   listed in the RELAP-7 code V&V RTM          │
              ▼                       └──────────────────────────────────────────────┘
┌─────────────────────────────┐      ┌─ - Use exact solution or fine mesh ─┐
│ 3. Construct Reference       │      │   numerical solution               │
│    Solution                  │      └────────────────────────────────────┘
└─────────────────────────────┘
              │
              ▼
┌─────────────────────────────┐      ┌─ - Grid size and/or time step refinement ─┐
│ 4. Perform the Test          │      │ - Compute the observed order-of-accuracy  │
└─────────────────────────────┘      └───────────────────────────────────────────┘
              │
              ▼
┌─────────────────────────────┐      ┌─ - Compare the observed order-of-accuracy ─┐
│ 5. Compare Order-of-Accuracy │      │   to the theoretical order-of-accuracy     │
└─────────────────────────────┘      └────────────────────────────────────────────┘
              │
              ▼
```

Report to Developers for Trouble Shooting

Observed order ≠ Theoretical order

Result?

Observed order = Theoretical order

(Code Verification Completed (Go to Step 3 for the Next Test))

Check List

1. Mistake in test setup (e.g., code input)
2. Mistake in the evaluation of results (e.g., error order calculation)
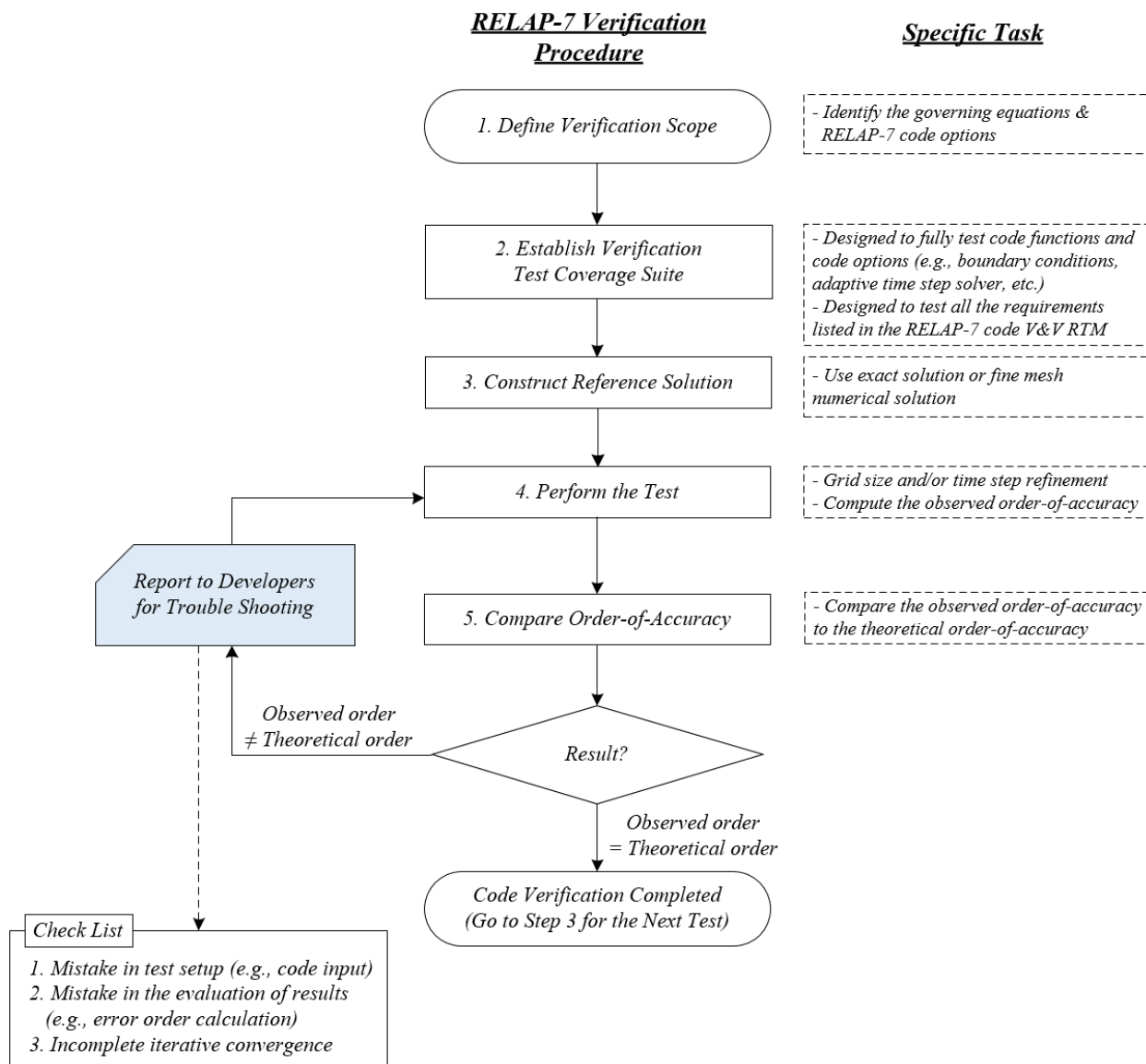3. Incomplete iterative convergence

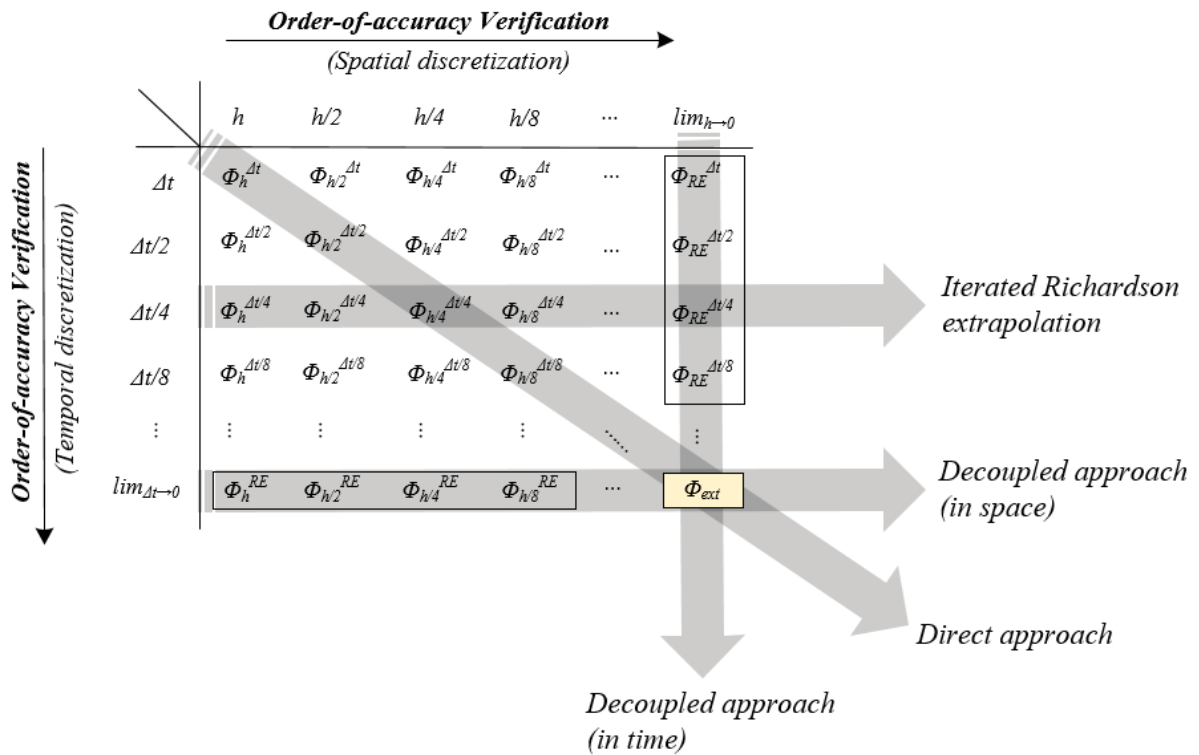Figure 6. Independent code verification procedure for RELAP-7

Figure 7. Three refinement strategies for the order-verification test

Table 6 shows the verification test coverage suite that will be used to verify the hydrodynamic (or flow) equations implemented into RELAP-7. The order-verification test for the pipe component will be performed based on the test problems given in this table. Table 6 is specially designed such that the code can be verified for all the options available in RELAP-7 for the pipe component (e.g., boundary conditions, stabilization schemes). Considering that the theoretical order-of-accuracy can be achieved only when there is no error in any options selected for each test, the existence of coding errors can be thoroughly examined using this table. The similar test plan should be established for the other major components used in RELAP-7 (e.g., branch) and for the heat equations. In principle, the exact solution will be used as reference solution in estimating the global discretization error, but fine mesh numerical solution will be used instead if the exact solution is not available for a given test problem. It is noted that the specific test plan shown in Table 6 may change as the RELAP-7 development or IV&V work and/or plan progresses.

Given the strategy and procedure described above, the actual work for order-verification was performed using RELAP-7 for the Task No. 1 (hydrostatic test) in Table 6. The first-order stabilization scheme was applied with solid-wall boundary conditions on both ends of vertical pipe. The result is shown in Figure 8, which indicates that the observed order-of-accuracy converges to the theoretical order-of-accuracy as the mesh size is refined. This verifies that there is no coding error for the flow equations as well as the RELAP-7 options (e.g., boundary conditions, stabilization scheme) used for the Task No. 1. The "RELAP-7 Test Status" in the *code V&V RTM* (i.e., VR-4 ~ VR-7) will be able to be marked as "tested" after all the tests listed in the verification coverage test suite is completed successfully. Note that Table 6 is only for verifying the hydrodynamic equations applied to the pipe component in RELAP-7. The similar verification test coverage suite should be created in the future for verifying the correctness of heat conduction equations (1D and 2D) and the other components implemented into RELAP-7.

Table 6. RELAP-7 verification test coverage suite for flow problems (pipe component)

Task No.	Title (Req. No for RTM)	Test type (1D, std/trn)	Geom. (Component)	B.C Left (inlet)	B.C Right (outlet)	B.C Reversible flow option	Time integration	Time stepper	Stabilization method
1	Single-phase test without flow (VR-1, 4)	1D, std (Single-phase)	Pipe (vertical)	Solid Wall	Solid Wall	No	BDF2	AdaptiveDT	evm (1st order)
2				Solid Wall	Solid Wall				evm (2nd order)
3				Inlet	Outlet				evm (1st order)
4				TDV	TDV				evm (1st order)
5	Two-phase test without flow (VR-2, 4)	1D, std (two-phase)	Pipe (vertical)	Solid Wall	Solid Wall	No	BDF2	AdaptiveDT	evm (1st order)
6				Solid Wall	Solid Wall	No	BDF2		evm (2nd order)
7				TDV	TDV	No	BDF2		evm (1st order)
8	Single-phase test with flow (VR-4) **B.C Tests**	1D, std (Single-phase)	Pipe (horizontal)	Inlet (vel, mfr)	Outlet (P=1 atm)	No	BDF2	FixedTimeStep	evm (1st order)
9		1D, trn (Single-phase)	Pipe (horizontal)	Inlet (vel, mfr)	Outlet (P=1 atm)			FixedTimeStep	evm (1st order)
10		1D, std (Single-phase)	Pipe (horizontal)	Inlet (vel, mfr)	TDV (P=1 atm)			FixedTimeStep	evm (1st order)
11		1D, std (Single-phase)	Pipe (horizontal)	TDJ (Inflow)	Outlet (P=1 atm)			FixedTimeStep	evm (1st order)
12		1D, std (Single-phase)	Pipe (horizontal)	Inlet	Outlet (P=1 atm)			FixedTimeStep	evm (2nd order)
13		1D, trn (Single-phase)	Pipe (vertical)	Inlet	Outlet (P=1 atm)			FixedTimeStep	evm (1st order)
14	Two-phase test with flow (VR-3) **B.C Tests**	1D, trn (Two-phase)	Pipe (horizontal)	Inlet	Outlet (P=1 atm)	No	BDF2	FixedTimeStep	evm (1st order)
15		1D, trn (Two-phase)		Inlet (Inflow)	TDV (P=1 atm)				evm (1st order)
16		1D, trn (Two-phase)	Pipe (horizontal)	TDJ (Inflow)	Outlet (P=1 atm)				evm (1st order)
17		1D, trn (Two-phase)	Pipe (horizontal)	Inlet	Outlet (P=1 atm)				evm (2nd order)
18		1D, trn (Two-phase)	Pipe (vertical)	Inlet	Outlet (P=1 atm)				evm (1st order)
19	Single-phase test with flow (VR-6) **Stab. Scheme Tests**	1D, trn (Single-phase)	Pipe (horizontal)	Inlet	Outlet (P=1 atm)	No	BDF2	FixedTimeStep	SUPG
20									LAPIDUS

Idaho National Laboratory

21	Two-phase test with flow (VR-6)	1D, trn (Two-phase)	Pipe (horizontal)	Inlet	Outlet (P=1 atm)	No	BDF2	FixedTimeStep	SUPG
22	**Stab. Scheme Tests**								LAPIDUS
23	Single-phase test with flow (VR-7)	1D, trn (Single-phase)	Pipe (horizontal)	Inlet	Outlet (P=1 atm)	No	Backward Euler	FixedTimeStep	evm (1st order)
24	**Temporal Scheme Tests**						C-N		evm (1st order)
25	Two-phase test with flow (VR-7)	1D, trn (Two-phase)	Pipe (horizontal)	Inlet	Outlet (P=1 atm)	No	Backward Euler	FixedTimeStep	evm (1st order)
26	**Temporal Scheme Tests**						**C-N**		**evm (1st order)**

[Abbreviation] std: steady test, trn: transient test, evm: entropy viscosity method, BDF: , vel: velocity, mfr: mass flow rate, C-N: Crank-Nicolson method, TDV: time-dependent volume, P: pressure
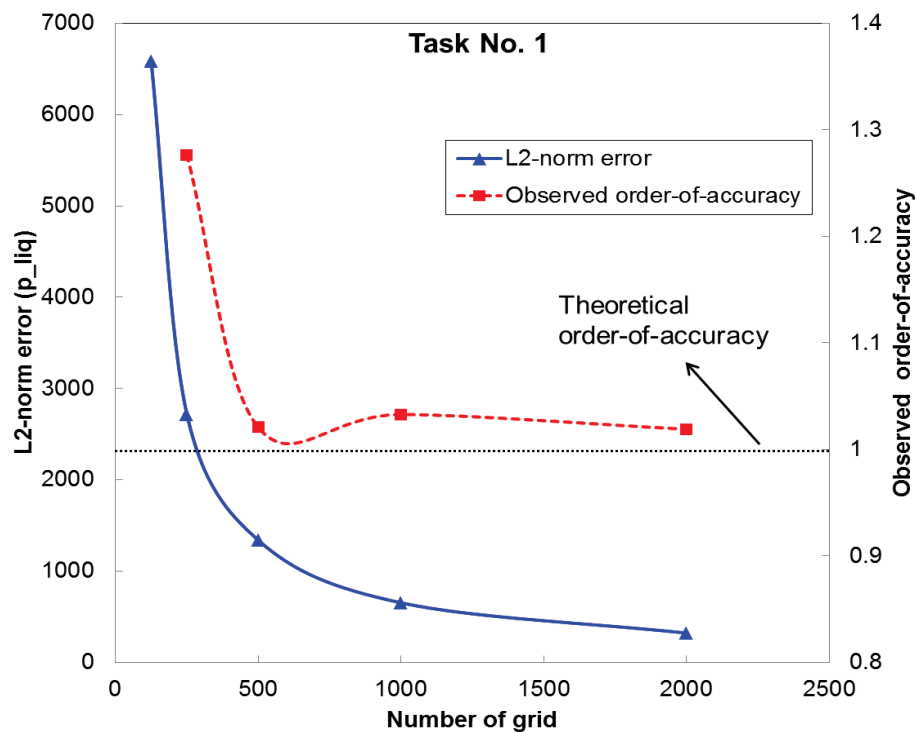
Figure 8. Order-of-accuracy test result for Task No. 1 using RELAP-7

Idaho National Laboratory

6. SUMMARY AND CONCLUSIONS

This document describes the recent work in RELAP-7 SVVP. The RELAP-7 RTM has been updated in three aspects, i.e., (i) adding the validation requirement items, (ii) rearranging the requirement items, and (iii) introducing the classifier to better define the RELAP-7 V&V status. Also, from the perspective of nuclear system code validation, we have identified the areas where the validation data is particularly lacking. Specifically, using the RELAP-7 RTM evaluation matrices, six items from the list of LWR safety-relevant phenomena were identified as validation data gaps. Also, the experimental effort of UIUC, supported by the NEUP program, is believed to be valuable in the context of reducing the validation data gaps. Lastly, RELAP-7 V&V team has established the code verification plan in response to the needs revealed from the previous RELAP-7 IV&V activities. The code verification method, procedure, and verification test coverage suite discussed in this document will be applied to the future work for the RELAP-7 independent verification.

7. REFERENCES

1. Zhang, H., et al., *Resource Loaded Development Schedule for RELAP-7*. 2017, Tech. Rep. INL/LTD-17-40858, Idaho National Laboratory, USA.
2. Yoo, J. and Y.J. Choi, *Additional Model Datasets and Results to Accelerate the Verification and Validation of RELAP-7*. 2016, Idaho National Laboratory (INL), Idaho Falls, ID (United States).
3. Yoo, J., Y.-J. Choi, and C.L. Smith, *RELAP-7 Software Verification and Validation Plan - Requirements Traceability Matrix (RTM) Part 2: Code Assessment Strategy, Procedure, and RTM Update*. 2016 Tech. Rep. INL/EXT-16-40015, Idaho National Laboratory, USA.
4. Choi, Y.J., J. Yoo, and C.L. Smith, *RELAP-7 Software Verification and Validation Plan: Requirements Traceability Matrix (RTM) Part 1–Physics and numerical methods*. 2015, Idaho National Laboratory (INL), Idaho Falls, ID (United States).
5. No, H.C., et al., *Korean Development of Advanced Thermal-Hydraulic Codes for Water Reactors and Htgrs: Space and Gamma*. Nuclear Technology, 2013. **181**(1): p. 24-43.
6. EPRI, *Data Sources for Capability Assessments of Next Generation Safety Analysis Codes*. 2014, EPRI: Palo Alto, CA, USA.
7. Aksan, N., et al., *Separate effects test matrix for thermal-hydraulic code validation: phenmena characterisation and selection of facilities and tests*. 1993.
8. *IAEA Safety Report Series No. 52 (2008). Best estimate safety analysis for nuclear power plants: uncertainty evaluation*. IAEA, Vienna.
9. OECD/CSNI, *Proceedings of the OECD/CSNI workshop on transient thermal-hydraulic and neutronic codes requirements. NEA/CSNI/R(97)4*. 1996.
10. *RELAP5-3D Code Manual Volume IV: Models and Correlations*. 2005: Idaho National Laboratory, Idaho Falls, Idaho, USA.
11. Society, I.C., *IEEE Standard for Software Verification and Validation*. 2004: New York, NY10016-5997, USA.
12. Knupp, P. and K. Salari, *Verification of computer codes in computational science and engineering*. 2002: CRC Press.
13. Etienne, S., A. Garon, and D. Pelletier. *Code verification for unsteady flow simulations with high order time-stepping schemes*. in *47th AIAA Aerospace Sciences Meeting including The New Horizons Forum and Aerospace Exposition*. 2009.
14. Salari, K. and P. Knupp, *Code verification by the method of manufactured solutions*. 2000, Sandia National Labs., Albuquerque, NM (US); Sandia National Labs., Livermore, CA (US).

APPENDIX A. RELAP-7 GENERAL RTM (AS OF 2017)

Req #	Category	Requirement Specification	Modification Date (mm/dd/yyyy)	Code V&V RTM No.	RELAP-7 Status
GR-1	Reactor Types & System Designs	Capability of simulating various LWR designs such as PWR and BWR	9/30/2015	All test cases falling into PWR or BWR category in Code V&V RTM.	Sample Test-45 for BWR (HEM model) Sample Test-152 for PWR (TMI loop)
GR-2		Capability of simulating various PWR designs (i.e., Westinghouse, Combustion Engineering, and Babcock&Wilcox)	9/30/2015	All test cases falling into PWR or PWR (B&W) category in Code V&V RTM.	PWR cores are tested but not compared for different manufactures
GR-3		Capability of simulating various containment design influencing LOCA simulation	9/30/2015	-	Not tested
GR-4		Capability of simulating various ECCS design influencing LOCA simulation (accumulators, safety injection systems such as UPI, cold-leg/hot-leg injection)	9/30/2015	VR-61, 62, 66-68, 105	Not tested
GR-5		Capability of modeling various plant components and systems for non-LOCA simulation	9/30/2015	All non-LOCA tests included in Code V&V RTM can be used to demonstrate this capability.	Not tested
GR-6	T/H System Safety Analysis (Design- and Licensing-Basis Transients/Accidents)	LBLOCA analysis capability	9/30/2015	SET: VR-57-59, 61-64, 66-68 IET/PT: VR-84, 89, 105	Not tested
GR-7		SBLOCA analysis capability	9/30/2015	SET: VR-55 IET/PT: VR-83, 90, 132	Not tested
GR-8		Capability of simulating excessive heat transfer events (non-LOCA)	9/30/2015	VR-93	Not tested
GR-9		Capability of simulating loss of heat transfer events (non-LOCA)	9/30/2015	VR- 91, 92, 96, 98, 101-103, 106, 107, 110, 111, 114, 117, 118, 121, 122-125, 127, 130, 134, 135, 137	Not tested
GR-10		Capability of simulating loss of flow events (non-LOCA)	9/30/2015	VR-92, 110, 124, 125, 137	Not tested
GR-11		Capability of simulating increase/decrease in reactor coolant inventory events (non-LOCA)	9/30/2015	-	Not tested
GR-12		Capability of simulating Station Blackout (SBO) and its consequence	9/30/2016	VR-104, 121	Not tested
GR-13		Capability of simulating BWR stability	9/30/2016	VR-108	Not tested
GR-14		Capability of simulating ATWS transients	9/30/2016	VR-88, 96	Not tested
GR-15		Generate physics parameters for reactor kinetics model in system code	9/30/2015	-	Sample Test 65-67

Idaho National Laboratory

GR-16	**Multi-physics Analysis (Reactor kinetics, fuel components behavior, chemical reactions, etc.)**	Capability of coupled simulation with neutronics code (to reflect a reactivity feedback with 1D, multi-D core power calculation)	9/30/2016	-	Not tested
GR-17		Capability of coupled simulation for fluid/mechanical interaction analysis (e.g., water hammer, LOCA-load analysis)	9/30/2016	-	Not tested
GR-18		Capability of coupled simulation for T/H effect on structural integrity (e.g., PTS)	9/30/2016	-	Not tested
GR-19		Capability of coupled simulation with fuel performance code such as BISON (to reflect the feedback from mechanical/ thermal behavior of fuel pellet, gap, and cladding depending on reactor conditions)	9/30/2015	-	Not tested
GR-20		Capability of simulating chemical effect (e.g., localized corrosion, CRUD)	9/30/2015	-	Not tested
GR-21		Capability of simulating containment analysis (e.g., FP, aerosol behavior)	9/30/2015	-	Not tested
GR-22		Capability of simulating radiological consequence analysis	9/30/2015	-	Not tested
GR-23	**Multi-D & Multi-scale Analysis**	Capability of simulating multi-dimensional fluid flow (e.g., PWR reflood phenomena after LOCA)	9/30/2015	SET: VR-66-71 IET/PT: VR-105, 138	Not tested
GR-24		Capability of simulating multi-dimensional fluid flow at microscale level of detail (e.g., flashing, critical flow, boiling, etc.)	9/30/2015	-	Not tested
GR-25	**Integrated/Improved Uncertainty Analysis**	Incorporating uncertainty quantification process into an integral part of the simulation (e.g., coupling with RAVEN)	9/30/2016	-	Not tested

APPENDIX B. RELAP-7 SPECIFIC RTM (AS OF 2017)

Req #	Category	Requirement Specification	Modification Date (mm/dd/yyyy)	Verification/Action Item	RELAP-7 Status
SR-1	Computer Science & Software Architecture	Use of the most advanced computer science technology (both computing power and numerical solvers) to optimize both accuracy and simulation speed	9/30/2015	Descritization scheme Time integration method Matrix solver Parallel computation capability	Written with C++. Capable of Multi-scale time integration, PCICE (operator split), JFNK (implicit nonlinear Newton method), and a point implicit method (long duration transients). New pipe network algorithm based upon Mortar FEM (Lagrange multipliers). Ability to couple to multi-dimensional reactor simulators
SR-2		Numerically robust and reliable (e.g., Need to check if it is not subject to failure as a result of numerical methods)	9/30/2015	Numerical stability test Steady-state initialization test	Not tested
SR-3		Multi-scale/multi-physics simulation capability for the following scope through coupling: (i) fuel rod, (ii) fuel assembly, (iii) reactor, (iv) primary RCS, (v) secondary coolant system and BOP, (vi) I&C, (vii) containment, (viii) site radiological consequences, (ix) offsite radiological consequences, (x) fluid/structure interaction for dynamic loads	9/30/2015	Coupling test with other MOOSE-based applications	RELAP-7 can be coupled with MOOSE framework application to simulate multi-scale / multi-physics problems
SR-4		User-friendly steady-state initialization and restart capabilities	9/30/2015	-	Both steady-state and transient cases can be simulated by restart option
SR-5		Clear and easy diagnostics to assist with debugging and workaround	9/30/2015	-	Code will show highlighted error signal. For example, if wrong model type was give then shows in red: ***ERROR*** Unknown model type
SR-6		Comprehensive GUI for pre/post-processing and on-line monitoring	9/30/2015	-	in progress
SR-7		Coupling capability with other MOOSE-based codes (e.g., RAVEN, BISON) and CFD codes	9/30/2015	Verification test for coupling with other MOOSE-based applications	Can be coupled with MOOSE-based BISON code for 3D neutron transport model.
SR-7	Code and Modeling Accuracy with Reliability	Capable of achieving CFD-like resolution (3D) in selected parts (i.e., easily adjust the grid resolution as needed)	9/30/2015	Mesh management test	RELAP-7 does not have 3D mesh generation model.
SR-8		Coordinate system to represent the actual design of a component with high fidelity	9/30/2015	-	Provides x, y, z coordination system for components, functions, etc

SR-9		Providing standard modules with limited options for various components or systems to lessen the user effect	9/30/2015	-	RELAP-7 supports standard component models
SR-10		Providing standard or recommended options to lessen the user effect on the result	9/30/2015	-	
SR-11	**Physical Phenomena**	Capability of addressing legacy issues associated with two-phase flow (e.g., (i) phase separation, (ii) flow-regime transition, (iii) level tracking, (iv) water-packing, (v) flooding, (vi) entrainment/de-entrainment, etc.)	9/30/2015	-	Both HEM and 7 equation two-phase model can be simulated
SR-12		Modeling capability of a droplet field for BWR core spray, containment spray (PWR/BWR), and core uncovery events	9/30/2015	-	Not tested
SR-13		Modeling capability of sources and transport of particles in vapor, gas, droplet and liquid	9/30/2015	Model V&V in RELAP 7 framework and/or code-to-code comparison	Not tested
SR-14		Modeling capability of non-condensable gas transport and its heat transfer effect	9/30/2015	Model V&V in RELAP 7 framework and/or code-to-code comparison	The compressible valve component can handle non-condensible gas model
SR-15	**Software Quality Assurance**	Writing the source code under a consistent programming standard for simplified maintenance and revision	9/30/2015	-	
SR-16		Providing detailed documentation of theory, programming, user manual, validation basis and user guidelines	9/30/2015	-	RELAP-7 provides revised theory manual. Other documents are in progress
SR-17		Check consistency of code results depending on computer hardware and software environment (e.g., compiler, libraries, etc.)	9/30/2017	-	
SR-18		Regression test and code coverage test after any updates in the source code	9/30/2017	-	

Idaho National Laboratory

APPENDIX C. RELAP-7 CODE V&V RTM (AS OF 2017)

(A: Available, N/A: Not applicable or not available, P/A: Partially available, ver: verification, val: validation, sol: solution)

Req #	Test Type		Requirement Specification (Target application, test feature)	Modification Date (mm/dd/yyyy)	NPP Design Targeted	Scale of Experiment	Reference	Data Availability	RELAP-7 Test Status
VR-1		ver	Single-phase analytical test without flow (uniform pressure, zero flow velocity, variable cross-sectional area)	9/30/2016	-	-	Suggested by RELAP-7 development team	N/A	Tested
VR-2		ver	Two-phase analytical test without flow (uniform pressure, zero flow velocity, spatially varying volume fraction)	9/30/2016	-	-	Suggested by RELAP-7 development team	N/A	Tested
VR-3		ver	Two-phase analytical test for volume fraction advection with uniform pressure and velocity field	9/30/2016	-	-	Suggested by RELAP-7 development team	N/A	Tested
VR-4	Code Ver	ver	Grid convergence study for single-/two-phase fluid flow problems (order-of-accuracy verification)	9/30/2015	-	-	- INL/EXT-14-33201 - RELAP-7 verification coverage suite (flow model)	N/A	In progress
VR-5		ver	Grid convergence study for heat conduction problems (order-of-accuracy verification)	9/30/2015	-	-	- INL/EXT-14-33201 - RELAP-7 verification coverage suite (heat conduction model)	N/A	Testable
VR-6		ver	Grid convergence study with available stabilization schemes (e.g., SUPG, Lapidus, Entropy based viscosity scheme)	9/30/2015	-	-	- INL/EXT-14-33201 - RELAP-7 verification coverage suite (flow model)	N/A	Testable
VR-7		ver	Time step convergence study with available options (order-of-accuracy verification) (e.g., Backward Euler, Crank-Nicolson, BDF2)	9/30/2015	-	-	- INL/EXT-14-33201 - RELAP-7 verification coverage suite (flow model)	N/A	Testable

RELAP-7 Software Verification and Validation Plan: Requirements Traceability Matrix (RTM) Update and Code Verification Strategy

35

ID		Description	Date			Reference		Status
VR-8	ver	Symmetry solution tests with various boundary conditions (e.g., fully developed channel flow problem)	9/30/2016	-	-		N/A	Testable
VR-9	ver	Solution independence tests to coordinate transformation (e.g., rotation, translation of physical domain)	9/30/2016				N/A	Partly Tested
VR-10	ver	Conservation tests in 0-D & 1-D components (e.g., Branches/Junctions, LWR components like steam generator or pressurizer, pipe)	9/30/2017	-	-	- INL/EXT-14-33201 - No et al. (2012) (SPACE code)	N/A	Testable
VR-11	ver	Conservation tests in system level of loop configuration	9/30/2015	-	-	- INL/EXT-14-33201 - Specific problems should be determined.	N/A	Testable
VR-12	ver	Propagation of a passive scalar property (related to the capability of particle transport simulation)	9/30/2016				N/A	Not ready
VR-13	ver	Gravitational head effect & Countercurrent flow development	9/30/2016	-	-	- Water faucet problem (RELAP5-3D) - Water over steam problem (RELAP5-3D)	N/A	Testable
VR-14	ver	Heat conduction (1D/Multi-D)	9/30/2016	-	-	Heat conduction enclosure (RELAP5-3D, TRACE)	N/A	Testable
VR-15	ver	Decay heat model test with various decay options	9/30/2015	-	-	Decay heat model test (RELAP5-3D)	N/A	Not ready
VR-16	ver	Reactor kinetics model	9/30/2015	-	-	Reactor kinetics model test (RELAP5-3D)	N/A	Need to check
VR-17	ver	Metal-water reaction model (e.g., Zr-cladding oxidation)	9/30/2015	-	-	Metal-water reaction model test (RELAP5-3D)	N/A	Not ready
VR-18	ver	Wall-to-fluid friction (single phase)	9/30/2015	-	FT	- Darcy pressure drop equation (horizontal pipe) (TRACE) - Wang's falling film data (TRACE)	N/A, A	Testable
VR-19	ver	Single-phase shock problem	9/30/2016	-	FT	- D. L. Youngs, "Shock Tube", Multiphase Science and Technology, Vol. 6 p653-662 - S. Mimouni and G. Serre, "List of benchmarks for simulation tools of steam-water two-phase flows", 2000	N/A	Testable

RELAP-7 Software Verification and Validation Plan: Requirements Traceability Matrix (RTM) Update and Code Verification Strategy

ID	Category	ver/val	Description	Date			Reference		Status
VR-20	Sol Ver	ver	Numerical error estimation for a given complex problem depending on spatial and temporal discretization	9/30/2016			- Specific problems should be determined.	N/A	Testable
VR-21		ver	Numerical error estimation for all non-linear solver settings (e.g., JFNK)	9/30/2016			- Specific problems should be determined.	N/A	Testable
VR-22	Model Val	val	Wall-to-fluid friction (two phase)	9/30/2015	FT	-	- Ferrell-Bylund uniform test section data (TRACE)	A	Testable
VR-23		val	Two-phase shock problem (boiling front propagation)	9/30/2016	FT	-	J.R. Simoes-Moreira and J.E. Shepherd (J. Fluid Mech., "Evaporation waves in superheated dodecane," 1999)	A	Testable
VR-24		val	Single-phase pressure drop at geometric discontinuities	9/30/2015	FT	-	- Ferrell-McGee pressure drop test (TRACE) (abrupt area change test section data)	A	Not ready
VR-25		val	Two-phase pressure drop at geometric discontinuities	9/30/2015	FT	-	- Ferrell-McGee pressure drop test (TRACE) (abrupt area change test section data)	A	Not ready
VR-26		val	Water hammer (single-phase)	9/30/2015	FT	-	- EPRI NP-6766, Vol.4, Part1 (1992) - NUREG/IA-0206 (2007) - Simpsons water hammer test (A.R. Simption's PhD Thesis, 1986; Serre and Bestion, "Two-Phase Water Hammer Simulation with CATHARE Code")	A	Testable
VR-27		val	Water hammer (two-phase)	9/30/2015	FT	-	- Tiselj and Cerne (Nucl. Sci. Eng., Vol. 134, 2000) - Cerne et al. (Trans ANS, Vol. 75, 1996) - Serre and Bestion ("Two-Phase Water Hammer Simulation with CATHARE Code")	A	Testable
VR-28		val	Flow split (T-junction)	9/30/2016	FT	-	- No et al. (2012) (SPACE code): Branch reentrant tee/cross-flow tee/cross tank problems (Table II)	N/A	Not ready

RELAP-7 Software Verification and Validation Plan: Requirements Traceability Matrix (RTM) Update and Code Verification Strategy

ID	ver/val	Description	Date		FT	References	Code	Status
VR-29	ver, val	Convective heat transfer (single-phase)	9/30/2015	-	FT	- Turbulent forced convection: Dittus-Boelter, Petukhov, Inayatov (for vertical bundles), etc. - Laminar forced convection: Nu=7.63 (ORNL/ANS/INT-5/V19, RELAP5-3D), Elenbaas, etc. - Natural convection: McAdams, Churchill-chu, etc. - Forced laminar or natural convection for vertical bundles (non-existent)	P/A	Testable
VR-30	val	Interphase friction in vertical flow	9/30/2015	-	FT	- CISE Adiabatic Tube (TRACE)	A	Testable
VR-31	val	Phase separation/distribution in vertical flow	9/30/2015	-	FT	- Wilson Bubble Rise test data (TRACE) - GE Vessel Blowdown Level Swell data (1 ft small diameter vessel; 4 ft large diameter vessel) (TRACE, RELAP5-3D) - Sedimentation test problem (RELAP-7 HPC repository)	A	Tested
VR-32	val	Phase separation/distribution in horizontal flow	9/30/2015	-	FT	- Edward's Pipe Blowdown data (RELAP5,RETRAN-3D): ISP-01 - TPTF Horizontal Flow (TRACE)	A	Testable
VR-33	val	Phase separation/distribution at branch	9/30/2016	-	FT	-	N/A	Need to check
VR-34	val	Level tracking during flow oscillation (single-phase)	9/30/2015	-	FT	- Fill-drain assessment problem - Manometer problem (RELAP5-3D, TRACE, SPACE) - Gravity wave tests (1D, 3D) (RELAP5-3D)	A	Need to check
VR-35	val	Two-phase mixture level swell	9/30/2015	-	FT	- Single tube flooding test (TRACE) - Bubbling steam through liquid (RELAP5-3D)	-	Testable

VR-36	val	Entrainment/de-entrainment in vertical flow	9/30/2015	-	FT	- GE Vessel Blowdown Level Swell data (1 ft small diameter vessel; 4 ft large diameter vessel) (TRACE, RELAP5-3D) - Cousin's vertical annular flow (SPACE)	A	Testable
VR-37	val	Entrainment/de-entrainment in horizontal flow	9/30/2017			- Mantilla horizontal annular flow (SPACE)	A	
VR-38	val	Flashing in vertical flow	9/30/2016	-	FT	- GE Vessel Blowdown Level Swell data (1 ft small diameter vessel; 4 ft large diameter vessel) (TRACE, RELAP5-3D)	A	Not ready
VR-39	val	Flashing in horizontal flow	9/30/2016	-	FT	- Edward's Pipe Blowdown data (RELAP5,RETRAN-3D): ISP-01 - TPTF Horizontal Flow (TRACE) - Saruel et al. (2008), "Modelling phase transition in metastable liquids: application to cavitating and flashing flows," J. Fluid Mech.	A	Not ready
VR-40	val	Counter-current flow	9/30/2015	-	FT	- Single tube flooding test (TRACE)	A+	Not ready
VR-41	val	Counter-current flow limitation (CCFL)	9/30/2015	-	FT	- Single tube flooding test (TRACE) - Bankoff CCFL test (TRACE) - Dukler-Smith Air-Water Flooding test (RELAP5-3D)	A	Not ready
VR-42	val	Convective boiling heat transfer	9/30/2015	-	FT	- Christensen Subcooled Boiling (RELAP5, RELAP5-3D) - Bennett Heated Tube (RELAP5, RELAP5-3D, RETRAN-3D)	A	Testable
VR-43	val	Critical Heat Flux (CHF)/dryout	9/30/2015	-	FT	- Bennett Heated Tube (RELAP5, RELAP5-3D, RETRAN-3D)	A	Testable
VR-44	val	Re-wetting heat transfer	9/30/2015	-	FT	- ORNL THTF Transient Blowdown test (TRACE) - GOTA BWR Reflood test (TRACE)	A	Testable
VR-45	val	Film Boiling (FB)/superheating heat transfer	9/30/2015	-	FT	- Bennett Heated Tube (RELAP5, RELAP5-3D, RETRAN-3D)	A	Testable

RELAP-7 Software Verification and Validation Plan: Requirements Traceability Matrix (RTM) Update and Code Verification Strategy

VR-46	val	Superheating due to compression	9/30/2016	-	FT	- MIT pressurizer (TRACE, RELAP5, RELAP5-3D, RETRAN-3D)	A	Need to check
VR-47	val	Radiation heat transfer	9/30/2016	-	FT	- GOTA BWR Radiation (Run 27, TRACE)	A	Partly Testable
VR-48	val	Interphase heat transfer	9/30/2016	-	FT	- UCB-Kuhn Condensation (TRACE) - MIT pressurizer (TRACE, RELAP5, RELAP5-3D, RETRAN-3D)	A	Testable
VR-49	val	Condensation heat transfer	9/30/2015	-	FT	- Dehbi-MIT Condensation With NCG (TRACE) - University of Wisconsin Condensation (TRACE)	A	Testable
VR-50	val	Critical flow and blowdown	9/30/2015	-	FT	- Marviken test data (NUREG/IA-0007) (TRACE, RELAP5, RELAP5-3D, RETRAN-3D) - Moby Dick nozzle tests (RELAP5-3D, TRACE) - Super Moby Dick - Edwards-O'Brien blowdown test (RELAP5-3D), ISP-01	A	Testable
VR-51	val	Non-condensable gas effects	9/30/2016	-	FT	- UCB-Kuhn Condensation Tests (TRACE) - Dehbi-MIT Condensation Tests (TRACE) - University of Wisconsin Condensation Tests (TRACE)	A	Not ready
VR-52	val	Single-phase natural circulation	9/30/2015	-	FT	NUREG/IA-0151 (1999)	A	Testable
VR-53	val	Boron mixing and transport	9/30/2015	-	FT		N/A	Not ready
VR-54	val	Offtake test	9/30/2017	-	FT	- Offtake test models		

Idaho National Laboratory

- Code V&V RTM for SET and CT (continued)

Req #	Test Type	Requirement Specification (Target application, test feature)	Modification Date (dd/mm/yyyy)	NPP Design Targeted	Scale of Experiment	Reference (Experiment, Test ID, Reference)	Data Availability	RELAP-7 Test Status
VR-55	val	SBLOCA (Boil-off, Void Distribution)	09/31/2016	PWR	SET	ORNL THTF SBLOCA test series data: - Tests 3.09.10I to 10N (core uncovered) - Tests 3.09.10AA to 10FF (core covered)* - NUREG/CR-2456, NUREG/CR-2640 - (TRACE, RELAP5, RELAP5-3D, RETRAN-3D)	A	Not ready
VR-56	val	Film Boiling Heat Transfer, CHF	09/31/2016	PWR	SET	ORNL THTF Film Boiling Bundle Uncovery CHF data: - Tests 3.07.9B, H, N, W - NUREG/CR-2640 - (TRACE, RELAP5, RELAP5-3D)	A	Testable
VR-57	val	Blowdown, Film Boiling Heat Transfer	09/31/2016	PWR	SET	ORNL THTF Transient Blowdown data: - Tests 3.03.6AR, 3.06.6B, 3.08.6C - NUREG/CR-2640 - (TRACE)	A	Testable
VR-58	val	Blowdown (Pressure/Void fraction Variation)	09/31/2016	-	SET	- GE Level Swell Test, 1 ft. diameter: Test 1004-3 - GE Level Swell, 4 ft. diameter: Tests 5801-15, 5702-16 (RELAP5-3D, TRACE)	A	Testable

VR-59	val	ECC Bypass (downcomer), CCFL	09/31/2016	PWR	SET	UPTF Downcomer CCFL Test - Test 6, Run 131 (RELAP5-3D) - Test 5, 6, 7, 21 (TRACE)	A	Not ready
VR-60	val	Phase Distribution in a BWR core	09/31/2016	BWR	SET	FRIGG experiments void data - FRIGG-2 Tests 313001 to 20, 24, 27, 30, 34, 37, 40, 43, 56, 60 - FRIGG-4 Tests 613001, 10, 13, 14, 19 (TRACE, RETRAN-3D)	A	Testable
VR-61	val	LBLOCA, Reflood	09/31/2016	BWR	SET	GOTA BWR Reflood test data: - Run 42 (reflood experiment) (TRACE)	A	Not ready
VR-62	val	LBLOCA, Reflood	09/31/2016	PWR	SET	1. FLECHT-SEASET Reflood Heat Transfer data: - Tests 31108, 31504, 31701, 31203, 31805, 32114, 32013, 31302 - (TRACE, RELAP5, RELAP5-3D, RETRAN-3D) 2. RBHT Reflood Heat Transfer test data: - Tests 1096, 1108, 1170, 1196, 1285, 1383 - (TRACE)	A	Not ready

RELAP-7 Software Verification and Validation Plan: Requirements Traceability Matrix (RTM) Update and Code Verification Strategy

VR-63		val	LBLOCA, Steam-Cooling	09/31/2016	PWR	SET	RBHT Reflood Heat Transfer test data: - Tests 3173A, 3216D, 3205A, 3216A, 3216G, 3205G, and 3214A - NUREG/CR-7152 (TRACE)	A	Not ready
VR-64		val	LBLOCA, Core Uncovery	09/31/2016	PWR	SET	RBHT Reflood Heat Transfer test data: - Tests 1560, 1566, 1570, 1572, 1582, 1637, 1648, 1651, 1659 (steady-state test) - Test 1690 (transient test) (TRACE)	A	Not ready
VR-65		val	Boil-off	09/31/2016	PWR	SET	FLECHT-SEASET Boil Off test data: - Test 35658 (RELAP5)	A	Testable
VR-66		val	LBLOCA, Reflood (Multi-D effects)	09/31/2016	PWR	SET	1. UPTF - Tests 5A, 6 (TRACE) - NUREG/IA-0127, GRS-100 (ISBN: 3-923875-50-9) 2. BCL - Test 29402 (Transient, CSNI Report (87)132) - NUREG-1230 3. CREARE - NUREG-1230, CSNI report (87)132	P/A	Not ready

ID		Description	Date	Plant		References		Status
VR-67	val	LBLOCA, Reflood (Multi-D effects)	09/31/2016	PWR (B&W)	SET	1. UPTF - NUREG/IA-0127 2. CCTF - NUREG/IA-0127	A	Not ready
VR-68	val	LBLOCA, Reflood (Multi-D effects)	09/31/2016	BWR	SET	SSTF - Test EA 3.1: LBLOCA recirculation line rupture (TRACE) - Test EA 3.3-1 LBLOCA 73% recirculation line rupture (TRACE)	A	Not ready
VR-69	val	BWR Core Spray Distribution (Multi-D TH effects)	09/31/2016	BWR	SET	SSTF - Tests CS-1.3, CS-1.3A (NUREG-1230)	P/A	Not ready
VR-70	val	Cold Leg and Downcomer ECCS Mixing (Multi-D TH effects)	09/31/2016	PWR	SET	* CREARE 1/5 Scale Facility * CREARE 1/2 Scale Facility - NUREG-1809 (App. B.3), * UPTF - Test 1 - NUREG-1809, App. B.7; NUREG/IA-0127	P/A	Not ready

RELAP-7 Software Verification and Validation Plan: Requirements Traceability Matrix (RTM) Update and Code Verification Strategy

VR-71	val	UPI ECCS during LOCA (Multi-D effects)	09/31/2016	PWR	SET	1. UPTF
						  - NUREG/IA-0127
						2. CCTF
						  - NUREG/IA-0127, NUREG-1230 (Rev. 4)
						3. SCTF
						  - NUREG/IA-0127, NUREG-1230 (Rev. 4)
							P/A	Not ready

VR-72	val	Jet Pump	09/31/2016	BWR	CT	1. INEL 1/6 Scale Jet Pump Test
						  - RELAP5-3D
						  - H. S. Crapo, Idaho National Engineering Report (EGG-LOFT-6063), Nov. 1979
						2. Small Scale Jet Pumps for the FIST facility
						  - NUREG/CR-2576
						3. Full Scale Jet Pumps
						  - For BWR4,
						    Boiling Water Reactor Turbine Trip (TT) Benchmark, Vol. 1: Final Specifications, NEA/NSC/2001-1.
						  - For BWR6,
						    Kudirka, A. A. and Glustz, D. M., Fluid Machinery and Nuclear Energy Groups Joint Convention, Pumps for Nuclear Power Plant, the Institution of Mechanical Engineers, Bath, England, April 22-25, 1974
							A	Not ready

VR-73	val	Recirculation pump	09/31/2016	BWR	CT	1. Small Scale Recirculation Pumps in FIST facility
						  - NUREG/CR-2576
						2. Full Scale Recirculation Pumps
						  - For BWR4,
						    Boiling Water Reactor Turbine Trip (TT) Benchmark, Vol. 1: Final Specifications, NEA/NSC/2001-1.
							A	Testable

RELAP-7 Software Verification and Validation Plan: Requirements Traceability Matrix (RTM) Update and Code Verification Strategy

VR-74		val	Separator	09/31/2016	BWR	CT	- Boiling Water Reactor Turbine Trip (TT) Benchmark, Vol. I: Final Specifications, NEA/NSC/2001-1.	A	Testable
VR-75		val	Reactor coolant pump steady-state, startup, and coastdown	09/31/2016	PWR	CT	- *OPR-1000 test data, OPR-1000 transient data (SPACE)*	A	Need to check

VR-76		val	Reactor coolant pump two-phase operation	09/31/2016	PWR	CT	1. Full scale RCP two-phase
							  - *TMI-2 accident*
							2. Scaled RCP
							  - LOFT tests
							  - ROSA-IV tests
							3. Scaled RCP two-phase
							  - EPRI/CE 1/5 scale (EPRI NP-1556)
							  - LOFT Tests L3-5 and L3-6
								A	Not ready

VR-77		val	Pressurizer	09/31/2016	PWR	CT	1. Full scale pressurizer
							  - *PWR startup test and event data*
							  - Doel 4 startup test (NUREG/IA-0020)
							2. Scaled pressurizer
							  - MIT pressurizer (TRACE, RELAP5, RELAP5-3D, RETRAN-3D)
							  - NEPTUNUS test (RELAP5-3D, NUREG/IA-0040)
							  - ISP-38
								A	Testable

VR-78		val	Accumulator	09/31/2016	PWR	CT	1. Full scale accumulator
							  - *PWR accumulator injection test data*
							2. Scaled accumulator
							  - LOFT accumulator blowdown test (L3-1)
							    (RELAP5, RELAP5-3D, RETRAN-3D)
								A	Testable

ID		Requirement	Date			Reference		Status

VR-79	val	U-tube steam generator	09/31/2016	PWR	CT	1. Full scale U-tube steam generator
						  - NUREG/IA-0113
						  - NUREG/IA-0106
						2. Scaled U-tube steam generator
						  - Westinghouse Model Boiler-2 (NUREG/IA-224)
						  - Kalra, S., Yao, L. S., and Davis, W. E. R. "Flow Behavior in a Static Vane Centrifugal Separator-Simulation Experiments and Analysis," Second International Topical Meeting on Nuclear Reactor Thermal Hydraulics, January, 1983.
						    (RELAP5-3D, TRACE)
							A	Not ready

VR-80	val	Once-through steam generator (OTSG)	09/31/2016	PWR (B&W)	CT	1. Scaled OTSG
						  - NUREG/CR-5395, NUREG/CR-4567
						  - "Simulation of a 30-Tube Once-Through Steam Generator with RELAP5/MOD3 and RELAP5/MOD2 Computer Codes," Hassan, Y. A., Salim, P., ANS Winter Meeting, November, 1990 (OSTI ID: 6780203)
							A	Not ready

VR-81	val	Hot leg (two-phase)	09/31/2016	PWR (B&W)	CT	1. Scaled hot leg
						  - NUREG/CR-5395
						  - NUREG/CR-4567
						2. Full scale
						  - No data exists
							A	Testable

VR-82	val	Reactor vessel internals vent valves (RVVV)	09/31/2016	PWR (B&W)	CT	1. Full Scale RVVV
						  - NUREG-1230, Section 6.4.3.11
						2. Scaled RVVV
						  - UPTF test data (NUREG/IA-0127)
						  - "Summary of Downcomer Injection Phenomena for UPTF and TRAC Post-Test Analysis," LACP-92-188, May 1992
						  - CCTF test data (NUREG/IA-0127): Test C2-AS2, Test C2-10
							A	Need to check

RELAP-7 Software Verification and Validation Plan: Requirements Traceability Matrix (RTM) Update and Code Verification Strategy

47

- Code V&V RTM for IET and PT (continued)

Req #	Test Type	Requirement Specification (Target application, test feature)	Modification Date (dd/mm/yyyy)	NPP Design Targeted	Scale of Experiment	Reference (Experiment, Test ID, Reference)	Data Availability	RELAP-7 Test Status
VR-83	val	SBLOCA	09/31/2016	BWR	IET	FIST (Full Integral System Test) facility - SBLOCA test 6SB2C - NUREG/CR-2576 - (TRACE)	A	Not ready
VR-84	val	LBLOCA	09/31/2016	BWR	IET	1. FIST facility - LBLOCA test 6DBA1B - NUREG/CR-2576, NUREG/CR-3711 2. FIST facility - LBLOCA test 4DBA1 - NUREG/CR-2576, NUREG/CR-4128 3. TLTA (Two Loop Test Apparatus) facility - LBLOCA Conservative test 6423 - NUREG/CR-2229, GEAP-23592 (TLTA facility description), GEAP-NUREG-23977 4. TLTA (Two Loop Test Apparatus) facility - LBLOCA test 6425 - NUREG/CR-2229, GEAP-23592 (TLTA facility description), GEAP-NUREG-23977 - (TRACE) 5. TLTA (Two Loop Test Apparatus) facility - LBLOCA tests 6425, 6424 - NUREG/CR-2229, GEAP-NUREG-23977 - (TRACE)	A	Not ready

RELAP-7 Software Verification and Validation Plan: Requirements Traceability Matrix (RTM) Update and Code Verification Strategy

48

VR-85	val	Natural Circulation	09/31/2016	BWR	IET	FIST program - Natural circulation test 6PNC2 - AURORA-B, ANP-10300 (2009), ML100040158 - NUREG/CR-2576, NUREG/CR-4128	A	Not ready
VR-86	val	Turbine Trip	09/31/2016	BWR	IET	FIST program - Turbine Trip test 4PTT1 - AURORA-B, ANP-10300 (2009), ML100040158 - NUREG/CR-2576, NUREG/CR-4128	A	Not ready
VR-87	val	SLB	09/31/2016	BWR	IET	FIST program - Steam Line Break test 6MSB1 - AURORA-B, ANP-10300 (2009), ML100040158 - NUREG/CR-2576, NUREG/CR-4128	A	Not ready
VR-88	val	ATWS (MSIV closure w/o HPCS)	09/31/2016	BWR	IET	FIST program - ATWS test 6PMC2 - NUREG-1230 (Rev. 4) - "Posttest data analysis of FIST experimental TRAC-BD1/MOD1 power transient experiment" (Report No.: *EGG-M-18884*) - NUREG/CR-2576, NUREG/CR-3711	A	Not ready
VR-89	val	LBLOCA	09/31/2016	PWR	IET	1. LOFT (Loss of Fluid Test) - Test L2-5 (ISP-13) (TRACE, RELAP5, RELAP5-3D) - Test LB-1 (TRACE) - NUREG/IA-28 2. PKL facility - Test K9 (ISP-10) - CSNI Report No. 64 (1981) 3. Achilles - CSNI Report No. 11 (ISP-25)	A	Not ready

RELAP-7 Software Verification and Validation Plan: Requirements Traceability Matrix (RTM) Update and Code Verification Strategy

49

VR-90	val	SBLOCA	09/31/2016	PWR	IET	1. LOFT (Loss of Fluid Test) - Test L3-1 (ISP-09) (TRACE) - Test L3-2 (reference?) - Test L3-5 (RCP running) (NUREG/IA-0024) - Test L3-6 (RCP tripped) (ISP-11) - NUREG/CR-3005, 3214 2. ROSA-IV - Test SB-CL-01 2.5% CLB with delayed ECCS (TRACE) - Test SB-CL-05 5% CLB with ECCS and AFW (TRACE) - Test SB-CL-08 5% CLB with no pump ECCS and no AFW (reference?) - Test SB-CL-09 10% CLB with ECCS (reference?) - Test SB-CL-14 10% CLB with ECCS with LPI only (TRACE) - Test SB-CL-15 0.5% CLB with no ECCS and no AFW (TRACE) - Test SB-CL-18 5% CLB with LPI only (TRACE, RELAP5, REAL5-3D) (NUREG/IA-0095, ISP-26, CSNI (91)13) - Test IB-CL-02 17% CLB	P/A	Not ready
VR-91	val	Loss of load	09/31/2016	PWR	IET	1. LOFT (Loss of Fluid Test) - Test L6-1 - NUREG/CR-1797	A	Not ready
VR-92	val	RCP trip	09/31/2016	PWR	IET	LOFT - Test L6-2 - NUREG/CR-1797	A	Not ready
VR-93	val	Excessive load increase	09/31/2016	PWR	IET	LOFT - Test L6-3 - NUREG/CR-1797	A	Not ready

VR-94	val	Overcooling (Increase in secondary heat removal)	09/31/2016	PWR	IET	LOFT - Tests L6-7, L9-2 - NUREG/CR-2277	A	Not ready
VR-95	val	LOAF with subsequent feed-and-bleed operation	09/31/2016	PWR	IET	1. LOFT - Tests L9-1, L3-3 - NUREG/IA-0114 (RELAP5/MOD3) - NUREG/IA-0228 (RELAP5/MOD3.3) 2. ROSA-IV program - No publicly available data or reference	P/A	Not ready
VR-96	val	ATWS (LOFW)	09/31/2016	PWR	IET	1. LOFT - Test L9-3 - NUREG/IA-0192 (RELAP5/Mod3.2.2) - NSAC-78 2. ROSA-IV - Test 3-2 - NUREG/IA-0410 (RELAP5)	A	Not ready
VR-97	val	Turbine Trip	09/31/2016	PWR	IET	ROSA-IV program - No publicly available data or reference	N/A	Not ready
VR-98	val	LOFW	09/31/2016	PWR	IET	ROSA-IV program - No publicly available data or reference	N/A	Not ready

RELAP-7 Software Verification and Validation Plan: Requirements Traceability Matrix (RTM) Update and Code Verification Strategy

VR-99	val	Natural circulation (single-phase)	09/31/2016	PWR	IET	1. ROSA-IV program (single-phase test) - Test 1.1 (NUREG/IA-0419, TRACE) 2. SEMISCALE experiment - S-NC-1, S-NC-10 (RELAP5-3D) - S-NC-2 (RELAP5-3D, TRACE) 3. PACTEL natural circulation experiment - ISP-33 4. PANDA natural circulation tests - ISP-42 (PCCS for ALWR is of main interest.) 5. PKL Exp. - Test 1D1-4 (TRAC-PF1, NUREG/CR-3280)	P/A	Not ready
VR-100	val	Natural circulation (two-phase)	09/31/2016	PWR	IET	1. SEMISCALE natural circulation tests (Mod-2A) - S-NC-2, S-NC-3 (RELAP5-3D, TRACE) - S-NC-10 (RELAP5-3D) 2. PACTEL natural circulation experiment - ISP-33 3. PANDA natural circulation tests - ISP-42 (PCCS for ALWR is of main interest.) 4. PKL facility - Tests PKL-B4.2, B4.3 (NUREG/IA-0170) - Tests PKL-1D1-9, 1D1-15 (NUREG/CR-3280) - CSNI Report No. 10 (1981) (ISP-10)	N/A	Not ready
VR-101	val	SGTR	09/31/2016	PWR	IET	1. ROSA-IV - Test SB-SG-06 - NUREG/IA-0130 2. BETHSY tests 4.3b, 3.4b (CATHARE-2) 3. LOFT tests L6-8C-1, L6-8C-2 (CATHARE-2)	P/A	Not ready

RELAP-7 Software Verification and Validation Plan: Requirements Traceability Matrix (RTM) Update and Code Verification Strategy

VR-102	val	Multiple SGTR	09/31/2016	PWR	IET	ROSA-IV program - No publicly available data or reference	N/A	Not ready
VR-103	val	SLB	09/31/2016	PWR	IET	1. ROSA-IV - Test SB-SL-01 (10 % MSLB) - NUREG/IA-0148 2. Westinghouse Model Boiler-2 test facility - SLB tests 100%, 50%, 8% (with SGTR) - SLB Test T-2013 100% break, SLB 50% break (AEEW-02476) - NUREG/CR-3661, NUREG/CR-4751 - NUREG/IA-0106 3. LOBI facility - Test BT12 (NUREG/IA-0079)	P/A	Not ready
VR-104	val	SBO	09/31/2016	PWR	IET	ROSA-IV - SBO tests w/ or w/o RCP seal leak (No publicly available data or reference)	N/A	Not ready
VR-105	val	Reflood during LOCA (Multi-D effects)	09/31/2016	PWR	IET	1. CCTF - Tests C2-4, C2-5, C2-8, C-12 (TRACE) - Test C2-11 - NUREG-1230, NUREG/IA-0127, GRS-100 (ISBN: 3-923875-50-9) 2. SCTF - Tests S2-01 (Run 606), S2-02 (Run 607), S2-06 (Run 611), S2-16 (Run 621), S2-17(Run 622) (TRACE) - Tests S2-SH1 (Run 604), S2-SH2 (Run 605) (TRACE) - Test S2-AC1 - NUREG-1230	P/A	Not ready

VR-106	val	Loss of decay heat removal	09/31/2016	PWR	IET	1. ROSA-IV - Four configurations were tested for Loss of Decay Heat Removal scenarios, each with three different opening areas (NUREG/IA-0143) (i. Loop intact, ii. Cold leg opening (RCP maintenance), iii. SG manway open, iv. Pressurizer manway open) 2. BETHSY - Tests 6.9a, 6.9c (ISP-38) - CSNI Report 2000(5), NUREG/IA-0188, NUREG/IA-0187 3. PKL - Tests E3.1, F2.2, F2.1 - NUREG/IA-256, NUREG/IA-257	A	Not ready
VR-107	val	Turbine Trip	09/31/2016	BWR	PT	1. Peach Bottom Unit 2 Turbine Trip Tests - NEA/NSC/2001-1, NEA/NSC/2004-21, NEA/NSC/2006-23, NEA/NSC/2010-11 - EPRI NP-563, EPRI NP-564, RETRAN-3D (code manual Vol. 4) 2. Cofrentes NPP turbine trip transient - NUREG/IA-0120, RETRAN-3D 3. Santa Maria De Garoña NPP turbine trip transient - NUREG/IA-0226	A	Not ready
VR-108	val	BWR core stability	09/31/2016	BWR	PT	Peach Bottom Unit 2 Stability Tests - EPRI NP-4498-Volume 9 - RETRAN 3D (code manual Vol 4)	P/A	Not ready
VR-109	val	BWR start-up tests	09/31/2016	BWR	PT	Grand Gulf Startup Transient Tests (EPRI NP-6230) - Test for loss of feedwater heater (No publicly available data or reference) - Test for generator load rejection from 100% power (No publicly available data or reference) - Test for recirculation pump trip	N/A	Not ready

RELAP-7 Software Verification and Validation Plan: Requirements Traceability Matrix (RTM) Update and Code Verification Strategy

						(No publicly available data or reference) - Test for MSIV closure at 74% power and 100% flow (No publicly available data or reference)		
VR-110	val	Recirculation pump trip	09/31/2016	BWR	PT	1. Santa Maria De Garoña NPP - Single Recirculation Pump Trip Transient (NUREG/IA-0193) 2. BWR-5 - One recirculation pump trip (RETRAN-3D)	A	Not ready
VR-111	val	Feedwater Pump Trip	09/31/2016	BWR	PT	Cofrentes NPP - One Feedwater Pump Trip Transient (NUREG/IA-0068) - Feedwater pump trip (RETRAN-3D)	A	Not ready
VR-112	val	MSIV closure	09/31/2016	BWR	PT	1. Laguna Verde NPP (RETRAN-3D) 2. BWR-5 (RETRAN-3D) - single MSIV closure - closure of all MSIVs 3. Santa Maria De Garoña NPP - MSIV Full Closure (NUREG/IA-0122)	A	Not ready
VR-113	val	Other BWR plant tests	09/31/2016	BWR	PT	RETRAN-3D (code manual Vol. 4) assessed its capability based on the following test data from various plants [EPRI 3002003110 (2014)]: 1. Cofrentes NPP - feedwater control failure - level setpoint change - recirc. pump speed transfer 2. BWR-5 - pressure setpoint change - level setpoint change 3. Kashiwazaki-Kariwa reactor internals pump trip	P/A	Not ready

VR-114	val	Loss of load	09/31/2016	PWR	PT	DOEL-4 NPP - Manual Loss of Load Test of November 23, 1985 - (NUREG/IA-0043)	A	Not ready

VR-115	val	PWR startup tests	09/31/2016	PWR	PT	1. Arkansas Nuclear One – Unit 2
						- 4 transient tests
						  - Test for loss of primary flow from 80% power
						  - Test for full-length control rod drop from 50% power
						  - Test for part-length control rod drop from 50% power
						  - Test for turbine trip from 100% power
						- EPRI NP-1707, EPRI NP-1708 (Rev. 1), EPRI NP-1709, ANL/LWR/NRC 83-1, EPRI NP-4260, EPRI NP-4263
						2. DOEL 2 NPP
						  - Pressurizer spray tests
						(NUREG/IA-0020)
							P/A	Not ready

VR-116	val	Turbine Trip	09/31/2016	PWR	PT	Arkansas Nuclear One – Unit 2 *- EGG-SAAM-6415* Vandellos II NPP (NUREG/IA-0108)	P/A	Not ready
VR-117	val	Loss of Off-Site Power	09/31/2016	PWR	PT	1. Arkansas Nuclear One – Unit 2 *- EGG-NTAP-6309* 2. McGuire 1 nuclear station *- Loss of offsite power event (RELAP5/MOD3, ML003780723)* 3. Kori 1 NPP (RETRAN-3D, NUREG/IA-0030)	P/A	Not ready

ID		val	Description	Date	Type	Method	Reference	P/A	Status
VR-118		val	SGTR	09/31/2016	PWR	PT	1. Prairie Island Unit 1 - No publicly available data or reference 2. R. E. Ginna NPP - Ginna 1/25/1982 steam generator tube rupture accident (NUREG-0909) 3. DOEL 2 NPP - NUREG/IA-0008, ISP-20 (CSNI report No. 154)	P/A	Not ready
VR-119		val	Load rejection	09/31/2016	PWR	PT	Comanche Peak Unit 1 (RETRAN-3D) Cofrentes NPP (RETRAN-3D) Laguna Verde NPP (RETRAN-3D) BWR-5 (load rejection with bypass) (RETRAN-3D) Kori 4 (RETRAN-3D) Vandellos II NPP (NUREG/IA-0107, NUREG/IA-0109)	A	Not ready
VR-120		val	Multiple failures	09/31/2016	PWR	PT	Kori 2 NPP (RETRAN-3D)	A	Not ready
VR-121		val	SBO	09/31/2016	PWR	PT	Asco NPP Blackout Transients (NUREG/IA-0119)	A	Not ready
VR-122		val	Feedwater line isolation	09/31/2016	PWR	PT	Ringhals 4 NPP (NUREG/IA-0038)	A	Not ready
VR-123		val	Steam Line Isolation Valve Closure	09/31/2016	PWR	PT	Ringhals 2 NPP (NUREG/IA-0041)	A	Not ready
VR-124		val	RCP trip	09/31/2016	PWR	PT	Almaraz I NPP (NUREG/IA-0233) Vandellos II NPP (NUREG/IA-0243)	A	Not ready
VR-125		val	Reactor trip	09/31/2016	PWR	PT	Tihange-2 NPP (NUREG/IA-0044) DOEL 4 NPP (NUREG/IA-0051)	A	Not ready

RELAP-7 Software Verification and Validation Plan: Requirements Traceability Matrix (RTM) Update and Code Verification Strategy

VR-126	val	Natural circulation	09/31/2016	PWR	PT	-Borssele NPP (NUREG/IA-0091) - Yong-Gwang Unit 2 NPP (NUREG/IA-0125) -TMI unit 1 (natural circulation test of 10/7/1985) (*B4W-10193NP-A*) -KNU-1 loss of offsite power (NUREG/IA-0030)	A	Not ready
VR-127	val	Load trip	09/31/2016	PWR	PT	Yong-Gwang Unit 2 -Net Load Trip Test Data (NUREG/IA-0092)	A	Not ready
VR-128	val	Other PWR plant tests	09/31/2016	PWR	PT	1. Kori Unit 3 - Inadvertent Safety Injection Incident (NUREG/IA-0105) 2. Vandellos II - Main Feedwater Turbopump Trip (NUREG/IA-0110) 3. Asco NPP - Pressurizer Spray Valve Faulty Opening Transient (NUREG/IA-0121) 4. Jose Cabrera Nuclear Station - Pressurizer Spray Valve Inadverted Fully Opening Transient and Recovery by Natural Circulation (NUREG/IA-0124) 5. Maanshan PWR NPP Transient Data (NUREG/IA-0241)	A	Not ready
VR-129	val	MSIV closure	09/31/2016	PWR	PT	Vandellos-II NPP (NUREG/IA-0197)	A	Not ready
VR-130	val	Loss of decay heat removal	09/31/2016	PWR	PT	1. Vogtle Unit 1 (NUREG-1410) 2. Diablo Canyon Unit 2 (NUREG-1269)	A	Not ready
VR-131	val	Turbine Trip	09/31/2016	PWR (B&W)	PT	Oconee Unit 3 - Oconee Unit 3 turbine trip with feedwater overfeed transient of 3/14/1980 (No publicly available data or reference)	N/A	Not ready

RELAP-7 Software Verification and Validation Plan: Requirements Traceability Matrix (RTM) Update and Code Verification Strategy

VR-132	val	SBLOCA	09/31/2016	PWR (B&W)	PT	TMI-2 Accident - No publicly available data or reference	N/A	Not ready
VR-133	val	Stuck-open PORV transient	09/31/2016	PWR (B&W)	PT	Crystal River-3 NPP - Crystal River Unit 3 stuck-open PORV transient of 2/26/1980 (NUREG/CR-3646, NSAC-3 (1980), NSAC-15 (1981) - No publicly available data or reference	N/A	Not ready
VR-134	val	Loss of Off-Site Power	09/31/2016	PWR (B&W)	PT	Arkansas Nuclear One – Unit 1 - EGG-SAAM-6381	N/A	Not ready
VR-135	val	LOAF	09/31/2016	PWR (B&W)	PT	Davis-Besse NPP - Davis-Besse loss of all feedwater event of 6/9/1985 (NUREG-1154, MAAP Code Manual Vol. 3, NUREG/CR-4946) - No publicly available data or reference	N/A	Not ready
VR-136	val	Loss of ICS	09/31/2016	PWR (B&W)	PT	Rancho-Seco NPP - Rancho-Seco loss of integrated control system (ICS) power event of 12/26/1985 (BAW-10193NP-A)	N/A	Not ready
VR-137	val	RCP trip	09/31/2016	PWR (B&W)	PT	Oconee Unit 1 and Crystal River Unit 3 - Trip of all RCP tests (BAW-10193NP-A) - No publicly available data or reference	N/A	Not ready
VR-138	val	Vessel Mixing (Multi-D TH effects)	09/31/2016	PWR (B&W)	PT	Oconee B&W PWR - Testing of thermal mixing in the lower plenum and core at Oconee Unit 1 - EPRI NP-3545, EPRI NP-3780 - No publicly available data or reference	N/A	Not ready