RELAP-7 Closure Model Verification and Benchmarking Plan

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Abstract

This document briefly describes the elements of performing a limited verification of the closure relations used in the Reactor Excursion and Leak Analysis Program (RELAP) version 7 systems analysis code. These elements are used to give confidence in both the compatibility of the closure relations with the numerical methods and the accuracy of the implementation. These tests are not considered sufficiently comprehensive to form a validation test suite, but many of the models are suitable to form part of an appropriate validation test suite to demonstrate adequacy as part of RELAP-7's Software Quality Assurance program.

In this context, verification is the process of ensuring that the implementation matches the design or theory laid out for the software. Validation is the method to ensure that the design adequately represents the important physical processes being modeled and hence, meets the design requirements for the specified problem domain.

For closure verification we pose both a set of verification point tests, and a series of benchmark problems which either have known properties or experimental results. Each of these tests is described briefly. The tests in supporting flow regimes that do not involve critical heat flux (Pre-CHF) will be executed and reported at the end of FY17.

Contents

Summary

The RELAP-7 code is the next generation nuclear reactor system safety analysis code being developed as a collaboration between Idaho National Laboratory (INL) and Los Alamos National Laboratory (LANL). The code is based on the 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 and TRACE's capabilities and extends their analysis capabilities for all reactor system simulation scenarios.

This document lays out how RELAP-7 will verify and benchmark the closure relations used to give the Light Water Reactor Sustainability (LWRS) program confidence that the closure relations used are correctly implemented. This constitutes the initial phase of a verification and validation program to meet NQA-1 standards.

In this context, verification is the process of ensuring that the implementation matches the design or theory laid out for the software. Validation is the method to ensure that the design adequately represents the important physical processes being modeled and hence, meets the design requirements for the specified problem domain.

Verification is generally accomplished with a combination of code reviews and unit tests. Formal code reviews provide assurance that the models are not only implemented correctly, but receive the correct inputs and send the outputs to all appropriate locations. Unit tests provide added assurance that the models provide accurate results at a number of discrete points throughout the domain and at the boundaries of the model domain. Depending on the implementation method, unit tests may not necessarily ensure that the models receive correct input or distribute the outputs appropriately. Data used in unit tests is ideally from separate effects tests (SET), experiments where a particular phenomena is sufficiently isolated as to allow its direct measurement, but also unit test data frequently comes from models and outputs of similar codes.

Validation goes beyond verification, as it attempts to show that the various models cooperate to form a meaningful result; validation shows that within the specified problem domain, results are acceptable. This is accomplished principally by testing and comparison to experiment.

1 RELAP-7 Models

RELAP-7 can be perceived as having been derived from 2 major theoretical foundations, the first being a set of mathematical models to describe the physical phenomena being simulated, and the second being a set of numerical methods to act on those mathematical models to obtain meaningful outputs.

We assign these models into 4 categories:

1. Basic equations models
2. Flow-field and other constitutive models
3. Component / Equipment models
4. Special-purpose models

1.1 Basic Equations Models

The *Basic equation models* category includes the fundamental conservation and transport PDEs, as well as the thermodynamic state relations for the fluid (equation of state):

- conservation of fluid mass
- conservation of fluid momentum
- conservation of fluid energy
- heat conduction
- equation of state

Because of the intrinsic nature of these models, they are verified implicitly with the tests for the other modules. However, the equation of state has a set of additional unit tests.

1.2 Flow-Field and Other Constitutive Models

To model transfers of mass, momentum, and energy, both between fluid phases and between the fluid and wall, the basic equations must be supplemented with an additional set of models. These transfer models are derived from the literature and form the majority of the empirical correlations in RELAP-7. Full descriptions of these models can be found in [1].

The *Flow-field and other constitutive models* category includes the following:

- flow regime maps
- fluid mass exchange models
  - wall mass transfer (boiling and condensation at the fluid-wall interface)
  - interphase mass transfer (evaporation/flashing and condensation at the phasic interface)
- fluid momentum exchange models
  - wall momentum losses (drag)
  - interphase momentum transfer (drag and entrainment)
  - localized pressure losses (e.g., orifice plate, grid spacer, etc.)
- fluid energy exchange
  - wall energy transfer
  - interphase energy transfer

Like TRACE, from which we derive most of our closures, RELAP-7 uses flow regime maps to determine which models to apply. Currently, RELAP-7 shares a map for interfacial drag and heat transfer, but has independent maps for wall drag and wall heat transfer.

1.3 Component / Equipment Models

RELAP-7, as a primarily 1D systems code, uses *Component / Equipment models* in situations where it is neither desirable, nor computationally feasible, to model components in full detail using only the fundamental basic equations models. Instead, *Component / Equipment models* use simplified input / output models to capture the relevant effects and performance of system components. Some subcategories of *Component / Equipment models* include the following:

- centrifugal pump
- jet pump (under development)

- check-valve
- valve

Component / Equipment Models will be verified under a separate test plan.

1.4 Special-Purpose Models

Special-purpose models are used to represent complex phenomena that occur either at boundaries or interior locations, but are not fundamental to a systems component. Special purpose models for RELAP-7 include the following:

- counter-current flow limitation model
- critical-flow model at boundaries

Unlike TRACE, RELAP-7 categorizes reflood models as part of the constitutive / closure package, as they can occur on any heated surface.

2 Code-to-Code Comparisons

Assurance that RELAP-7 properly implements the closure models, prior to full validation, is accomplished in three ways: developer review, code-to-code comparisons, and simple benchmark problems. This section describes our code-to-code comparisons. These code-to-code comparisons are made between RELAP-7 and a similarly instrumented version of TRACE.

The first phase of code-to-code comparisons are point-based comparisons. Here, "point" refers to a point of thermodynamic state and/or flow conditions. At each of these points, each of the closure terms (drag, heat transfer, and mass transfer, both at the wall and at the phasic interface) are compared between codes. These points include all flow regime transitions, core regions, and locations where there should be no contribution. Because of the need to simulate test facilities as well as PWR and BWR systems, each point will be evaluated at 3 pressures: atmospheric pressure, 7 MPa, and 15 MPa. In addition to code-to-code comparisons, these will also be compared with analytic solutions by way of spreadsheet analysis.

Because a number of these closure relations depend on others, the most fundamental closure relations are tested first. After these have been verified, the remaining correlations will be tested. With this strategy, the closures are tested in the following order:

1. single-phase wall drag
2. interfacial drag
3. subcooled and superheated wall heat transfer and adiabatic interphase heat transfer
4. wall and interphase heat transfer

As it is unfeasible to test the closures in this fashion for all conditions and pressures, we use a set of simple problems to cover a more comprehensive set of conditions and to verify that transitions between regimes are handled smoothly. The problems are described in the next section.

2.1 Code-to-Code Fine Comparison Tolerances

The tolerances that are considered acceptable depend on the degree to which we can coerce the comparable code to match physical conditions. All fine comparisons will be made between precise numbers (not just with plots), and comparison to analytic solutions will match to 8 digits, as the fluid state can be matched exactly.

3 Simple Benchmark Cases

This section details the benchmark problems that we use to demonstrate that the closure relations work across a variety of regimes and pressures. If there are any incompatibilities between the closure relations and RELAP-7's numerical methods, including the seven-equation model, they should show up here.

3.1 Pre-CHF problems

The Pre-CHF test problems are a mix of cases that are fictional, analytic, and experimental. Cases that are purely fictional, such as DRAIN and HRamp, are used for code-to-code comparisons, and later in a validation context, are used for mass and energy balance considerations.

These tests include the following:

- **DRAIN**: The TRACE standard faucet problem [2], pp. 3–5
- **UTUBE**: The TRACE standard manometer problem [2], pp. 19–20
- **Water over Steam**: A standard RELAP5 test problem [3], pp. 3-6–3-9
- **Bubbling Steam through Liquid**: A standard RELAP5 test problem [3], pp. 3-19–3-23
- **HRamp**: An increasingly 2-phase flow problem
- **Christensen Sub-cooled Boiling Test** [3], pp. 47–49
- **Akimoto Condensation Test** [4]
- **Marviken Test 4**: A critical-flow test [2], pp. 7–9
- **Edwards Pipe**: A horizontal critical-flow test [4], pp. 4.3-5–4.3-7

3.1.1 DRAIN

DRAIN is a vertical, 12-inch diameter, double-standpipe drain-and-fill transient. The top has a stagnation pressure boundary of 0.1 MPa and a small orifice (0.01 m^2) for a drain. The purpose of the test is to evaluate gravity head effect on coolant pressure, wall drag, and the behavior when a liquid/vapor interface crosses mesh-cell interfaces.

3.1.2 UTUBE

UTUBE is a 12-inch diameter, U-shaped vertical standpipe used to check gravity effects. When surface roughness is ignored and form losses are not entered, it behaves as an undamped manometer, which has an analytic solution for the period of the oscillations:

$$\tau = 2\pi\sqrt{L/(2g)} = 2.84\text{s} \tag{1}$$

With wall drag, non-uniform damping occurs, which is behavior that is good to verify.

3.1.3 Water over Steam

This test problem is simply a vertical pipe with the upper one-third of the pipe filled with water and the lower two-thirds of the pipe filled with steam .

Both the liquid water and steam are initially saturated, and are at a pressure of 413 kPa. The pipe has length $L = 4.16448$ m and has a flow area of 1.0 m^2. As the transient begins, the water falls, displacing the steam, eventually filling the bottom one-third of the pipe. For a free-fall scenario, the time for the liquid to drop a distance h is given by

$$\tau_{\text{freefall}} = \sqrt{2h/g} \tag{2}$$

Therefore with a free-fall distance of $h = 2/3L = 2.77632$ m, the drop time is $\tau_{\text{freefall}} = 0.75$ s. However, since the liquid must fall against the upward movement of the steam, the free-fall drop time is a lower bound: $\tau \leq \tau_{\text{freefall}}$.

3.1.4 Bubbling Steam through Liquid

This test case was designed to qualitatively examine the progression of mixture liquid levels as a function of steam flow rate and to create conditions in which the entrainment of liquid droplets into the steam flow is established. This case is a thought problem in which saturated steam is bubbled up through a column of saturated liquid water. The steam flow rate is increased in steps, allowing quasi-steady conditions to be established. The flow rate is then increased linearly to a value high enough to entrain liquid out of the top of the column.

3.1.5 HRamp

HRamp is a test case to verify the progression of horizontal flow regimes. Starting in the *Fully Stratified* (smooth) flow regime, the problem progresses by increasing flow to arrive at *Stratified-Wavy*, followed by *Horizontal Slug* and finally, *Annular Flow*. This is a purely qualitative code-to-code comparison problem.

3.1.6 Christensen Sub-cooled Boiling Test

A series of electrically-heated experiments was performed in the early 1960s to investigate void profiles in vertical tubes using a range of inlet conditions. RELAP codes have used Test 15 from that series for developmental assessment for a number of versions. This problem has advantages over the TRACE tests in that it is limited to only the Pre-CHF regime, whereas TRACE relies on LEHIGH which goes from subcooled nucleate boiling through CHF and reflood. This test assesses wall heat flux partitioning between subcooled heat transfer and wall mass transfer.

3.1.7 Akimoto Condensation Test

The Akimoto Test Facility uses a horizontal, rectangular cross-section flow channel to mix steam and water and measure the resulting condensation rate. The facility can be used with varying flow rates to cover mist, plug, and oscillatory flow conditions. The Akimoto Test Facility tests horizontal flow conditions, interfacial area, and interfacial heat and mass transfer.

3.1.8 Marviken Test 4

The Marviken Test program was one of the full-scale critical flow tests (CFT) conducted in Sweden. The 27 CFT experiments were conducted between mid-1977 and December 1979 as a multinational project at the Marviken Power Station. The tests were performed to obtain data for critical flows in short pipes of large diameter at subcooled and low-quality stagnation conditions. The Marviken tests were conducted by discharging water and a steam-water mixture from a full-sized reactor vessel through a large diameter pipe that was connected to the test nozzle. The test nozzles had rounded entrances and were nominally 0.2 m, 0.3 m, or 0.5 m in diameter. The nozzle lengths ranged from 0.166 m to 1.809 m. Most tests were conducted with a nominal initial steam dome pressure of 5 MPa with the water subcooled between 1 K and 50 K with respect to the steam dome pressure. The vessel, discharge pipe, and nozzle were instrumented to determine the test behavior and to provide a basis for evaluating the stagnation conditions and mass fluxes at the nozzle inlet. Marviken CFT 4 had the longest minimum flow area test nozzle. The model tests both choked-flow modeling and and blowdown in a vertical pipe with abrupt flow area changes. Gravity head terms and evaporation/condensation play significant roles as well.

3.1.9 Edwards Pipe

The Edwards Blowdown test facility was built in England in the late 1960s to study depressurization phenomena of stagnant subcooled water. Unlike the Marviken tests, the Edwards pipe tests were much smaller than any component of a full-scale reactor system. The test section is a horizontal pipe initially closed on both ends with a glass rupture disk. The pipe is initially filled with subcooled liquid maintained at temperature by an insulated and electrically-heated section. Experimental data includes pressure at 4 points as well as void fraction and fluid temperature at the midsection of the pipe.

3.2 CHF and Reflood Test Problems

The Post-CHF test problems will be addressed later in the development but are presented here for completeness. We will assess Counter-Current Flow Limitation (CCFL) model with the Post-CHF tests as it is most commonly seen in reflood events, though that is not a requirement of the model. All of these models come from experiments, and can be compared with measured data.

These tests include the following:

- **LEHIGH**: The TRACE standard subcooled-to-CHF rod bundle test [2], pp. 32–35
- **Cylindrical Core Test Facility (CCTF)**: A refill and reflood simulation of a PWR [4] pp. 4.7-1–4.7-40

3.2.1 LEHIGH

The TRACE Standard Test set problem LEHIGH is a separate effects test to verify the reflood model using the Lehigh University rod-bundle subcooled-liquid-to-post-CHF experiment. During the experiment, CHF is initiated and subsequently quenched from below. Unlike PWR loss-of-coolant accident (LOCA) conditions, there is no CCFL model required. The LEHIGH test case progresses through *Bubbly*, *Churn*, and *Annular Mist Pre-CHF* flow regimes as as well as through all inverted flow regimes, and it tests the code's ability to transition back from post-CHF to pre-CHF closure relations.

3.2.2 Cylindrical Core Test Facility

The Cylindrical Core Test Facility (CCTF) was built and operated by the Japan Atomic Energy Research Institute (JAERI) to provide information on the thermal-hydraulic behavior during refill and reflood phases of a LOCA in a PWR. Unlike other tests, the blowdown period is not simulated. Two series of tests were run in the facility, with the core modified between the two. This test is Run 14 on the Core-1 configuration. It, unlike other LOCA simulations, demonstrates nearly 1D behavior [5].

3.3 Other Benchmark Cases

Finally, in the course of examining the previously listed benchmark cases, it may become apparent that there are others that should be examined; and the possibility for inclusion/substitution of the any such identified benchmark cases is certainly reserved. For example, there may be other benchmark cases that align better to the idiosyncrasies of the 7-equation two-phase model of RELAP-7, as opposed to the classical 6-equation two-phase model of TRACE. Also, there may even be some new or additional benchmark cases identified that should be constructed for TRACE and RELAP-7 to produce further, pertinent comparisons.

4 Conclusions

The test methodology outlined previously was specifically chosen to test the thermal hydraulic-closure relations that were drawn from TRACE and used in RELAP-7. Because of this, nearly all of these problems are very simple in geometry and use a minimum number of components. We also have not tested most component models, but the tests here, once calculated and compared with TRACE, and where applicable, experimental and analytical results, we believe will give strong confidence that the coding is correct and that the TRACE closure relations are compatible with the differing numerical methods used in RELAP-7.

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