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Code Verification/Validation Needs for RELAP-7

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NUCLEAR ENERGY ADVANCED MODELING & SIMULATION PROGRAM

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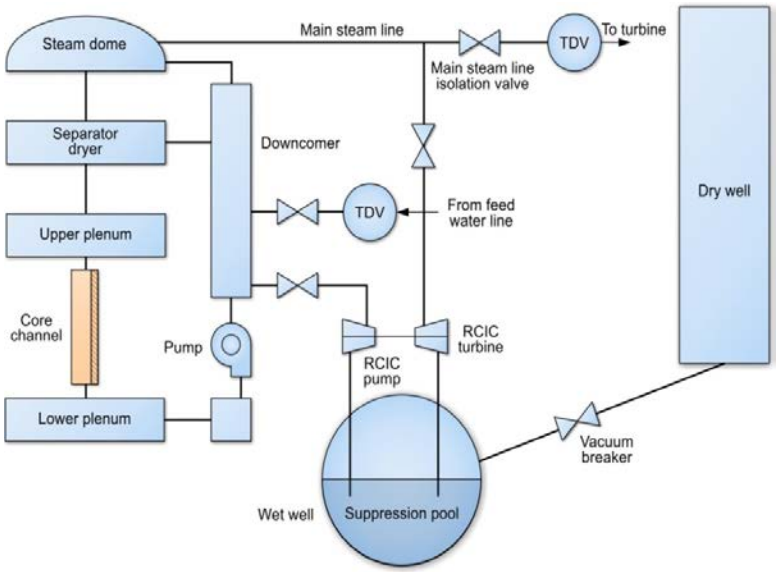
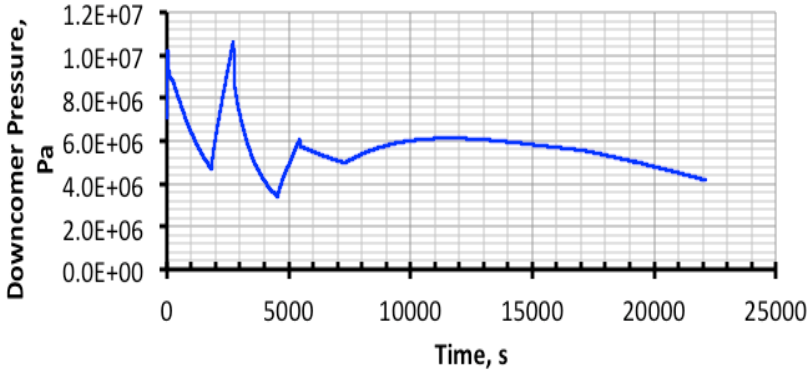
RELAP (Reactor Excursion and Leak Analysis Program)





- **RELAP-7 development began in 2011 to support the Risk Informed Safety Margins Characterization (RISMC) Pathway of the Light Water Reactor Sustainability (LWRS) program.**
- **First lines of code were committed to the repository on 11/07/2011. Proof of concept result, TMI-1 single phase, 06/13/2012.**
- **Funding Source: LWRS (NEAMS in 2012).**
- **Collaborators**

TEXAS A&M UNIVERSITY

Argonne NATIONAL LABORATORY

Idaho National Laboratory

EPRI ELECTRIC POWER RESEARCH INSTITUTE

Los Alamos NATIONAL LABORATORY EST. 1943

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RELAP-7 Design Concept

The overall design goal of RELAP-7 development is to leverage 30 years of advancements in software design, numerical integration methods, and physical models.

- **Modern Software Design:** ***What MOOSE brings to the table.***
  - Object-oriented C++ construction (www.mooseframework.org)
  - Designed to be easily extended (modular physics) and maintained
  - Strict adherence to SQA (meeting NQA-1 requirements)
- **Advanced Numerical Integration Methods:**
  - Multi-scale time integration, PCICE (in progress), JFNK (implicit nonlinear Newton method), and a point implicit method. Second-order accurate spatial discretization (linear finite elements or reconstructed Discontinuous Galerkin).

RELAP-7 Design Concept

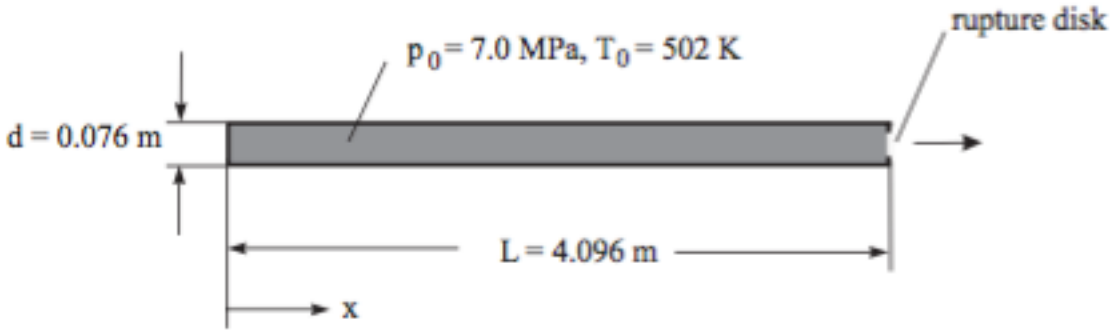
- **State-of-the-Art Physical Models:**
  - All-speed, all-fluid (vapor-liquid, gas, liquid metal) flow – agnostic of reactor concept (PWR, BWR, SMR, SFR, MSR, FHR, HTGR, etc.).
  - 7-equation two-phase flow model incorporating IAPWS-95 equation of state.
  - New two-dimensional core heat transfer model based upon fuel, gap, clad.
  - Closure relations from the TRACE V5.0 code.
  - Designed for multiphysics analysis (BISON and MAMBA) or to couple to multi-D core simulators (CASL's VERA or NEAMS Pronghorn) with MOOSE MultiApp and Transfers.

Two-Phase Simple Geometry Validation Tests for RELAP-7

- Cavitation Shock Tube
- Expansion Tube
- Two-Phase Shock Tube (liquid and vapor)
- Edwards Pipe
- Cannon and Super Cannon
- Deich Nozzle Test
- ASTAR Nozzle Test (CEA)
- Moby Dick Nozzle Test (CATHARE)

Edwards' Pipe Blowdown Experiment

- The blowdown transient is initiated by the rupture of a bursting disk allowing the rapid discharge to the environment at atmospheric pressure.
- Actual bursting disk resulted in a constriction equivalent to a 13% reduction in cross-sectional area.



- Discretized with 1024 elements.
- Constriction is discretized with three elements.

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Edwards' Pipe Blowdown Experiment: Preliminary RELAP-7 Result

Two-Phase Simple Geometry Validation Tests for RELAP-7

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- Richard's Pipe

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7-Equation Two-Phase Flow Model: Interfacial mass transfer & interfacial heat transfer, gravity force, wall and interphase viscous drag, and simple wall heat transfer

liquid

$$\frac{\partial \alpha_l A}{\partial t} + u_{\text{int}} A \frac{\partial \alpha_l}{\partial x} = A\mu(p_l - p_g) - \frac{\Gamma A_{\text{int}} A}{\rho_{\text{int}}} \qquad \left(or\ \alpha_g = 1 - \alpha_l\right)$$

$$\frac{\partial \alpha_l \rho_l A}{\partial t} + \frac{\partial \alpha_l \rho_l u_l A}{\partial x} = -\Gamma A_{\text{int}} A$$

$$\frac{\partial \alpha_l \rho_l u_l A}{\partial t} + \frac{\partial \alpha_l A(\rho_l u_l^2 + p_l)}{\partial x} = p_{\text{int}} A \frac{\partial \alpha_l}{\partial x} + p_l \alpha_l \frac{\partial A}{\partial x} + A\lambda(u_g - u_l)$$
$$-\Gamma A_{\text{int}} u_{\text{int}} A - f_l \alpha_l \rho_l u_l^2 \left(\pi A\right)^{\frac{1}{2}}$$
$$-f_l' \tfrac{1}{2} \rho_l \left(u_l - u_{\text{int}}\right)^2 A_{\text{int}} A + \alpha_l \rho_l \vec{g} \cdot \hat{n}_{axis} A$$

$$\frac{\partial \alpha_l \rho_l E_l A}{\partial t} + \frac{\partial \alpha_l u_l A(\rho_l E_l + p_l)}{\partial x} = p_{\text{int}} u_{\text{int}} A \frac{\partial \alpha_l}{\partial x}$$
$$-\bar{p}_{\text{int}} A\mu(p_l - p_g) + \bar{u}_{\text{int}} A\lambda(u_g - u_l)$$
$$+\Gamma A_{\text{int}} \left(\frac{p_{\text{int}}}{\rho_{\text{int}}} - H_{l\,\text{int}}\right) A$$
$$+A_{\text{int}} h_{Tl} (T_{\text{int}} - T_l) A$$
$$+\alpha_l h_{lw} (T_w - T_l) \left[4\pi A + \left(\frac{\partial A}{\partial x}\right)^2\right]^{\frac{1}{2}}$$
$$+\alpha_l \rho_l u_l \vec{g} \cdot \hat{n}_{axis} A$$

vapor

$$\frac{\partial \alpha_g A}{\partial t} + u_{\text{int}} A \frac{\partial \alpha_g}{\partial x} = A\mu(p_g - p_l) + \frac{\Gamma A_{\text{int}} A}{\rho_{\text{int}}} \qquad \left(or\ \alpha_g = 1 - \alpha_l\right)$$

$$\frac{\partial \alpha_g \rho_g A}{\partial t} + \frac{\partial \alpha_g \rho_g u_g A}{\partial x} = \Gamma A_{\text{int}} A$$

$$\frac{\partial \alpha_g \rho_g u_g A}{\partial t} + \frac{\partial \alpha_g A(\rho_g u_g^2 + p_g)}{\partial x} = p_{\text{int}} A \frac{\partial \alpha_g}{\partial x} + p_g \alpha_g \frac{\partial A}{\partial x} + A\lambda(u_l - u_g)$$
$$+\Gamma A_{\text{int}} u_{\text{int}} A - f_g \alpha_g \rho_g u_g^2 \left(\pi A\right)^{\frac{1}{2}}$$
$$-f_g' \tfrac{1}{2} \rho_g \left(u_g - u_{\text{int}}\right)^2 A_{\text{int}} A + \alpha_g \rho_g \vec{g} \cdot \hat{n}_{axis} A$$

$$\frac{\partial \alpha_g \rho_g E_g A}{\partial t} + \frac{\partial \alpha_g u_g A(\rho_g E_g + p_g)}{\partial x} = p_{\text{int}} u_{\text{int}} A \frac{\partial \alpha_g}{\partial x}$$
$$-\bar{p}_{\text{int}} A\mu(p_g - p_l) + \bar{u}_{\text{int}} A\lambda(u_l - u_g)$$
$$-\Gamma A_{\text{int}} \left(\frac{p_{\text{int}}}{\rho_{\text{int}}} - H_{g\,\text{int}}\right) A$$
$$+A_{\text{int}} h_{Tg} (T_{\text{int}} - T_g) A$$
$$+\alpha_g h_{gw} (T_w - T_g) \left[4\pi A + \left(\frac{\partial A}{\partial x}\right)^2\right]^{\frac{1}{2}}$$
$$+\alpha_g \rho_g u_g \vec{g} \cdot \hat{n}_{axis} A$$

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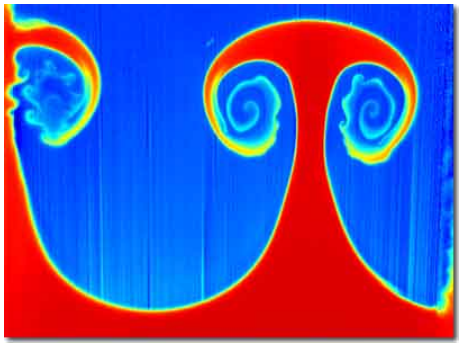
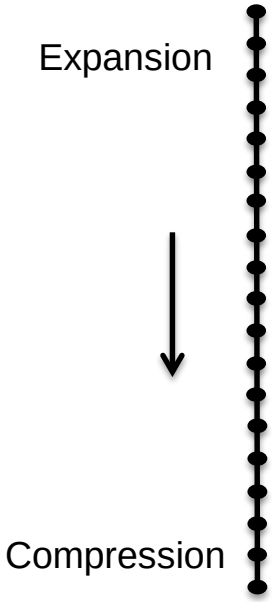
Richard's Pipe

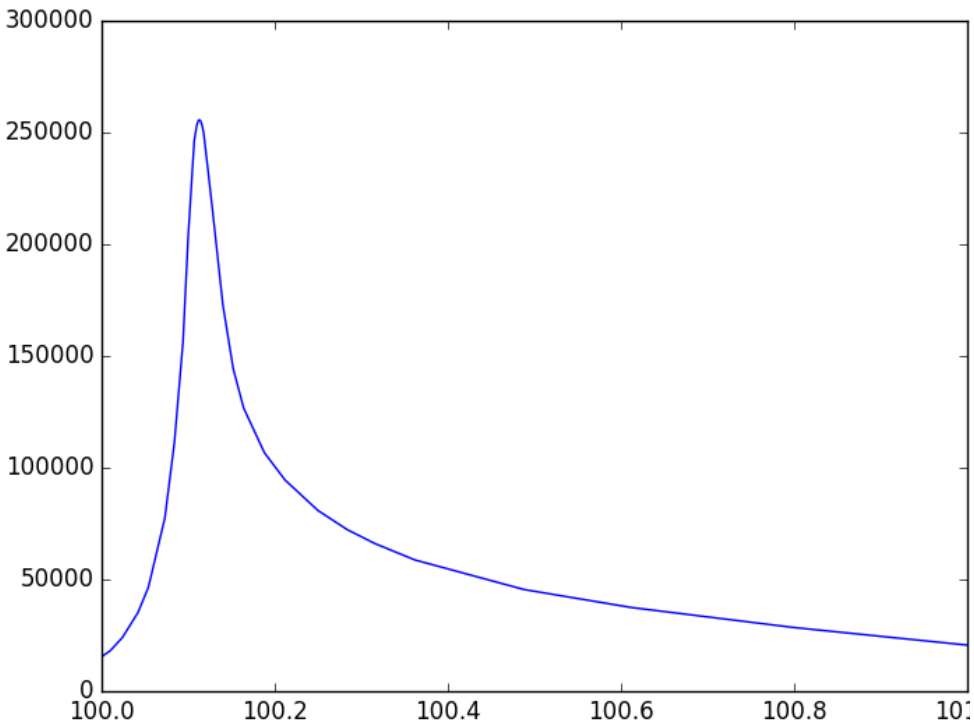
- **Drop towers are common for shock induced Richtmeyer-Meshkov instability studies.**
- **Richard's Experiment: Designed by a Computational Scientist (me) and approved by an Experimentalist (Philip Bardet) to provide validation of the 7-equation model.**
- $$\frac{\partial \alpha_l A}{\partial t} + u_{\text{int}} A \frac{\partial \alpha_l}{\partial x} = A\mu(p_l - p_g) - \frac{\Gamma A_{\text{int}} A}{\rho_{\text{int}}}$$
- **Adiabatic experiment to isolate the pressure relaxation term (rate to mechanical equilibrium).**
- **Apparatus to be built at University of Wisconsin**

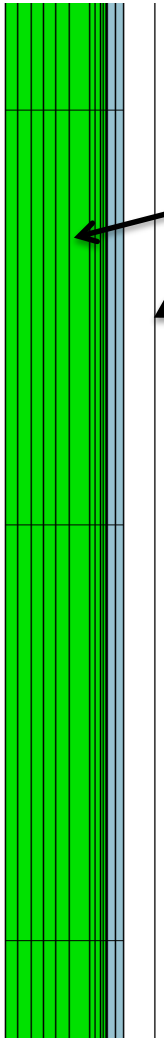




BISON/RELAP-7 Reactivity Insertion Accident (PWR)

Pin Power Profile (BNL)





P = 15.5 MPa

RELAP-7 Conditions

g = 9.81 m/s^2

$(\rho u)_l$ = 3632.3 Kg/(m^{2}s)
H_l = 1.19128 MJ/kg
α = 0.995
$(\rho u)_g$ = 304.2 Kg/(m^{2}s)
H_g = 2.85184 MJ/kg

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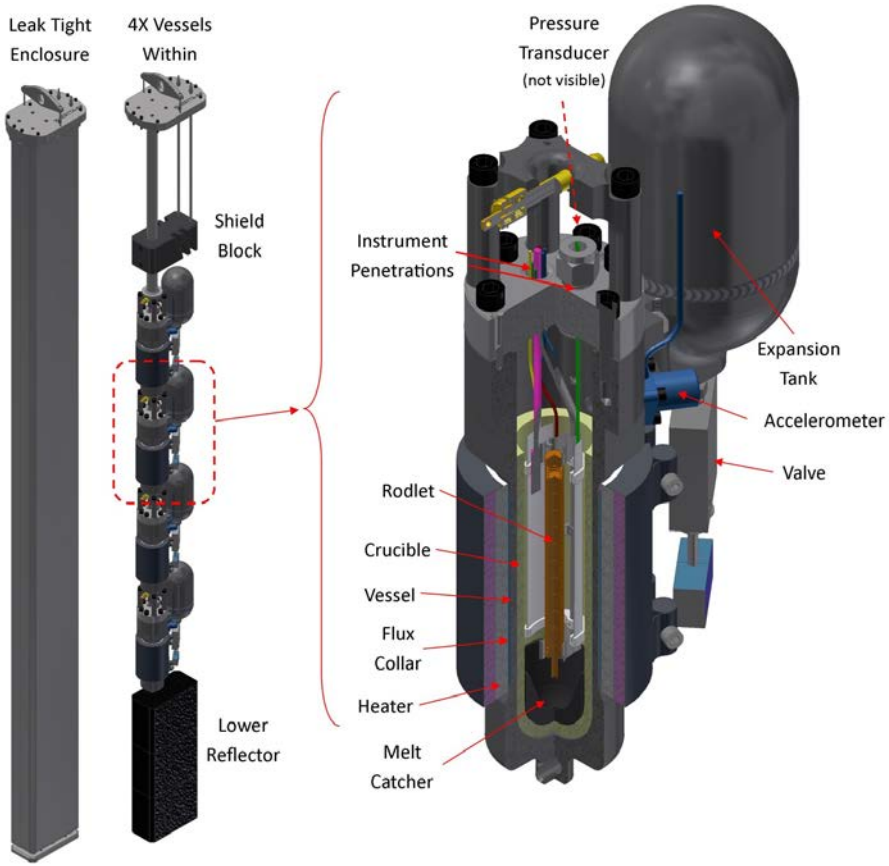
BISON/RELAP-7 Reactivity Insertion Accident (PWR)

TREAT Multi-SERTTA Vessel

- **Fast transient boiling data under PWR conditions to obtain CHF and post-CHF correlations using clad surface temperature and void sensors under different pulse energies and clad surfaces.**

- **BISON/RELAP-7 model integration and validation using the experimental RIA validation data to quantify the total validation uncertainty for RIA simulation.**



BWXT Integrated System Test Facility (IST), Forrest, Virginia

Key features of the IST include:

1. **Core Heaters**
2. **Steam Generator**
3. **Pressurizer and Emergency Core Cooling System**
4. **Balance of Plant – complete feed and steam system**
5. **Reactor Coolant Inventory and Purification**
6. **Test control algorithms**
7. **Quality Program – NQA-1 / 10 CFR Appendix B to Part 50.**

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Questions?

The Marviken Critical Flow Test Program

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