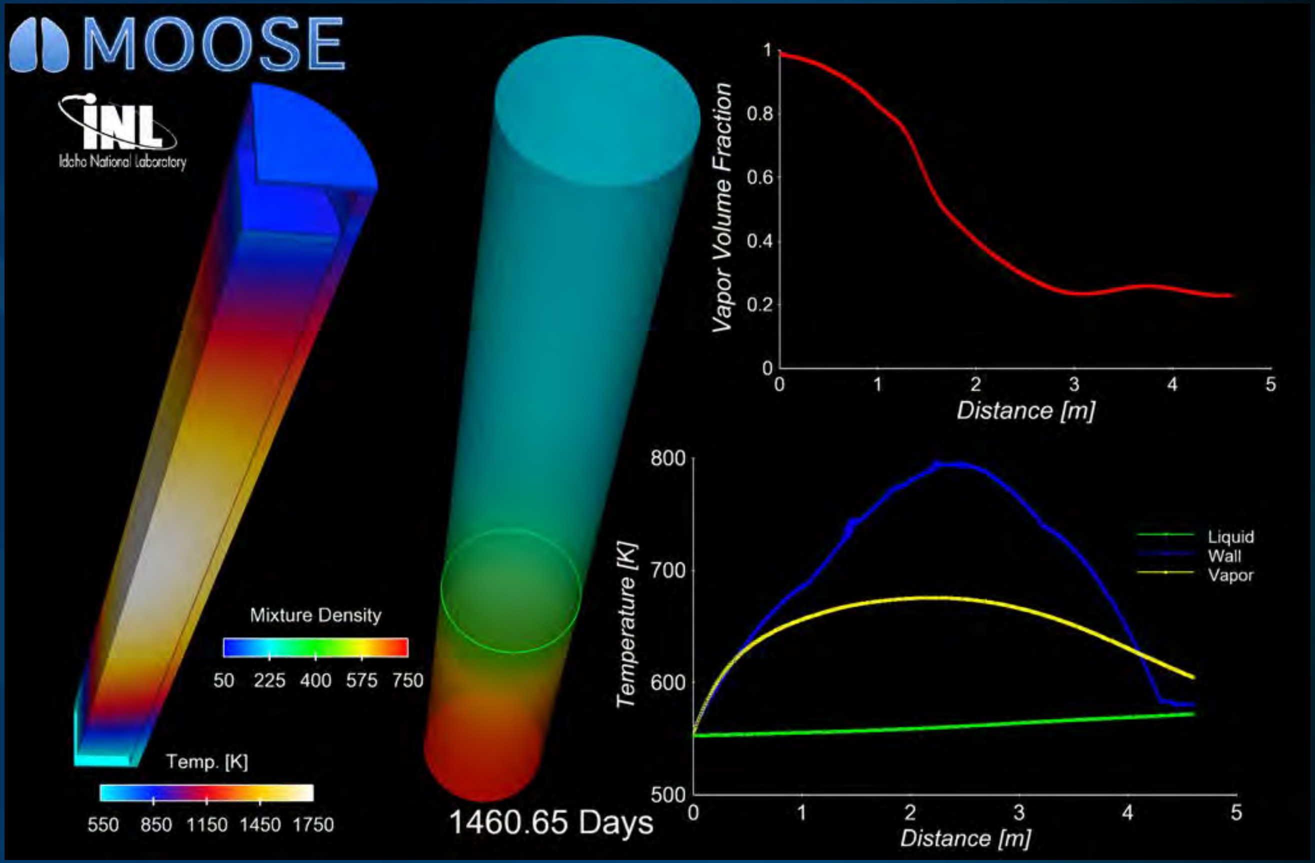
RELAP-7 Current Status and Future Development

International RELAP5 Users Group Meeting , October 3 - 7, 2016



Richard C. Martineau, Ph.D., Director of NS&T Modeling and Simulation and RELAP-7 PI

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INL
Idaho National Laboratory

Since 1949, INL Researchers Pioneered Many of the World's First Nuclear Reactor Prototypes and Advanced Safety Systems (LOFT and Semiscale)

The INL is the lead nuclear energy research and development laboratory for the Department of Energy (DOE)

- **Prime Contract States:** Establish a *world-class capability in the modeling and simulation* of advanced systems such as Generation-IV Nuclear Energy Systems.

The INL has the nuclear expertise, infrastructure and strategic partnerships necessary to advance the state-of-the-art in:

1) Nuclear safety analysis
2) Material Irradiation
3) Management of used nuclear fuel
4) Advanced nuclear fuels, materials, and separations
5) Development of advanced reactor concepts

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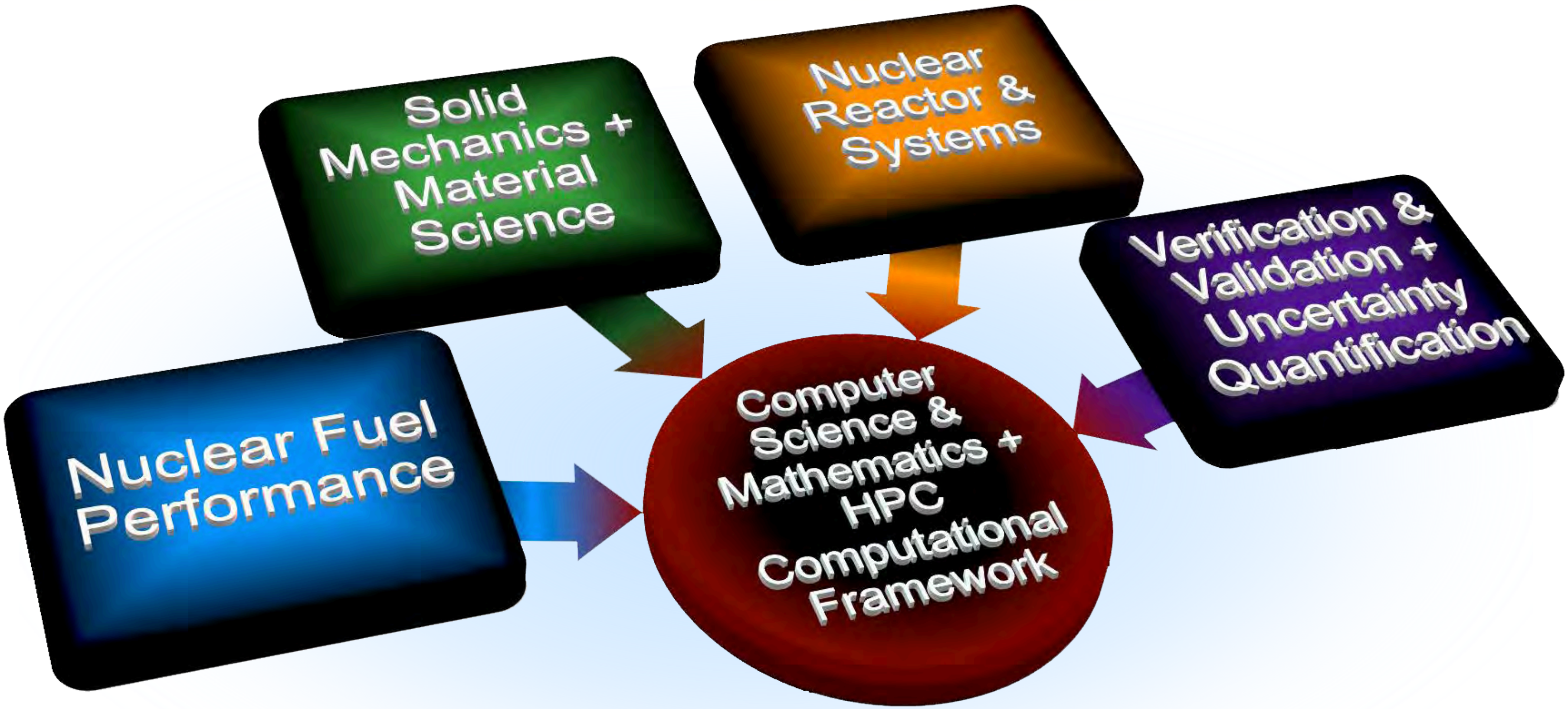
1), 4), and 5) are the main drivers of the INL's mission in Advanced Modeling and Simulation. 2) and 3) are emerging modeling and simulation capabilities.

Synergistic Approach to Modeling and Simulation



Objective: "*To develop a multi-scale, multi-physics simulation capability for nuclear energy applications in support of DOE-NE missions that span basic first principles (atomistic and molecular dynamics) to the engineering scale, including nuclear physics, materials, thermal fluids, applied mathematics (numerical methods), and nuclear, mechanical, and chemical engineering, all linked together under a single computational framework*"

Leveraging Support from Multiple DOE Programs:

- **DOE-NE Nuclear Energy Advanced Modeling and Simulation** Program is to enhance research and development through the use of advanced computational methods.

  NEAMS
  NUCLEAR ENERGY ADVANCED MODELING & SIMULATION PROGRAM

- **The Consortium for Advanced Simulation of Light Water Reactors** Program was established to provide modeling and simulation capability to improve the performance of operating light water reactors

  CASL
  Consortium for Advanced Simulation of LWRs

- **Fuel Cycle Technologies** program was adopted as a results-oriented, science-based approach towards nuclear fuel R&D that takes advantage of advances in high-performance computing to integrate theory and experiment with modeling and simulation

  Fuel Cycle TECHNOLOGIES
  safe • secure • sustainable

- **The Light Water Reactor Sustainability** Program is developing the scientific basis to extend existing nuclear power plant operating life beyond the current 60-year licensing period and ensure long-term reliability, productivity, safety, and security

  LWRS

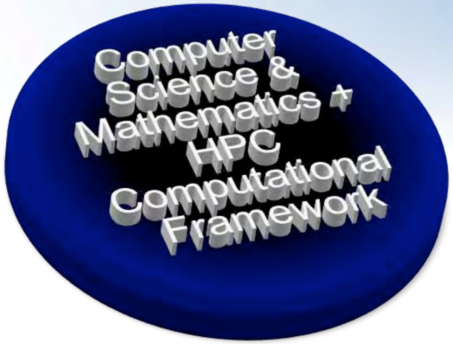
- **Laboratory Directed Research and Development**

  LDRD
  LABORATORY DIRECTED RESEARCH & DEVELOPMENT

- **Reduced Enrichment for Research and Test Reactors**

  RERTR

A Brief Overview of INL's MOOSE HPC Runtime and Development Framework



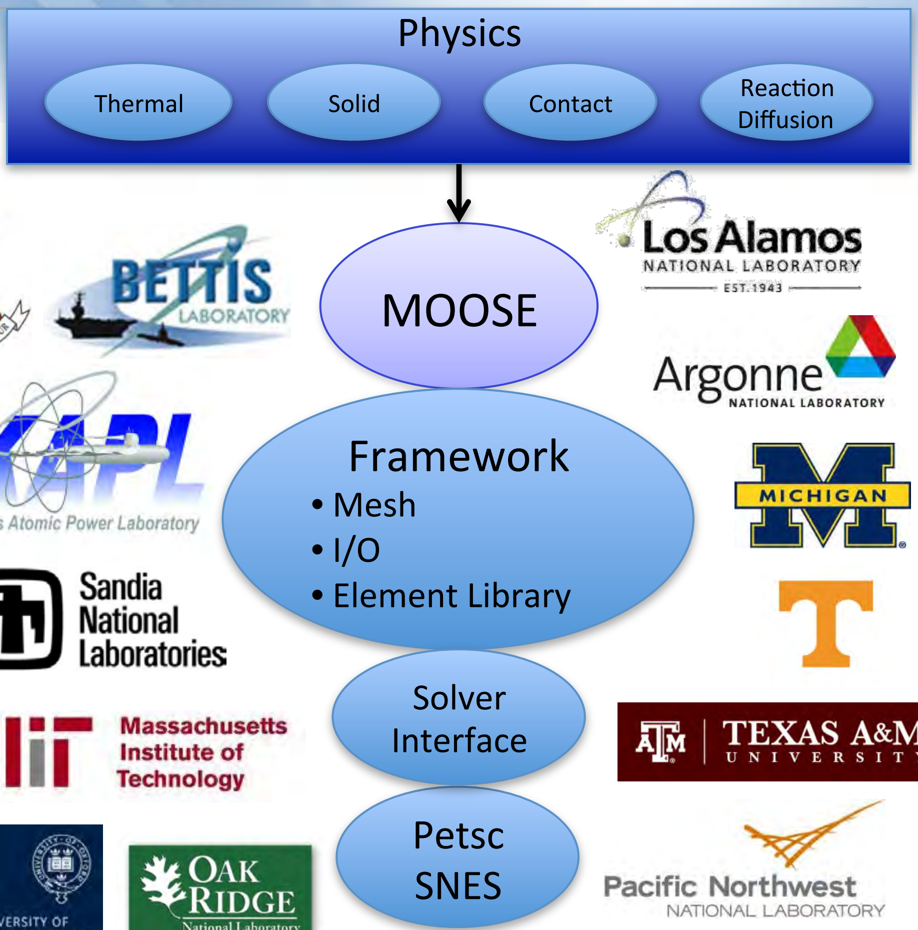
"MOOSE: The cornerstone of INL's HPC M&S effort"

MOOSE: (Multi-physics Object-Oriented Simulation Environment), Derek Gaston and Cody Permann (Leads)

- MOOSE makes INL's synergistic approach to multi-scale, multi-physics modeling & simulation possible.
- *Design Goal:* To incorporate all computational science disciplines (physics, engineering, software design, and mathematics) under one computational framework
- *Result:* All MOOSE-based applications can be cohesively coupled for multiphysics simulations.
- Collaborators: Massachusetts Institute of Technology, Idaho National Laboratory, Argonne National Laboratory

MOOSE Project

- Started in May of 2008 (LDRD).
- MOOSE is an C++ object-oriented software framework allowing rapid development of new simulation tools.
- 1D, 2D or 3D FEM (CG, DG and XFEM) with both mesh and time step adaptivity.
- Massively parallel, from 1 to 100,000's of processors.
- Subjected to multiple peer-reviews and found to meet NQA-1 requirements.
- Application development focuses on implementing physics (PDEs) rather than numerical implementation issues.
- Leverages multiple DOE and university developed scientific computational tools.
- Derek Gaston received PECASE award for work on MOOSE (July of 2012).
- Obtained Free Software Foundation, Inc.'s Lesser General Public License Version 2.1 on February 12, 2014.
- 2014 R&D 100 Award.



Idaho National Laboratory

Why is MOOSE different?

MOOSE-based Animals: There are now 40+

Kernels make MOOSE-based application code different:

- The heart of a MOOSE application is the kernel. A kernel is a “piece” of physics. It’s convenient to think of a kernel as a mathematical operator, such as a Laplacian or a convection term in a PDE.
- A kernel is typically composed of single lines of C++ code for the mathematical operator, the exact or approximate Jacobian, and one for each boundary condition.
- In MOOSE, kernels may be swapped or coupled together to achieve different application goals.
- It is these kernels, which now number in the hundreds, that allow a scientist or engineer to pick up MOOSE and develop an application so quickly.

Code Example

Strong Form

$$\rho C p \frac{\partial T}{\partial t} - \nabla \cdot k(T,B) \nabla T = f$$

Weak Form

$$\int_\Omega \rho C p \frac{\partial T}{\partial t} \psi_i + \int_\Omega k \nabla T \cdot \nabla \psi_i - \int_{\partial\Omega} k \nabla T \cdot \mathbf{n} \psi_i - \int_\Omega f \psi_i = 0$$

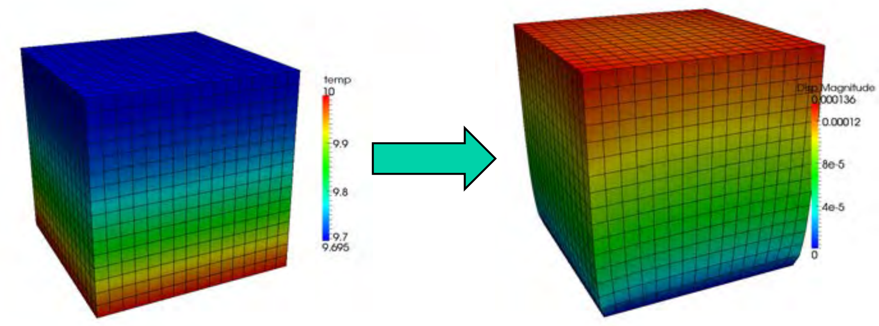
Kernel Kernel BoundaryCondition Kernel

Actual Code

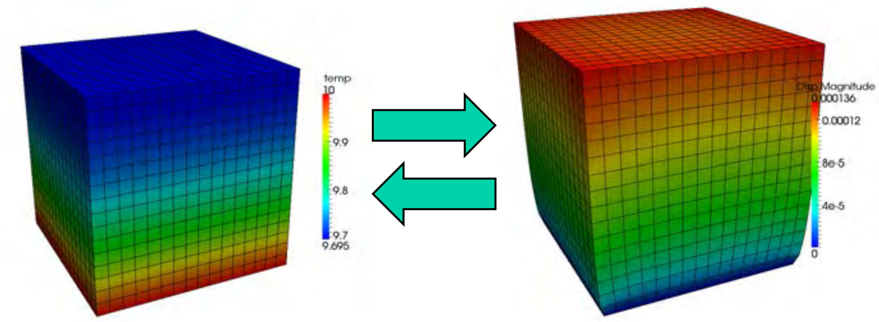
```
return _k[_qp]*_grad_u[_qp]*_grad_test[_i][_qp];
```

Multiphysics Coupling

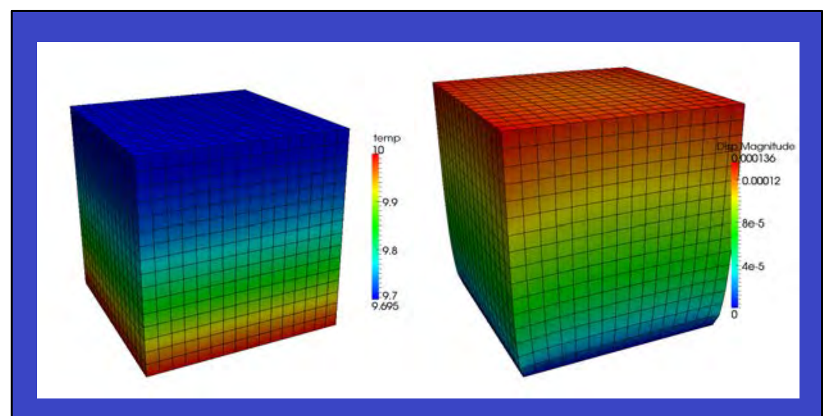
- Loose Coupling (Linear)
  1. Solve PDE1
  2. Pass data
  3. Solve PDE2
  4. Move to next time step



- Tight Coupling (Picard)
  1. Solve PDE1
  2. Pass data
  3. Solve PDE2
  4. Pass data
  5. Return to 1 until convergence
  6. Move to Next time step

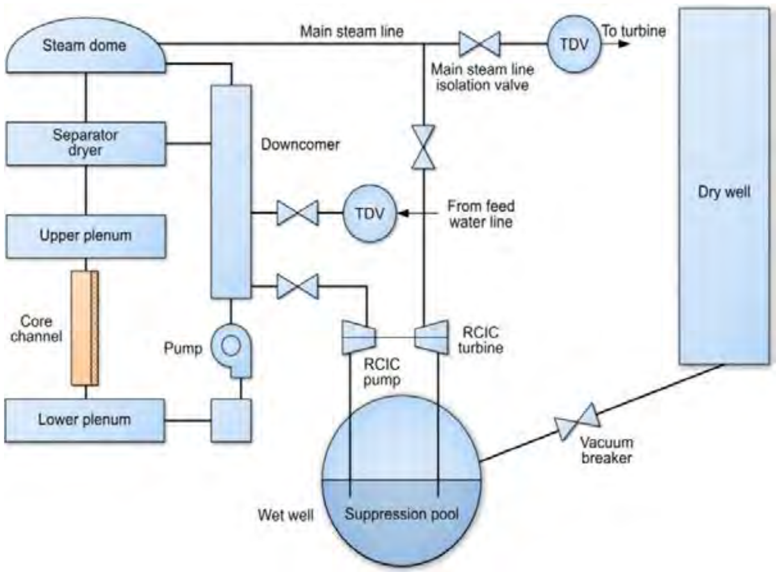


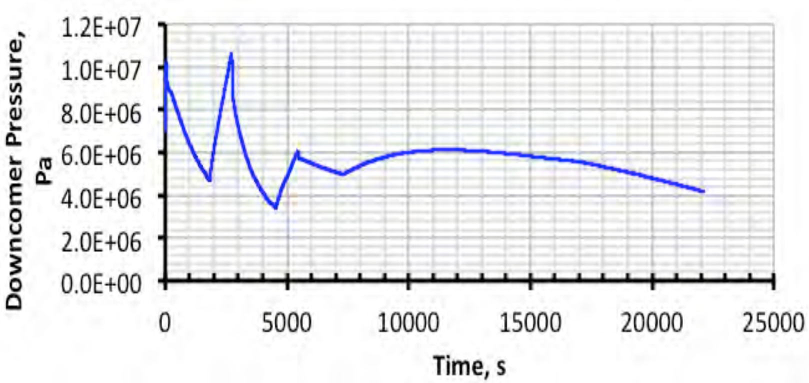
- Fully Coupled (Nonlinear Newton)
  1. Solve PDE1 and PDE2 simultaneously in one system
  2. Move to next time step



Overview of RELAP-7: Present and Future

RELAP (Reactor Excursion and Leak Analysis Program)





RELAP-7: The Next Generation Nuclear Reactor System Analysis Tool

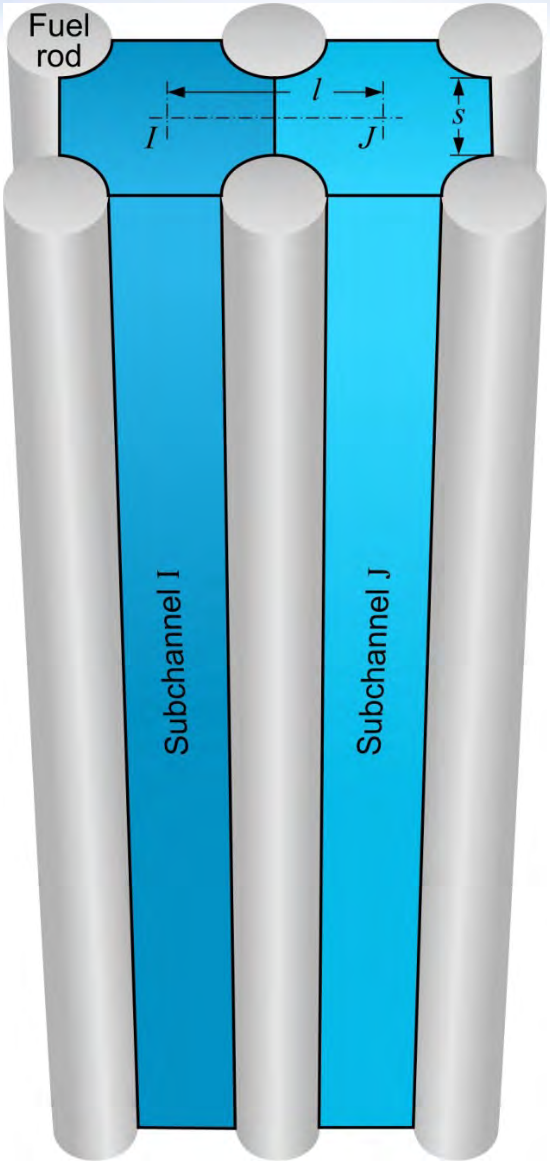
- RELAP-7 is the current nuclear systems safety analysis code being developed at INL and expected to be the next in the RELAP reactor safety/systems analysis application series.
- RELAP-7 development began in 2011 to support the Risk Informed Safety Margins Characterization (RISMC) Pathway of the Light Water Reactor Sustainability (LWRS) program.
- The overall design goal of RELAP-7 development is to leverage 30 years of advancements in software design, numerical integration methods, and physical models.
- Industry interest: EPRI, WEC, Areva, Holtec, COG.
- Funding Source: LWRS (NEAMS in 2012)
- Collaborators:

Idaho National Laboratory | EPRI ELECTRIC POWER RESEARCH INSTITUTE | Argonne NATIONAL LABORATORY | Los Alamos NATIONAL LABORATORY EST. 1943 | TEXAS A&M UNIVERSITY

RELAP-7 Design Concept

- **Modern Software Design:** *What MOOSE brings to the table.*
  - Object-oriented C++ construction (provided by the MOOSE framework)
  - Designed to reduce the expense and time of RELAP-7 development
  - Designed to be easily extended (modular physics) and maintained
  - Strict adherence to SQ (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 (prototyped). Second-order accurate spatial discretization (linear finite elements).
- **State-of-the-Art Physical Models:**
  - All-speed, all-fluid (vapor-liquid, gas, liquid metal) flow – agnostic of reactor concept (PWR, BWR, SMR, SFR, HTGR, etc.).
  - Well-posed 7-equation two-phase flow model.
  - IAPWS-95 equation of state.
  - New two-dimensional core heat transfer model based upon fuel, gap, clad.
  - Closure relations from the TRACE V5.0 Theory Manual.
  - Designed to couple to higher fidelity physics (BISON, Rattlesnake, MAMBA) with MOOSE MultiApp and Transfers.

Proposed Subchannel Capabilities in RELAP-7

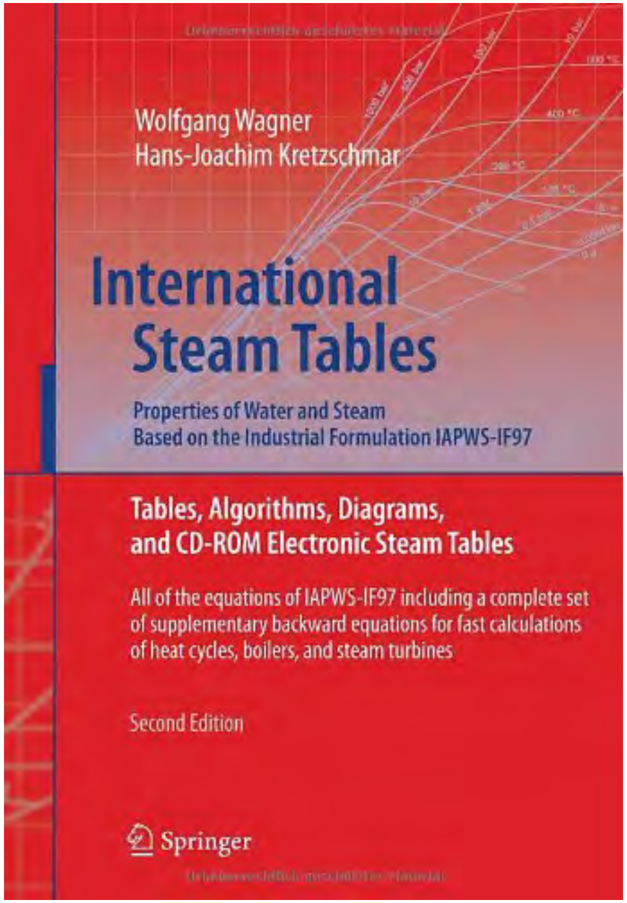


Subchannel model for the reactor core simulation:

- Standard suchannel approach is currently prototyped in RELAP-7 for single-phase flow (without CRs for CIs).
- Ability to fully couple with other system components and physics applications, a major improvement over current industry practice which loosely couples a reactor system code and a stand-alone subchannel code, i.e., WEC COBRA-TF.
- Compatible single-phase and 7-eqn two-phase flow formulations are being developed.
- Easily coupled to the BISON for 2D (r-z) and 3D fuels performance applications. Thus, RELAP-7 subchannel capability will not need a pin heating model and provides for fuels performance analysis.

RELAP-7 Water/Steam EOS, IAPWS-95

- **International Association for Properties of Water and Steam, IAPWS-95 steam/water properties. Contract for source code from Zittau/Görlitz University of Applied Sciences.**
- **EOS input modified for internal energy and specific volume.**
- **Additional features include:**
  - Steam, water, and mixture sound speeds
  - Exact property derivatives for implicit Jacobians



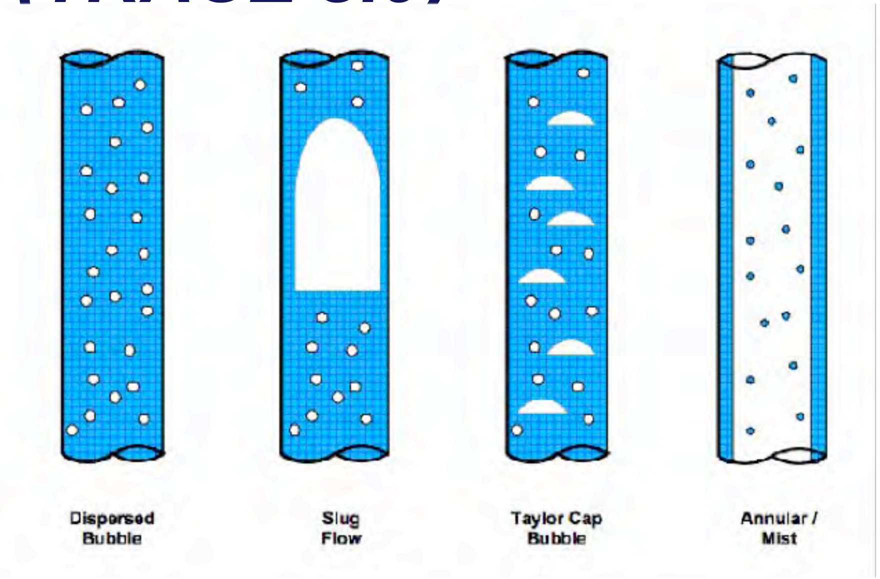
The Present: Current Reactor Components Available

RELAP-7 Component	Dimensionality			Flow Model			3D Linkage
	0D	1D	2D	Single	HEM	7-Eqn	Application
Pipe	n/a	☑	n/a	☑	☑	☑	n/a
PipeWithHeatStructure	n/a	☑	☑	☑	☑	☑	n/a
CoreChannel	n/a	☑	☑	☑	☑	☑	BISON
HeatExchanger	n/a	☑	☑	☑	☑	☐	n/a
TimeDependentVolume	☑	n/a	n/a	☑	☑	☐	n/a
TimeDependentMassFlowRate	☑	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
CheckValve	☑	n/a	n/a	☑	☐	☐	n/a
Pump	☑	n/a	n/a	☑	☐	☐	n/a
PointKinetics	☑	n/a	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
Reactor	☑	n/a	n/a	n/a	n/a	n/a	Rattlesnake+ MAMMOTH
Turbine	☑	n/a	n/a	☑	☐	☐	n/a
Accumulator	☑	n/a	n/a	☑	☐	☐	n/a
Pressurizer	☑	☐	n/a	n/a	☑	☐	n/a
Once-Through Steam Generator	n/a	☑	☑	☑	☑	☑	n/a

Note: More complex reactor components are constructed from these building blocks. For example:

1. The safety relief valve (SRV) is constructed from CompressibleValve strongly coupled to WetWell and Pipe (connected to main steam line).
2. The reactor core isolation cooling (RCIC) component is assembled from Pump and Turbine on a common shaft.
3. In the future, the steam generator and downcomer will combine two 2-D CoreChannel components.

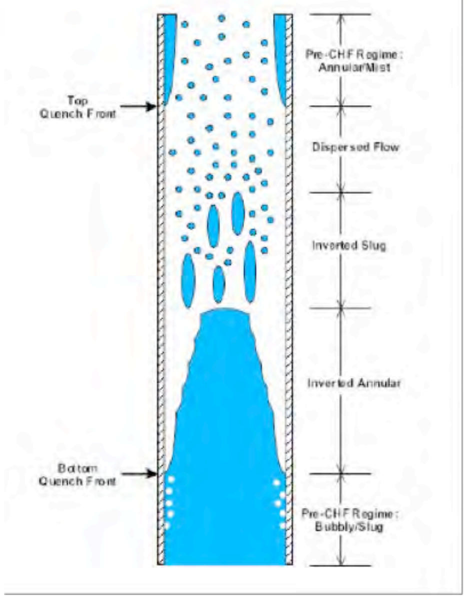
Current Status on Flow Topology-Dependent Correlations (TRACE 5.0)



A. Vertical pipes, pre-CHF

	Bubbly	Slug/Cap	Annular Mist
Wall friction	■	■	■
Interfacial friction	■	■	■
Interfacial heat/ mass transfer	■	■	■

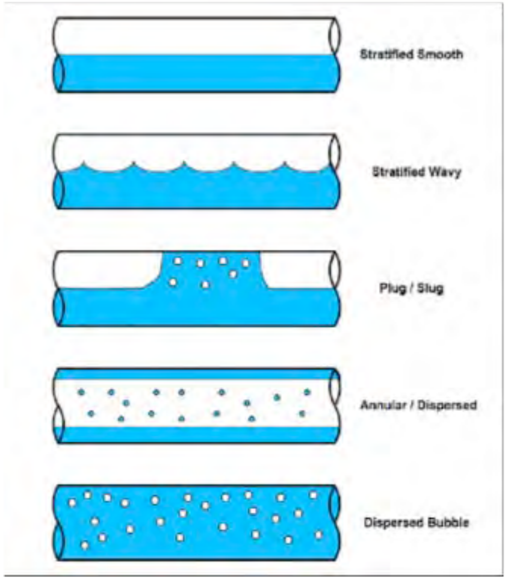
Current Status on Flow Topology-Dependent Correlations



C. Vertical pipes, post-CHF

	Inverted annular	Inverted slug	Dispersed flow
Wall friction	■	■	■
Interfacial friction	□	□	□
Interfacial heat/ mass transfer	■	■	■

Current Status on Flow Topology-Dependent Correlations



B. Horizontal pipes, pre-CHF

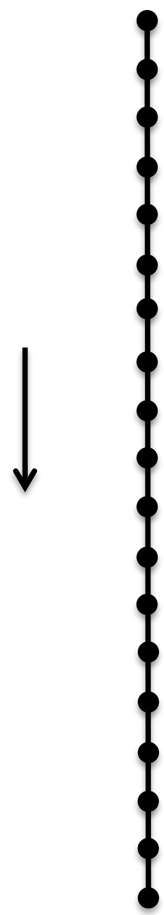
	Stratified smooth	Stratified wavy/Plug/ Slug	Annular/ dispersed	Dispersed bubbly
Wall friction	☐	☐	☐	☐
Interfacial friction	☐	☐	☐	☐
Interfacial heat/ mass transfer	☐	☐	☐	☐

The Future: Major RELAP-7 Capability Development Tasks

- Improved closure relationships (TRACE) with IAPWS steam/ water properties.
- Improved LWR components (1D-2D downcomer, 1D pressurizer, optional steam generator designs) to provide improved water level tracking and LOCA temporal accuracy.
- Tightly coupled multi-physics fuels performance and reactor physics (NEAMS MOOSE-based applications) for improved design and safety analysis.
- Integrated single and two-phase 3D subchannel, tightly coupled to 2D (r-z) and 3D fuels performance capability for improved design and safety analysis.
- Validation of selected integral effects tests and non-vender specific reactor plants

Simple yet Important RELAP-7 Results

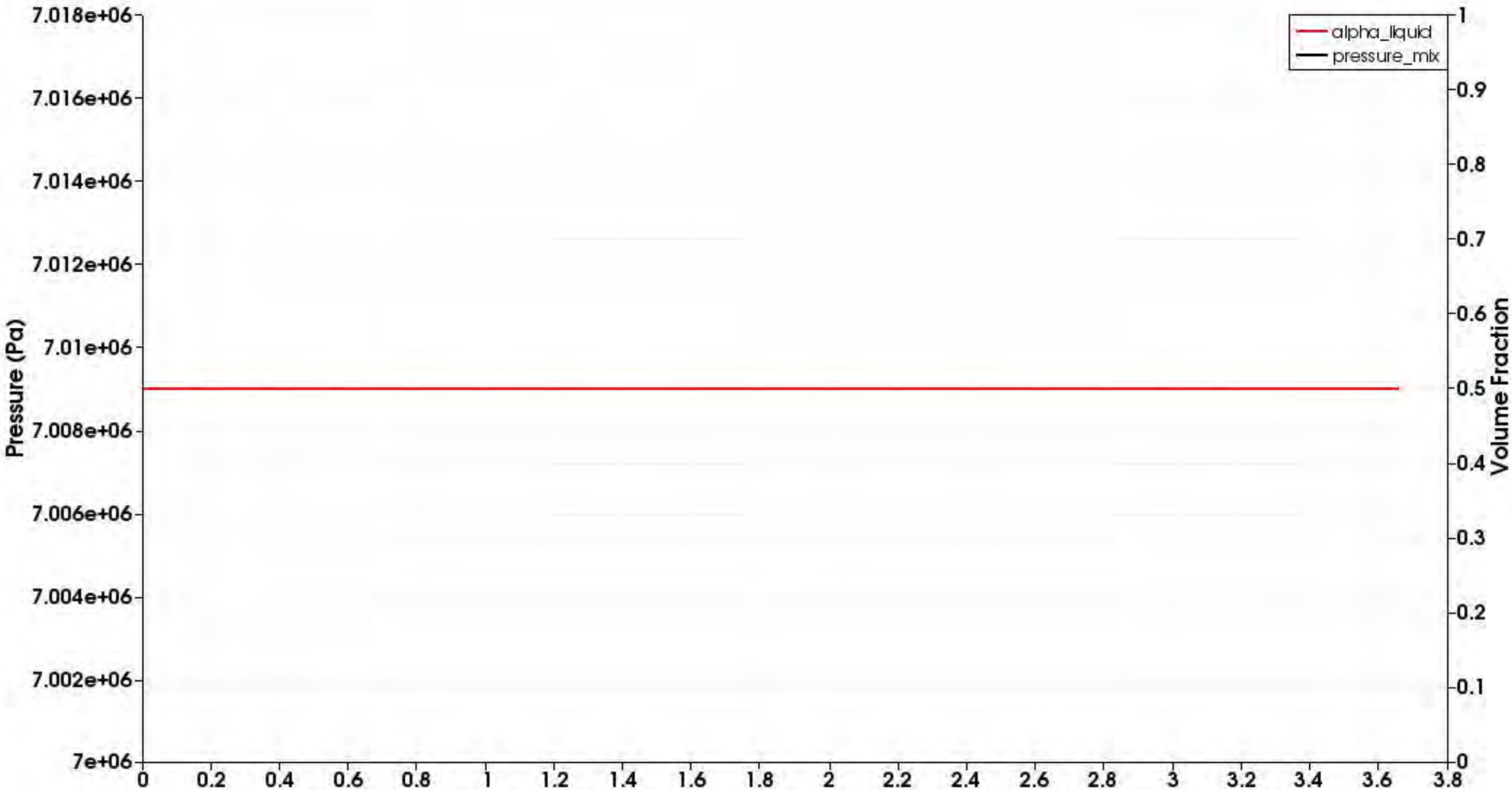
7-equation Two-Phase Hydrostatic Flow Example: Phase Separation



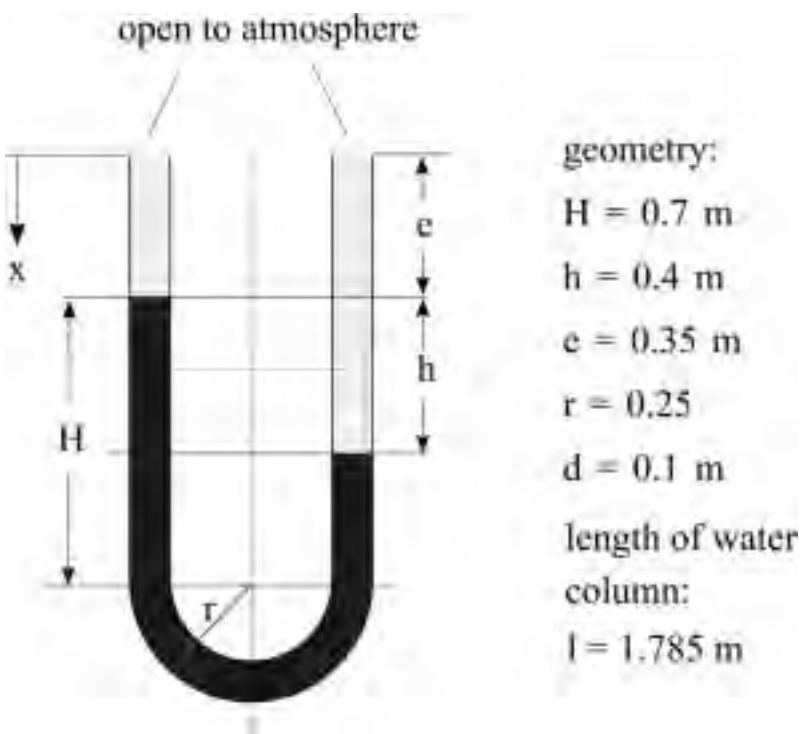
Geometry:
Length = 3.66 m
$A = 2.0 \times 10^{-4}\ m^2$

Initial Conditions (t = 0):
P = 7 Mpa
T = 513 K
u = 0.0 m/s
α = 0.5

7-equation Two-Phase Hydrostatic Flow (600s simulation): Mixture pressure and volume fraction



Oscillating Manometer Problem (it's harder than it looks)



Analytical Solution:

- Frequency and Period,

$$\omega = \frac{1}{T} = \sqrt{\frac{g}{2\pi^2 l}}$$

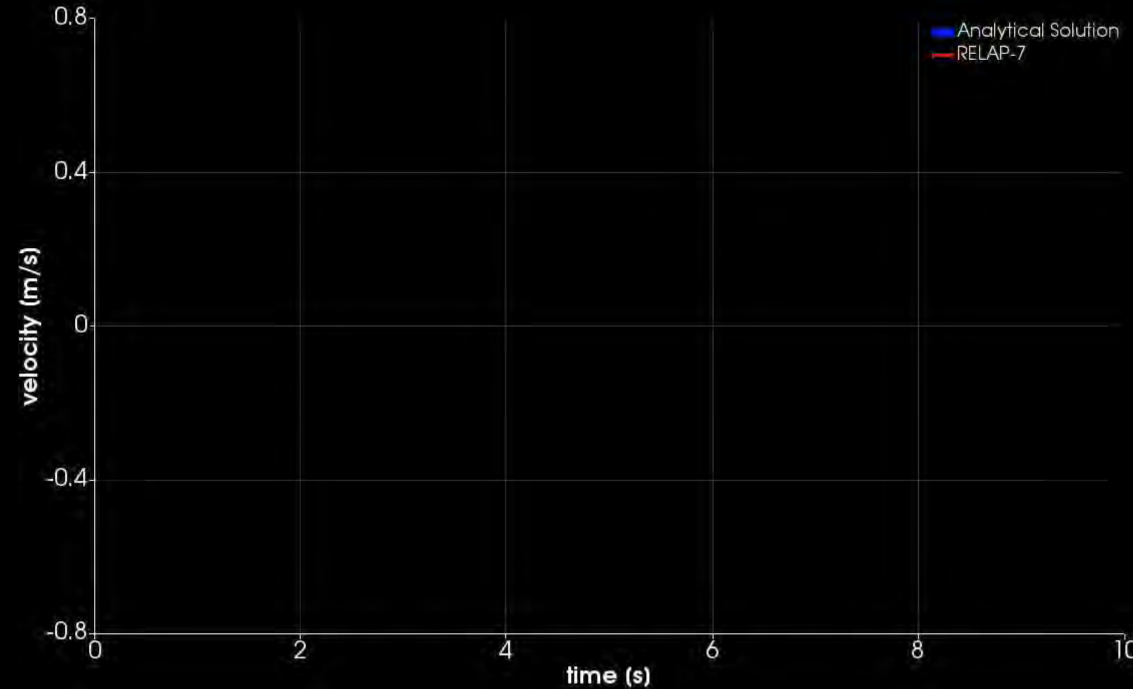
- Maximum Velocity

$$u_l^{max} = \sqrt{\frac{g}{2l}} h$$

- Velocity vs. Time

$$u_l(t) = u_l^{max} sin\left(\frac{t}{\omega}\right)$$

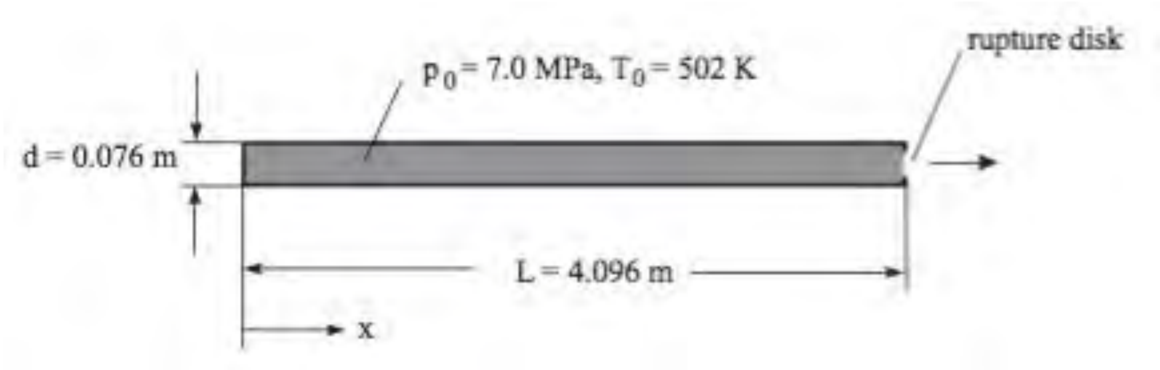
Oscillating Manometer (Pressure and Volume Fraction)



U-tube oscillator
RELAP-7

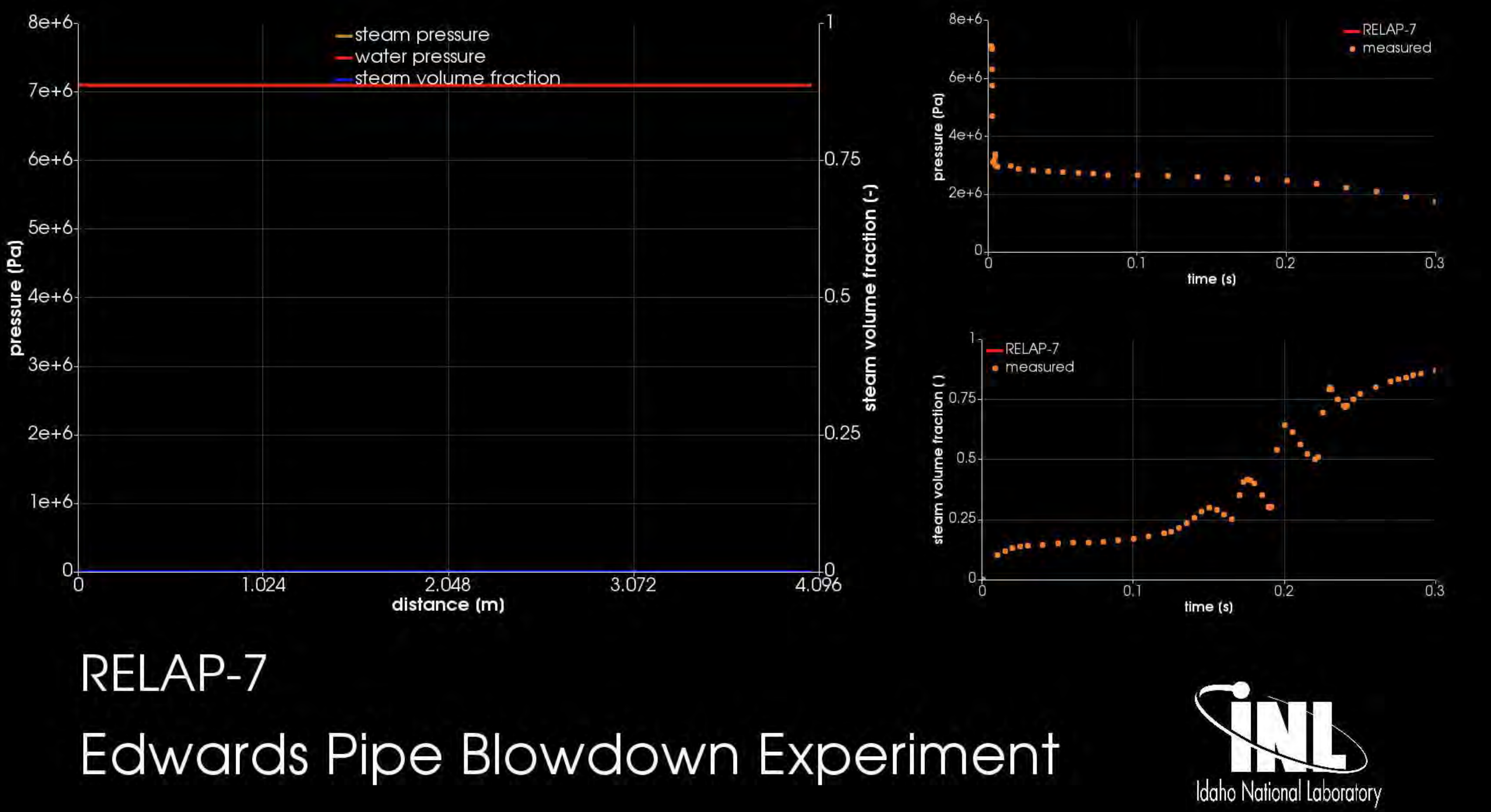
Edwards' Pipe Blowdown Experiment

- 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.

Edwards' Pipe Blowdown Experiment: Preliminary RELAP-7 Result



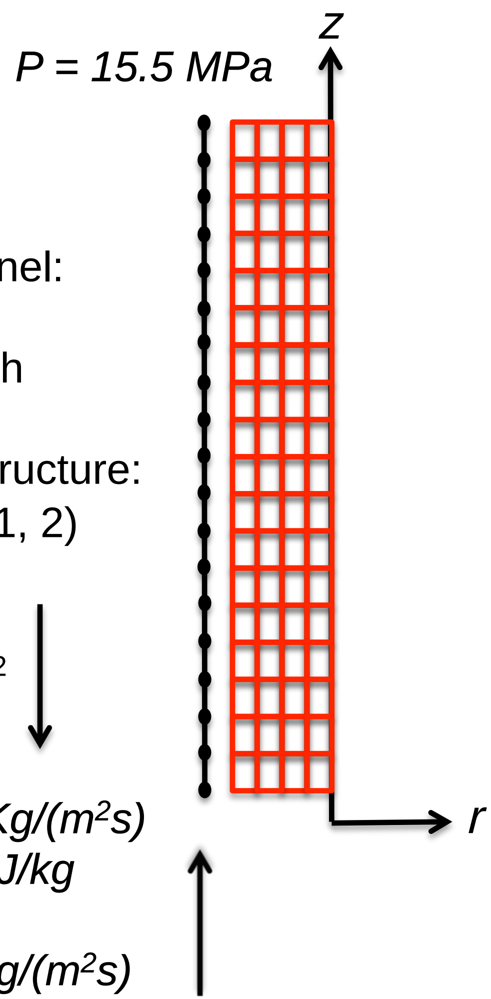
Preliminary RELAP-7 SBO Result

RELAP-7 PWR Two-Phase Core Channel SBO (4-year simulation)

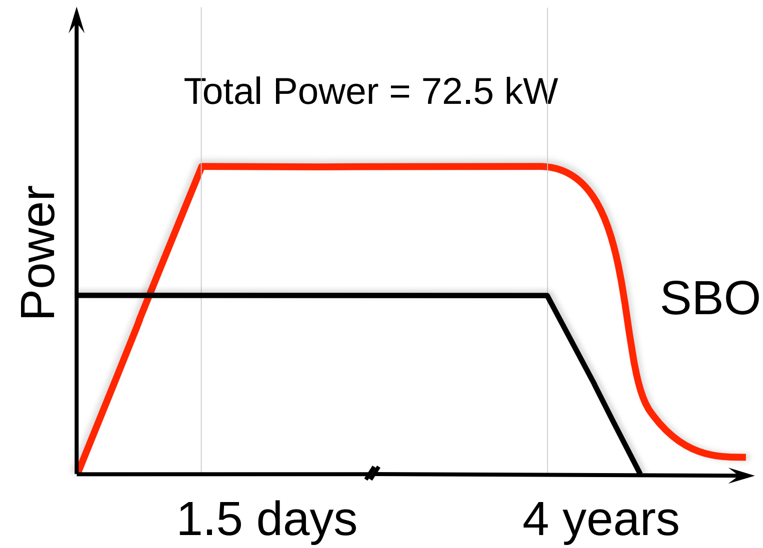
Core Channel:
230 FEs
4.6 m length

2D Heat Structure:
3-zone (5, 1, 2)

$g = 9.81\ m/s^2$

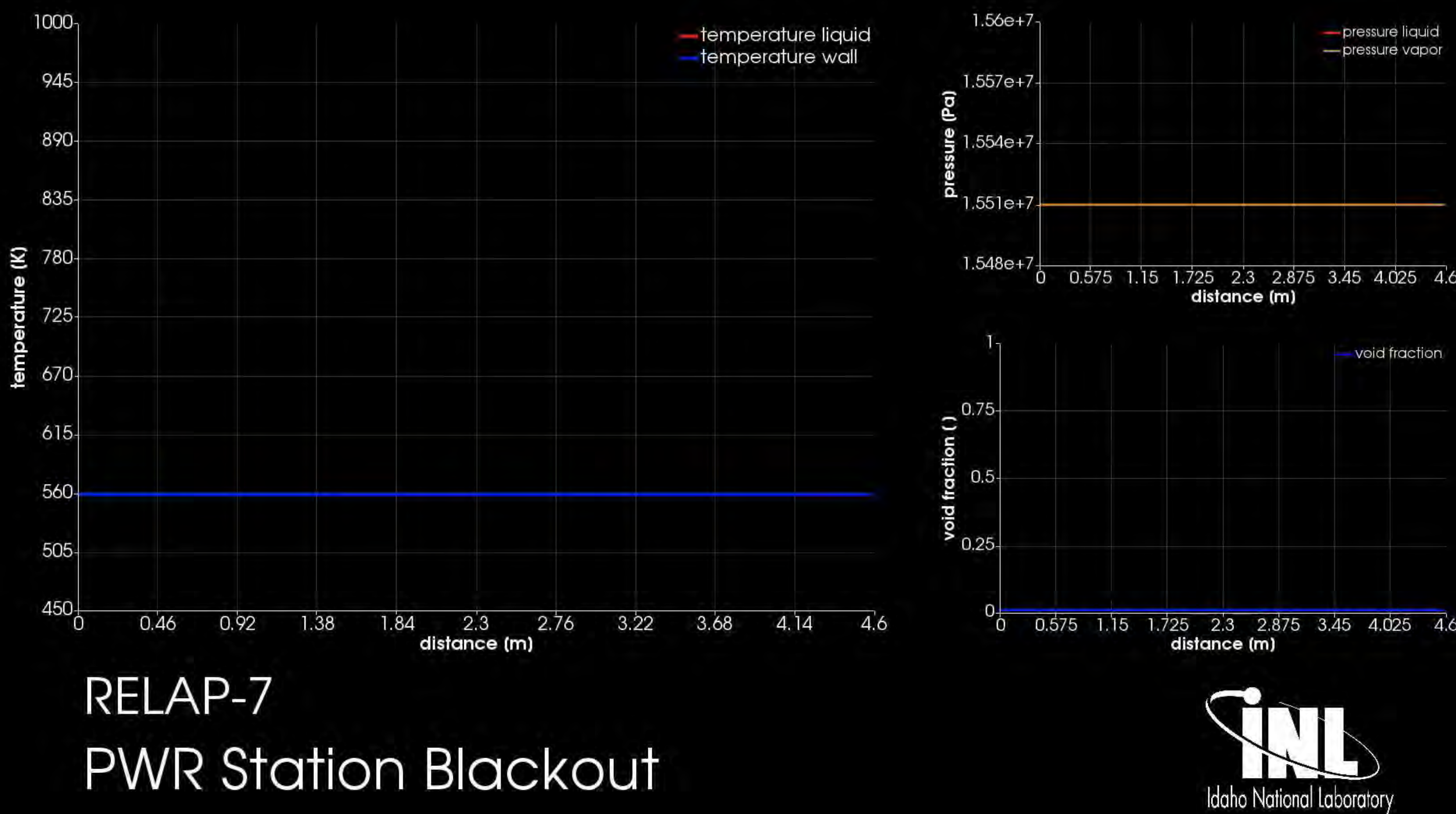


$(\rho u)_l = 3632.3\ Kg/(m^2 s)$
$H_l = 1.19128\ MJ/kg$
$\alpha = 0.995$
$(\rho u)_g = 304.2\ Kg/(m^2 s)$
$H_g = 2.85184\ MJ/kg$

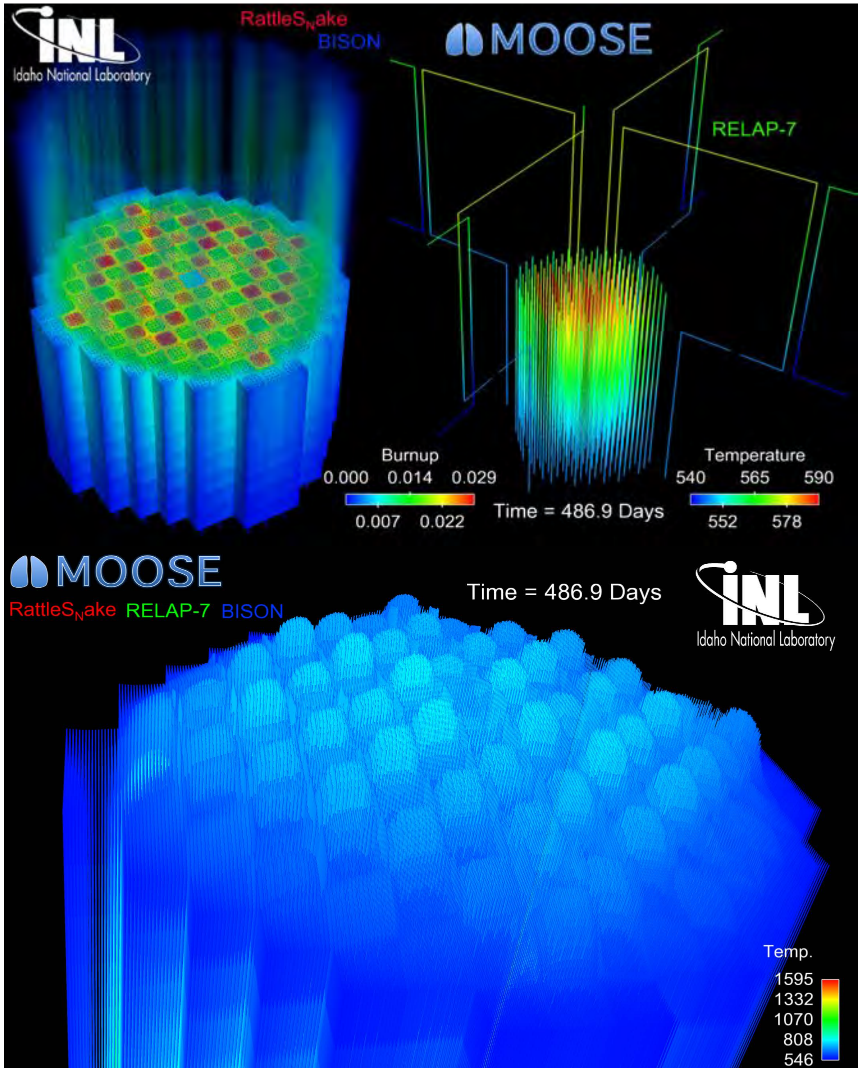


- 1.5-day power-up
- 4-year run (heavy FP content)
- 1 minute pump failure
- Simulation stops when clad temperature reaches 1150K
- Empirical burnup and decay heat

RELAP-7 PWR Two-Phase Core Channel SBO (4-year simulation)



Demonstration of Multi-Physics Integration for Investigation of LOCA Fuels Performance



Multi-Physics through MOOSE:

- *RELAP-7* by itself does not provide the physics to analyze fuel under normal reactor or accident conditions.
- NRC has proposed a new rule, 50.46c, which introduces new more restrictive performance-based requirements. This rule may require re-analysis of all existing U.S. LOCA basis.
- This rule essentially states that every in-core fuel rod needs to be analyzed…
- *MOOSE* provides the capability to easily integrate MOOSE-based applications, such as RELAP-7 with *BISON, Rattlesnake, MAMMOTH, MAMBA and Vulture* (CASL), …

Multi-physics RIA Results with RELAP-7 and BISON

Nuclear Fuels Performance: *"The centerpiece of any nuclear physics M&S effort. Without nuclear fuel there are no challenges with safety, materials, waste, or politics. Nor is there nuclear power"*

BISON: Engineering-scale Fuel Performance Application

- All-fuels: Models LWR, TRISO, plate, and metal fuels in 1D, 2D and 3D.
- Adheres to NQA-1 requirements.
- BISON is leveraged across multiple DOE programs.
- Funding Sources: NEAMS, FCRD, LWRS, NGNP, and CASL.
- Collaborators:

University of South Carolina

CASL

UC Davis University of California

Idaho National Laboratory

Los Alamos National Laboratory Est. 1943

PennState

National Nuclear Laboratory

ANATECH

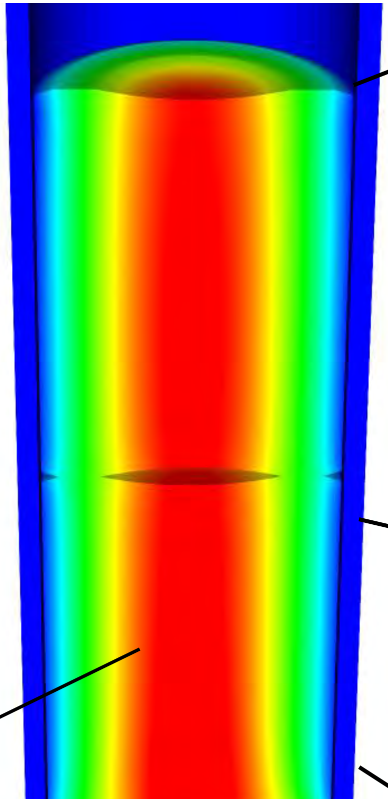
BISON LWR (UO_2) Capabilities

General Capabilities

- Finite element based 1D spherical, 2D axisymmetric and 3D fully-coupled thermo-mechanics with species diffusion
- Linear or quadratic elements with large deformation mechanics
- Steady and transient operation
- Massively parallel computation
- Meso-scale informed material models

Oxide Fuel Behavior

- Temperature/burnup/porosity dependent conductivity
- Heat generation with radial and axial profiles
- Thermal expansion
- Solid and gaseous fission product swelling
- Densification
- Thermal and irradiation creep
- Fracture via relocation or smeared cracking
- Fission gas release (two stage physics)
  - transient (ramp) release
  - grain growth and grain boundary sweeping



Temperature

Gap/Plenum Behavior

- Gap heat transfer with k_g= f (T, n)
- Mechanical contact (master/slave)
- Plenum pressure as a function of:
  - evolving gas volume (from mechanics)
  - gas mixture (from FGR model)
  - gas temperature approximation

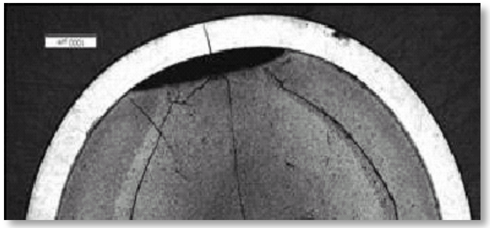
Cladding Behavior

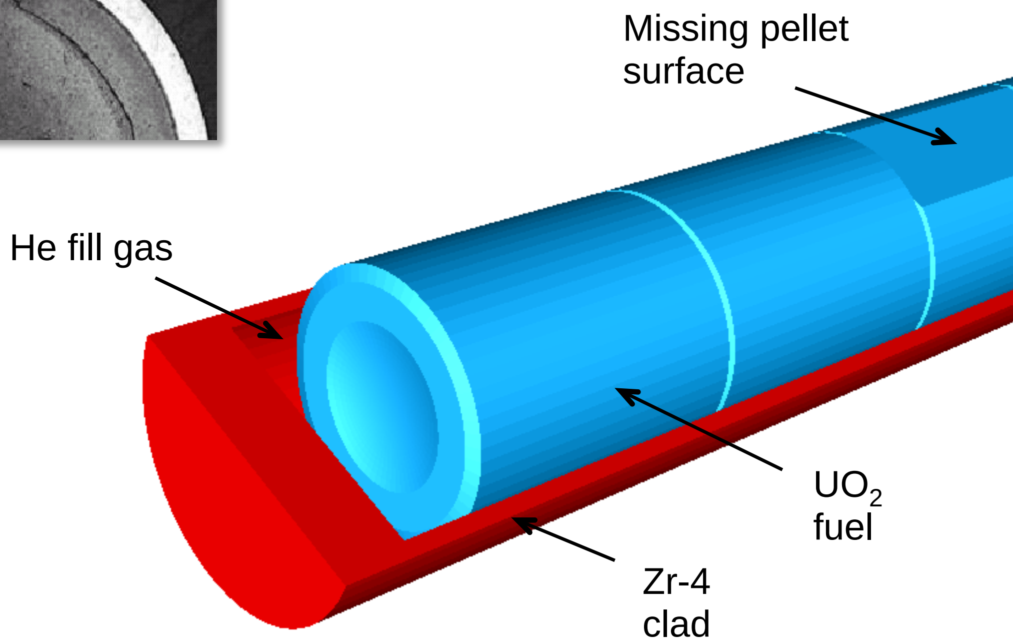
- Thermal expansion
- Thermal and irradiation creep
- Irradiation growth
- Oxide layer growth
- Gamma heating
- Combined creep and plasticity
- Hydride damage

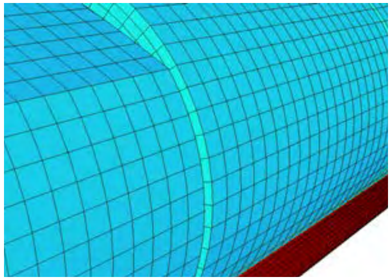
Coolant Channel

- Closed channel thermal hydraulics with heat transfer coefficients

PCMI - Missing Pellet Surface Analysis

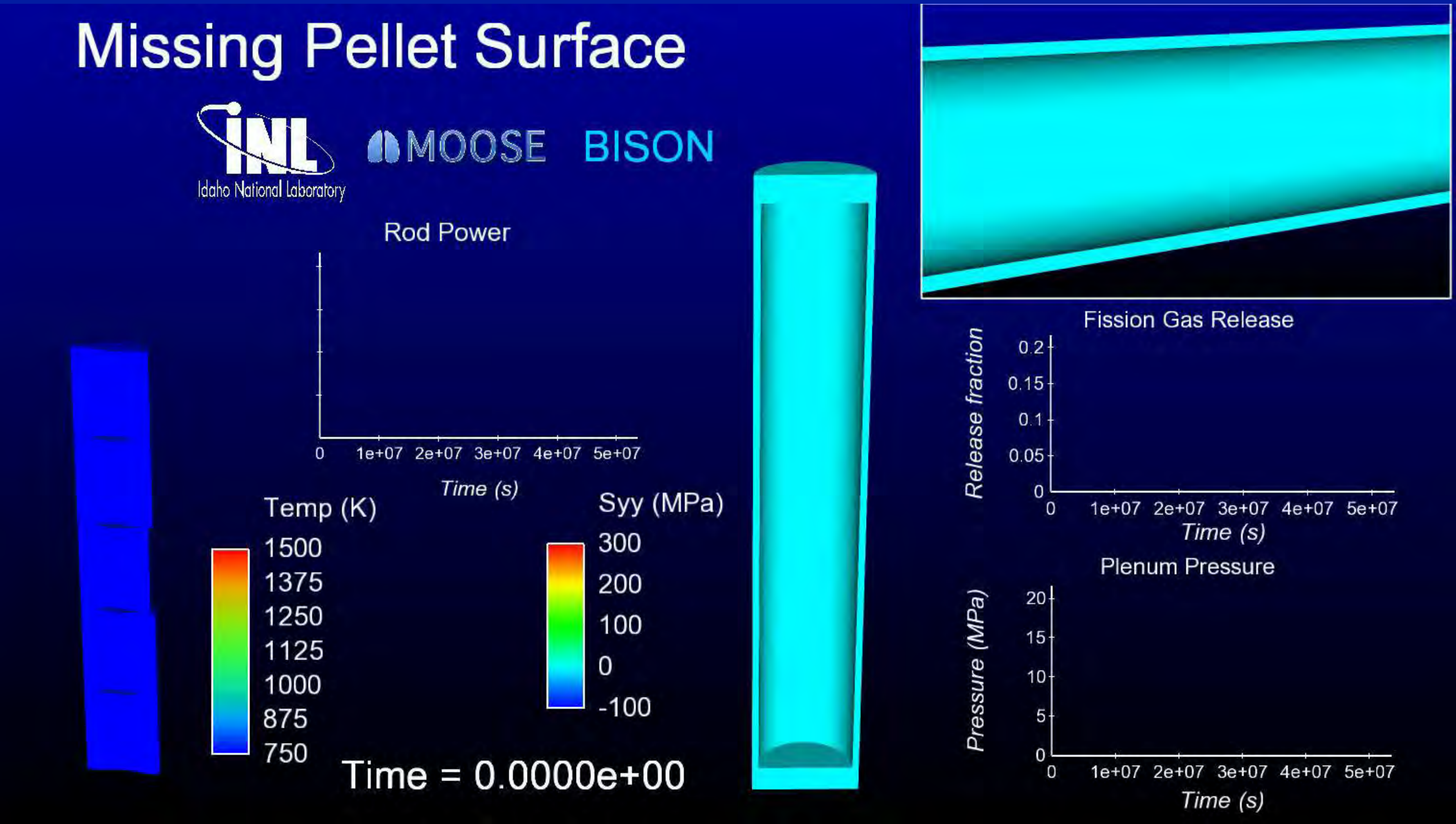






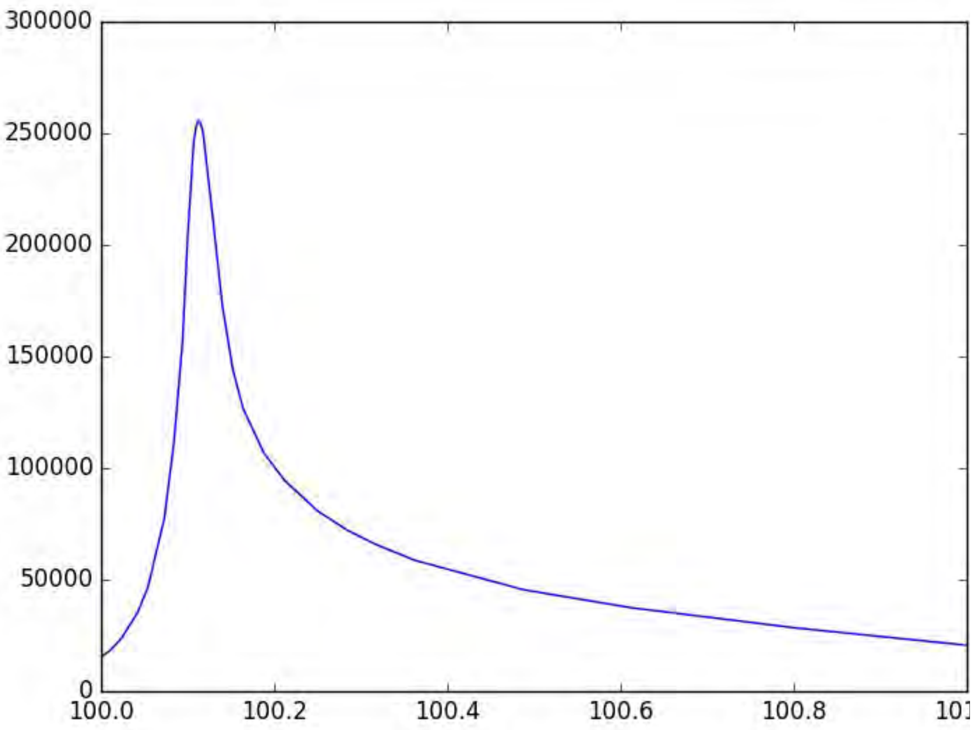
- High resolution 3D calculation (250,000 elements, 1.1×10^6 dof) run on 120 processors
- Simulation from fresh fuel state with a typical power history, followed by a late-life power ramp

Animation – Missing Pellet Surface with Power Ramp

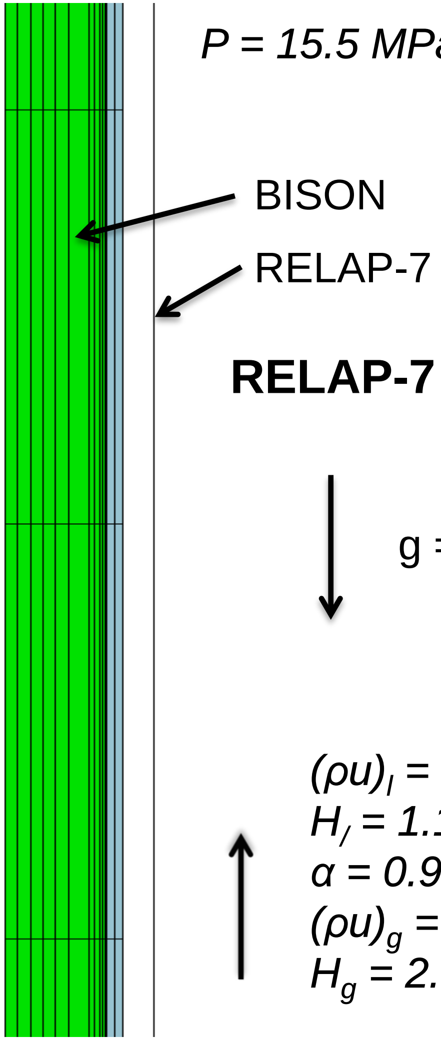


BISON/RELAP-7 Reactivity Insertion Accident

Pin Power Profile (BNL)



P = 15.5 MPa



RELAP-7 Conditions

↓ $g = 9.81\ m/s^2$

↑

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

Preliminary Multi-physics SBO LOCA Results with MAMMOTH, Rattlesnake, BISON, and RELAP-7

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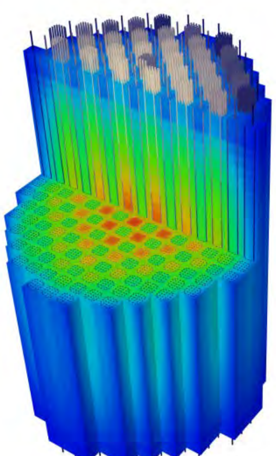
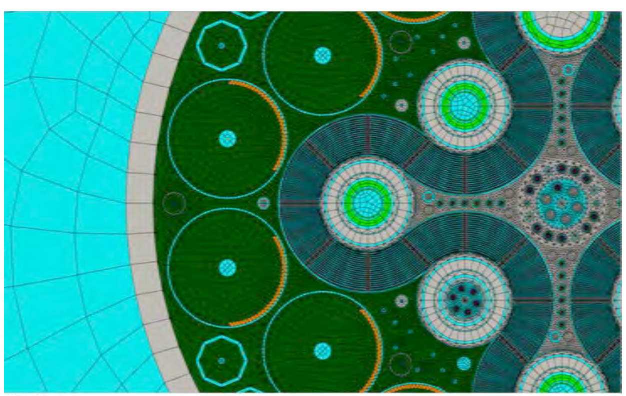
Determining the Power: Fission rate in the fuel

Rattlesnake: Multi-scale Multi-level Radiation Transport

- Multi-scale: Assembly homogenized, pin-homogenized, fuel-resolved simultaneously in one simulation.
- Simultaneous Arbitrary-order Integration: *Time-dependent* Multi-group diffusion, P_N, and 2^{nd}-order S_N.
- Designed to support tightly coupled nonlinear multiphysics simulations, *primarily focused on fuel performance analysis*, both locally and core-wide for safety issues and ATF design (strong transients).
- ATR and TREAT simulation capability design goals.
- Thermal radiation.
- Funding Source: NEAMS
- Collaborators:





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TEXAS A&M UNIVERSITY

Massachusetts Institute of Technology

Reactor/Radiation Physics

MAMMOTH: Advanced Multi-Scale Nuclear Reactor Physics and Fuel Management System

- ***Core Management:***
  - Supports macroscopic, microscopic, and hybrid isotope depletion.
  - State-of-the-art depletion solver with Chebyshev Rational Approximation Method (CRAM).
  - Customizable nuclide inventory.
  - Cross-sections from Serpent or DRAGON5.
  - Pin-wise power and burnup distributions.
  - Fuel loading and assembly shuffling optimization.
- ***Fuel modeling:***
  - Isotopic composition to BISON and MARMOT (fuel performance) to update local fuel thermal conductivities and fission gas inventories.
  - Isotope, density, and temperature feedback (to account for burnup) for cross-sections.
  - Thermo-mechanical-chemical property evolution.
  - DPA for radiation damage characterization.
  - Determination of high burn-up structures (HBS).
- **Funding Source:** NEAMS
- **Collaborators:**

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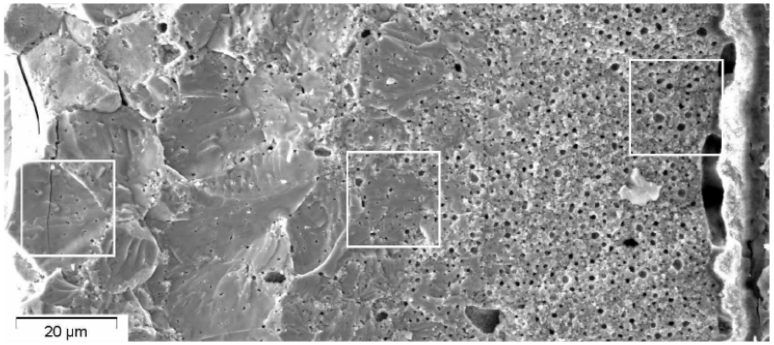
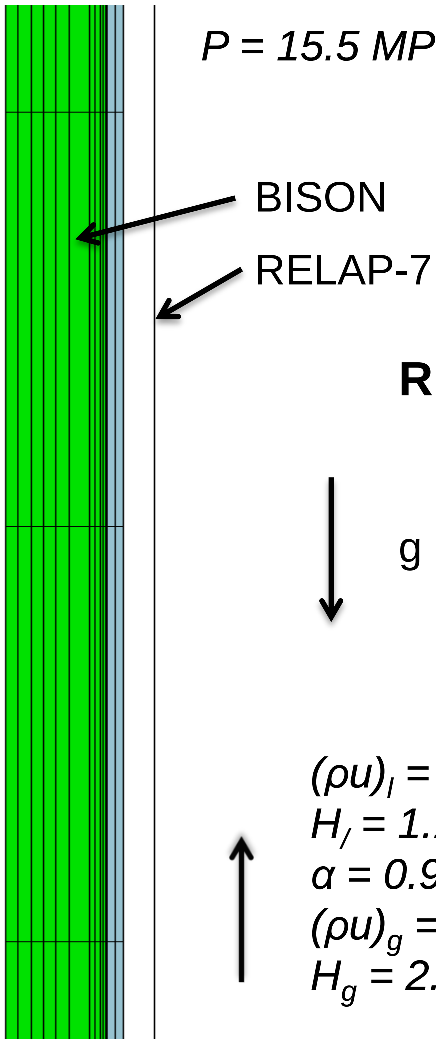
Massachusetts Institute of Technology



PWR SBO LOCA Description



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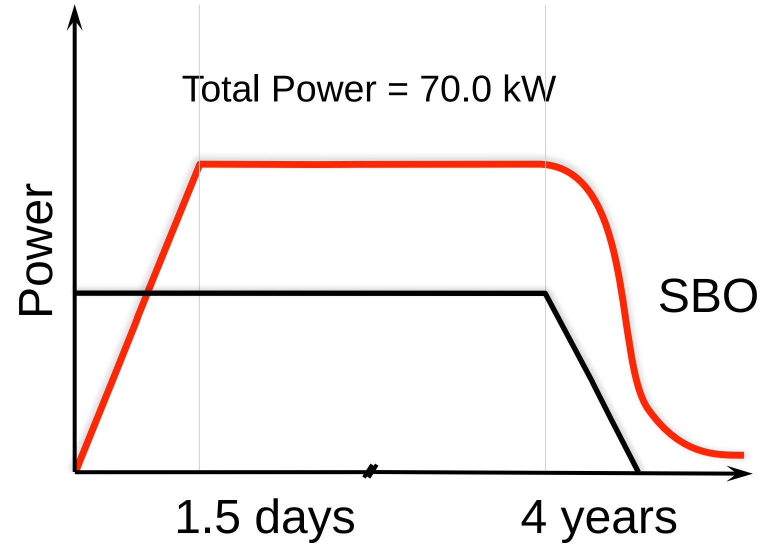
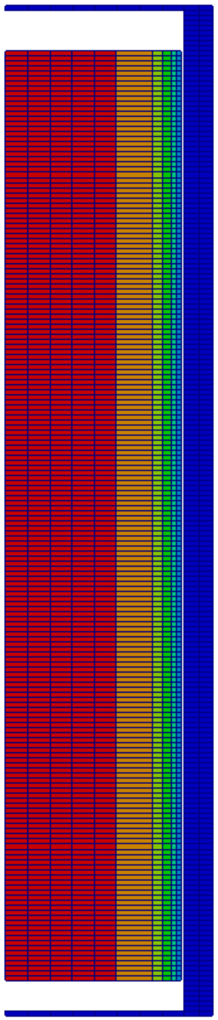


- 1.5-day power-up
- 4-year run
- 1 minute pump failure
- Simulation stops when clad temperature reaches 1150K
- Power from *Rattlesnake,* decay heat from *MAMMOTH,* and fuel performance from *BISON*

Nuclear Fuel Performance Geometry for BISON

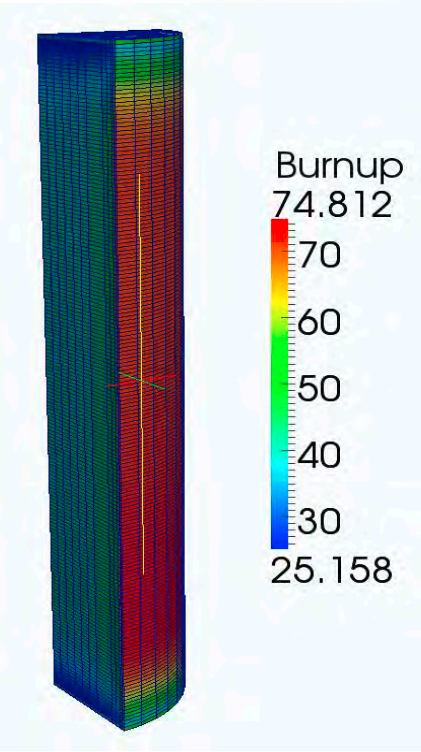


- 2D Axisymmetric Mesh (r-z).
- Matches neutronics mesh for height, radius etc…
- Radial ring structure that matches the neutronics mesh.
- 184 axial subdivisions in fuel and 200 total in cladding.
- No mesh in radial gap, upper and lower plenums.

Takahama-3 Pin Depletion - Outline

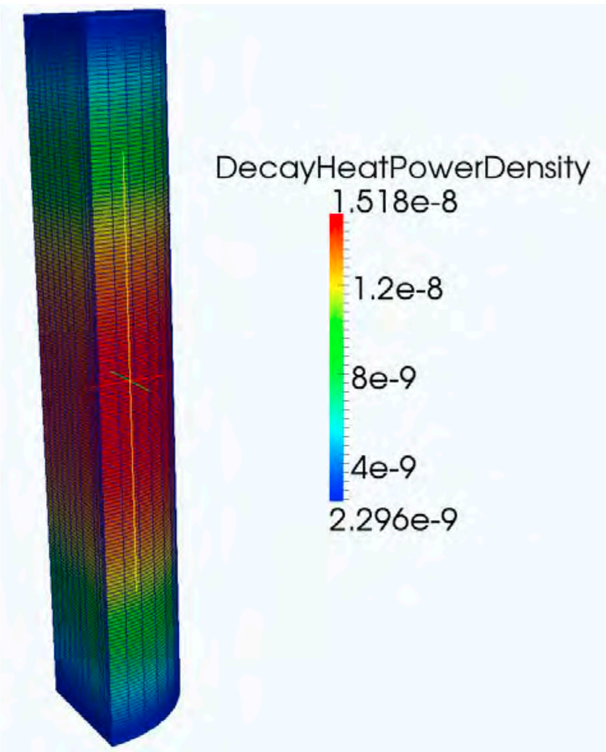
- Based on the TAKAHAMA-3 sample (SF97-3)
  - Sample location represents average power behavior in the pin.
- Cross sections from *DRAGON5* tabulated as a function of:
  - Burnup in each of 6 radial rings,
  - Fuel temperature, and
  - Moderator density.
- Depletion calculation
  - Macro depletion with no history effects.
  - Fixed boron concentration at 500 ppm.
  - Burn straight through (no down time) up to 1343 EFPD.
  - Cycle 5, 6, 7 power densities (35.19, 37.53, 33.31 MW/MTU).
  - Linear heat generation rate ~ 70 kW.

2D Burnup Distribution and Decay Heat Power



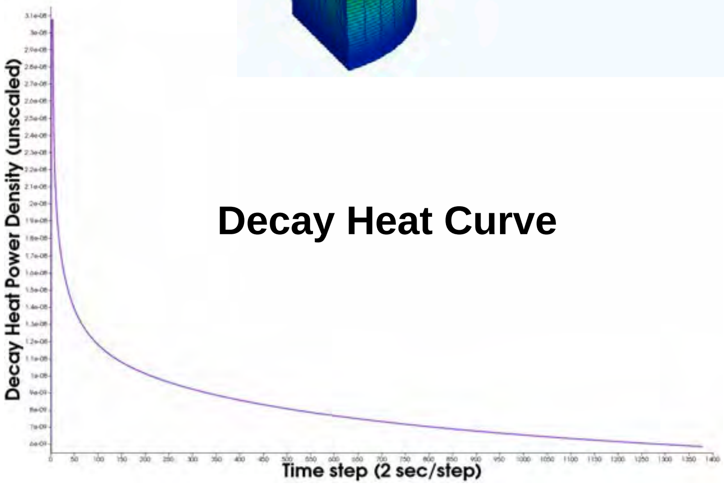
Decay heat calculation:

- Implementation of ANSI/ ANS-5.1-2005.
- Fractional powers from ^{235}U, ^{238}U, ^{239}Pu, and ^{241}Pu depend on burnup for each element in each radial ring.
- No correction for neutron capture in fission products.
- No ^{239}U and ^{239}Np decay taken into account.

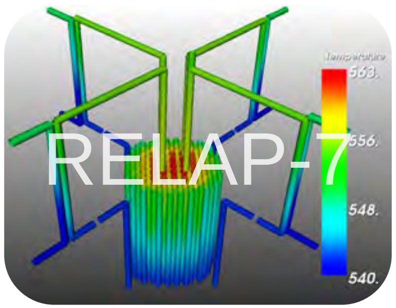


Burnup Calculation:

- Burnup at 3.7 years.
- Rim effect clearly captured.
- Burnup structure affects the thermal conductivity in the fuel performance.

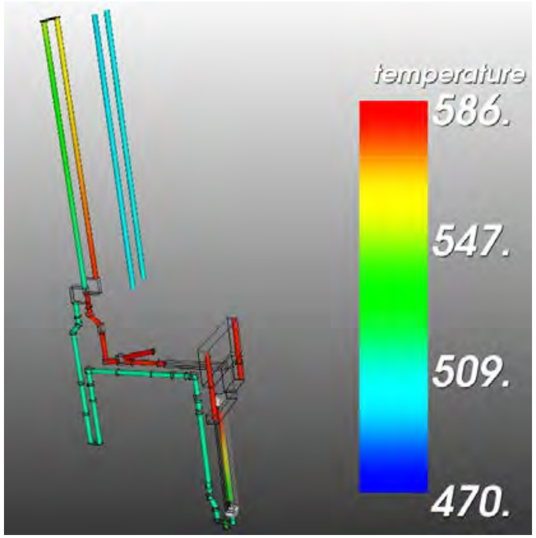


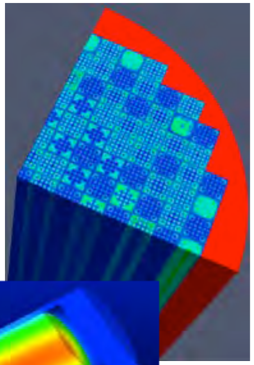
This is what multi-physics fuels performance M&S looks like



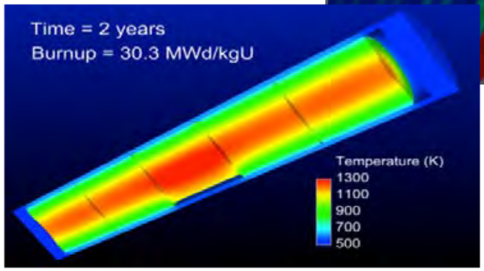
Reactor Physics

Thermal Fluids

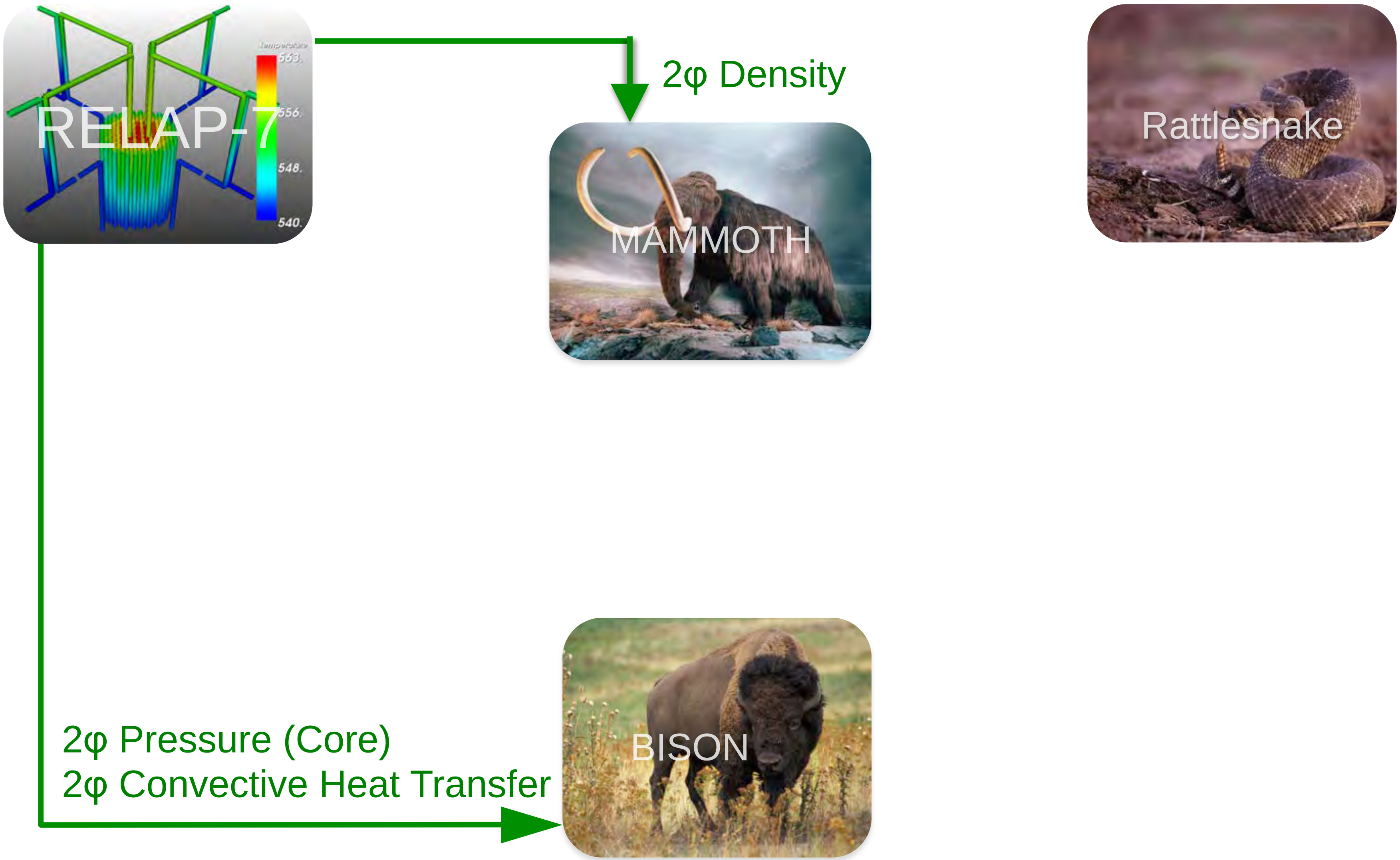




Nuclear Fuels Performance



This is what multi-physics fuels performance looks like



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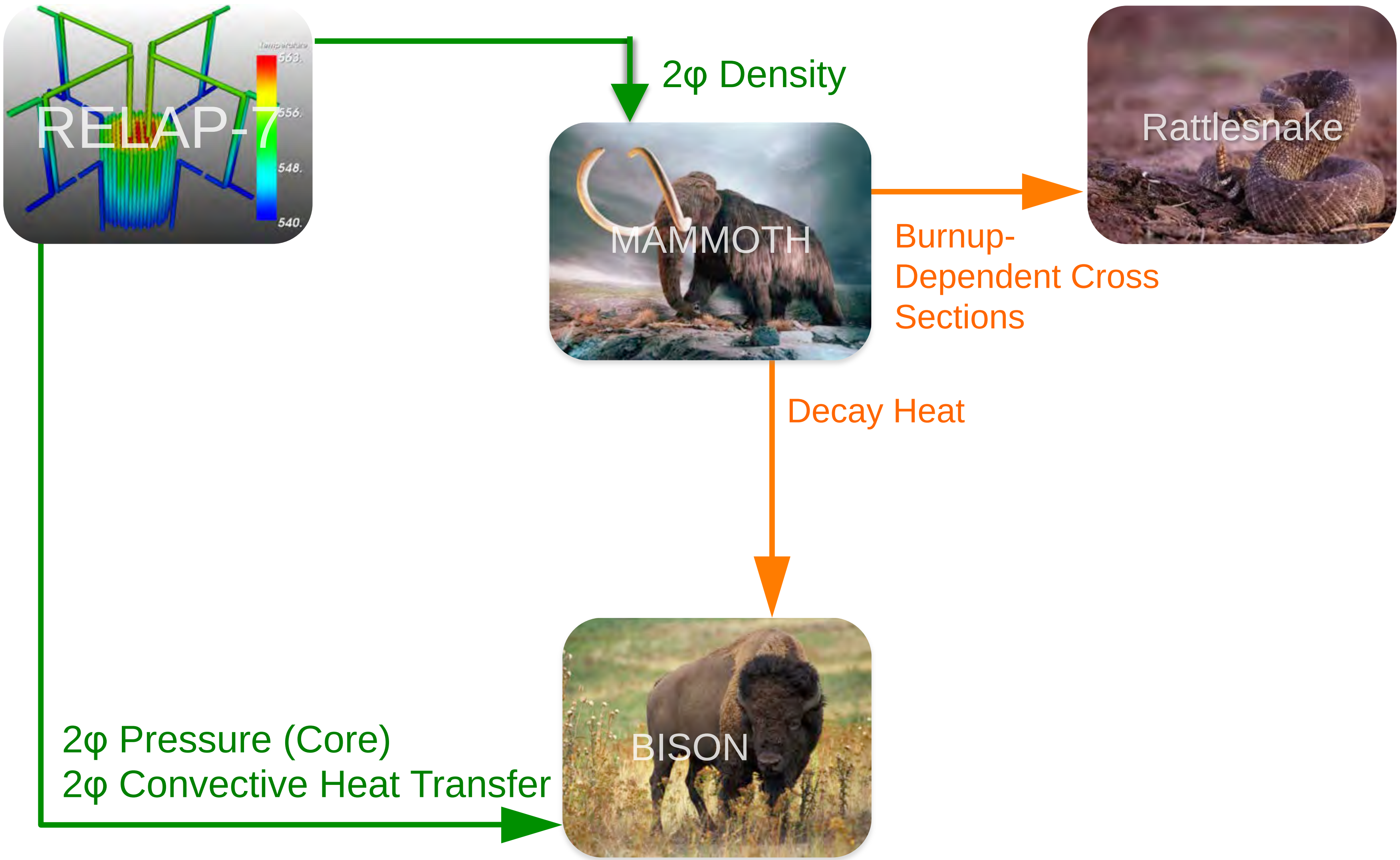

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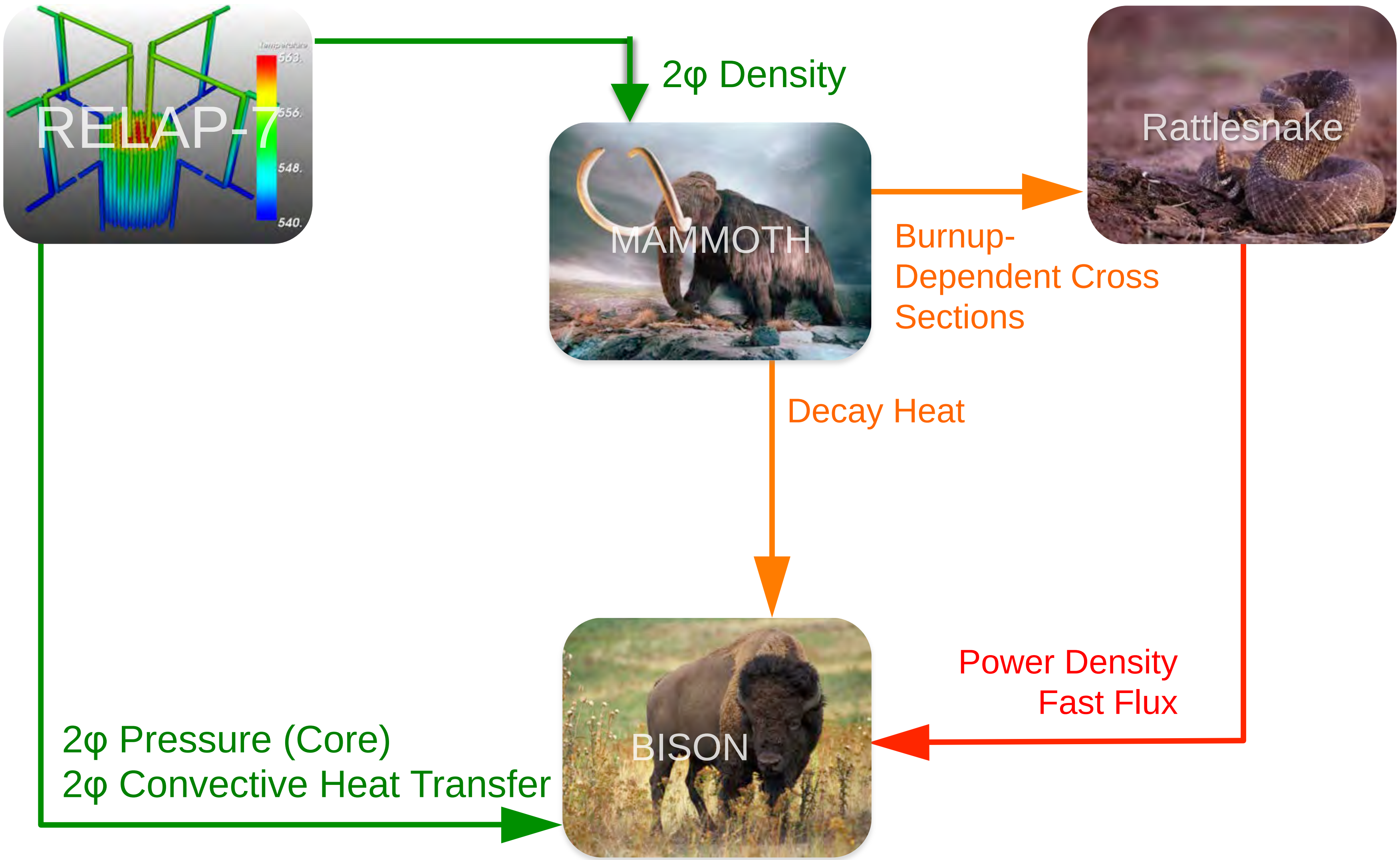

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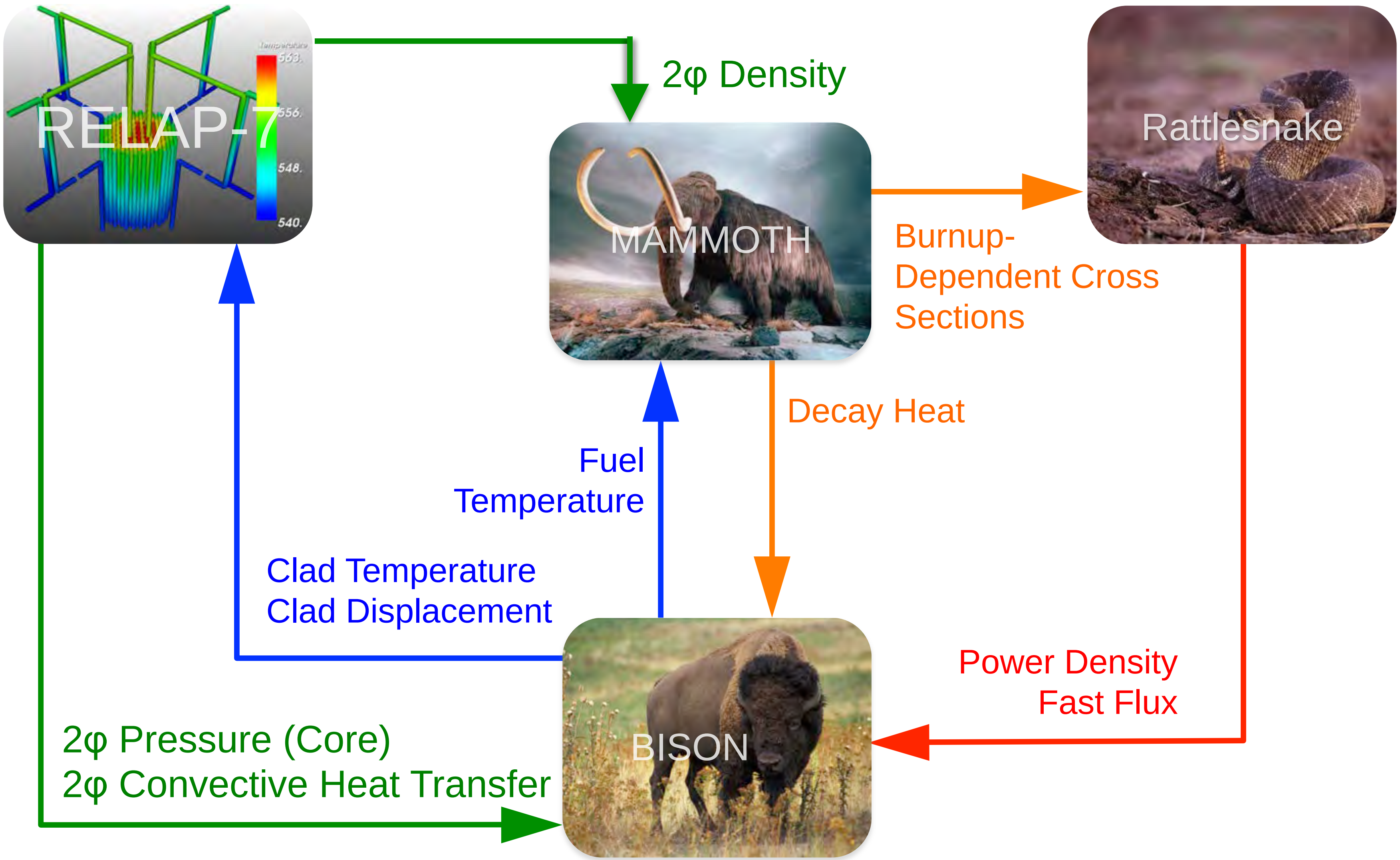
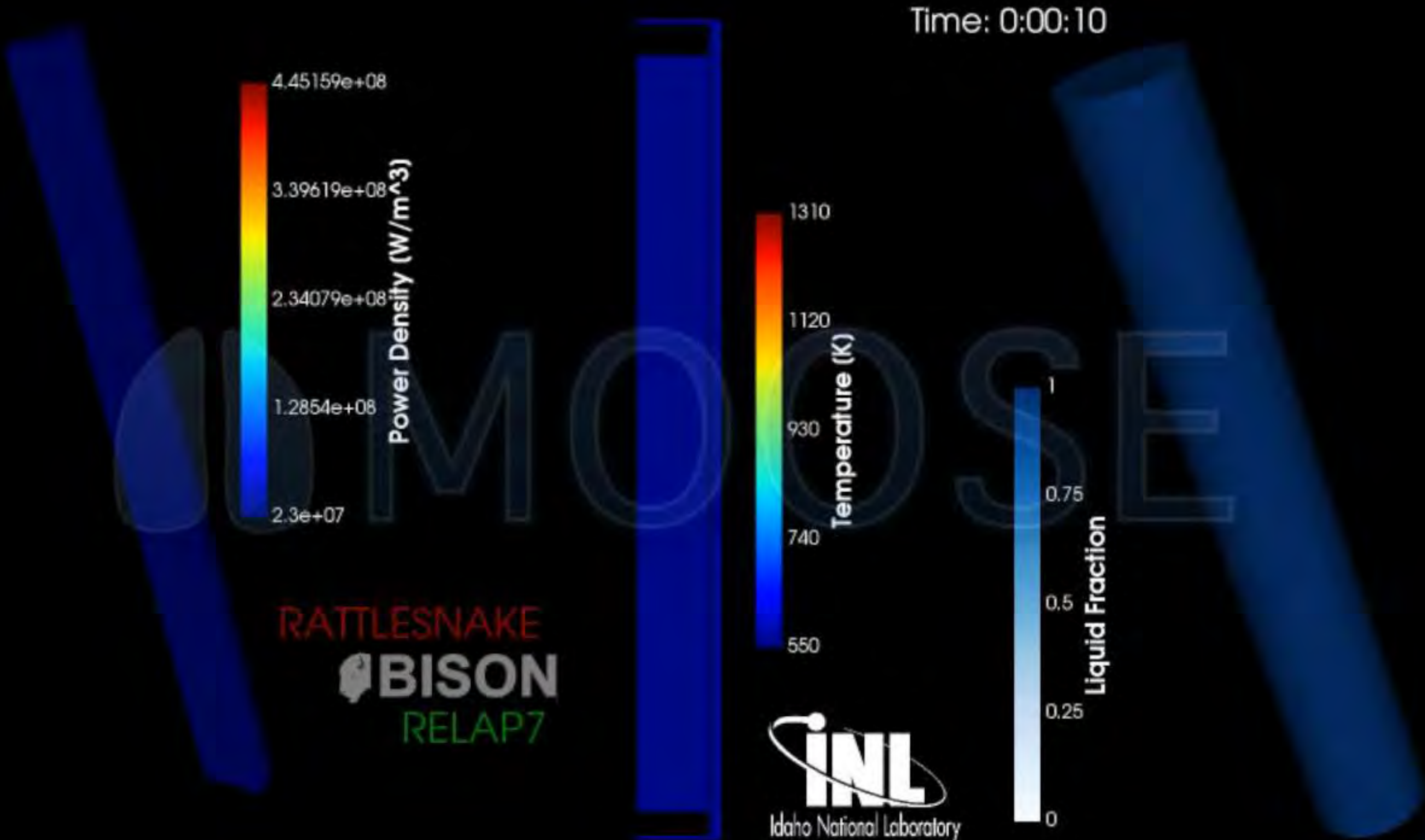


PWR Burnup, Power, Fuel Temperature, and Two-Phase Flow Channel for SBO

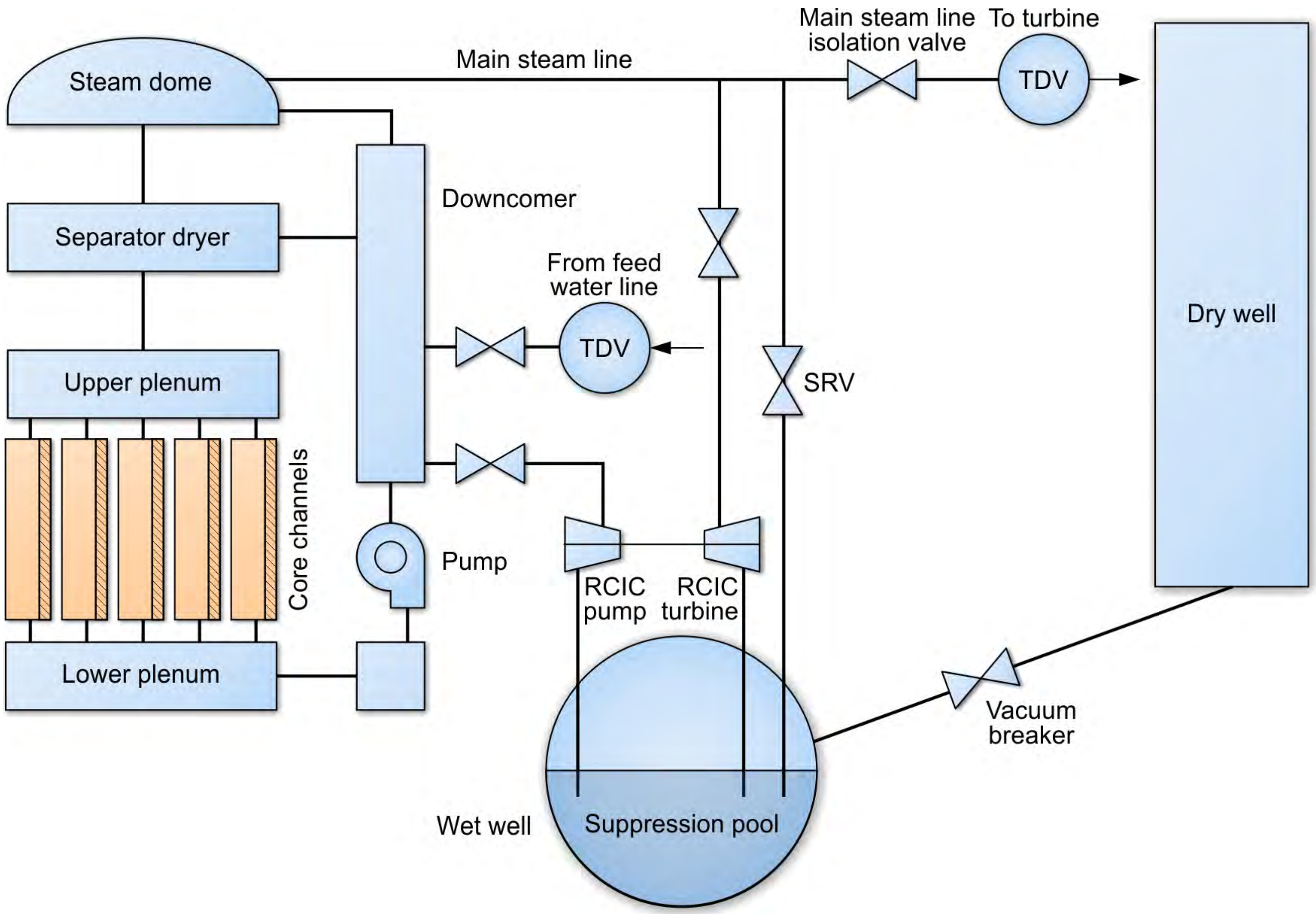


Clad Displacement and Two-Phase Flow Core Channel Boil-Off for SBO

In the Future, Full Plant Analysis

Multiphysics Core:

- BISON
- Marmot
- Hyrax
- Vulture
- Rattlesnake
- MAMMOTH
- MAMBA
- Hognose
- etc.



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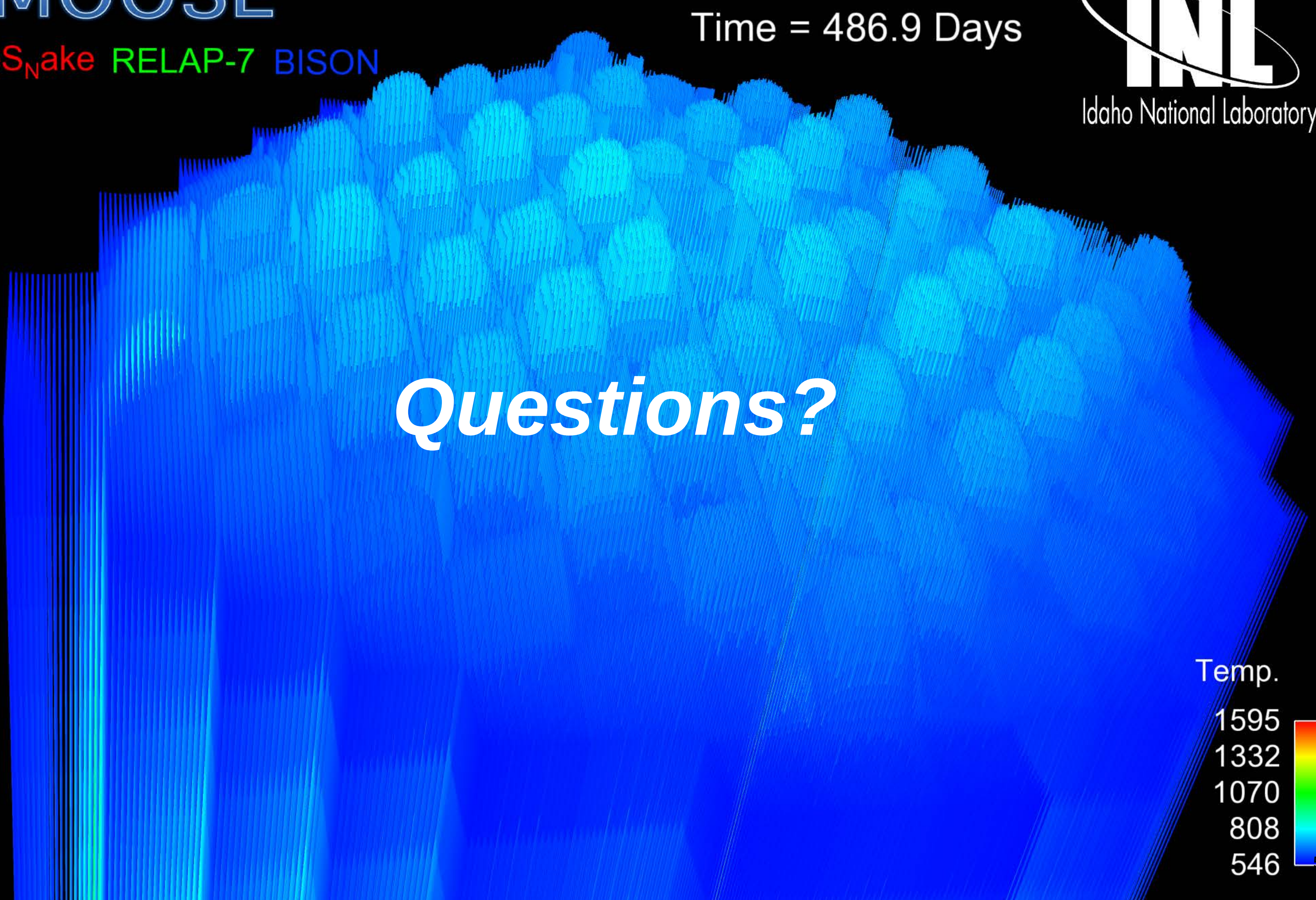
MOOSE

RattleS$_N$ake RELAP-7 BISON



Questions?