RELAP-7 Code Development Status Update and Future Plan

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RELAP-7 Team:

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- Simulation: Haihua Zhao, Ling Zou, and Hongbin Zhang
- Framework: David Andrs and John W Peterson
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  Steve Hess and Gregg Swindlehurst from EPRI

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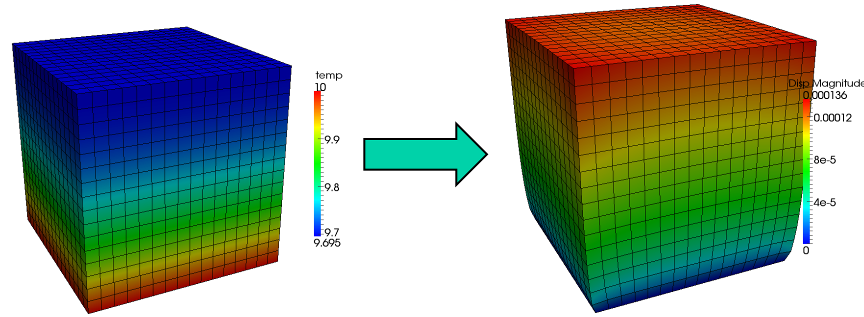
Idaho National Laboratory

RELAP-7 Overview

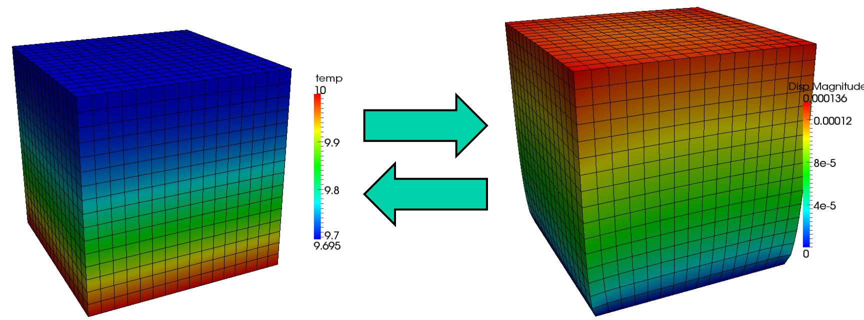
- The RELAP-7 application is the next generation nuclear reactor system safety analysis code.
- The code is based upon the MOOSE (Multi-Physics Object-Oriented Simulation Environment) framework: continuous finite element method (CFEM), implicit fully coupled components, mesh and time adaptivity, parallel software
- Fully implicit solver achieved by Jacobian-Free Newton Krylov (JFNK) method (MOOSE's main solver). Other time integration schemes include PCICE (operator split, being implemented) and a point implicit method (long duration transients, prototyped not yet implemented)
- 2nd-order accurate temporal and spatial discretization (reduces the traditional numerical errors)
- Well-posed 7-equation two-phase flow model
- Ability to couple to multi-dimensional reactor simulators through MOOSE

Multiphysics Coupling (Credit to Derek Gaston at INL)

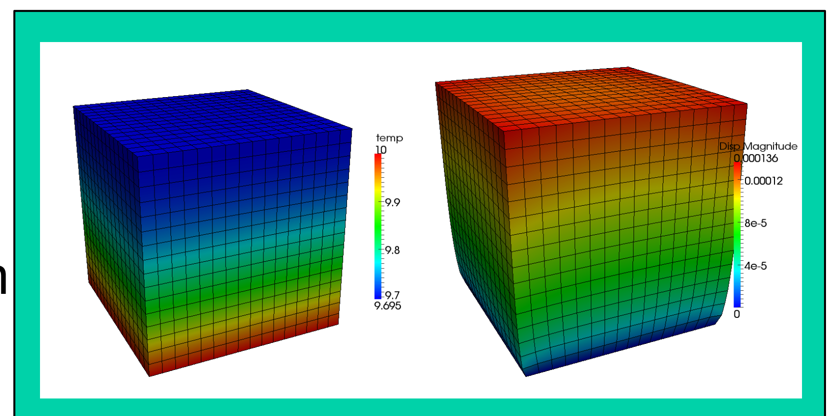
- Loose Coupling / Operator Split
  1. Solve PDE1
  2. Pass Data
  3. Solve PDE2
  4. Move To Next Timestep



- Tight Coupling
  1. Solve PDE1
  2. Pass Data
  3. Solve PDE2
  4. Pass Data
  5. Return to 1 Until Convergence
  6. Move To Next Timestep



- **Fully Coupled** (**RELAP-7**)
  1. Solve PDE1 and PDE2 simultaneously in _one_ system
  2. Move To Next Timestep



Components Completed

Component Name	Descriptions
TimeDependentVolume	Time Dependent Volume to set pressure and temperature boundary conditions
TimeDependentJunction	Time Dependent Junction to set velocity and temperature boundary conditions
TDM	Time Dependent Mass flow rate (TDM) to set mass flow rate and temperature boundary conditions
Branch	Multiple in and out 0-D volume/junction, which provides form loss coefficients (K), for either isothermal flow or non-isothermal flow
Pump	Simple pump model to provide a head and reverse flow form loss coefficients (K), for either isothermal flow or non-isothermal flow
Pipe	1-D fluid flow within 1-D solid structure with wall friction and heat transfer
PipeWithHeatStructure	Simulating real 1-D pipe with solid walls (fluid flow coupled with 1-D/2-D conduction through the pipe wall); can take Adiabatic, Dirichlet, or Convective boundary conditions at the outer surface of the pipe wall
CoreChannel	Simulating flow channel and fuel rod thermal hydraulics, including 1-D fluid flow and fuel rod heat conduction for either plate type or cylinder type of fuel
HeatExchanger	Co-current or counter-current Heat exchanger model, including fluid flow in two sides and heat conduction through the solid wall

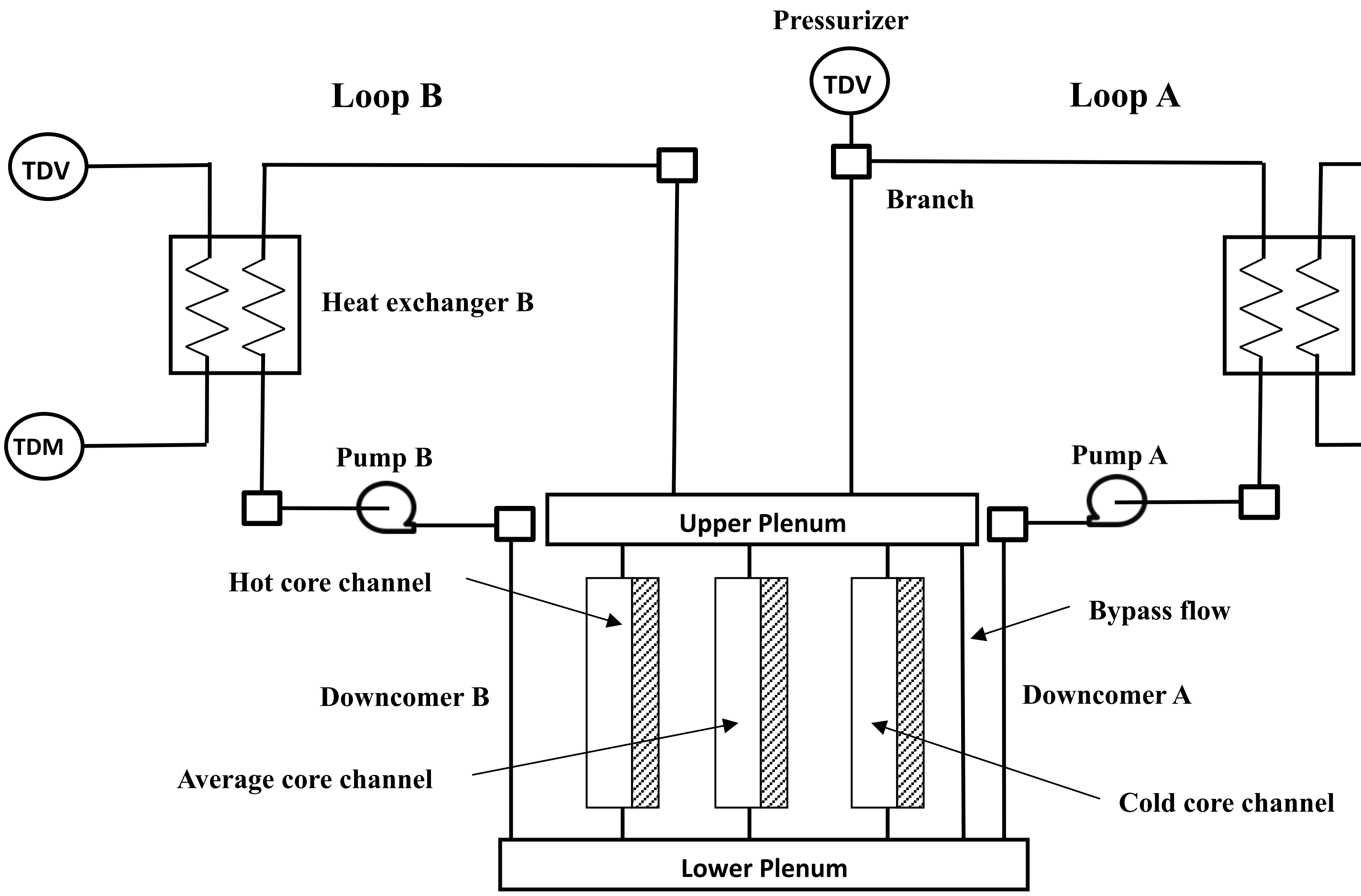
Components Completed - Continues

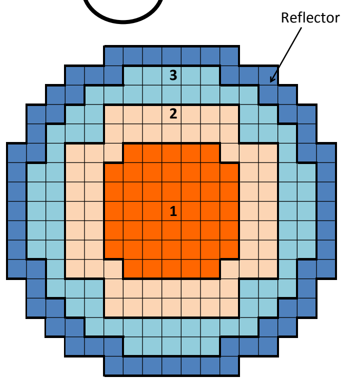
Component Name	Descriptions
DownComer	Large volume to mix different streams of water and steam and to track the water level
Valve	Simulate control mechanisms of real valves in a hydrodynamic system
Turbine	A simplified dynamical turbine model to simulate a reactor core isolation cooling (RCIC) turbine, which drives the RCIC pump through a common shaft
WetWell	Simulate a BWR suppression pool and its gas space
Reactor	A virtual component that allows users to input the reactor power
SeparatorDryer	Separating steam and water with mechanical methods, 1 in and 2 outs, 0-D volume
PointKinetics	0-D point kinetic neutronics model to simulate reactor kinetics and decay heat generation

FY12 Accomplishments

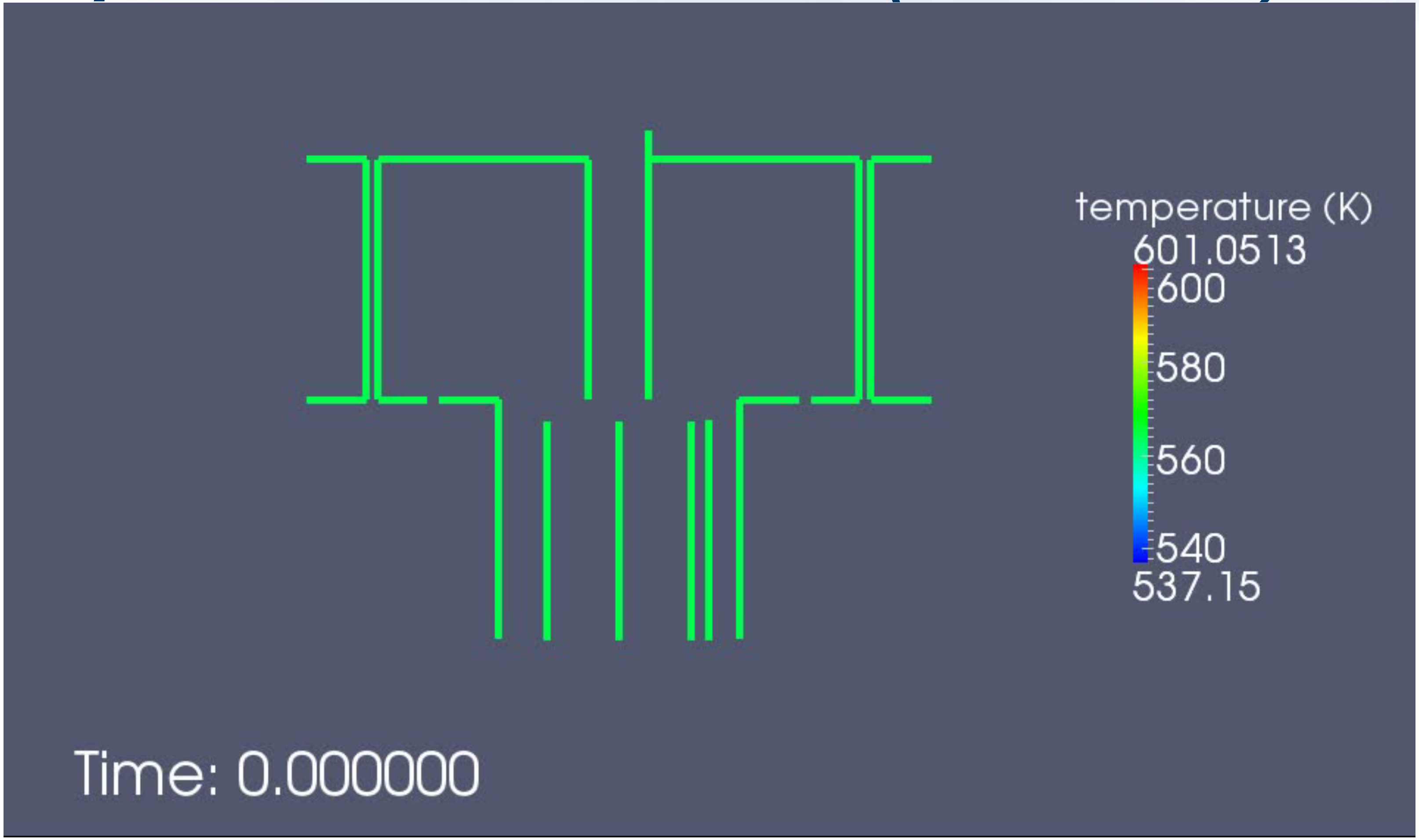
- **Established the software framework**
- **Developed components to demonstrate single-phase capability**
- **Completed a Level 2 Milestone report - INL/EXT-12-25924: "Demonstration of a Steady State Single Phase PWR Simulation with RELAP-7"**

Simplified TMI-1 NPP Test



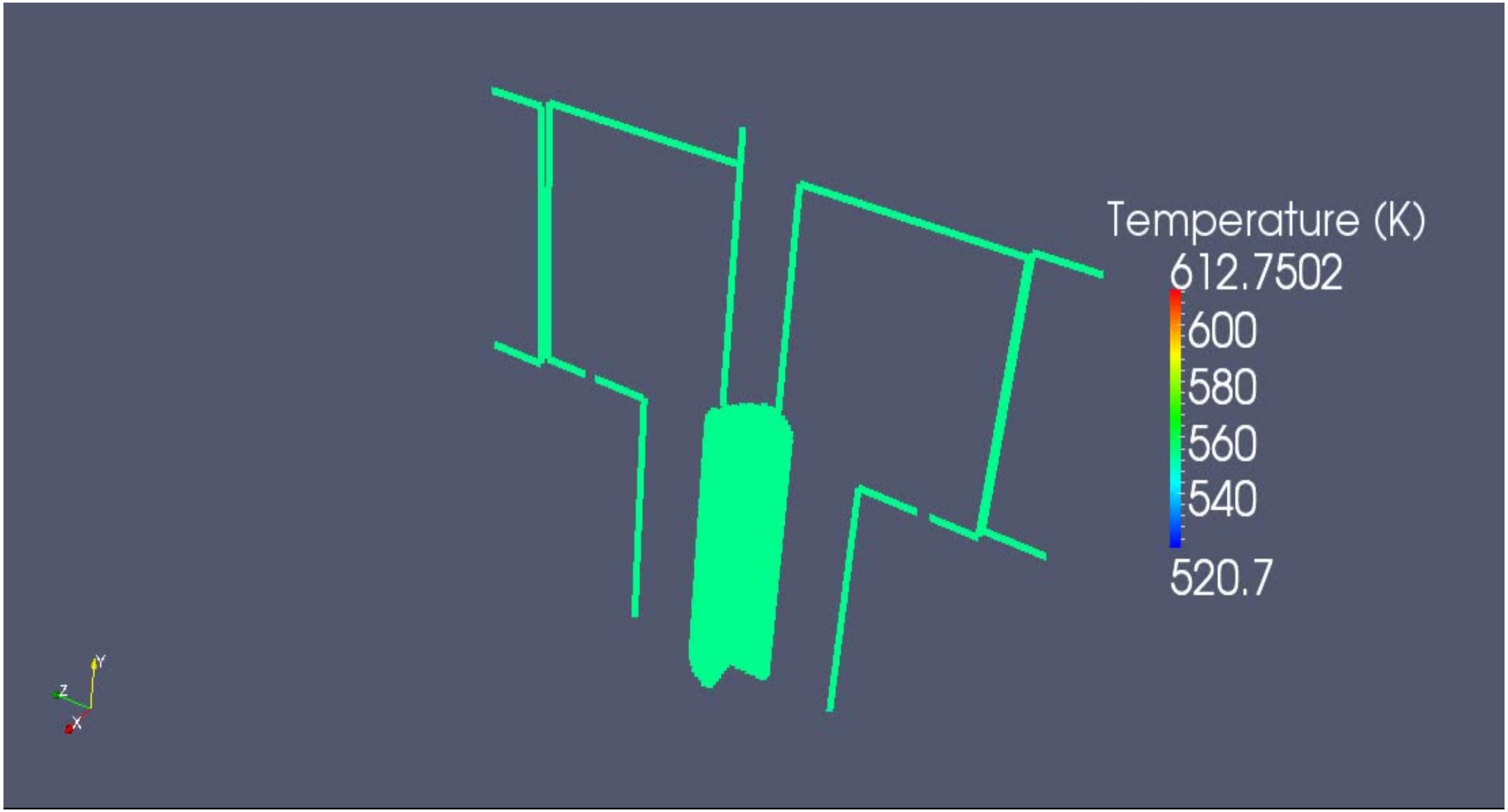


Simplified TMI-1 NPP test (continued)



Expected core inlet/outlet temperature: 564.15K/ 591.15K
Calculated core inlet/outlet temperature: 564.05K/ 590.92K

Advanced PWR Design with 157 Channels



FY13 Accomplishments

- Extended the capability to two-phase flow
- 7-equation model has been implemented and demonstrated with a Pipe, SeparatorDryer, & CoreChannel
  - Level 2 Milestone report - “RELAP7: Demonstrating Seven-Equation, Two-Phase Flow Simulation in a Single-Pipe, Two-Phase Reactor Core and Steam Separator/Dryer (INL/EXT-13-28750)”
- Demonstrate Simplified BWR Station Blackout Simulations with homogeneous equilibrium model (a subset of the 7-equation model)
  - Level 2 Milestone report: “RELAP-7 Simulation Resolving an SBO Scenario on a Simplified Geometry of a BWR (INL/EXT-13-29887)”

7-Equation, Well-Posed, Compressible Two-Phase Flow Model (1-D Variable Area)

(volume fraction evolution, mass balance, momentum balance, and total energy balance for each phase)

Liquid Phase

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

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

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

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

Vapor Phase

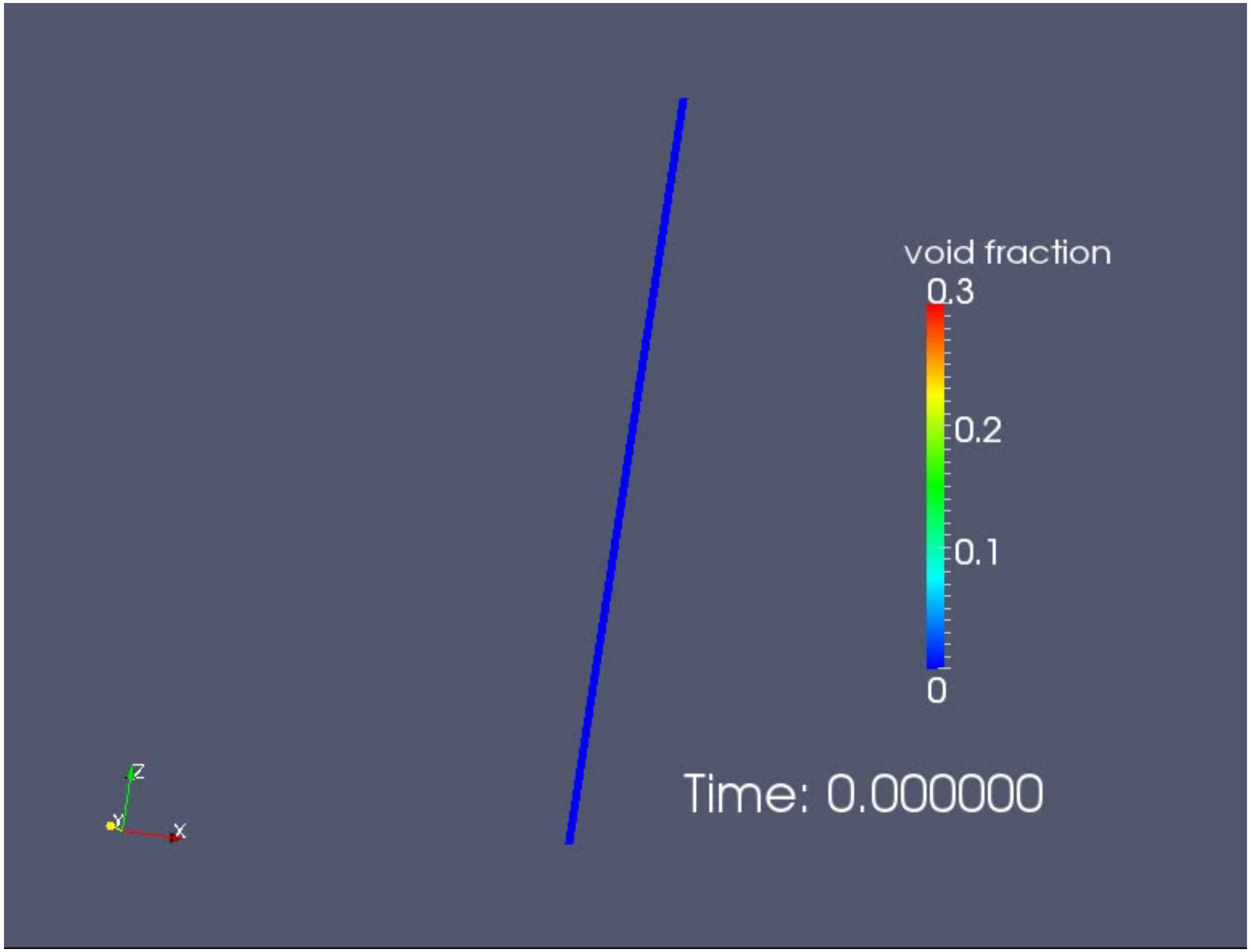
$$\frac{\partial \alpha_g A}{\partial t} + u_{\text{int}} A \frac{\partial \alpha_g}{\partial x} = A\mu(p_g - p_l) + \frac{\Gamma A_{\text{int}} A}{\rho_{\text{int}}} \qquad \left(or\ \alpha_g = 1 - \alpha_l \right)$$

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

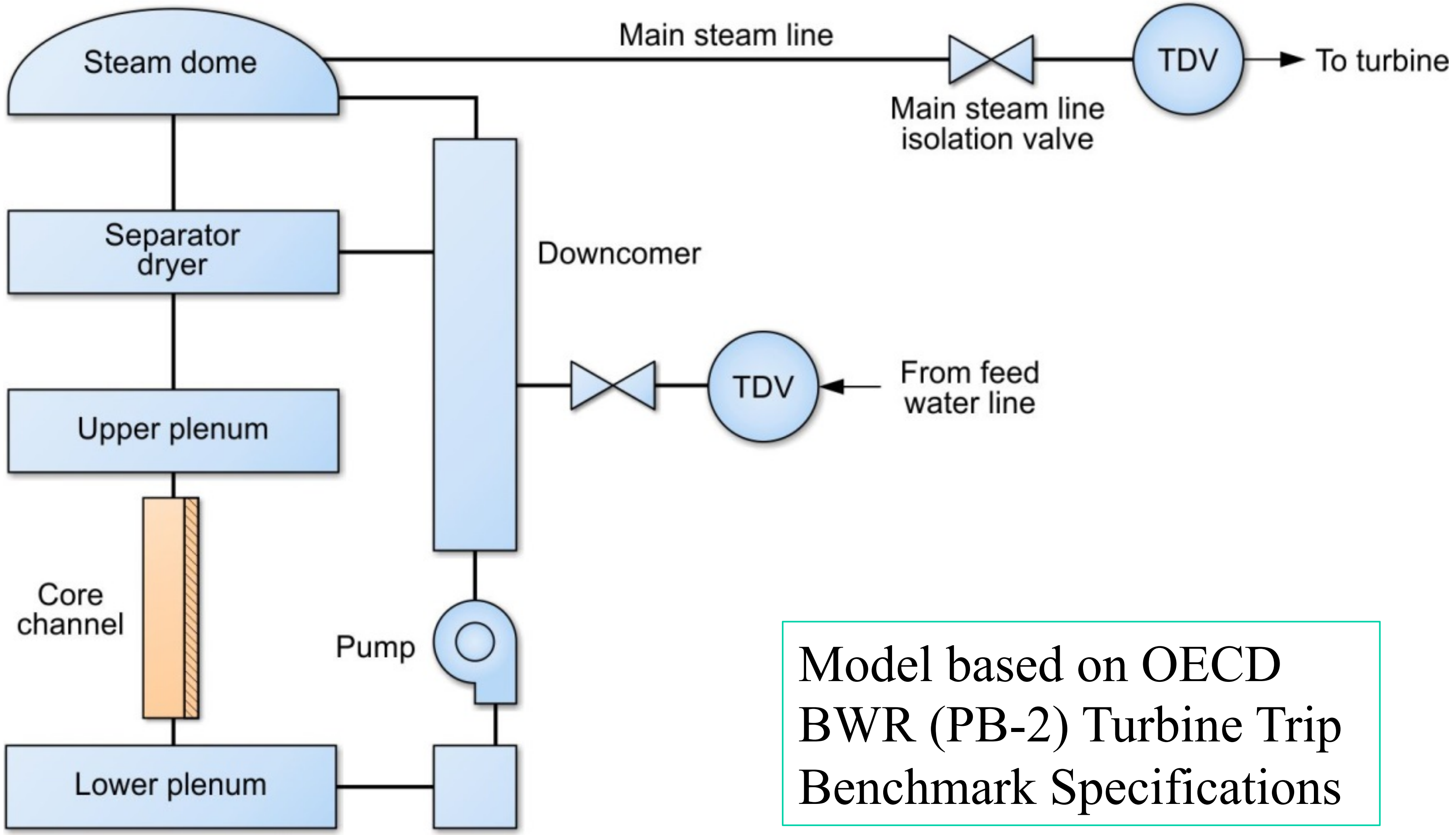
$$\begin{aligned}\frac{\partial \alpha_g \rho_g u_g A}{\partial t} + \frac{\partial \alpha_g A(\rho_g u_g^{\,2} + p_g)}{\partial x} &= p_{\text{int}} A \frac{\partial \alpha_g}{\partial x} + p_g \alpha_g \frac{\partial A}{\partial x} + A\lambda(u_l - u_g) \\ &\quad + \Gamma A_{\text{int}} u_{\text{int}}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

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

7-Equation Model Demonstration

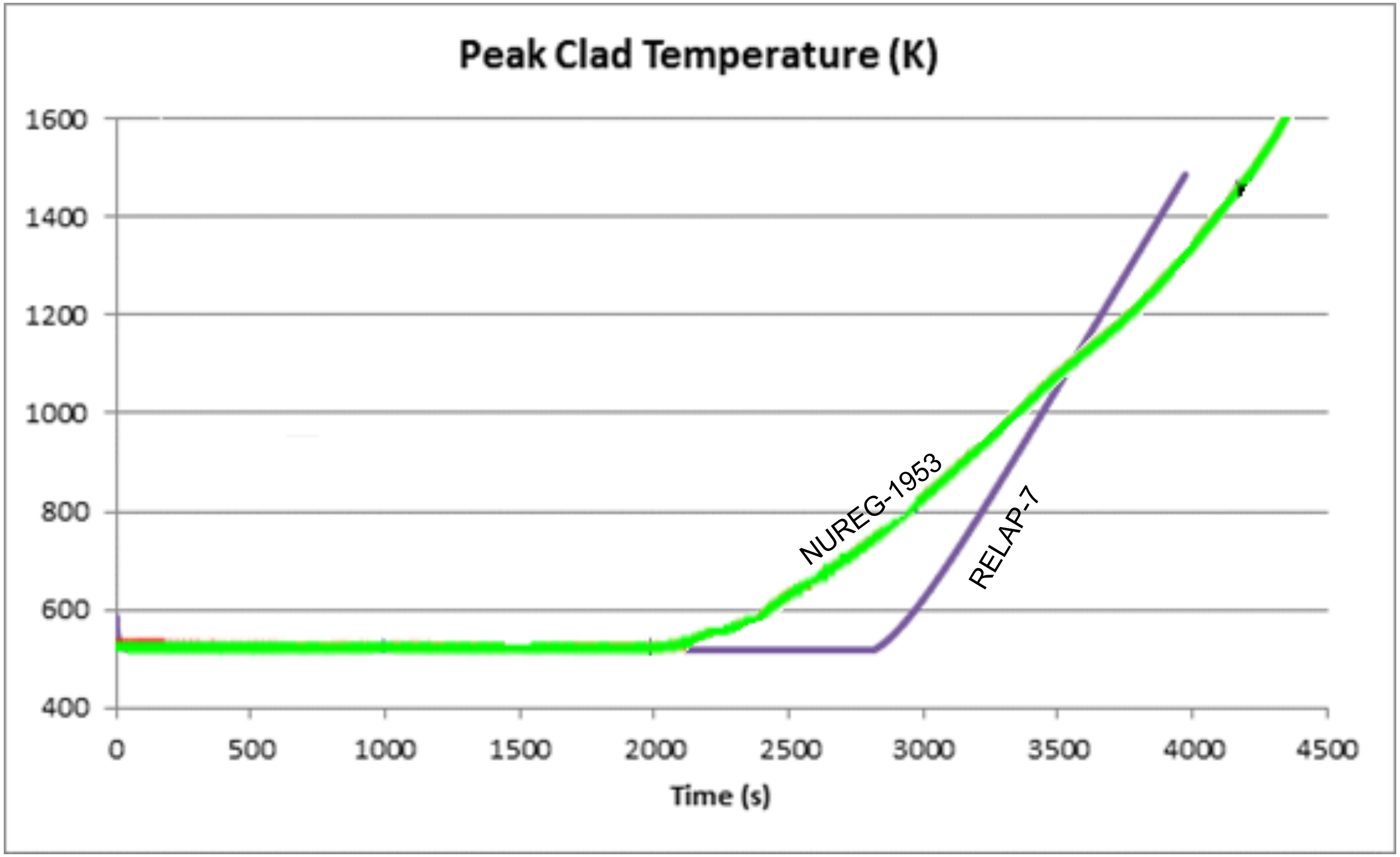


BWR SBO Scenario I – No Safety Injection



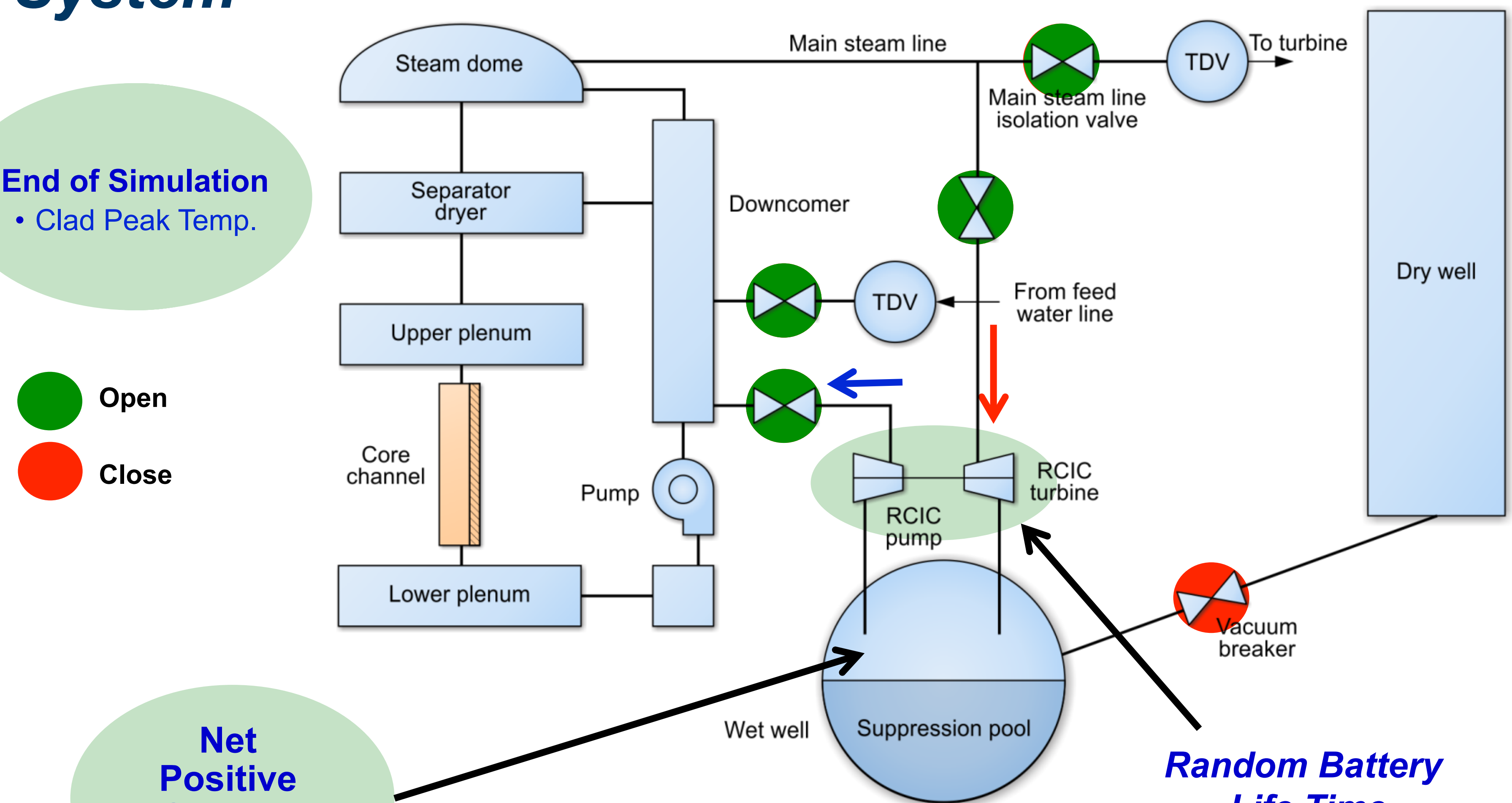
Model based on OECD BWR (PB-2) Turbine Trip Benchmark Specifications

Peak Clad Temperature



BWR SBO Scenario II – Fully Coupled RCIC System

End of Simulation
- Clad Peak Temp.



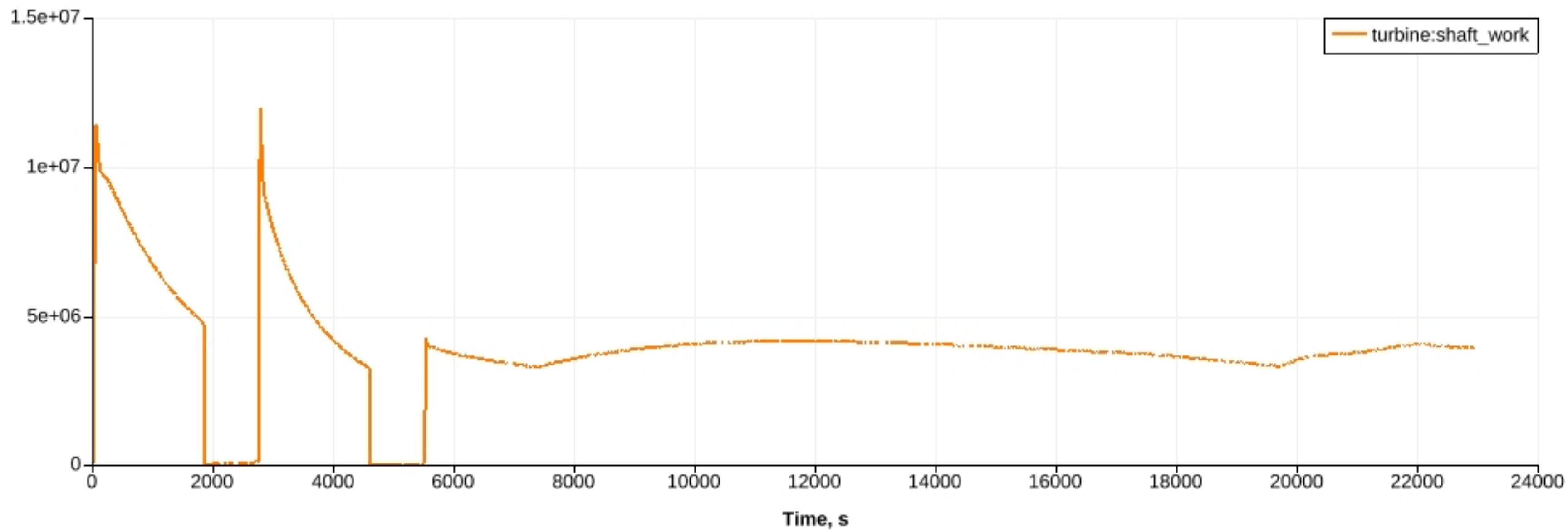
Net Positive Suction Head

Random Battery Life Time

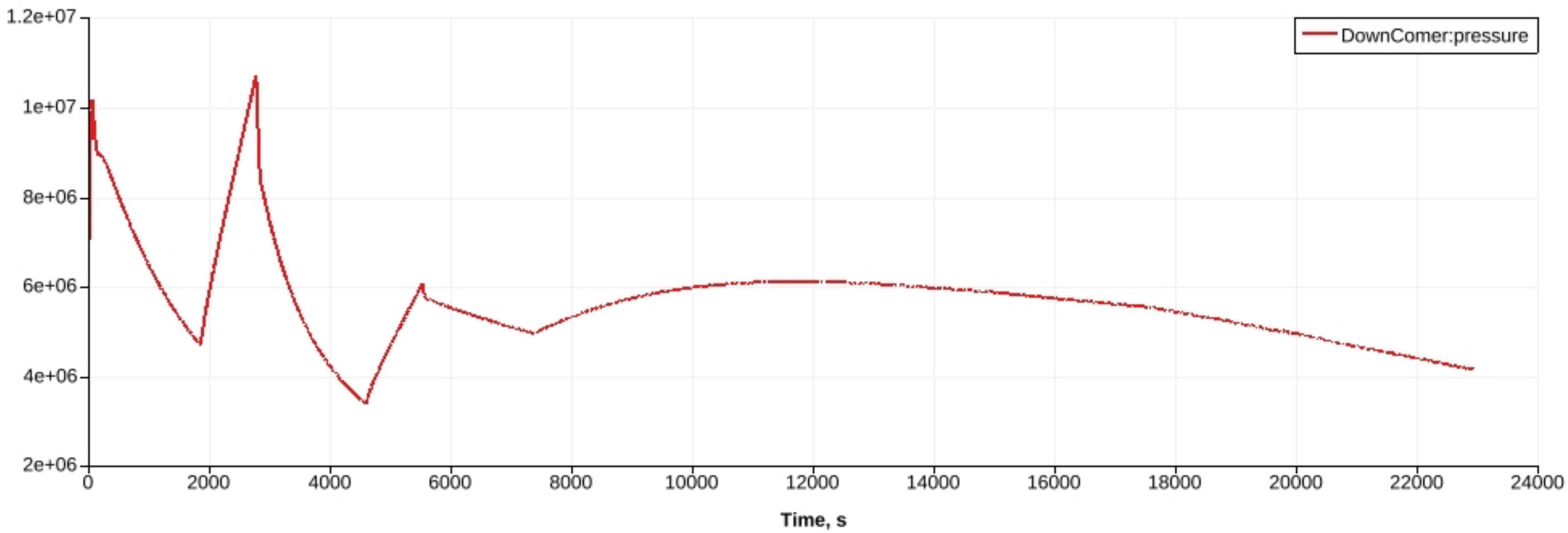
Major Simulation Sequences

- Initializing the simulation to steady state:
  - All the safety valves close, primary system valves open.
  - Run to steady state with rated thermal power.
- At t = 0 s, Reactor scrams and SBO begins
- At t = 1 second:
  - Feedwater line valve begins to close and becomes fully closed at t = 2 s.
  - Main steam isolation valve begins to close and becomes fully closed at t = 11 s.
- From t = 10 second to 7,270 second, the RCIC system is turned on and off for three periods with a transition time of 10s between all the changes of status
  - 1st period of turning on RCIC system for 30 minutes (same mass flow rate at 40 kg/s for steam release through RCIC turbine as water injection through RCIC pump)
  - 1st period of turning off RCIC system for 15 minutes
  - 2nd period of turning on RCIC system for 30 minutes (mass flow rate at 40 kg/s)
  - 2nd period of turning off RCIC system for 15 minutes
  - 3rd period of turning on RCIC system for 30 minutes (mass flow rate at 20 kg/s)
- From t = 7,270 second and on, maintains pressure release through turbine with mass flow rate at 20 kg/s and shuts off makeup water supply through the RCIC pump
- At t = 22,937 second, simulation stops when the PCT approaches 1477.6 K (2200F).

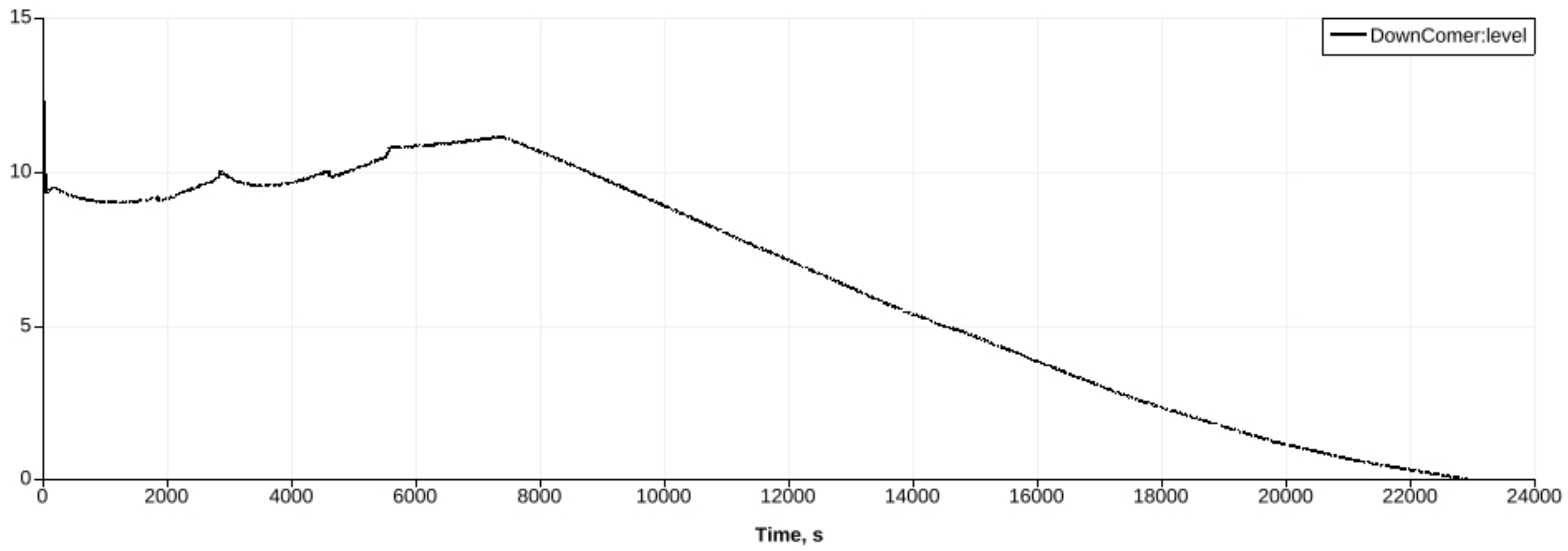
RCIC Turbine Shaft Work



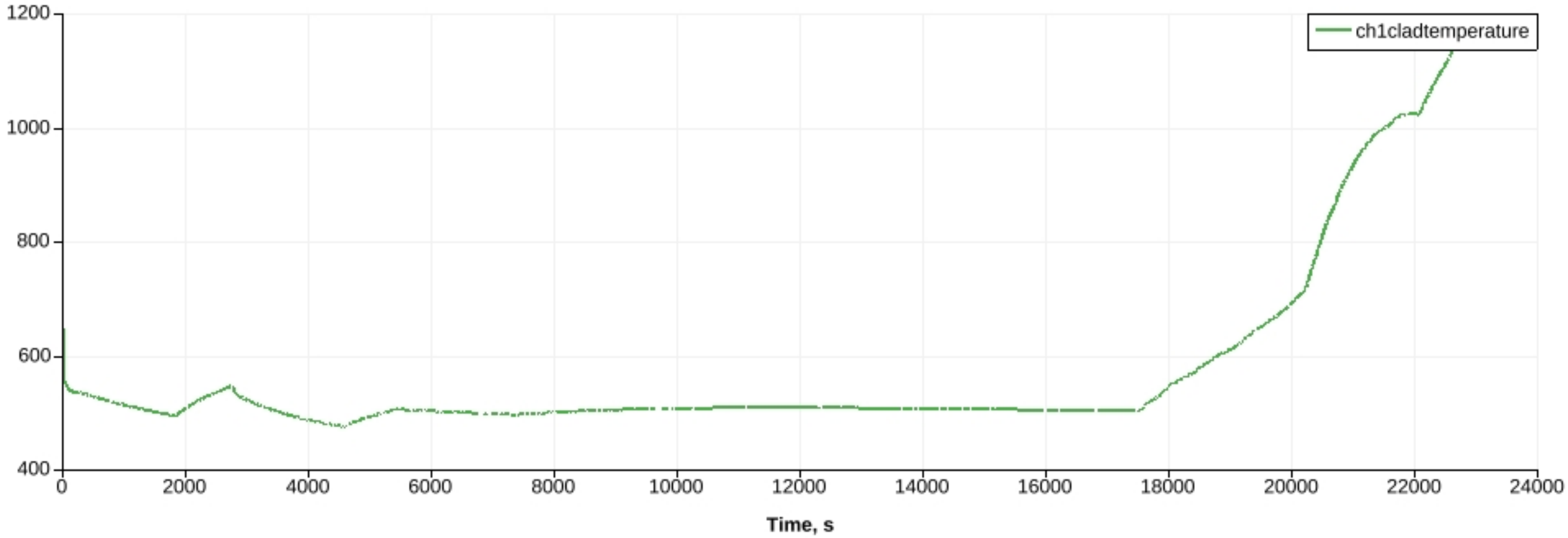
Reactor Vessel Pressure



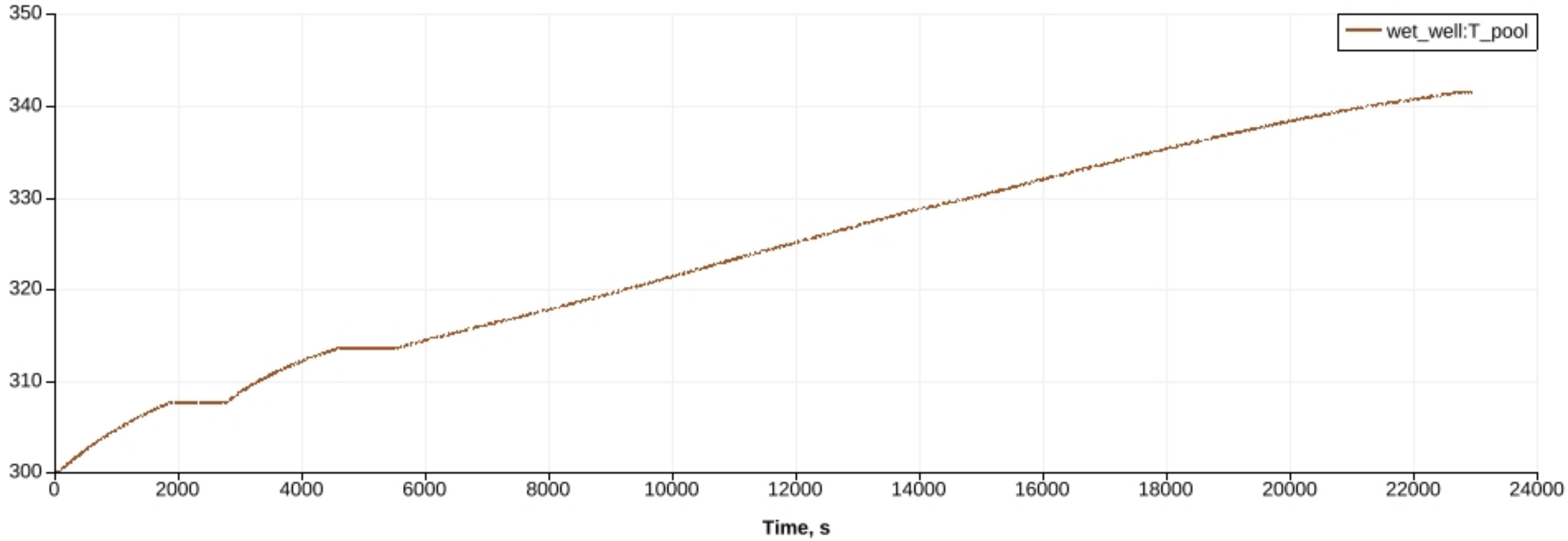
DownComer Liquid Level



Peak Clad Temperature



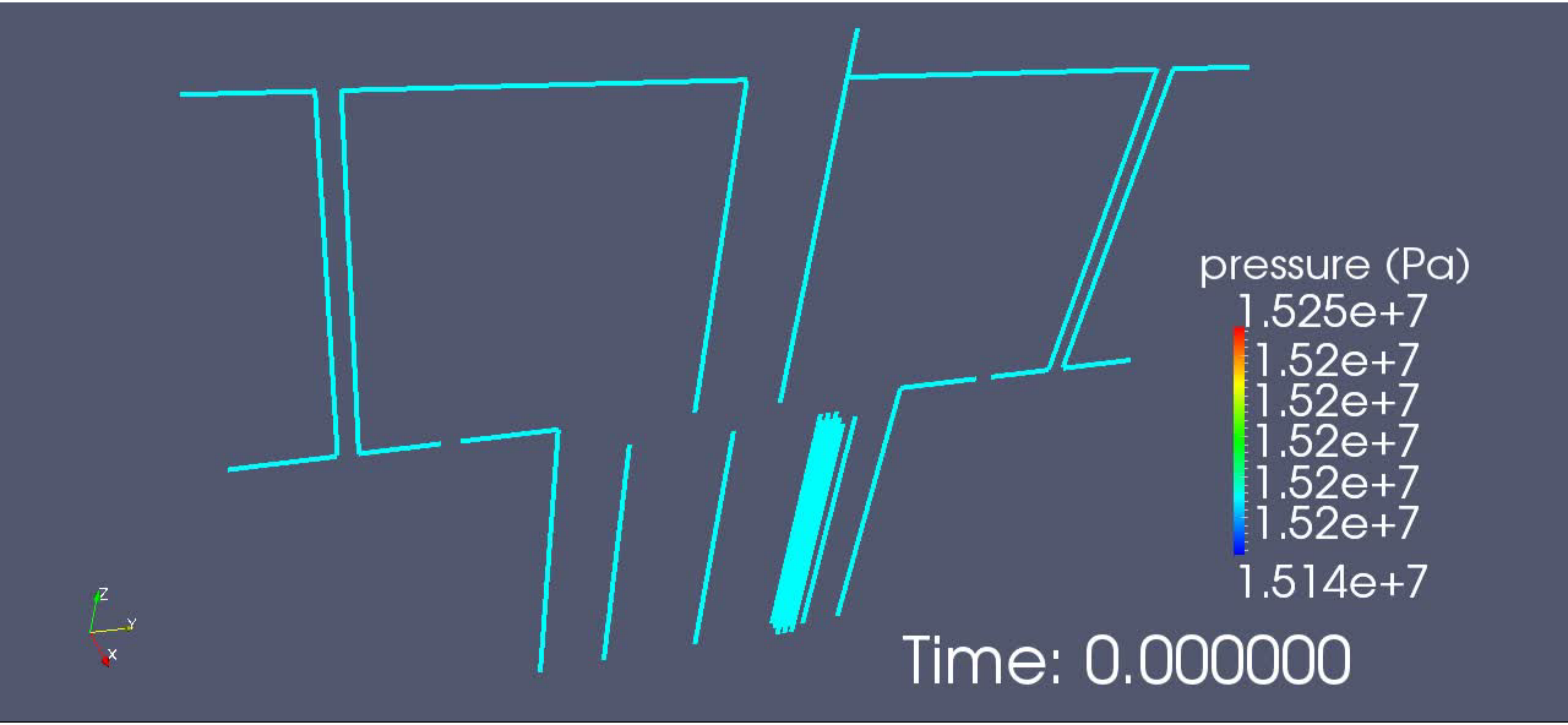
Wet Well Suppression Pool Temperature



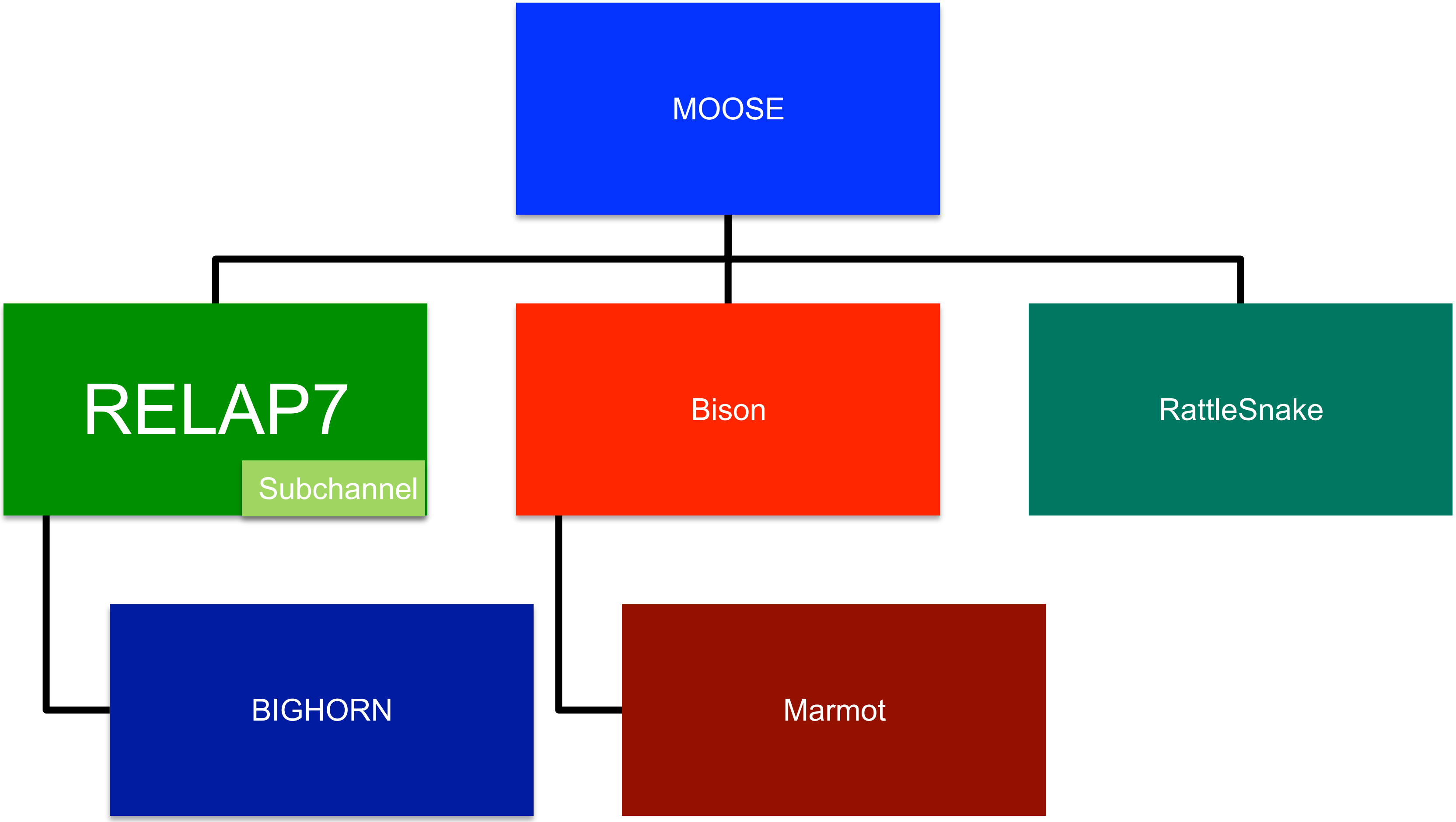
RELAP-7 Timeline

FY 2012	FY 2013	FY 2014	FY 2015 and beyond
- 3 equation single phase - Heat structures - Basic components	-7 equation two phase flow - Additional relevant components and physics for SBO	- Develop the full set of components to perform SBO for a BWR - Prepare the code for external release	- Develop and upgrade closure laws. Improve physical modeling of equation parameters - Extend the number of available components
Demonstration of a steady state PWR simulation	BWR SBO simulation on simplified system with relevant components	- Initial beta release - SBO for a BWR with Mark I containment	- Comprehensive Verification & Validation (V&V) & Uncertainty Quantification (UQ) - Delivering a large set of validating benchmarks

Demonstration of Fully Coupled Subchannel Capability (TMI-1 Steady State Case)



Multi-Dimensional Capability



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