Molten Salt–Fueled Nuclear Reactor Model for Licensing and Safeguards Investigations

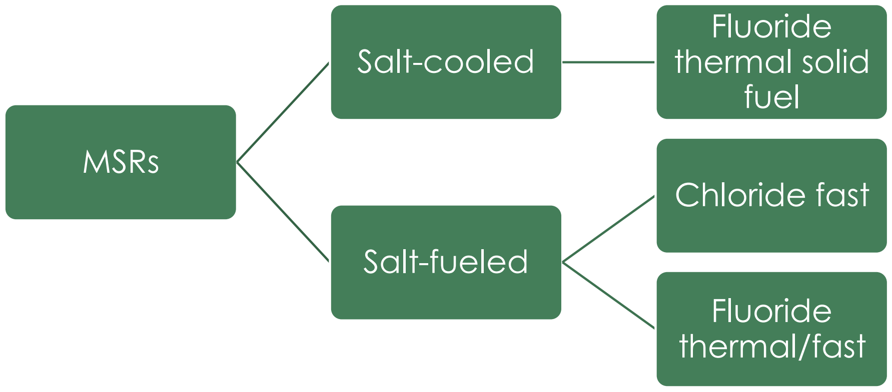
M. Scott Greenwood, PhD

Oak Ridge National Laboratory
Advanced Reactor Engineering (ARE) Group

October 8-10, 2018
The American Modelica Conference 2018

Molten Salt Reactors – An Introduction

- An advanced nuclear reactor concept
- Two principle groups:
  - Salt-cooled reactors:
    - A solid fuel undergoes fission and is cooled by a separate non-fueled primary system salt
  - Salt-fueled reactors:
    - A flowing fueled salt contains fissile material that fissions when in the core and flows throughout the primary system, serving as fuel and coolant
- This work focuses on salt-fueled MSRs



High-level categorization of MSRs

Licensing and Safeguards for Salt-Fueled Systems

- Licensing
  - Ensure protection and safety of public health and environment
  - Primary importance are source terms and their release pathways
- Safeguards
  - The timely detection/deterrence of diversion of nuclear material from peaceful nuclear activities
- Common Needs

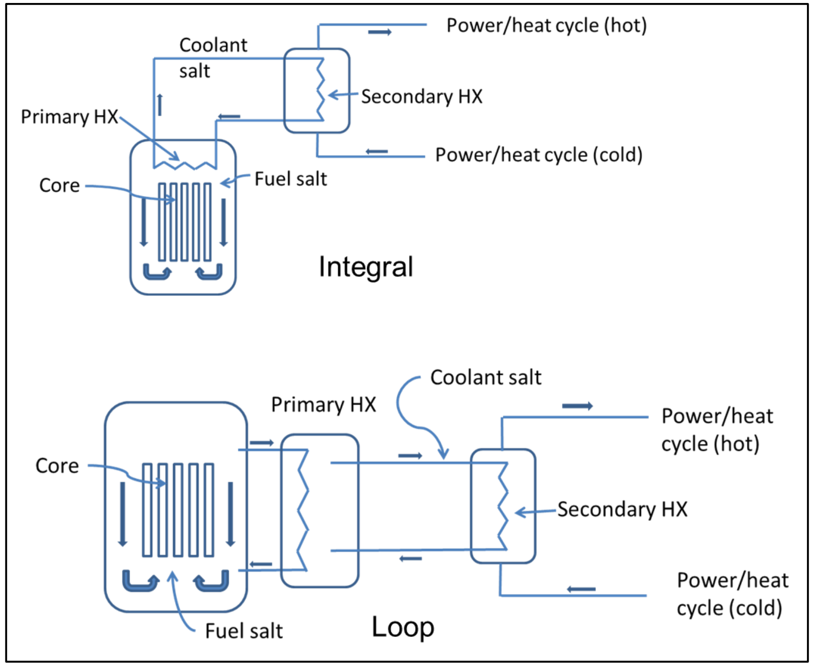
1. Precursor drift models that account for delayed neutron production throughout the primary loop and their reintroduction into the core
2. Radionuclide inventory accounting, including source term production, holdup, and release mechanism models
3. Thermal hydraulic analyses of sufficient fidelity to capture flow and power dynamics in salt-fueled concepts
4. Time-, temperature-, flux-, and flow-dependent materials, and salt interaction data, and models to predict corrosion, erosion, and irradiation effects

- **Existing tools do not exist which can investigate the system-level dynamics of fluid-fueled MSRs**

Source
Greenwood, Michael Scott, Benjamin R. Betzler, and A L. Qualls. 2018. “Dynamic System Models for Informing Licensing and Safeguards Investigations of Molten Salt Reactors.” ORNL/TM-2018/876, 1456790. https://doi.org/10.2172/1456790.

General MSR Modeling and Simulation (M&S) Needs

- Recent report outlined high priority M&S needs for MSRs
  1. Source term definition, material accountancy, and radiological consequences
  2. Safety analysis (AOO and DBA) (i.e., transient behavior)
  3. Analysis and design of steady state neutronics and thermal hydraulics
- To meet those needs, this work developed methods for modeling MSRs
  - Example: Modified point kinetics, thermal-hydraulic models

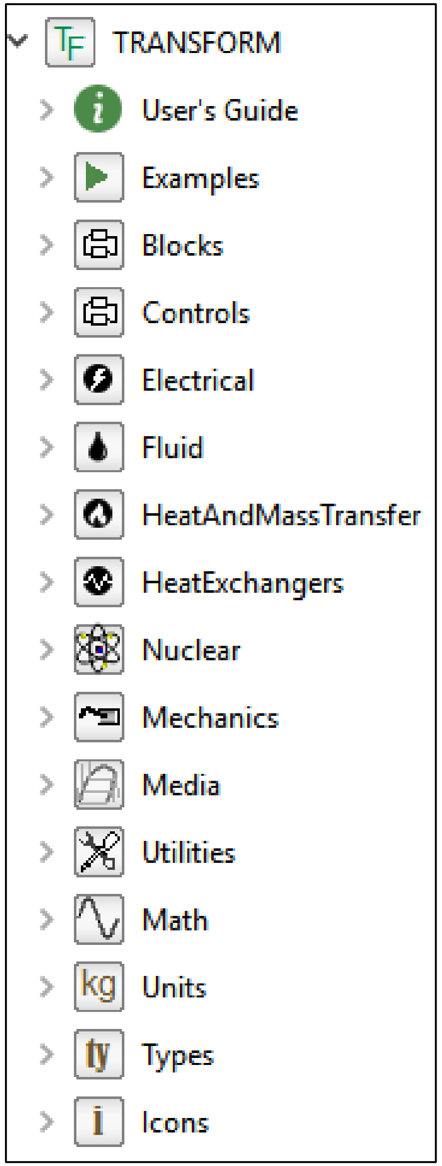


Terminology of high-level systems for salt-fueled MSRs

Source
Rader, Jordan D., Michael Scott Greenwood, and Paul W. Humrickhouse. 2018. “Verification of Modelica-Based Models with Analytical Solutions for Tritium Diffusion.” *Nuclear Technology*, March, 1–8. https://doi.org/10.1080/00295450.2018.1431505.

ORNL Modelica Library – TRANSFORM:
TRANSient Simulation Framework Of Reconfigurable Models

- TRANSFORM – An ORNL developed Modelica "library"
  - Focus on modeling system-level behavior of advanced reactors
  - Built-in flexibility to handle custom applications
  - Thermal hydraulics, reactor kinetics, control systems, etc.
  - https://github.com/ORNL-Modelica/TRANSFORM-Library
- ModelicaPy
  - Repository of python files to interact with Modelica
  - https://github.com/ORNL-Modelica/ModelicaPy



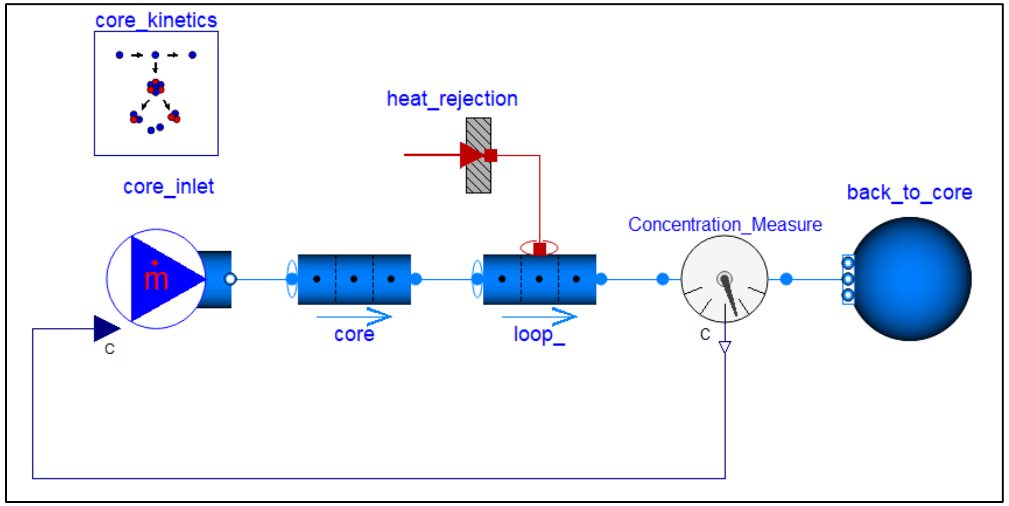
Trace Substance Approach Used to Track Source Terms

```
connector FluidPort
  "Interface for quasi one-dimensional fluid flow in a piping network
  (incompressible or compressible, one or more phases, one or more substances)"

  replaceable package Medium = Modelica.Media.Interfaces.PartialMedium
    "Medium model" ∃ ;

  flow Medium.MassFlowRate m_flow
    "Mass flow rate from the connection point into the component";
  Medium.AbsolutePressure p "Thermodynamic pressure in the connection point";
  stream Medium.SpecificEnthalpy h_outflow
    "Specific thermodynamic enthalpy close to the connection point if m_flow < 0";
  stream Medium.MassFraction Xi_outflow[Medium.nXi]
    "Independent mixture mass fractions m_i/m close to the connection point if m_flow < 0";
  stream Medium.ExtraProperty C_outflow[Medium.nC]
    "Properties c_i/m close to the connection point if m_flow < 0";
end FluidPort;
```

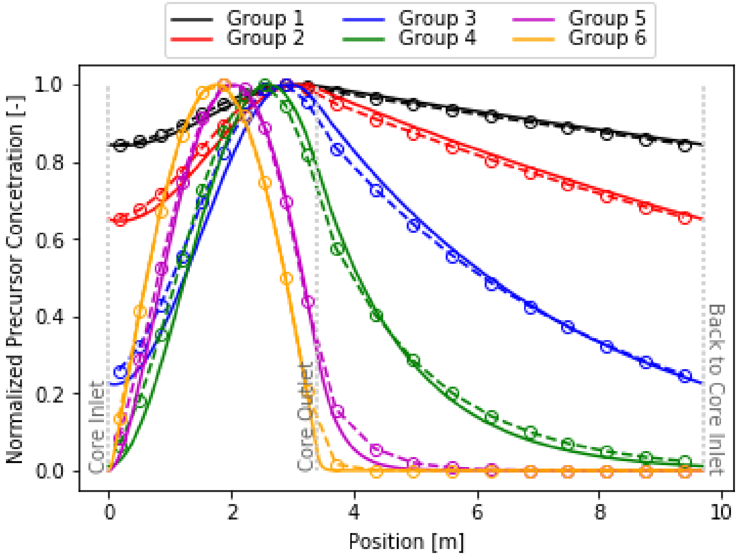
- Trace Substances:
  - Are carried along with the main fluid flow
  - Each substance has its own mass balance
    - Amount of any substance is tracked
  - Are able to be generated, decay, separated, diffuse through solids, etc. as appropriate
  - Properties that govern physical behavior can be incorporated from existing databases/nuclear codes (e.g., ORIGEN)
- Examples:
  - Neutron precursors, tritium, and other fission products

TRANSFORM Applications: Modified Kinetic Models

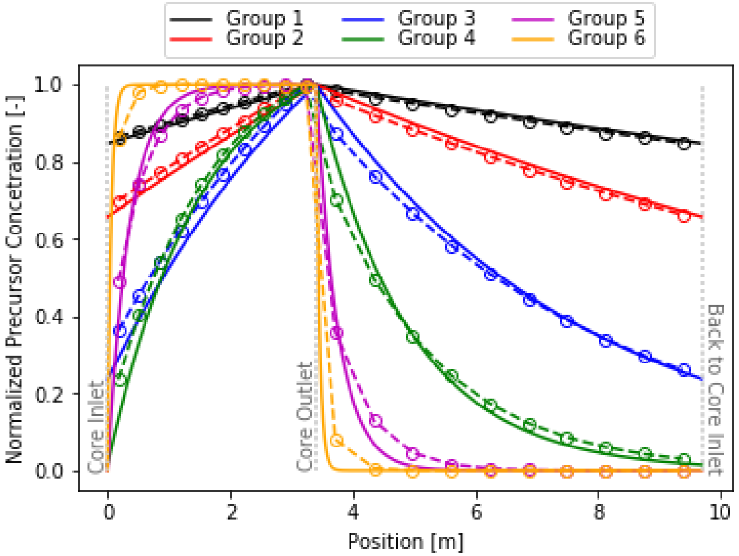
- Modified point kinetic model captures dynamics for fluid-fueled MSRs
  - Neutron precursor drift
  - Fission products (including poisoning)
  - User definable reactivity feedback



Simple closed-loop fluid model in TRANSFORM



Sinusoidal Profile



Flat Profile

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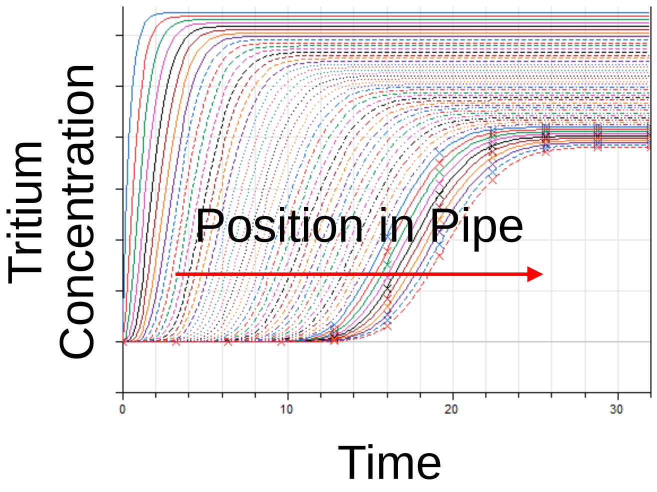
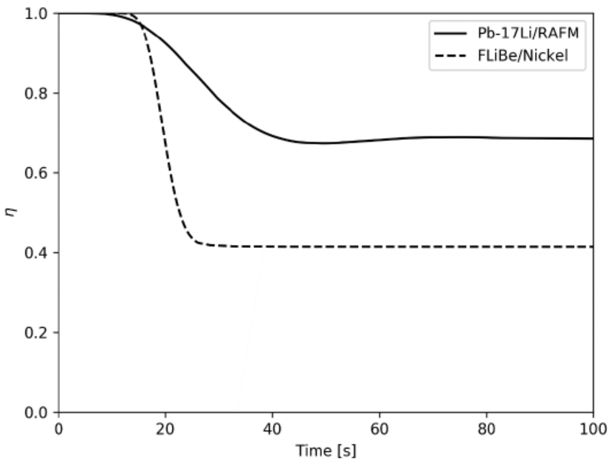
Source

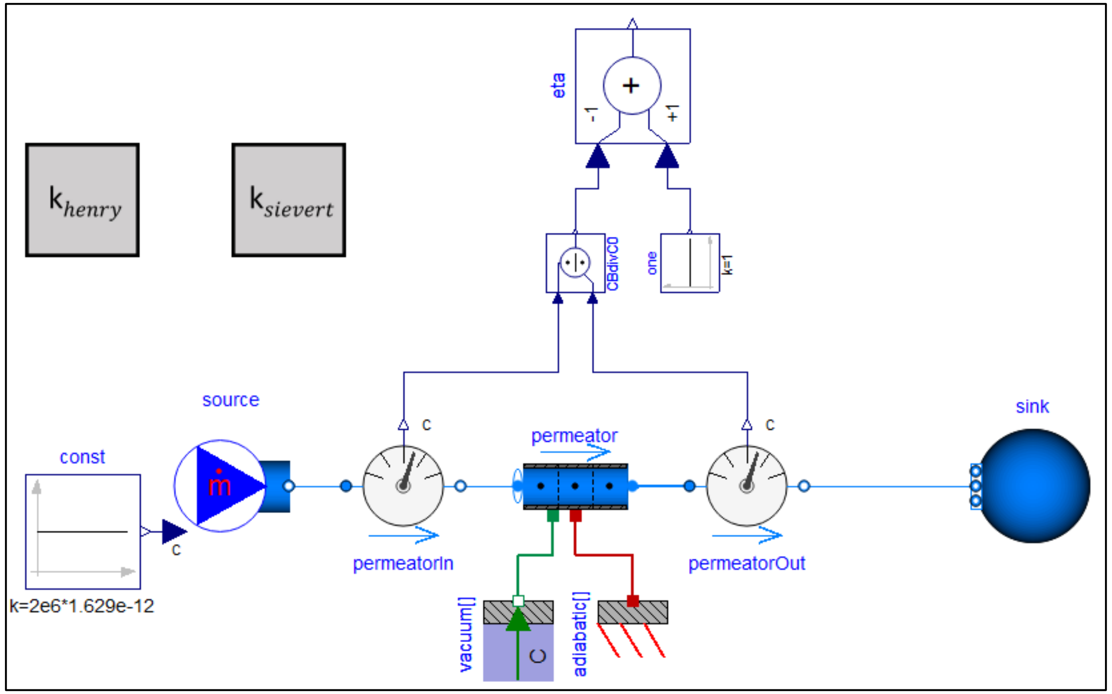
Greenwood, Michael Scott, and Benjamin R. Betzler. In Press. "Modified Point Kinetic Model for Neutron Precursors and Fission Product Behavior for Fluid-Fueled Molten Salt Reactors." Nuclear Science and Engineering. https://doi.org/10.1080/00295639.2018.1531619.

TRANSFORM Applications:
Tritium Diffuser

- Demonstrates complex transport
- Tritium diffuses through the wall according to the physical settings
- Matches analytical solution







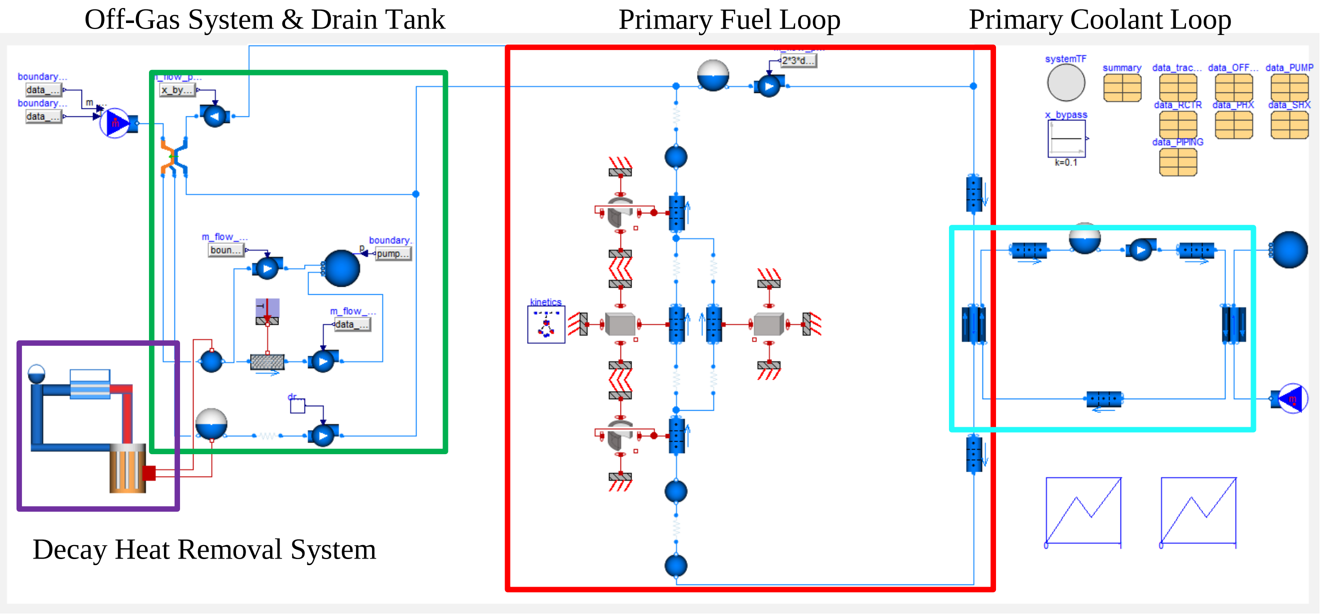
Model of Tritium through a diffusing wall

$$Removal\ Efficiency = \eta = 1 - \frac{C_{out}}{C_{in}}$$

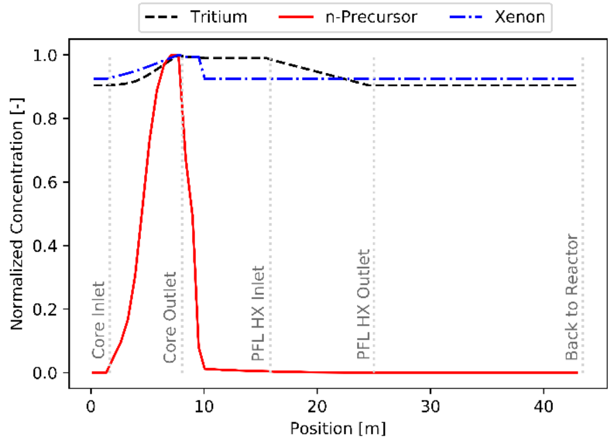
Source
Rader, Jordan D., Michael Scott Greenwood, and Paul W. Humrickhouse. 2018. "Verification of Modelica-Based Models with Analytical Solutions for Tritium Diffusion." *Nuclear Technology*, March, 1–8. https://doi.org/10.1080/00295450.2018.1431505.

Molten Salt Demonstration Reactor (MSDR)

- Relatively generic concept
- 750 MWt, salt-fueled
- Thermal reactor
  - Graphite moderated
- Key features include:
  - Drift kinetics behavior
  - Fission product behavior
  - Graphite mass and surface area
  - Off-gas system
  - Drain tank
  - Decay heat removal system



Dynamic model of the fluoride salt-fueled, thermal MSDR

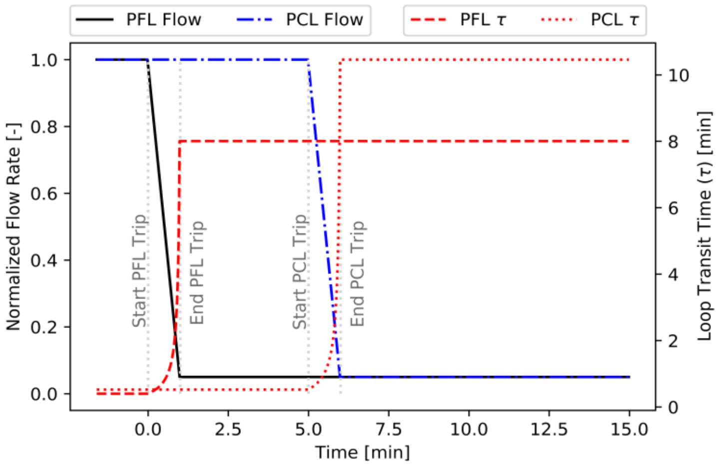


Steady-state behavior of various trace substances

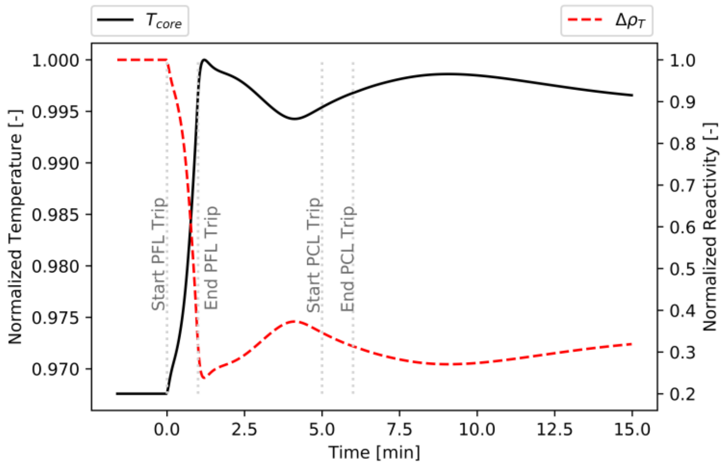
Example 1: Sequential Pump Trips

- Event
  - Sequential trip of the Primary fuel loop (PFL) and the primary coolant loop (PCL) pumps (PCL)
  - Flows reduce to 95% of full flow rate over 60 seconds
- Sequence Description (plots on next slide)
  1. Upon PFL pump trip, the temperature within the core of the reactor heats up due to the decreased flow rate
  2. As the temperature increases, the temperature feedback of the reactor drives the power down as it attempts to correct the discrepancy between the reference and measured nodal temperatures
  3. The oscillations in temperature, and therefore reactivity and power, is associated with the influx of colder-than-nominal fluid returning from the PFL HX.
     - This fluid is cooled more than usual due to the continued operation of the PCL pump.
  4. A new steady state is eventually achieved

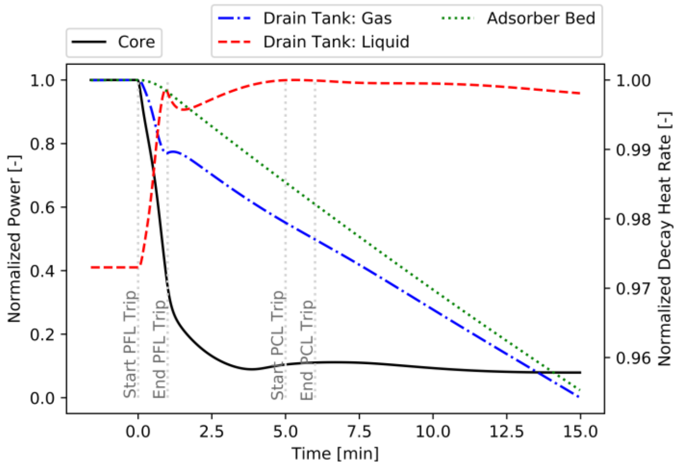
Example 1: Sequential Pump Trips cont’d



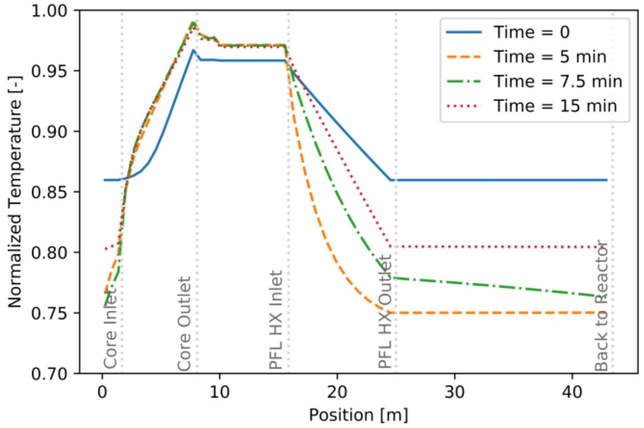
Flow rate and loop transit time



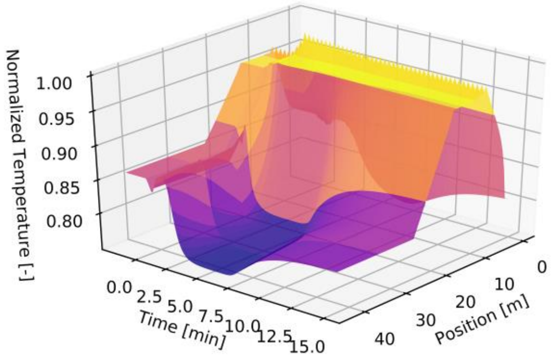
Average Core Temperature and Reactivity



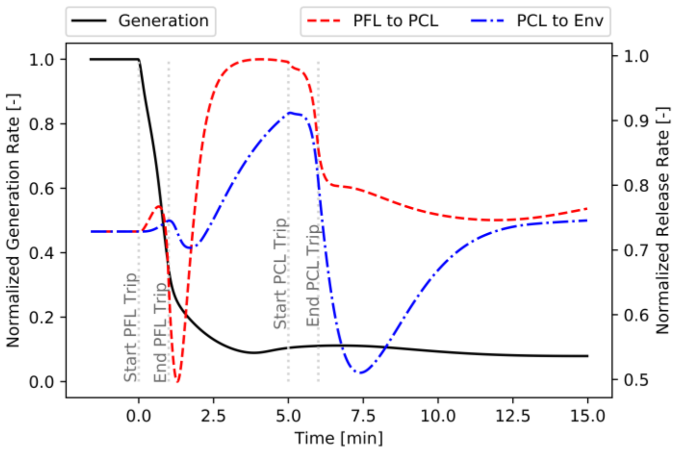
Power Deposition



Temperature as a function position in PFL for a few specific times



Temperature as a function of time and position in PFL



Tritium generation and diffusion behavior

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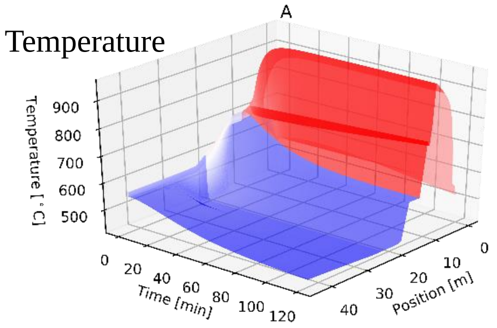
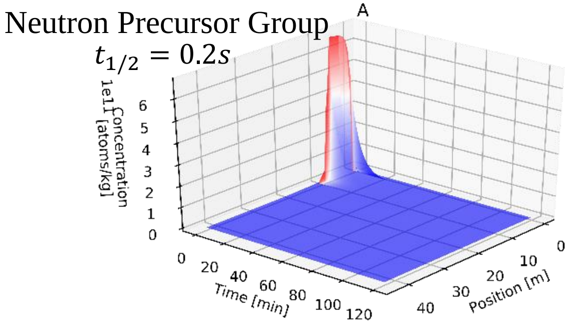
Example 2: Pump Coast Down and Reactivity Feedback

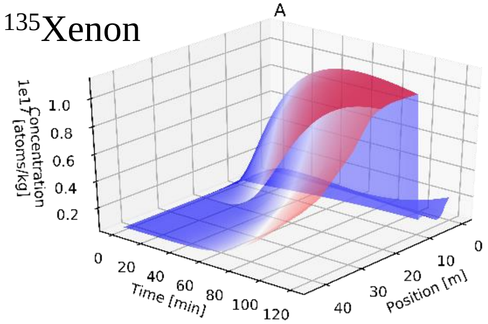
- Start at steady-state, full-power
- Scenarios investigate pump coast down (λ) and control rod (ρ_{CR}) worth impact
- Control rod inserted over 150 seconds
- Demonstrates ability to investigate various transients and impact on system

Scenario Parameters

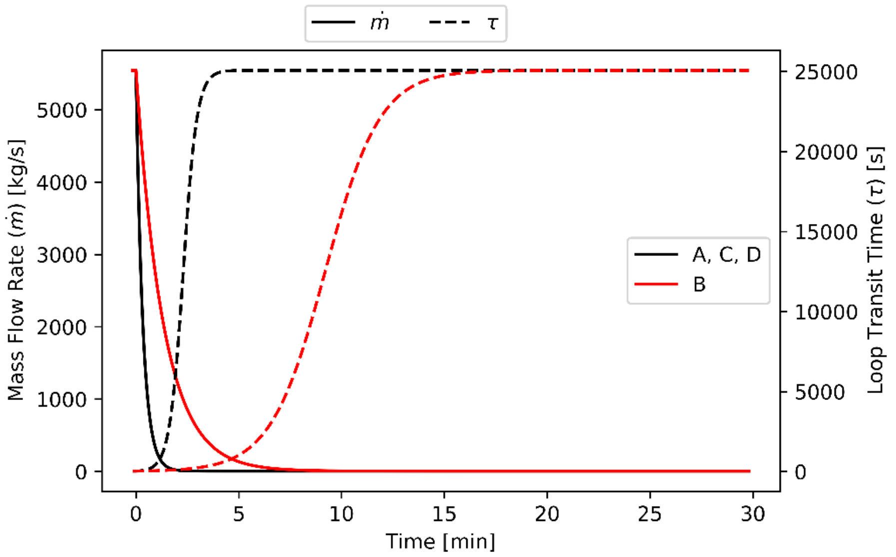
Scenario	λ [s^{-1}]	ρ_{CR} [pcm]
A	1/40	0
B	1/20	0
C	1/40	-300
D	1/40	-3000



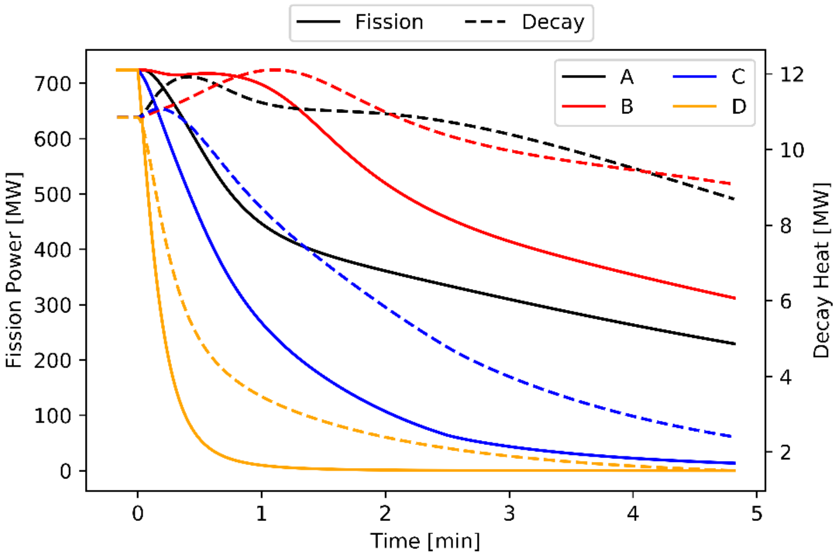




Transient behavior as a function of position



Change in flow rate and loop transit time



Impact on reactor power

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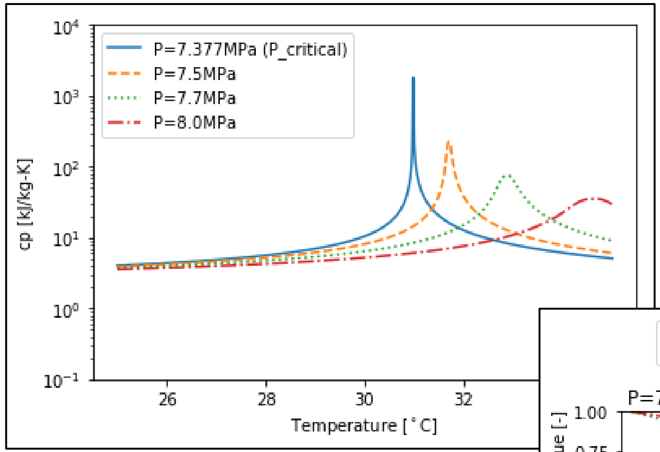
Takeaway: This Work is a Base Line to Understanding MSRs

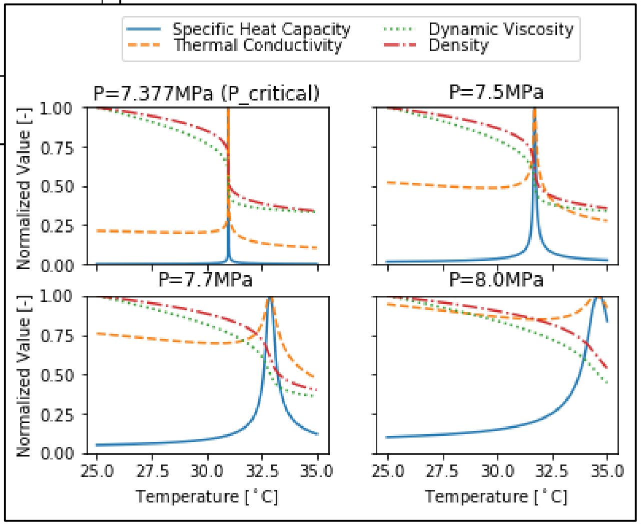
- Reactor physics and thermal-hydraulics have been successfully integrated with fission product behavior
- Will be used to investigate various scenarios important to licensing and safeguards (i.e., safety and source term)
  - These scenarios and figures of merit(s) (i.e., fission products of importance) will be identified in the future
  - Model will help explore instrumentation and control
    - Instrument placement, uncertainty, drift, time lag, etc.
  - These studies coupled with reactor behavior in a truly dynamic model have never been performed and are critical to deploying MSRs
- Will be updated as necessary with additional capabilities
  - Corrosion, fuel burn-up, coupled with nuclear codes (e.g., ORIGEN), etc.

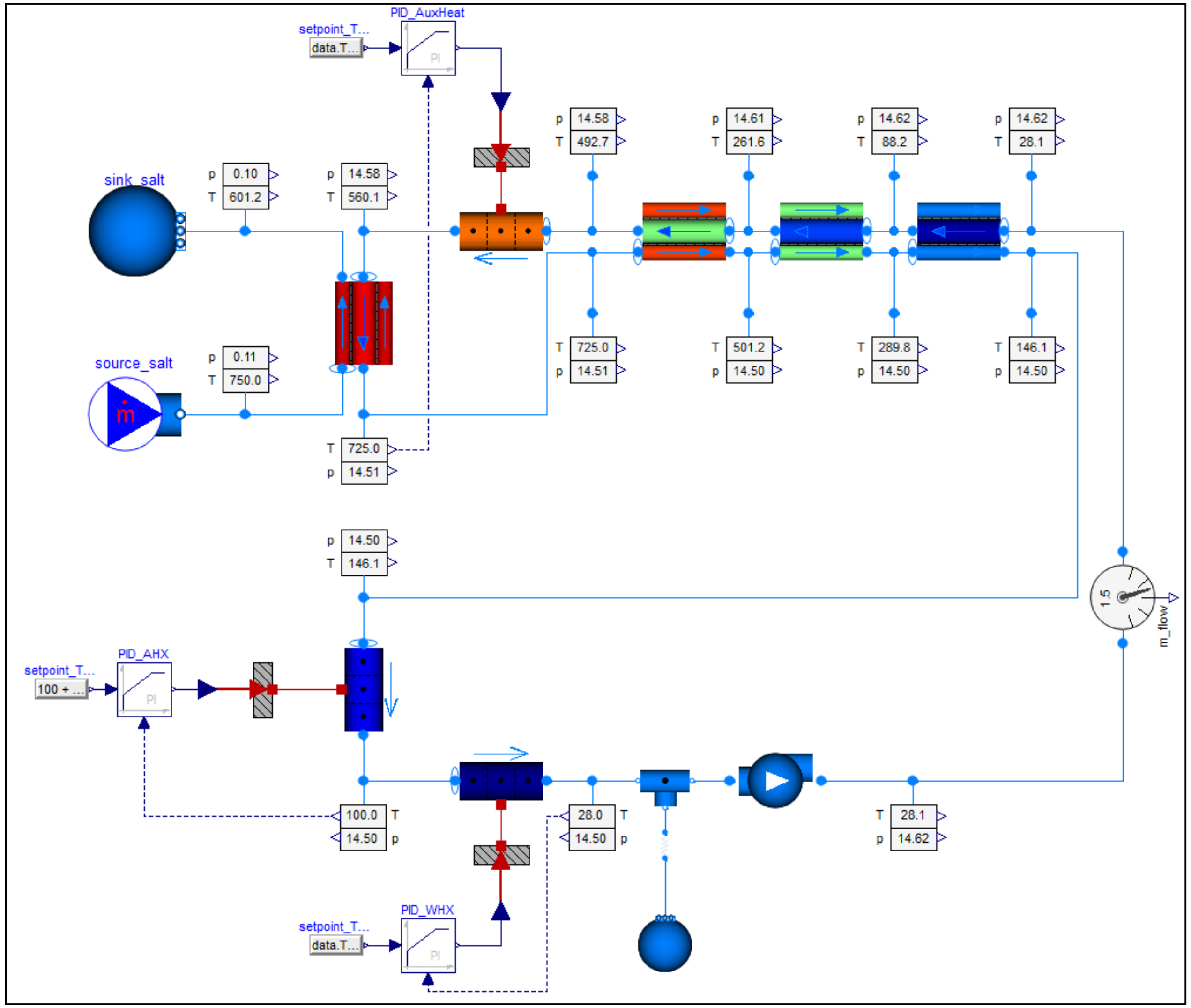
TRANSFORM
Additional Applications

TRANSFORM Applications: SCO_2 Loop Model

- TRANSFORM is able to use complex media properties
  - E.g., CO_2 models from CoolProp and $KClMgCl_2$ salt media from TRANSFORM



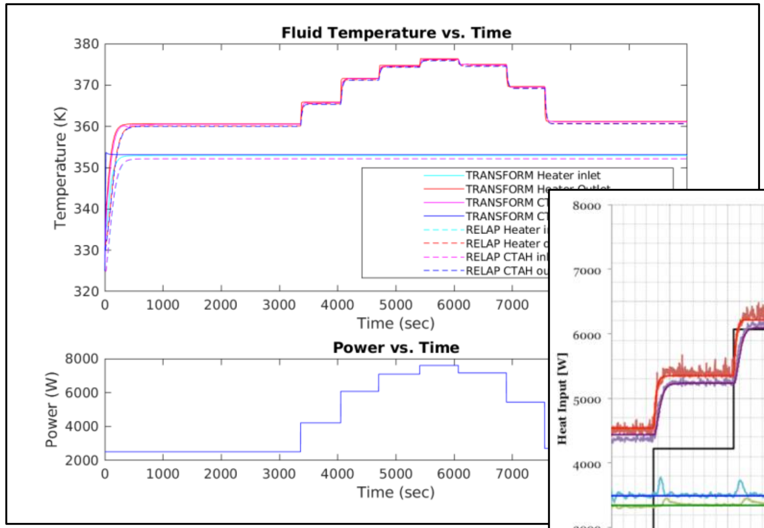


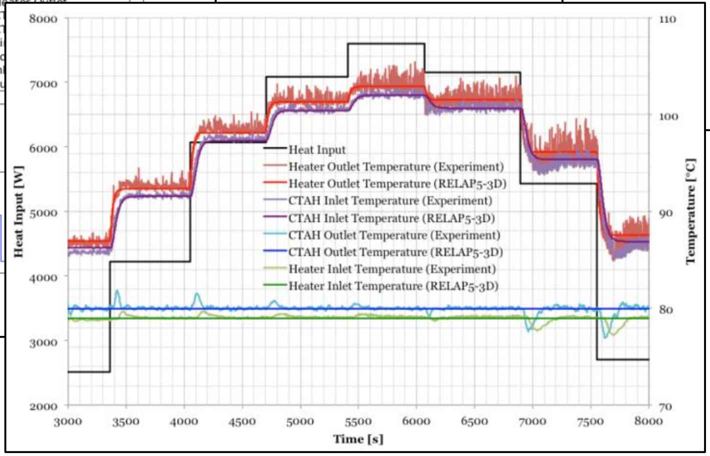


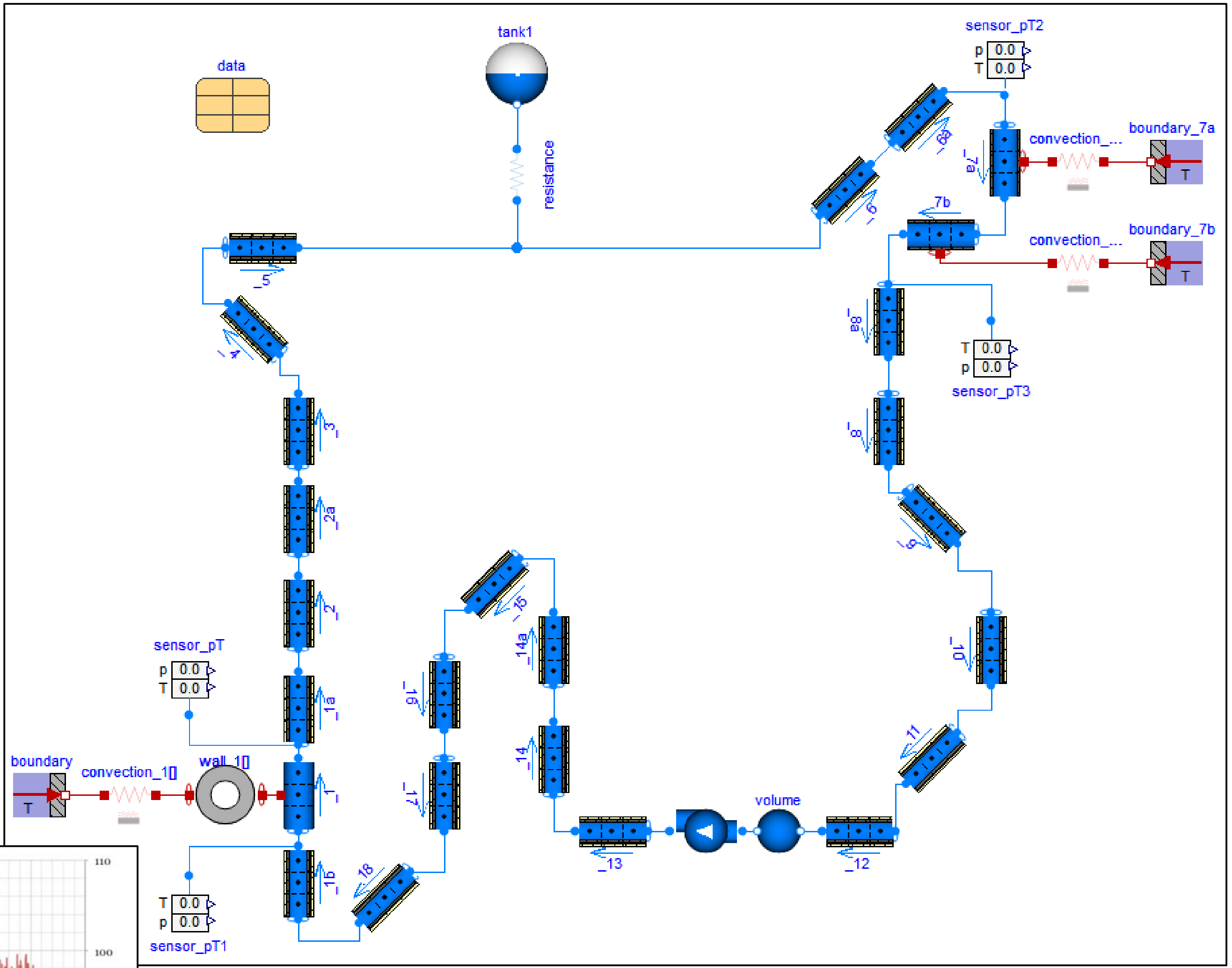
Model of a supercritical CO_2 loop

TRANSFORM Applications: UCB CIET Facility

- Uses Dowtherm A oil as a simulant fluid for fluoride salts
- Compared favorable with traditional nuclear codes (i.e., RELAP5-3D) and experimental data







Model of the UCB CIET Facility

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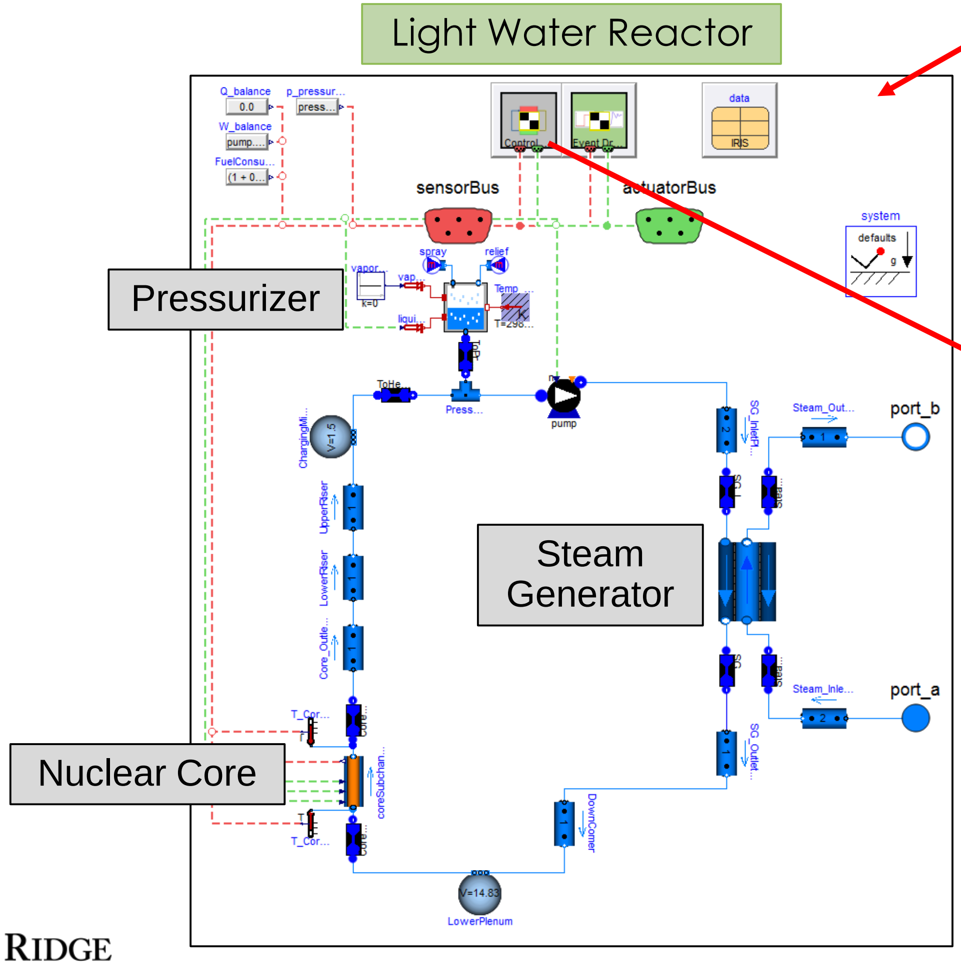
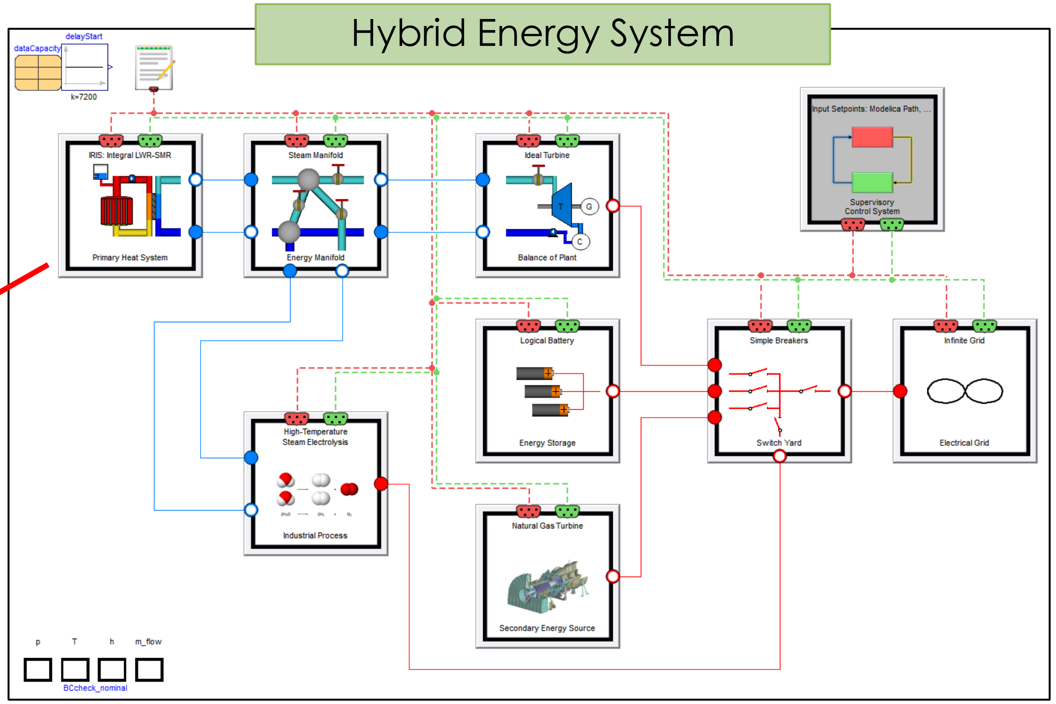
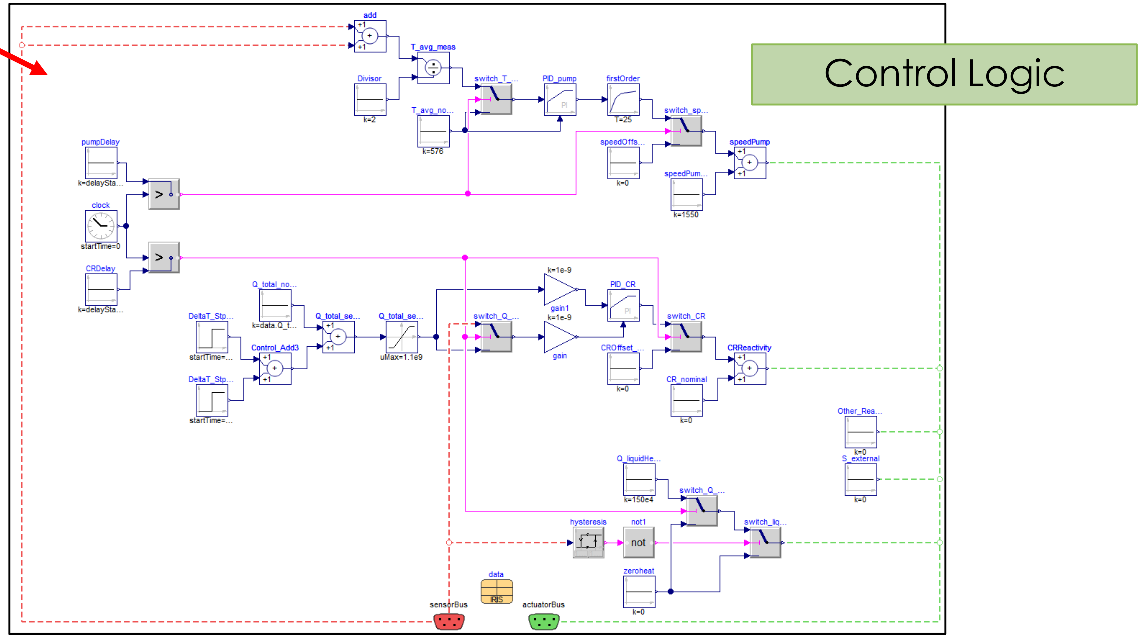
TRANSFORM Applications:
Nuclear Hybrid Energy Systems

- Investigate complex energy systems







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Summary

- MSRs, especially salt-fueled, require new modeling and simulation capabilities
- Meeting the needs of licensing and safeguards is of primary importance
- Source term tracking and transient reactor behavior are critical
- Modified kinetic model and thermal hydraulic models have been added to TRANSFORM which can track the birth, transport, and decay of source terms
- These models will continue to be developed and integrated with other nuclear tools to facilitate the deployment of advanced nuclear reactors
- TRANSFORM is valuable for investigating a range of problems
  - https://github.com/ORNL-Modelica/TRANSFORM-Library

Thank you.

Scott Greenwood

greenwoodms@ornl.gov