CYBER-PHYSICAL SMALL MODULAR REACTOR EMULATOR

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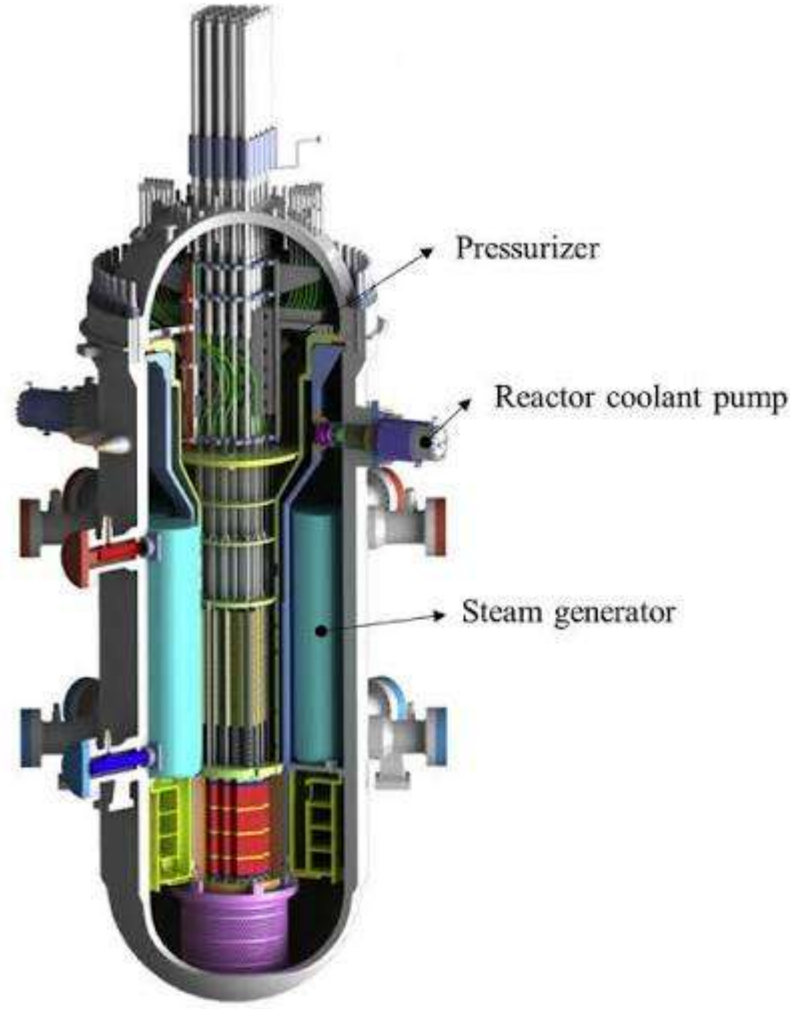
Outline

- Background
- CORE²S
  - Control-Oriented Research Environment for Energy Systems
- Thermal modeling
- Nuclear reactivity modeling
- Power generation modeling
- Time constant matching
- Live model updating

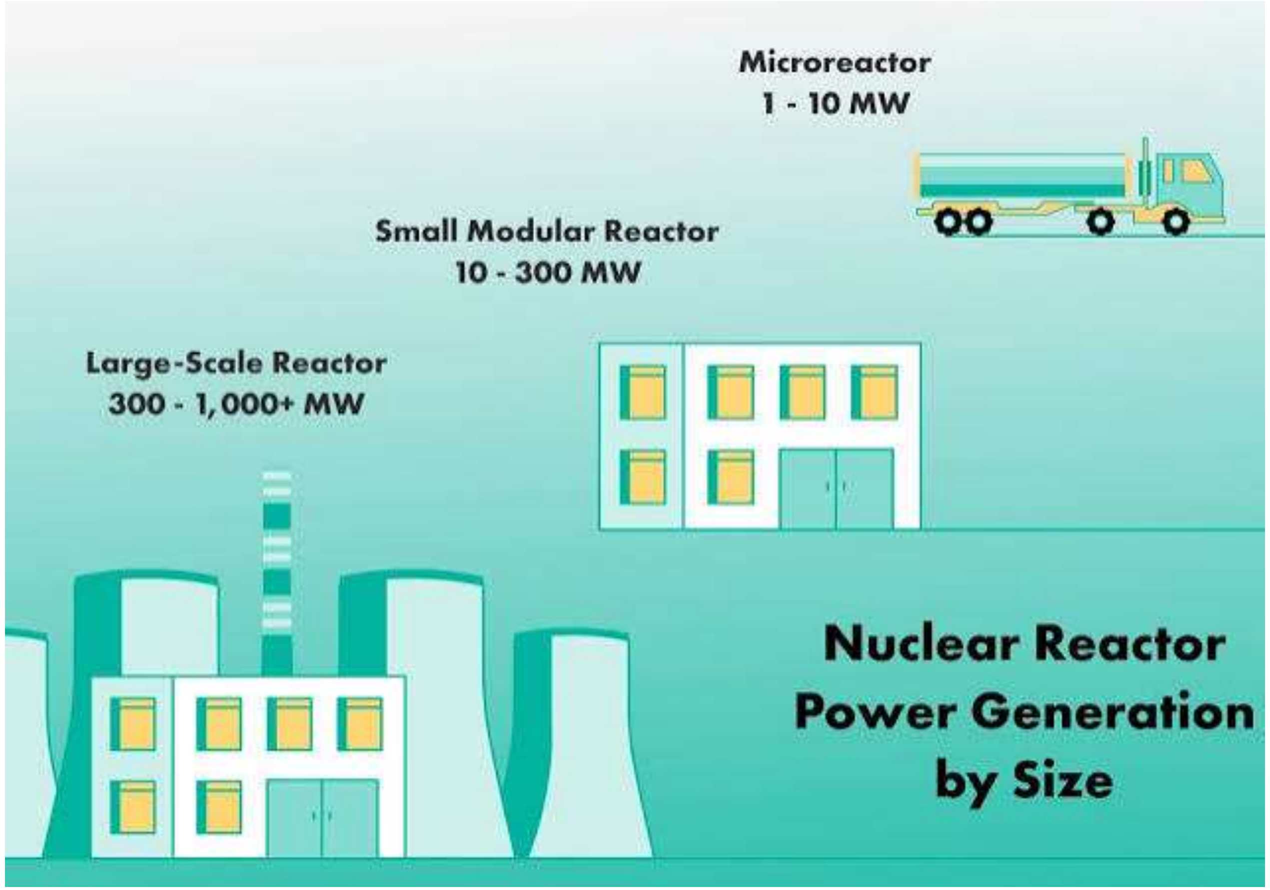


Schematic of a small modular reactor
(Analytic springback prediction in cylindrical tube bending for helical tube steam generator)

BACKGROUND

What is an SMR?

- Small modular reactors
- Advanced nuclear fission plants that produce low-carbon electricity.
- Electrical output: 1-300MW
- Application areas: ships, military installations, distributed grid applications



Nuclear Reactors
(BKV Energy)

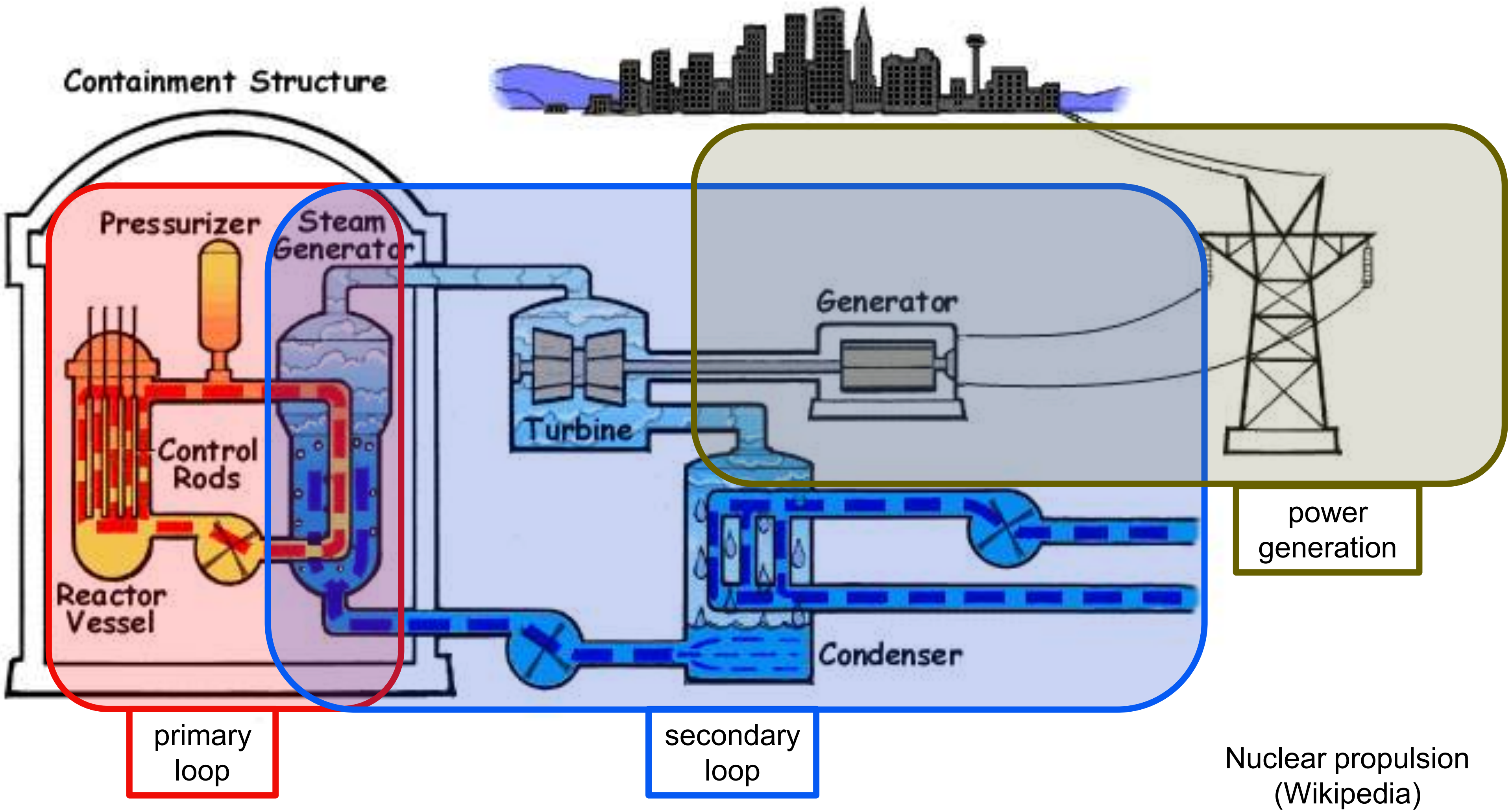
Control for SMR

- What was done previously?
  - Digital models evaluate control strategies before physical implementation.
- Controls research in SMR
  - Model-based and predictive control for load following.
- What is an emulator?
  - Physical testbed reproducing thermal, hydraulic and dynamic behaviour of the primary loop.
  - Reproduces important SMR dynamics without requiring a nuclear heat source.

SMR control panel
(Power Technology)

CORE^{2}S
(Control-Oriented Research Environment for Energy Systems)

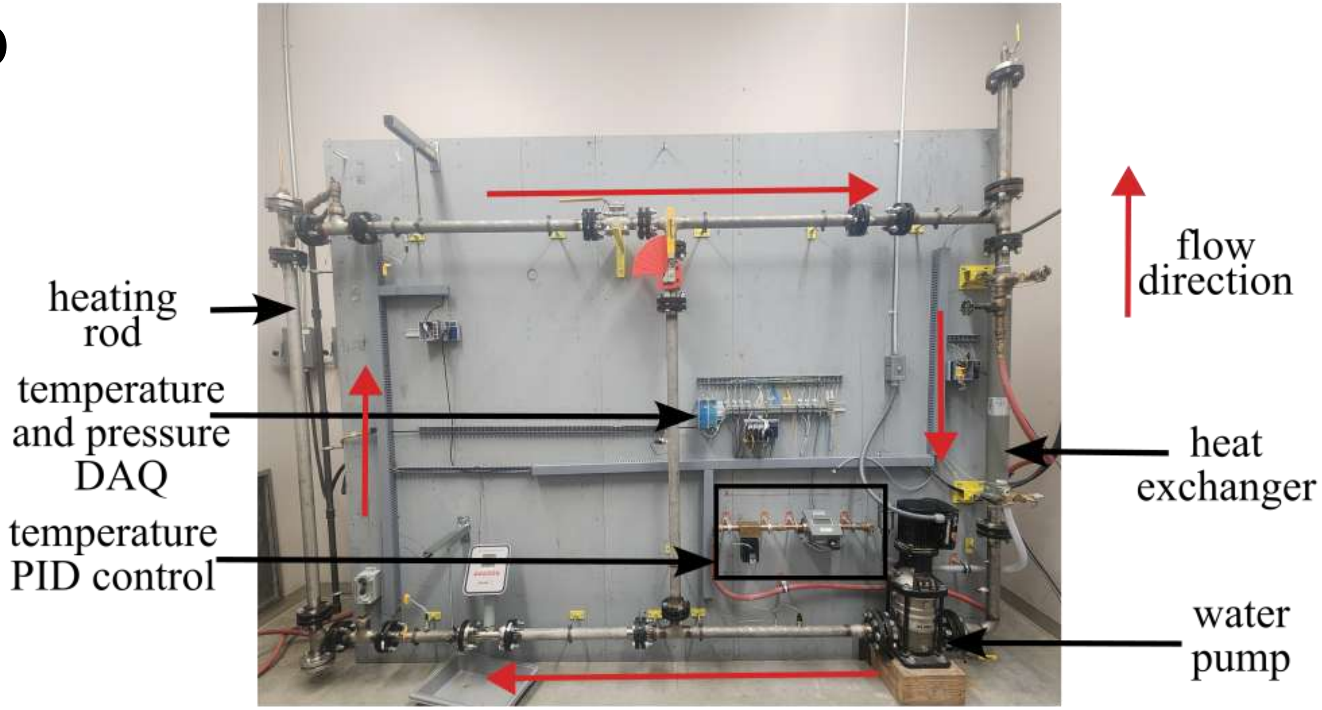
Parts of an SMR



Nuclear propulsion (Wikipedia)

Thermal Testbed

- Represents the primary loop
- Serves as the physical testbed for the models' application
- 7 thermocouples
- 3 pressure sensors
- 3 valves

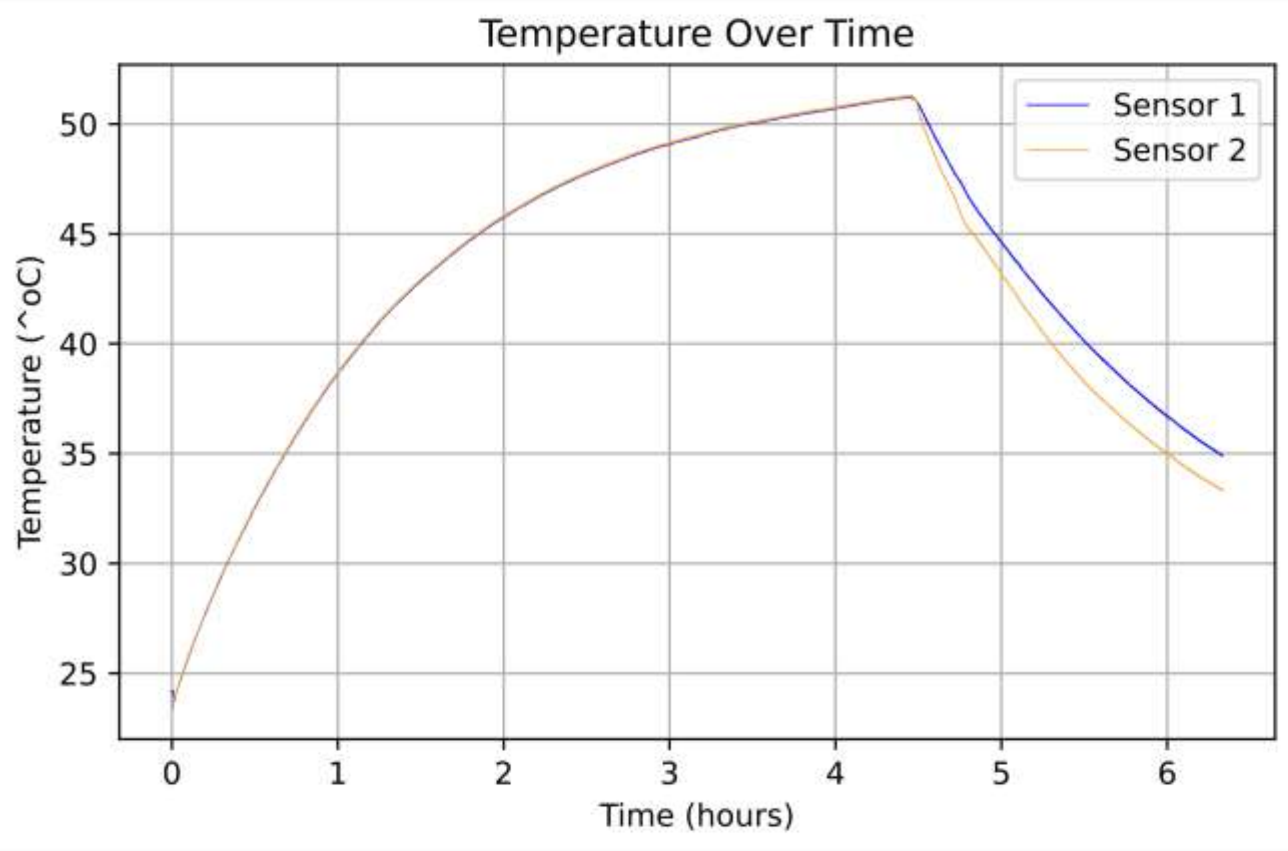


PID Control System

- PID control system keeps the loop temperature constant
- Controls temperature from flow rate of heat exchanger
- Testbed design with temperature-controlled feedback cooling

Results

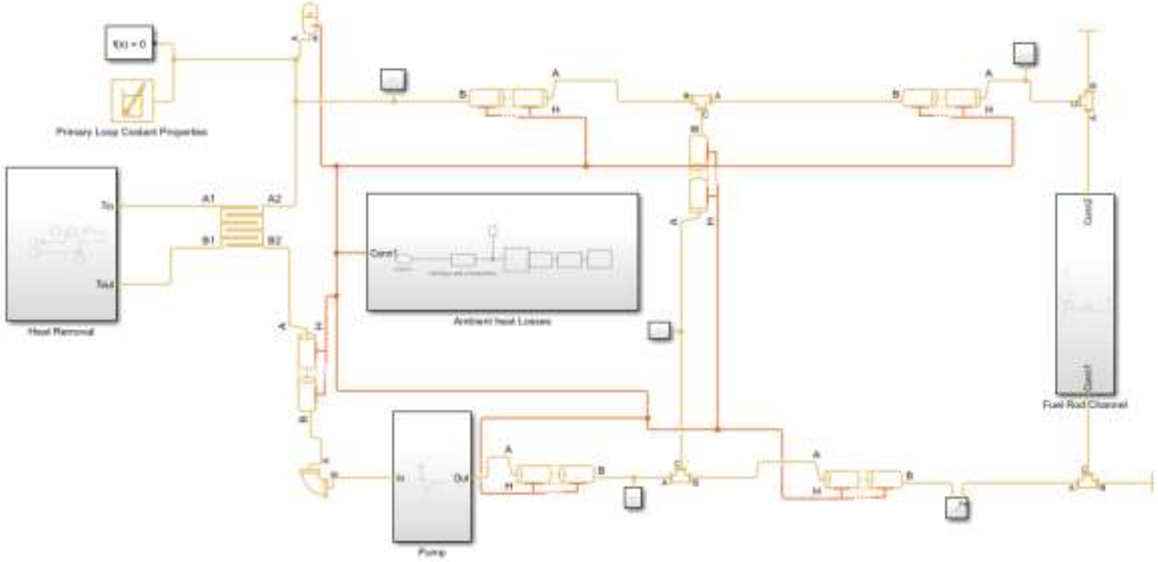
- Thermal loop test
- Middle Valve open
- Upper Valve open
- At 4.45 hours Pump and Rod turned off
- Without heat exchanger
- Sensor 1 is located after the rod
- Sensor 2 is located before the rod



THERMAL MODELING

Simscape Thermal Testbed Model

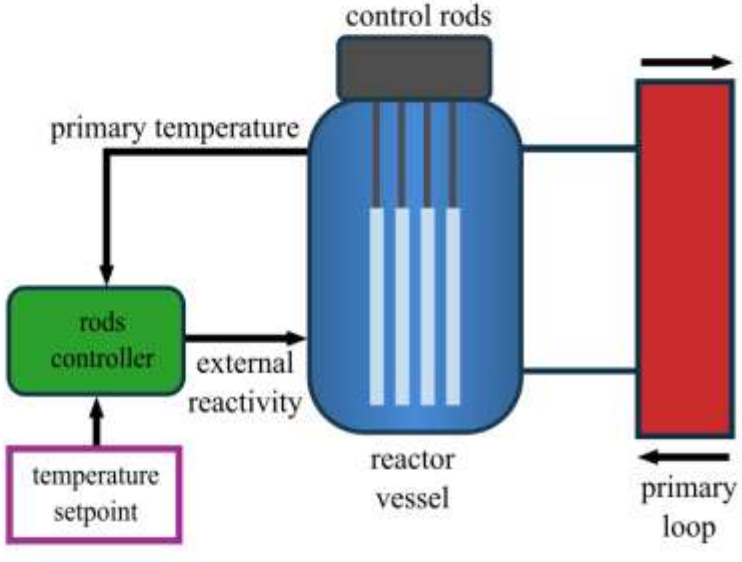
- Modeled items;
  - Heat exchanger
  - Ambient heat losses
  - Heating rod
  - Pump



NUCLEAR REACTIVITY MODELING

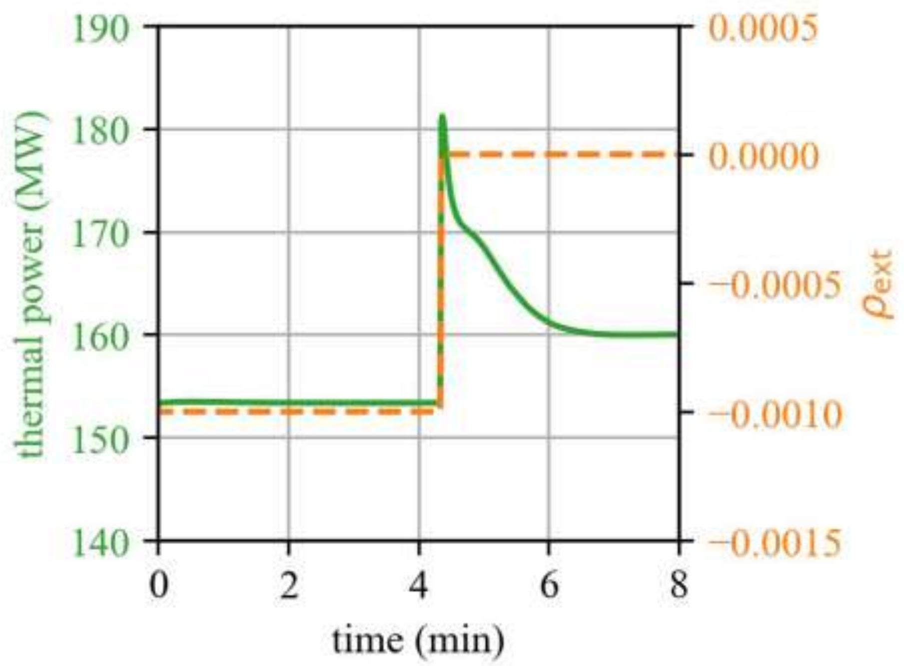
Nuclear-thermal Modeling

- Effect of rod controls on heat generated
- Using point kinetics equations
- $\rho = \rho_{ext} + \alpha_f(\Delta T_f) + \alpha_c(\Delta T_c)$
- ρ_{ext} – reactivity due to control rod operation
- α_f – fuel temperature coefficient
- α_c – coolant temperature coefficient
- T_f – fuel temperature
- T_c – coolant temperature



Results

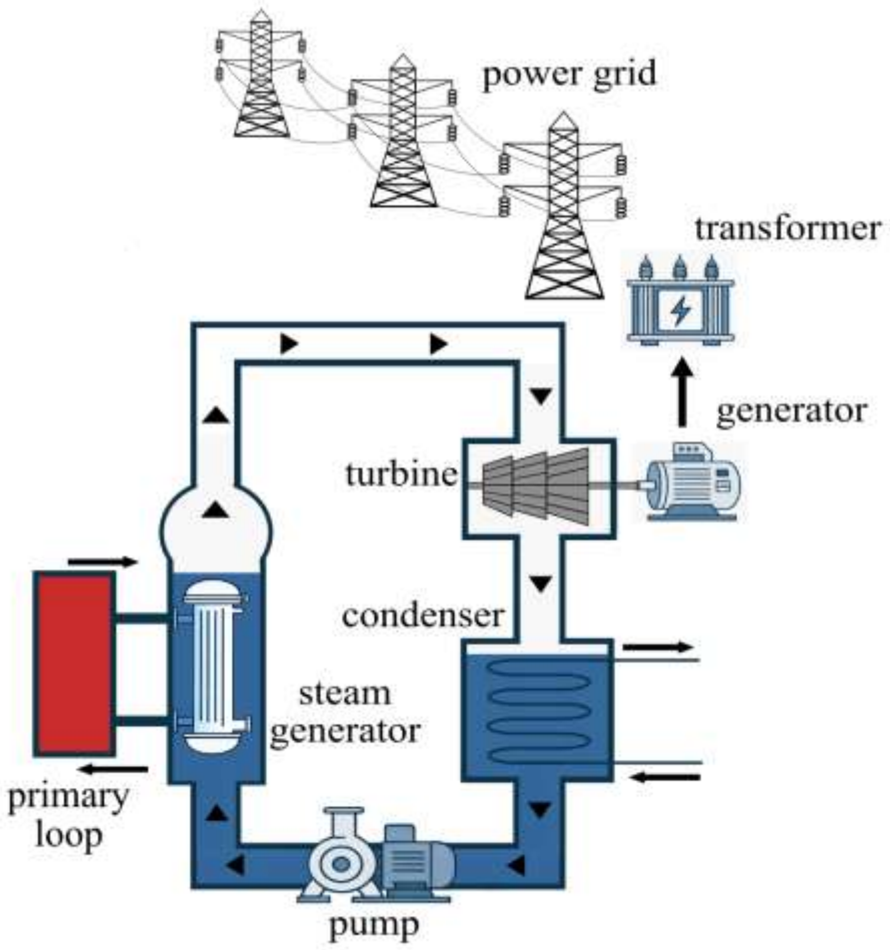
- Step increase in the system's reactivity from actuating a control rod
- Thermal changes resulting from withdrawing a control rod



POWER GENERATION MODELING (SECONDARY LOOP)

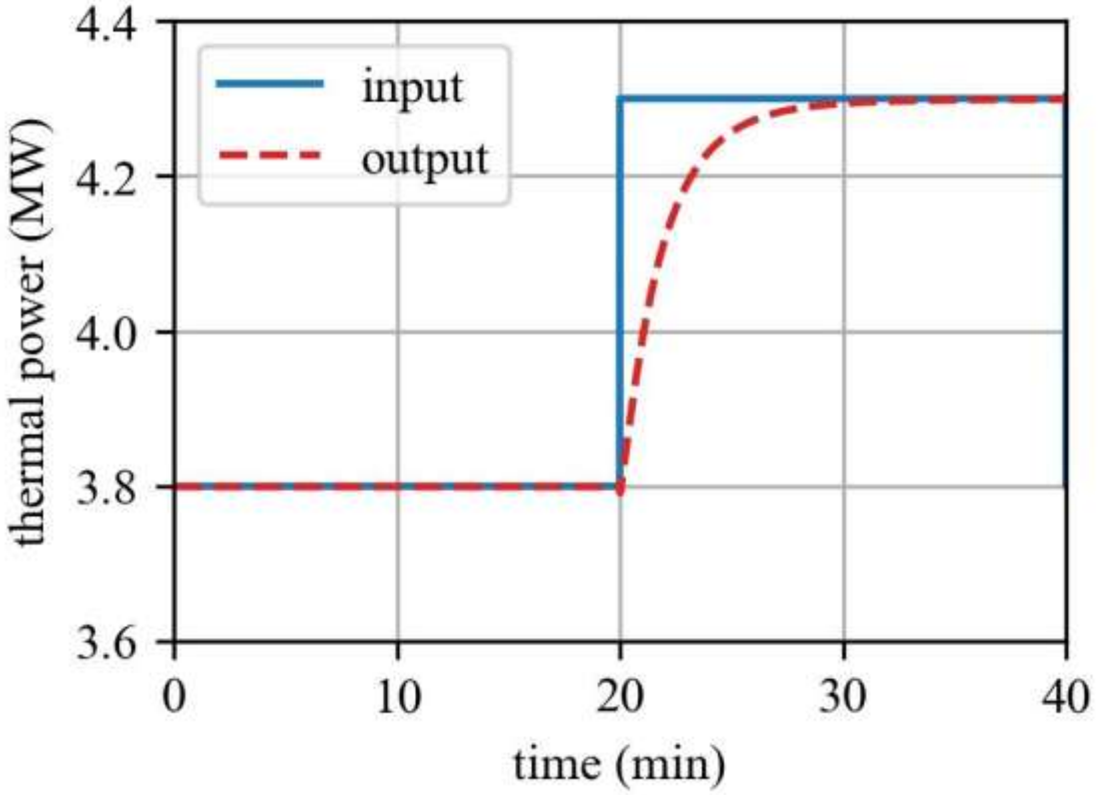
Secondary Loop Modeling

- Using Simscape, the heat exchanger thermal output to turbine output is generated
- Steam generator links the primary loop to the secondary
- Predicts changes in generator output based on thermal input
- Electrical output: 1MW



Results

- Step increase in steam generator increase
- Model shows changes in
  - Turbine power
  - Fluid temperature
  - Fluid pressure



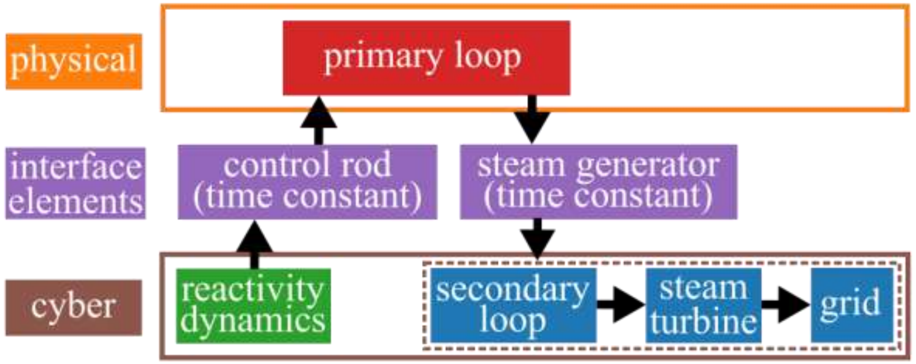
TIME CONSTANT MATCHING

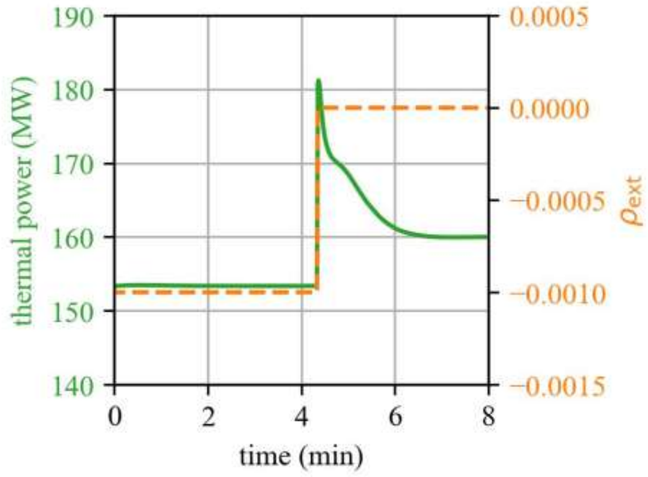
Target Time Constant

- Time constant interfaces

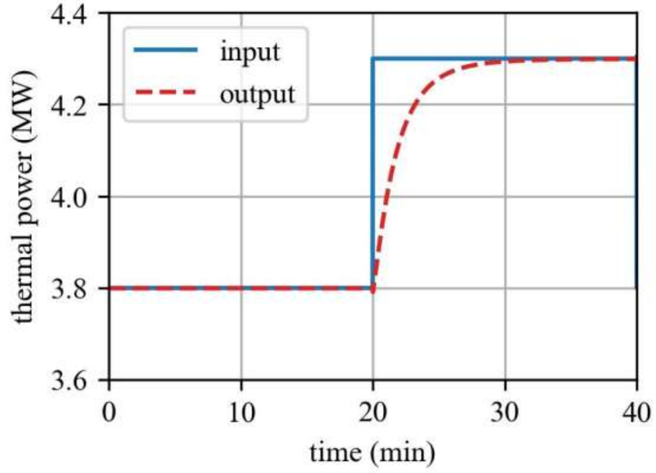
interfaces	Rod (initial)	Rod (later)	Heat exchanger
Time constant	0.7s	50s	180s

- The largest time is the target time constant value





Heating rod



Heat exchanger

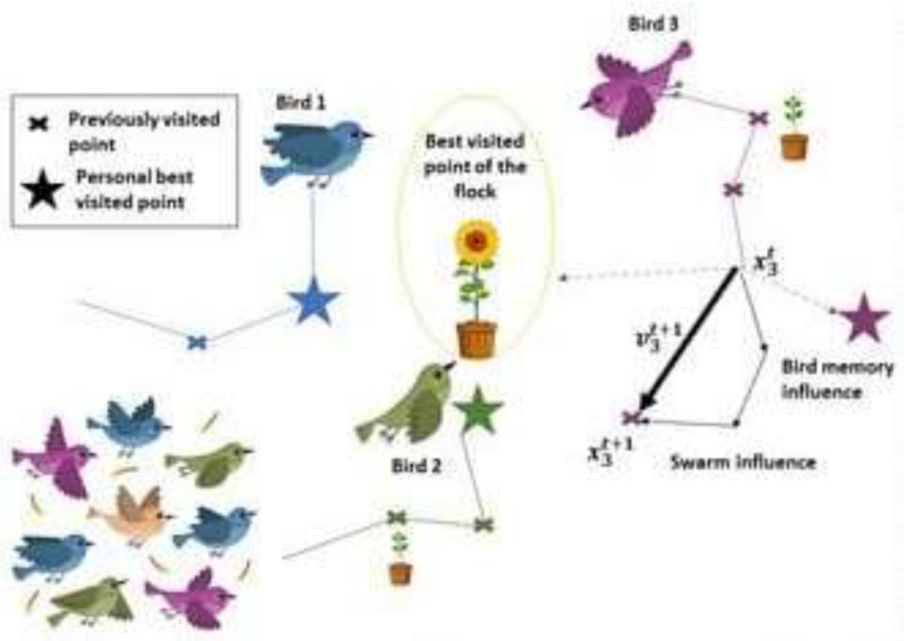
PSO Matching

Part 1

- Calibrating thermal model to testbed results

Part 2

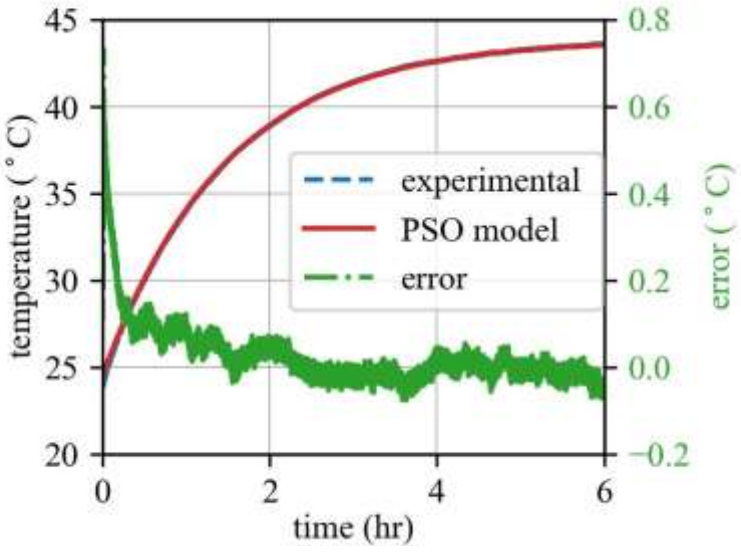
- Matching operating parameters to achieve target time constant
- $$v_i(t+1) = \omega v_i(t) + c_1 r_1\big(p_i - x_i(t)\big) + c_2 r_2(g - x_i(t))$$
- $$x_i(t+1) = x_i(t) + v_i(t+1)$$

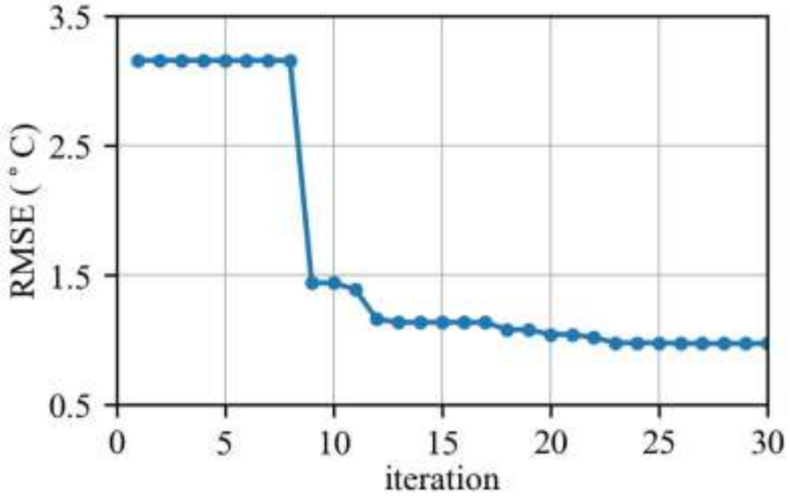


Particle Swarm Optimization algorithm
(Rapid protocols to support Covid-19 clinical diagnosis based on hematological parameters)

PSO THERMAL MODEL CALIBRATION

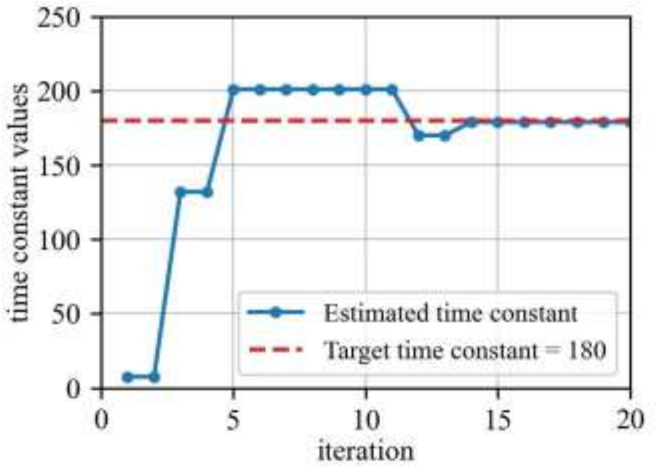
- Parameters
  - Swarm size – 20 particles
  - Maximum iterations - 30
- 11 thermal loop variables
- Best RSME – 0.9695°C

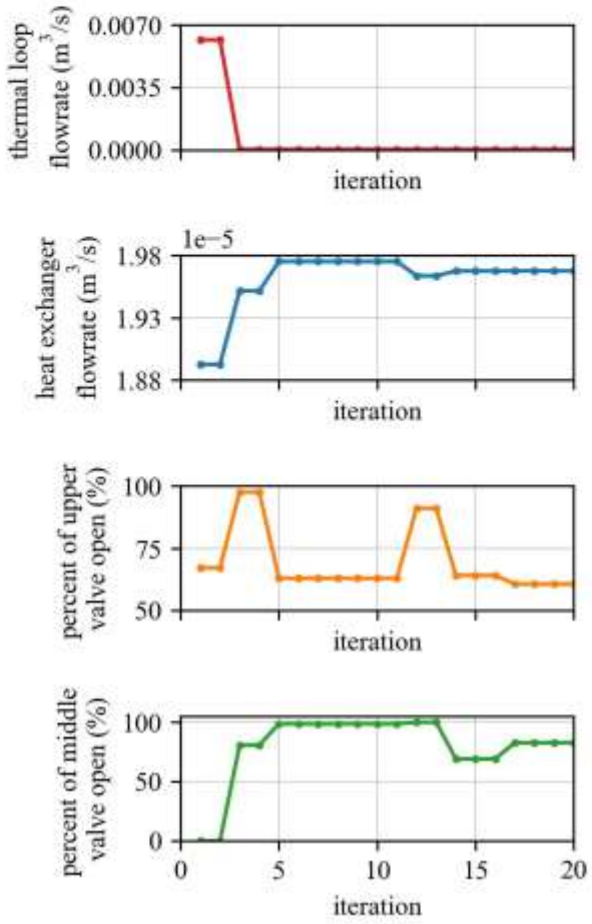




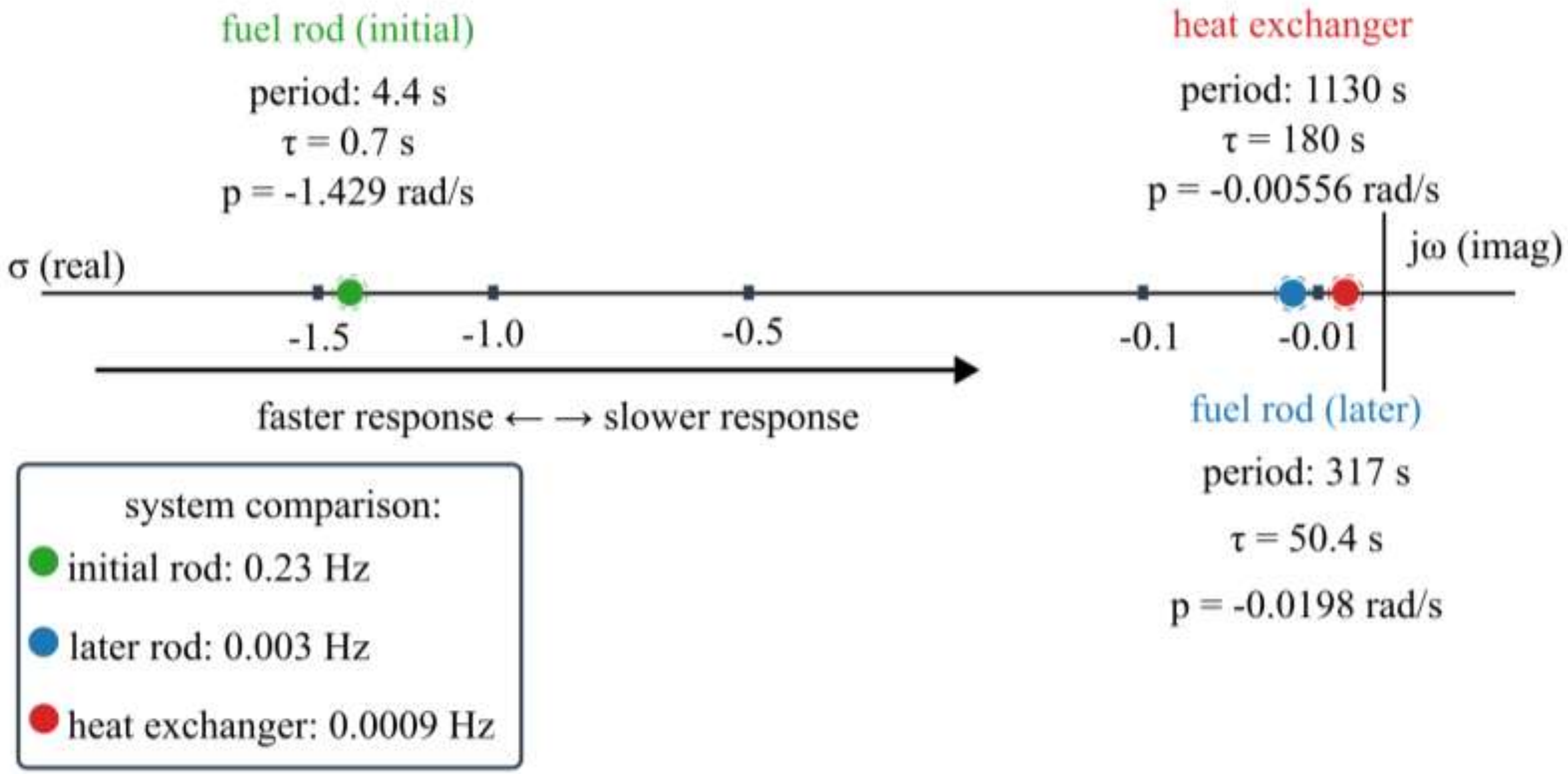
PSO Time Constant Matching

- Parameters
  - Swam size – 15 particles
  - Maximum iterations - 20
- 4 thermal loop variables
- Target – 180 seconds
- Criterion – 0.2% of target
- Final value – 180.36 seconds





Interface Pole Locations

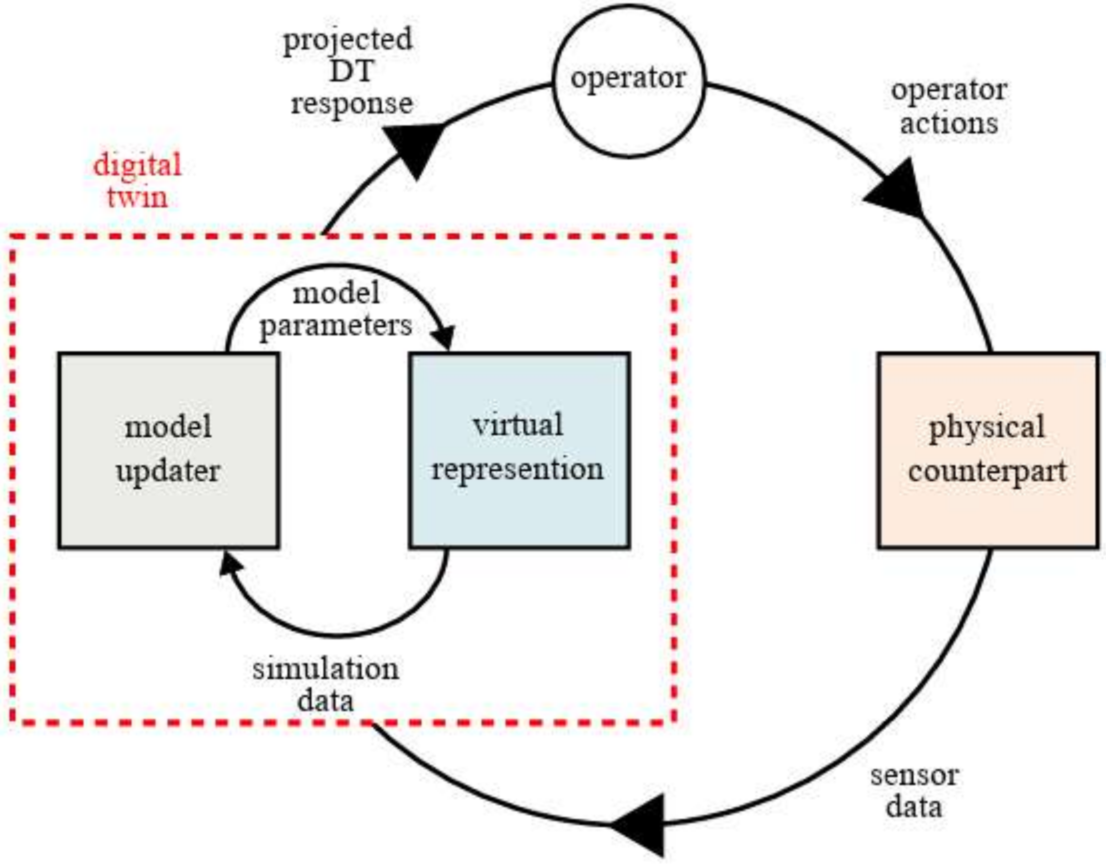


Higher negative value = more stability

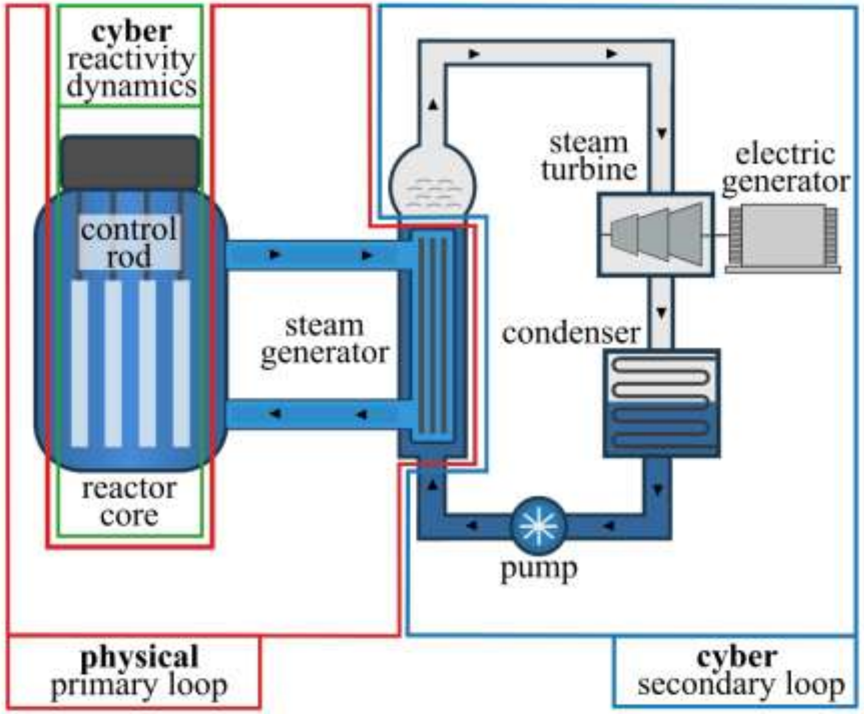
REAL-TIME CYBER-PHYSICAL COUPLING

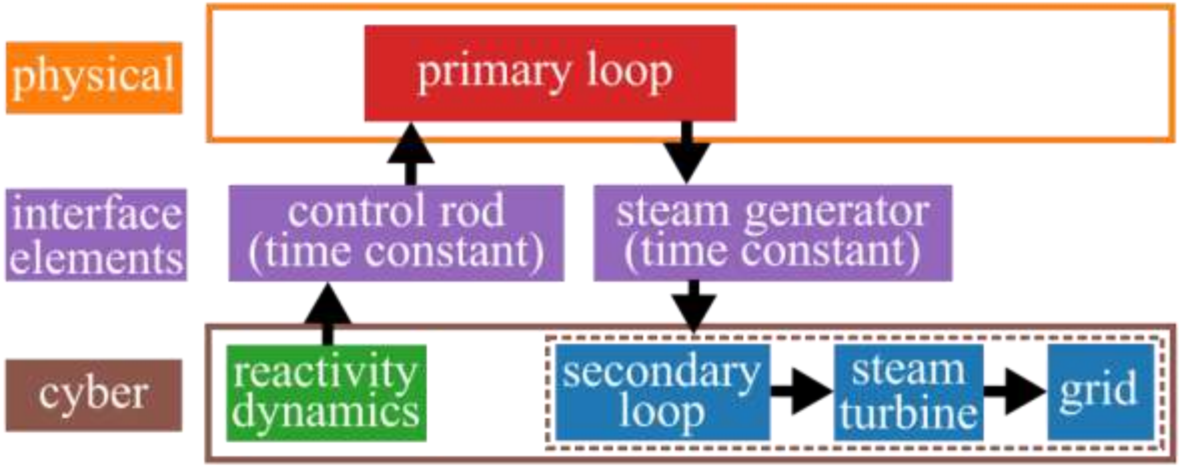
SMR Digital Twin Architecture

- Digital twins contain our cyber models (nuclear and secondary loop)
- Physical counterpart (thermal loop testbed)



Digital Twin



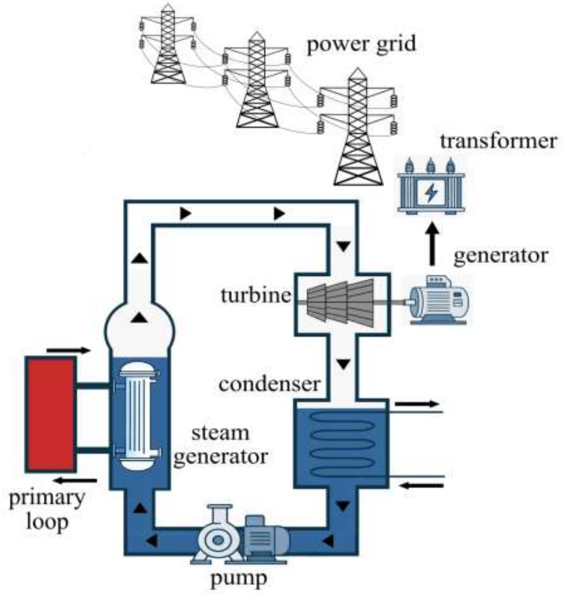


Time constants are derived from model results showing the step increase

REAL-TIME CONTROLLER

- This is real time computer used for Hardware in the Loop testing
- To be integrated with MATLAB and the testbed

Speedgoat



Thank You !

https://github.com/ARTS-Laboratory/core2s

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