U.S. DEPARTMENT OF ENERGY | Office of NUCLEAR ENERGY
Advanced Sensors and Instrumentation

Design and Prototyping of Advanced Control Systems for Advanced Reactors Operating in the Future Electric Grid

Advanced Sensors and Instrumentation (ASI)
Annual Program Webinar
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PI: Roberto Ponciroli
Argonne National Laboratory

Project Overview

Project Goal: Improve economic competitiveness of advanced reactors through

- Enhance operational flexibility by coupling advanced reactor concepts with thermal energy storage (TES) technologies.
- Integration of control, diagnostics, and automated reasoning in a suitable architecture ensuring semi-autonomous operation.
- Reduction of O&M costs by optimizing plant availability and maintenance schedule.

Participants

Argonne National Laboratory

Roberto Ponciroli (PI)
Akshay Dave
Haoyu Wang
Tat Nghia Nguyen
Richard B. Vilim

University of Michigan

Brendan Kochunas
Shai Kinast
Deep Patel

Kairos Power

Anthonie Cilliers

Schedule: FY21 - FY23

Project Overview

- Schedule

FY21

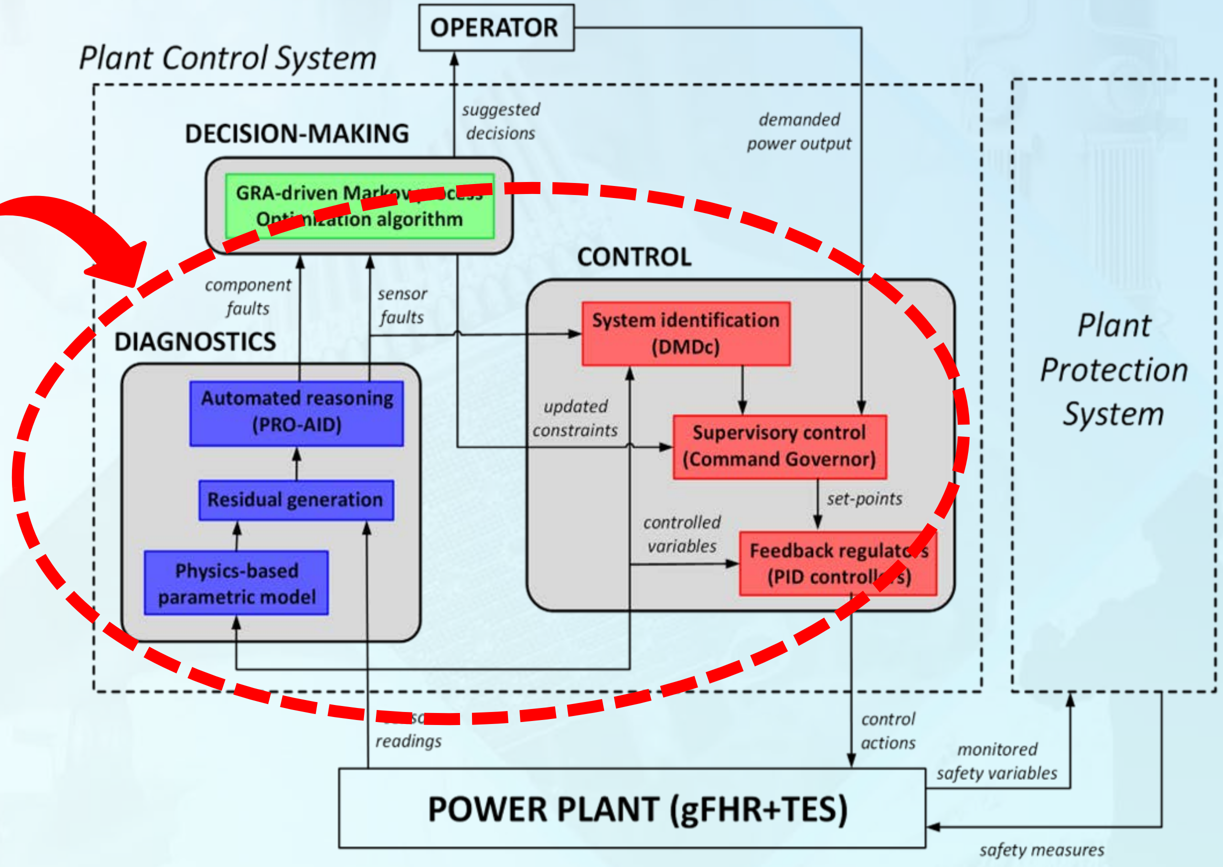
- Definition of the IES system reference configuration
- Development of the high-fidelity simulator

FY22

- Selection of Diagnostics/Control algorithms
- Derivation of necessary DTs
- Adaptation of available Diagnostics and Control capabilities

FY23

- Implementation of the selected algorithms in the proposed architecture
- Cost-benefit analysis



Project Overview

- System definition and Simulator development (FY21)
  - Selection of the Integrated Energy System (IES) design that will serve as the reference case.
  - Identified the most appropriate TES technology that can be driven by a fluoride salt-cooled, high temperature reactor (FHR).
  - Developed a high-fidelity simulator by using SAM (System Analysis Module) code.

- Development of Diagnostics and Control methods (FY22)
  - Simulation of operational transients, e.g., charging/discharging, load-following, etc.
  - Implementation of regulators foreseen by the control strategy, Supervisory control layer.
  - Selection of diagnostics algorithms.

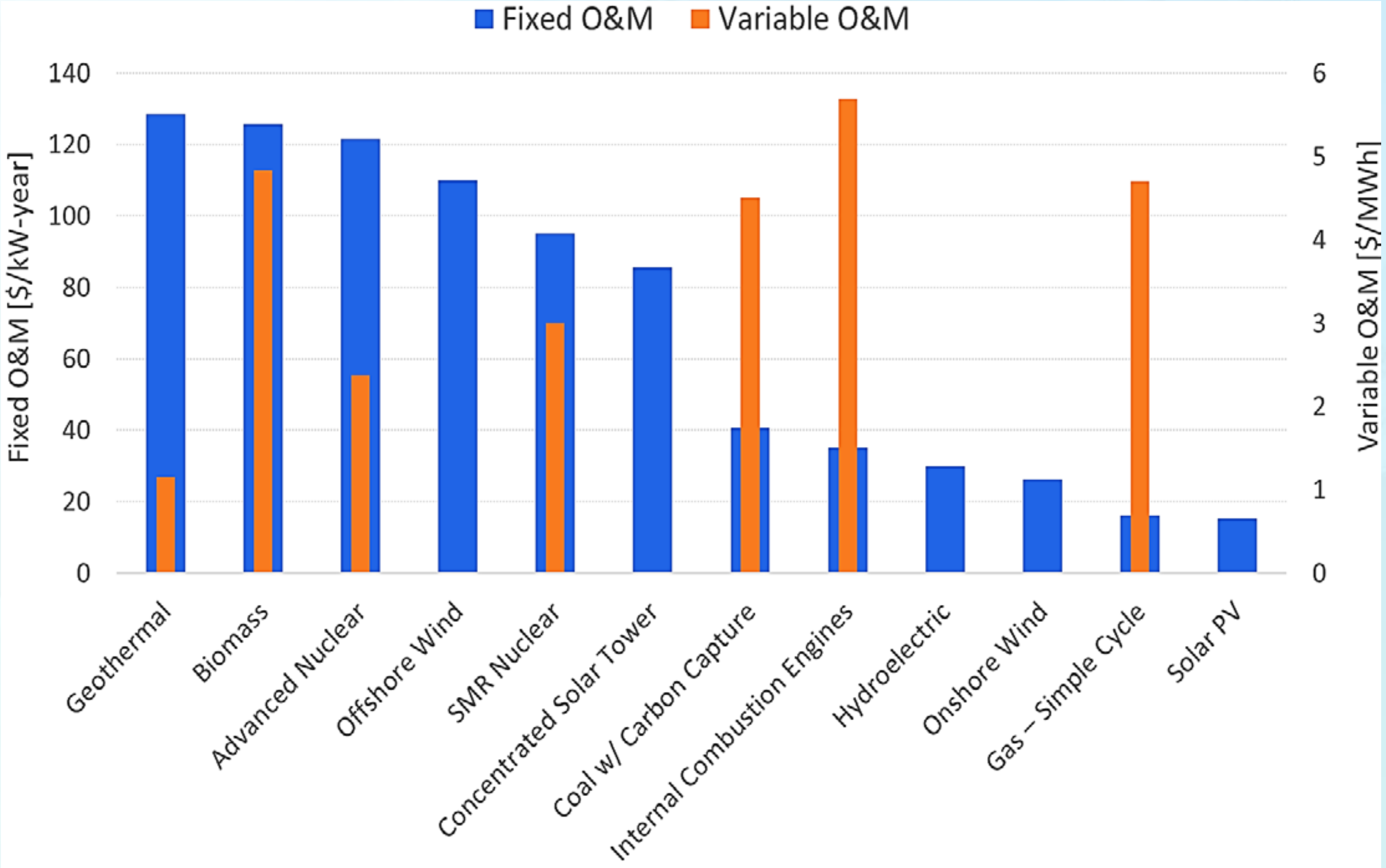
- Demonstration of the performance of the proposed Architecture (FY22-FY23)
  - Formulation of the Markov decision process that will constitute the heart of the decision-making capabilities.
  - Coupling the different components of the architecture and validation by adopting the developed high-fidelity simulator.

Results and Accomplishments: Analysis of Nuclear O&M costs

Performed an exhaustive literature review on O&M costs for nuclear units to identify the major drivers.

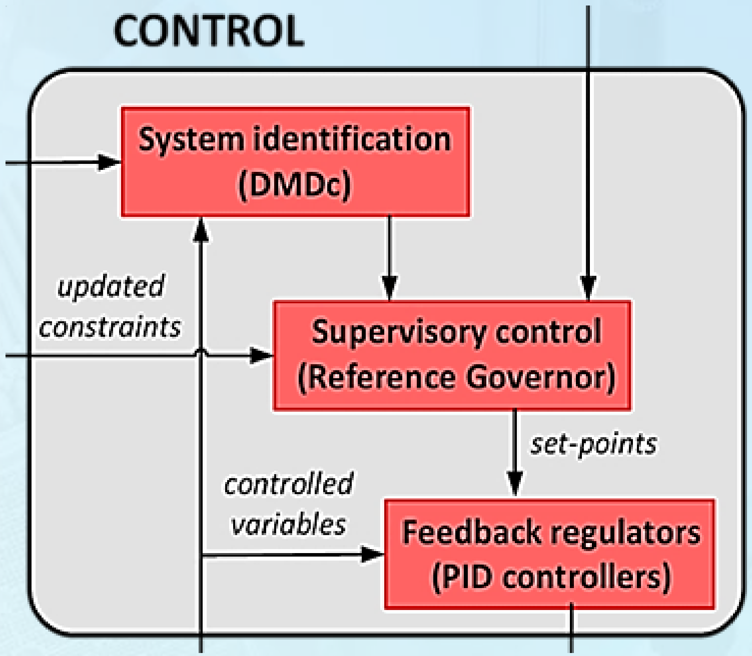
Conclusions

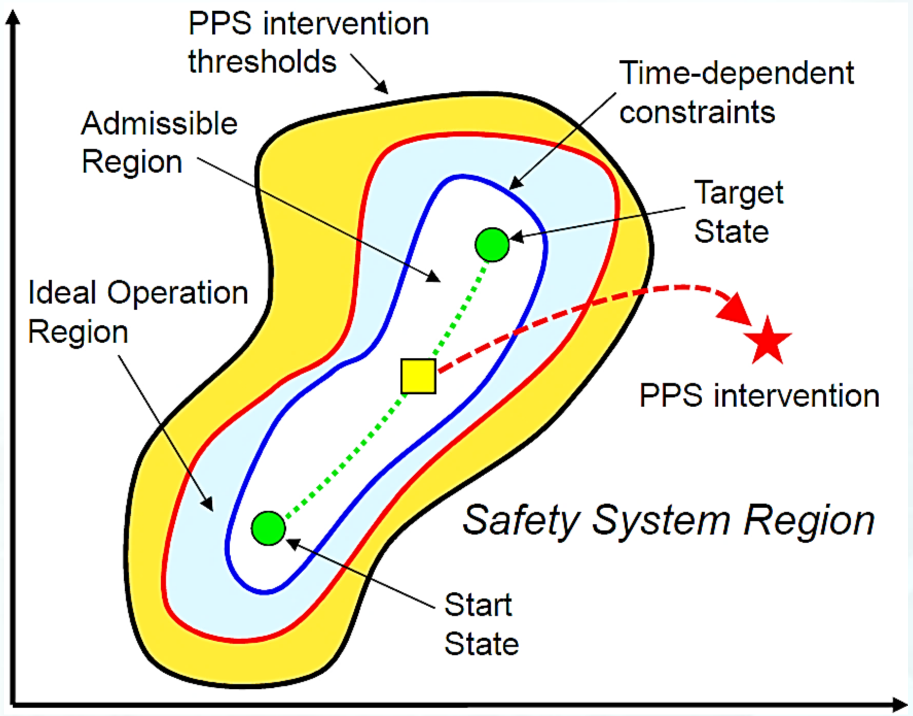
- MCR operations staff is relatively small compared with the overall plant staffing, i.e., having a fully autonomous control room would have a minimal effect on O&M costs.
- Part of the O&M costs include those incurred from scheduling procedures and work/systems control and optimization (these activities are likely going to increase with increased operational flexibility).
- There are three techniques to reduce maintenance costs, i.e., condition-based monitoring, prognostics and health management, maintenance optimization.
- Studies estimated potential maintenance cost savings of more than $1B over the life of GW scale nuclear plants.



Results and Accomplishments: “CONTROL” module description

ITEM	ALGORITHM	DESCRIPTION
System Identification	Dynamic Mode Decomposition with Control (DMDc)	Derives the DT to be used by the Supervisory control by tracking the evolution of process variables
Supervisory Control	Reference Governor	Enforces the imposed constraints by adjusting the set-point trajectories issued by the Operator.
Feedback Regulators	Proportional-Integral (PI) regulators	Set of Single Input Single Output (SISO) controllers

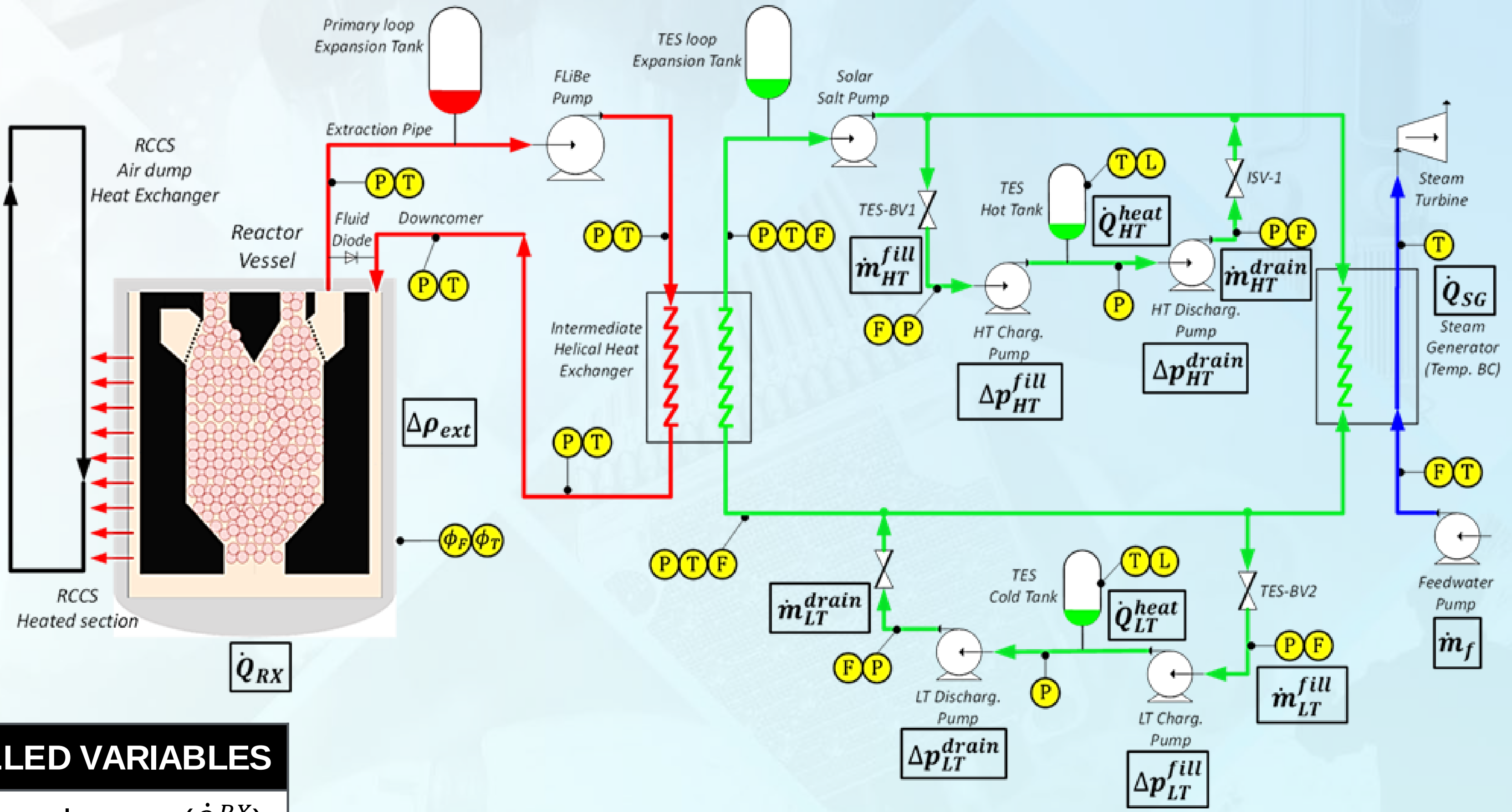




- **Normal Operation Envelope**: set of limits to be respected to ensure conformance with the safety analysis.
- Envelopes usually represented as two-dimensional surfaces. To ensure the safe operation of a nuclear unit, hundreds of process variables need to be simultaneously monitored (***n*-dimensional polytope**).
- Time-dependent constraints crucial for **integrating diagnostics and control capabilities**.

Results and Accomplishments: Control Strategy (1/2)

- Selection of the **variables to be controlled** for Primary and Intermediate Circuits
- Selection of pairings between control/controlled variables for all the operating modes (**control strategy**)
- Designed and implemented the **PI controllers** (tank electrical heaters adopt **ON-OFF controllers)**

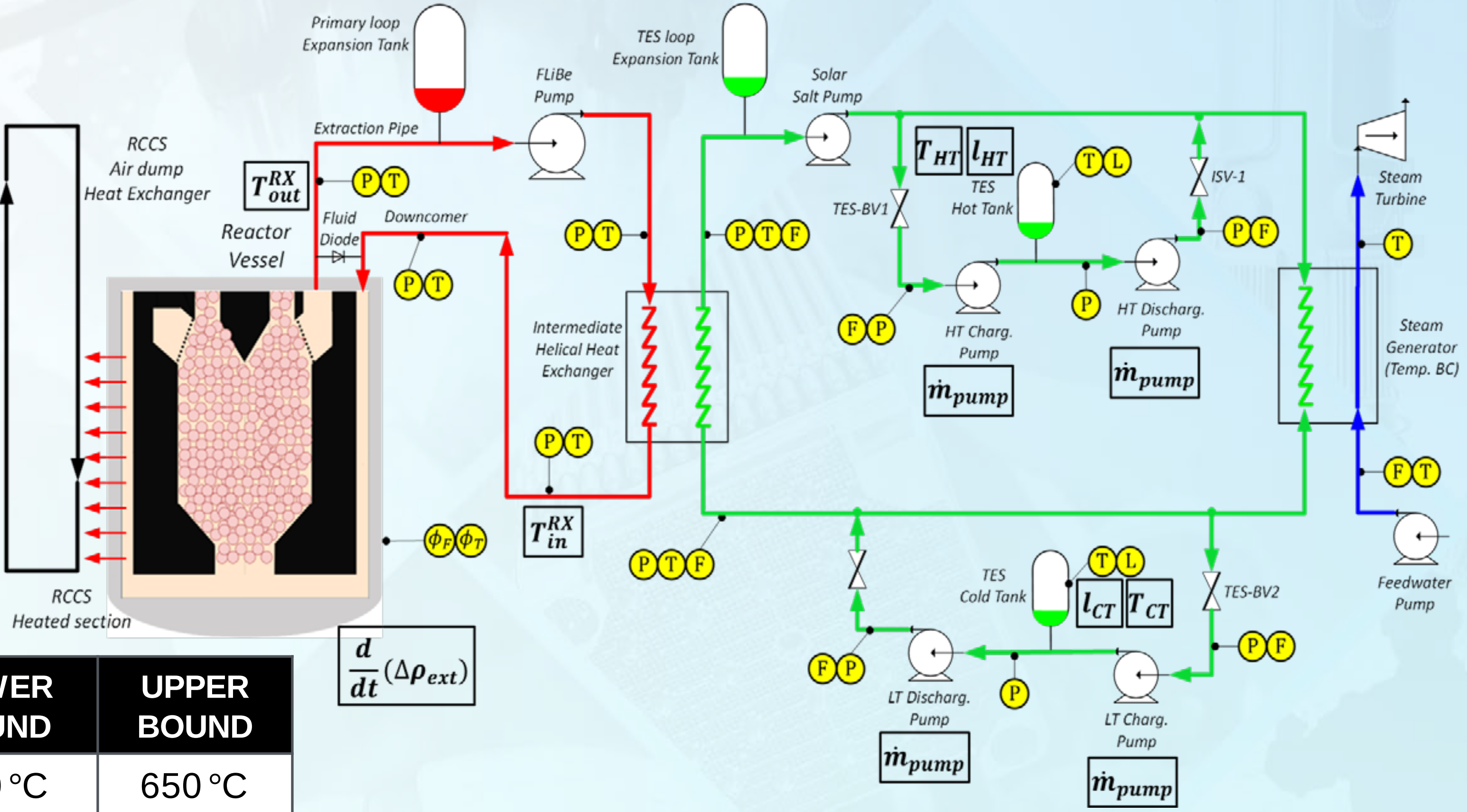


CONTROL VARIABLES	CONTROLLED VARIABLES
Control rods reactivity ($\Delta\rho_{ext}$)	Reactor thermal power ($\dot{Q}^{RX}$)
HT discharging pump head (Δp_{HT}^{drain})	TES thermal power ($\dot{Q}^{TES}$)
LT charging pump head (Δp_{LT}^{fill})	LT tank inlet flowrate ($\dot{m}_{LT}^{fill}$)
Feedwater flowrate ($\dot{m}_f$)	SG electrical power ($\dot{Q}^{SG}$)

- The operation of TES tanks (charging/discharging transients) is achieved by adopting variable speed pumps (valves are not sufficient)

Results and Accomplishments: Control Strategy (2/2)

- Definition of the set of **variables to be constrained** between upper/lower bounds during operation.
- Core temperatures are **constrained, not controlled**.
- “FLiBe pump” and “Solar Salt pump” operated at **constant speed** (reduction of wear & tear).



CONSTRAINED VARIABLE	REFERENCE VALUE	LOWER BOUND	UPPER BOUND
Core inlet temperature (T_{in}^{RX})	645.4 °C	640 °C	650 °C
Core outlet temperature (T_{out}^{RX})	742.9 °C	740 °C	750 °C
HT tank level (l_{HT})	3.54 m	0.5 m	6.5 m
LT tank level (l_{LT})	3.50 m	0.5 m	6.5 m
HT tank temperature (T_{HT})	594.0 °C	310 °C	601 °C
LT tank temperature (T_{LT})	557.5 °C	310 °C	601 °C

- Valves are subject to **faults due to corrosion and salt local solidification** that affect their operability (dedicated salt temperature constraints are imposed).

Results and Accomplishments: Identification of the Operation Modes

Mode#1: "Discharging"

- SG electrical power output increases
- Reactor at constant power (base-load)
- Load met by the TES only (discharging)

Mode#2: "Charging"

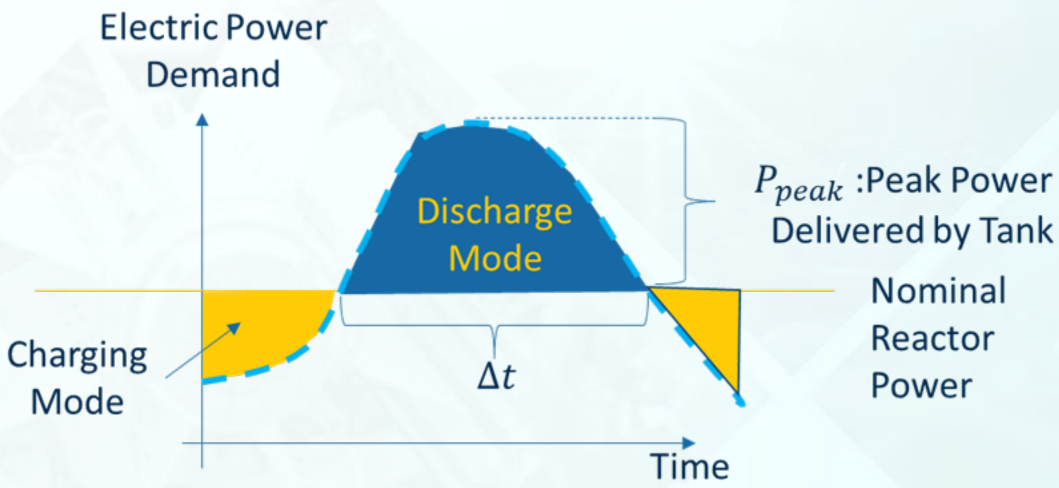
- SG electrical power output decreases
- Reactor at constant power (base-load)
- Load met by the TES only (charging)

Mode#3: "Prolonged Discharging"

- SG electrical power output increases
- TES immediately starts discharging
- Reactor power progressively increases

Mode#4: "Prolonged Charging"

- SG electrical power output decreases
- TES immediately starts charging
- Reactor power progressively decreases

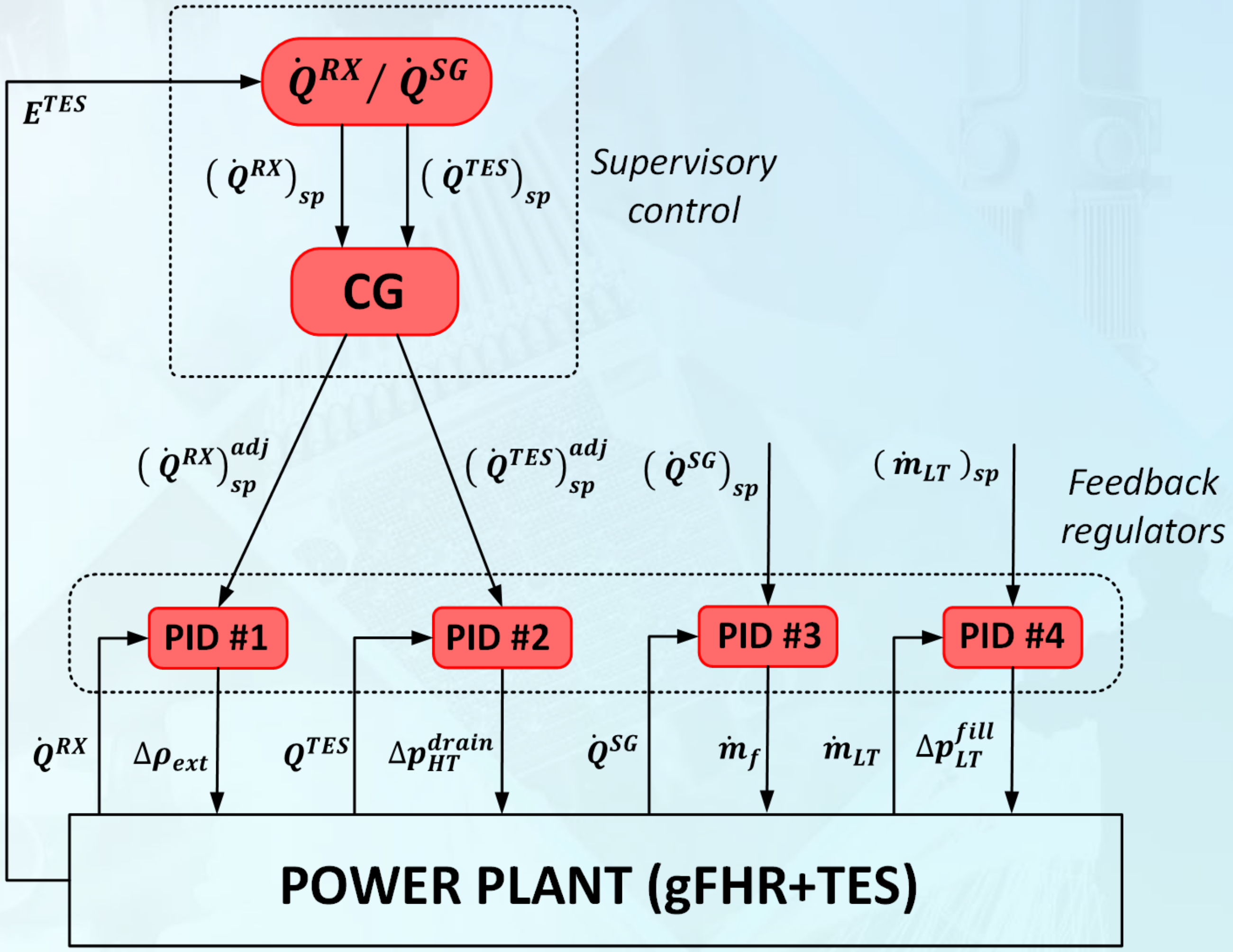


Mode#5: "Reactor load-following"

- SG electrical power output changes
- TES is completely by-passed
- Reactor-follows-turbine
- Possible reasons: Exhausted storage capacity, TES maintenance, fast-runback

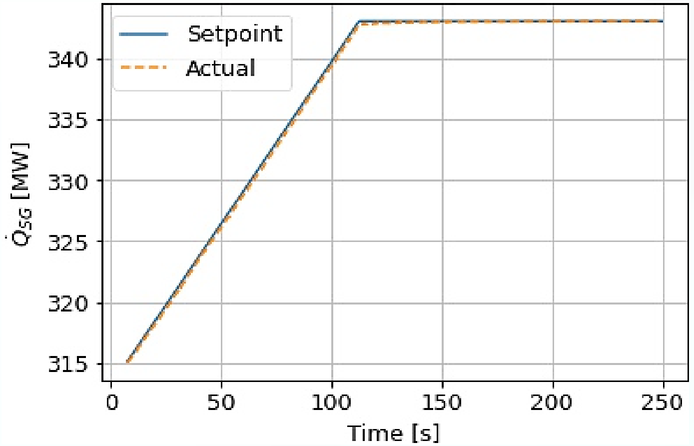
Results and Accomplishments: Design of the Supervisory Control

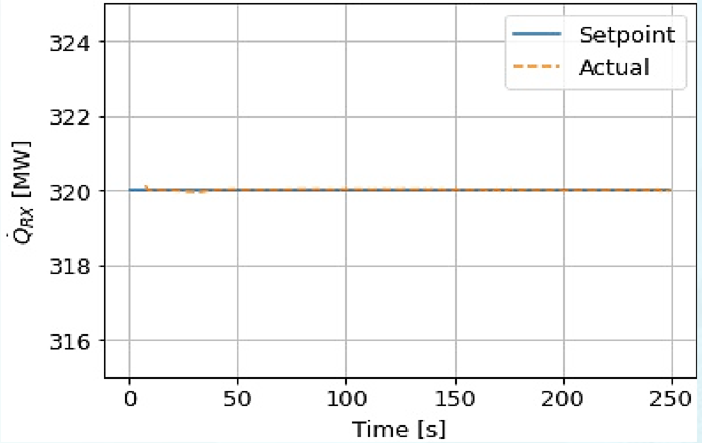
- Starting from the current conditions of the TES system (E^{TES}) and the demanded power variation, the operation mode is selected and the tentative set-points are evaluated ($(\dot{Q}^{RX})_{sp}$ and $(\dot{Q}^{TES})_{sp}$).
- A **single Command Governor** (MIMO version of the Reference Governor) adjusts tentative set-points and issues adjusted trajectories to low-level controllers.
- Pairings change as the operation modes changes (the shown architectures refer to Mode#3).
- **Current status**: CG was applied to both Primary and Intermediate Circuits.
- **Next step**: implement the automated switching between Operating modes (Finite State Machine).

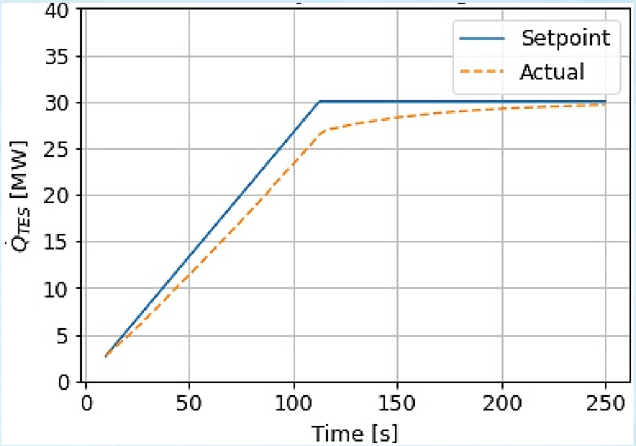


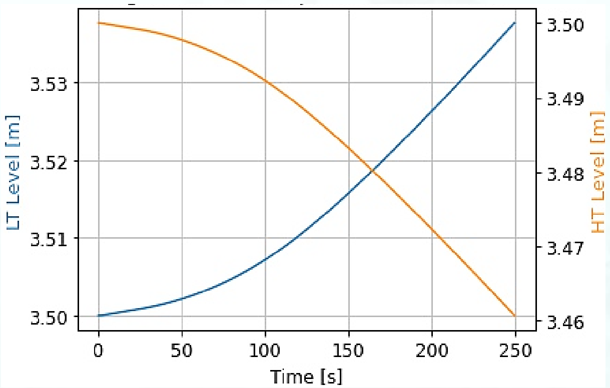
Results and Accomplishments: Simulation of Operating modes (1/2)

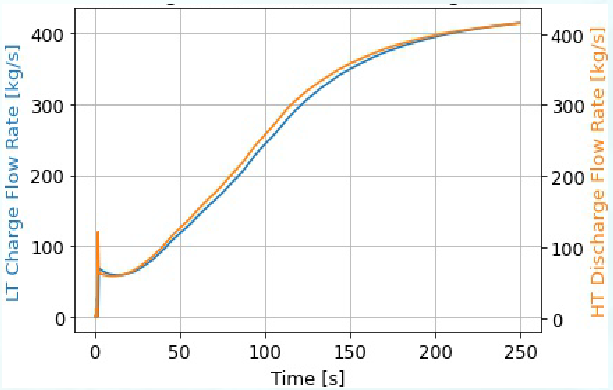
“Discharging” mode results (Mode#1)

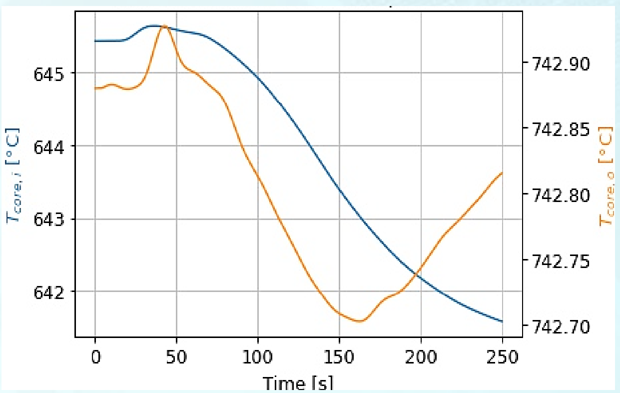


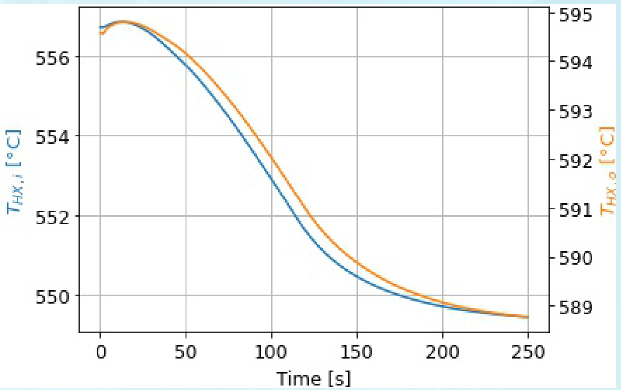






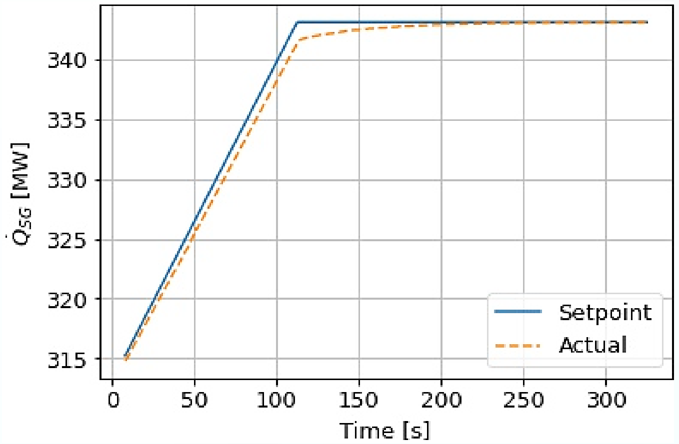


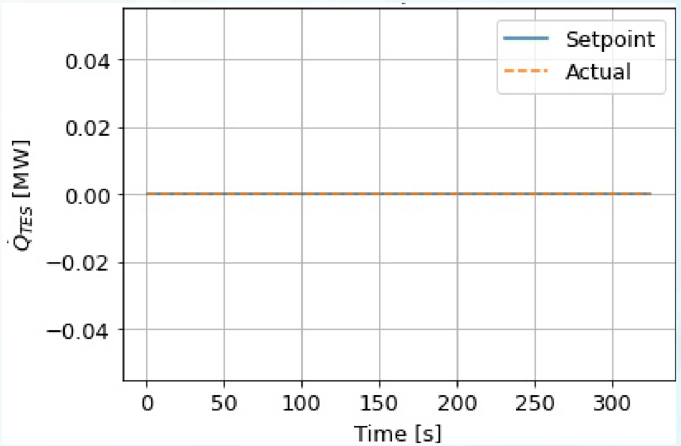


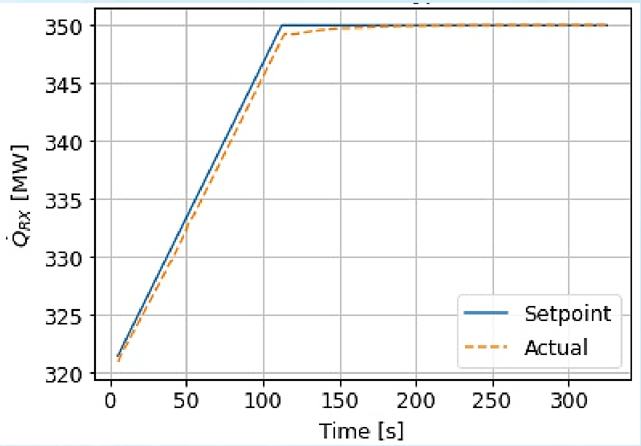


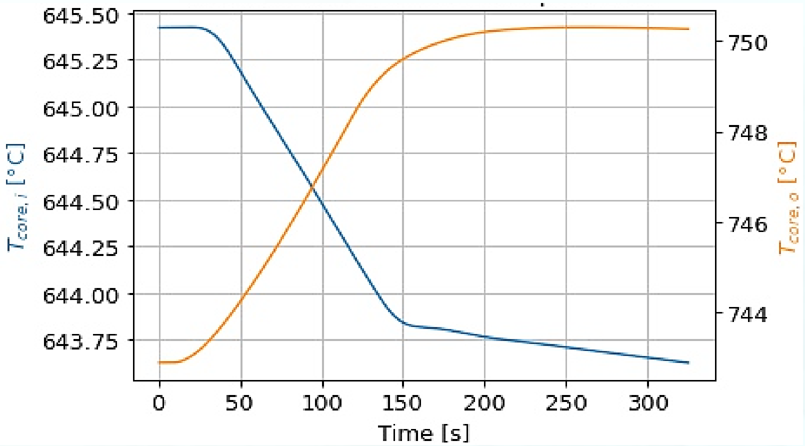
Results and Accomplishments: Simulation of Operating modes (2/2)

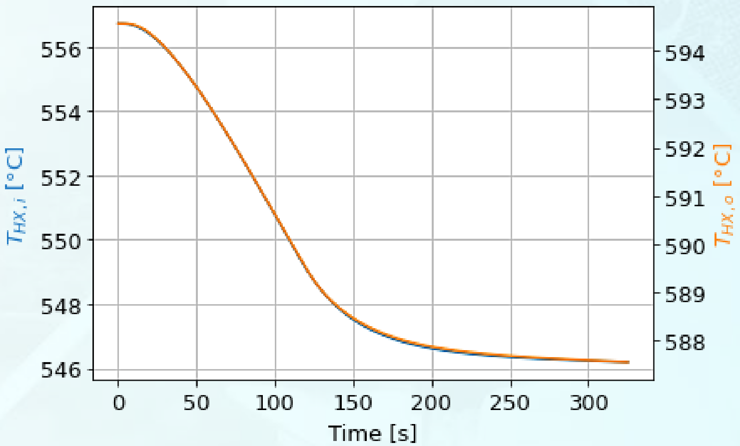
"Load-following" mode results (Mode#5)

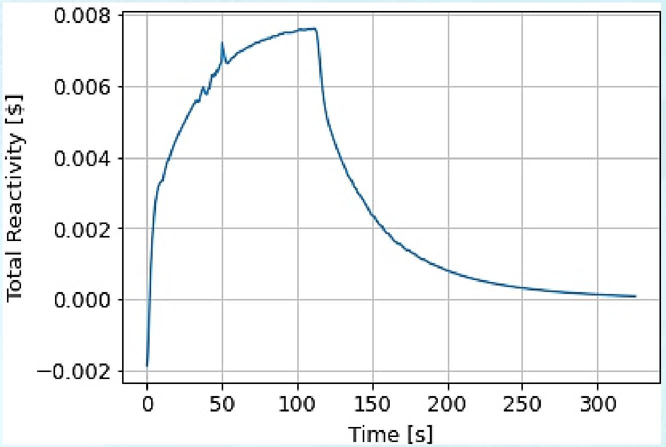






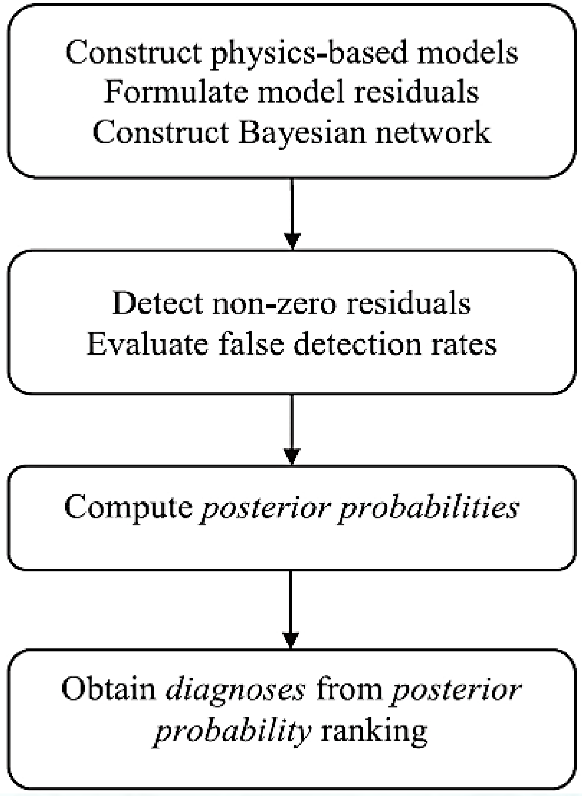




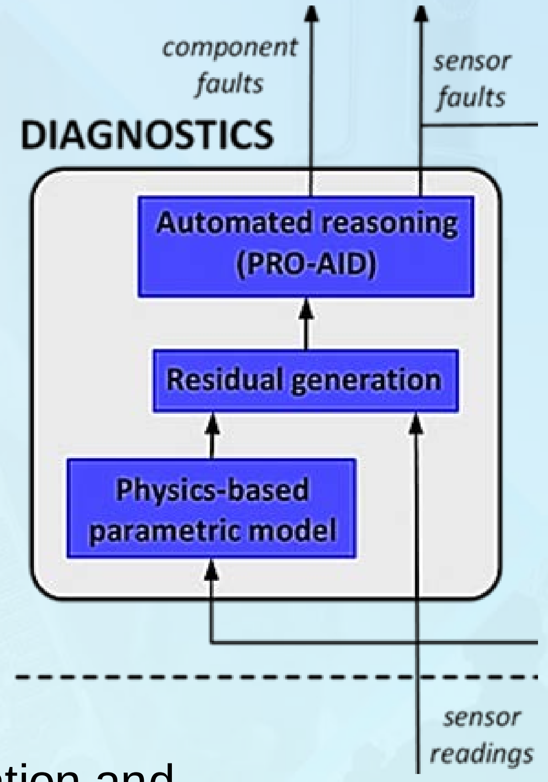


Results and Accomplishments: "DIAGNOSTICS" module description

ITEM	ALGORITHM	DESCRIPTION
Physics-based parametric model	Interpolating polynomials	Predicts the system response
Residual generation	Algebraic tool	Evaluates differences between model predictions and sensors readings for selected variables
Automated Reasoning	Forward chaining procedure (Bayesian approach)	Diagnoses component faults and sensors that are out of calibration or failed



- Currently used data-driven diagnostic methods reconstruct the relationship between the input/output variables
  - **Not physics-based** (unreliable for detecting equipment and sensor anomalies).
  - **Large and exhaustive datasets needed**.
- Parameter-Free Reasoning Operator for Automated Identification and Diagnosis (**PRO-AID**) is used in this project. It is a **physics-based probabilistic framework** for fault diagnostics of thermal-hydraulic systems.
- The performance of each component described by mass, momentum or energy balances. **Component-level and sensor-level faults** can be detected and discriminated.

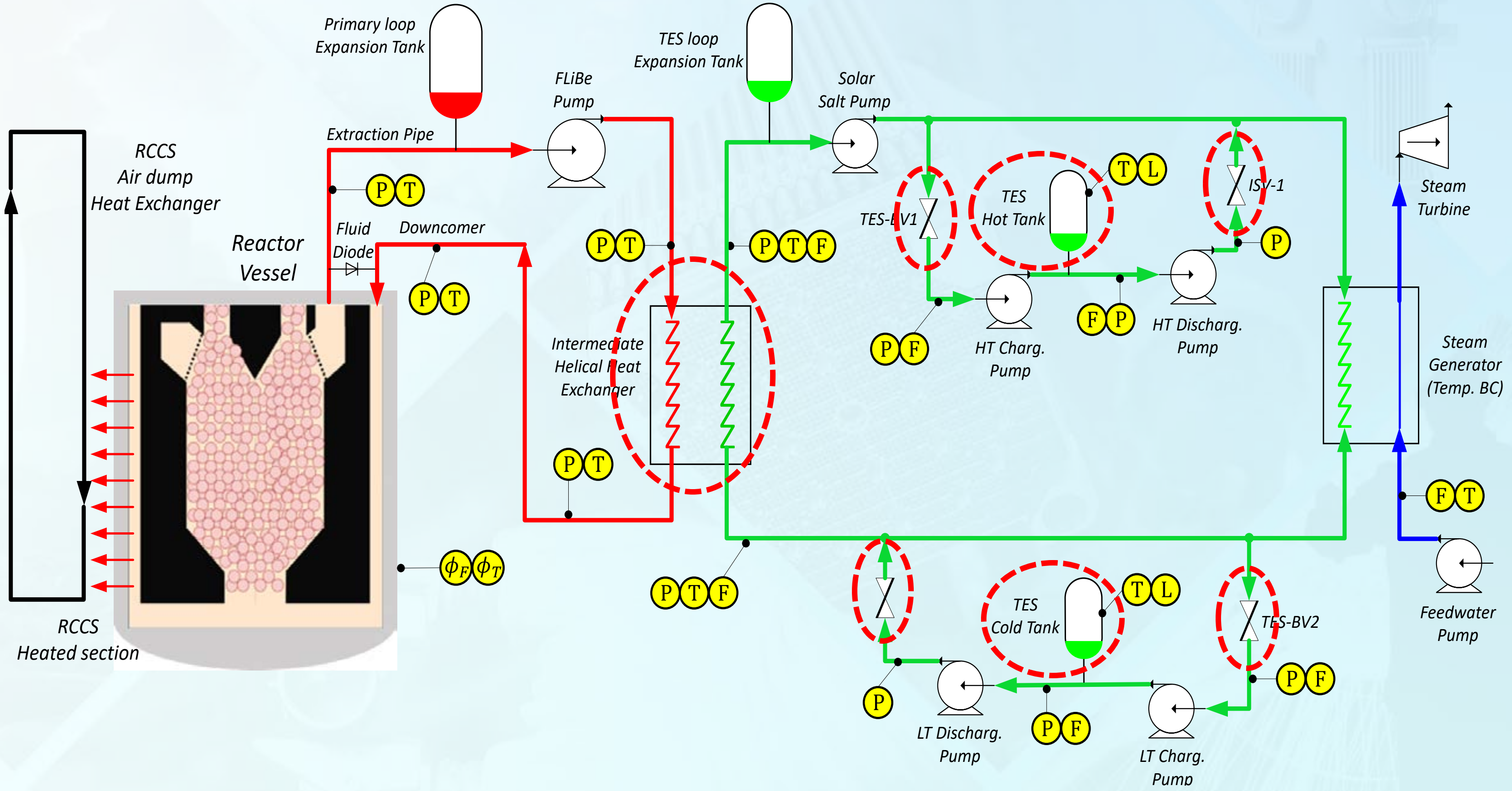


Results and Accomplishments: Diagnostics of the Intermediate Circuit

- For demonstration purposes, we will focus on the **monitoring/diagnostics of the Intermediate Circuit**. Major components are the Intermediate Helicoidal Heat Exchanger (IHX), the centrifugal pumps, the tanks and the valves.

- **A model for Centrifugal pump is not available in SAM**. Ideal components providing the needed head are adopted. Flexible operation capabilities are ensured by actuating charging/discharging valves.

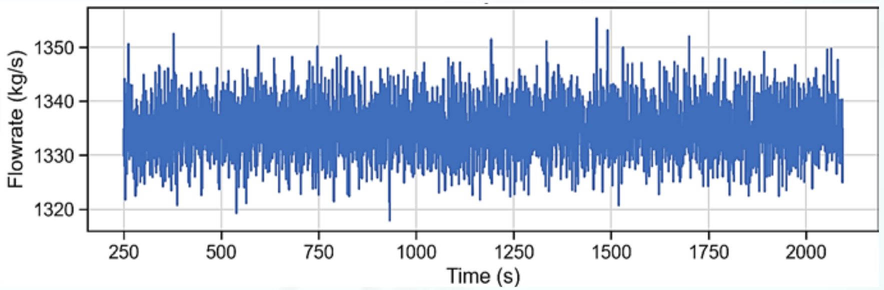
- Sensor faults and faults affecting the **IHX** (fouling, leaks), **valves** (leaks, blockages) and **tanks** (leaks, heat losses) are simulated with SAM simulator and detected/diagnosed with PRO-AID.

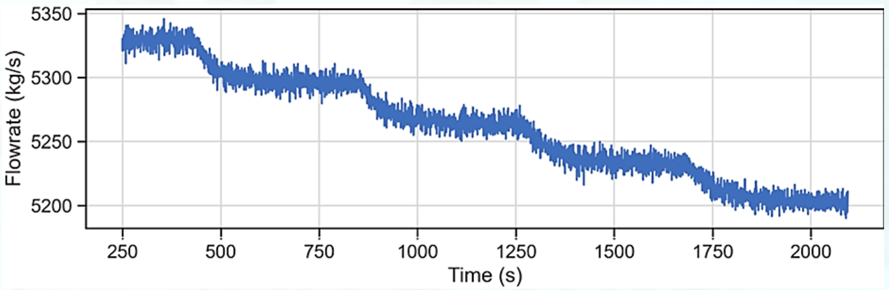


Results and Accomplishments: PRO-AID model for IHX (1/2)

- In this project, PRO-AID is applied to a molten salt reactor for the very first time. Database with thermo-physical properties used in SAM was implemented. Heat exchanger model for molten salt was derived.

- Training dataset generation (multiple operating points during shutdown sequence) and parametric IHX model derivation



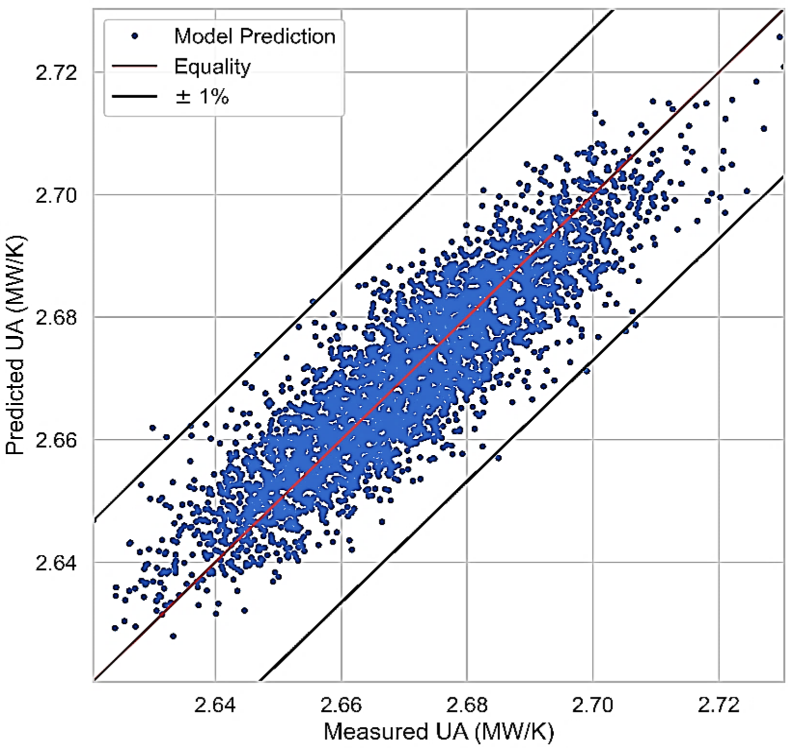


$$Q = UA\frac{\Delta T_o - \Delta T_i}{\ln\left(\frac{\Delta T_o}{\Delta T_i}\right)}$$

$$\frac{1}{UA} = \theta_h {w_h}^{-0.8} + \theta_c {w_c}^{-0.6} + \theta_0$$

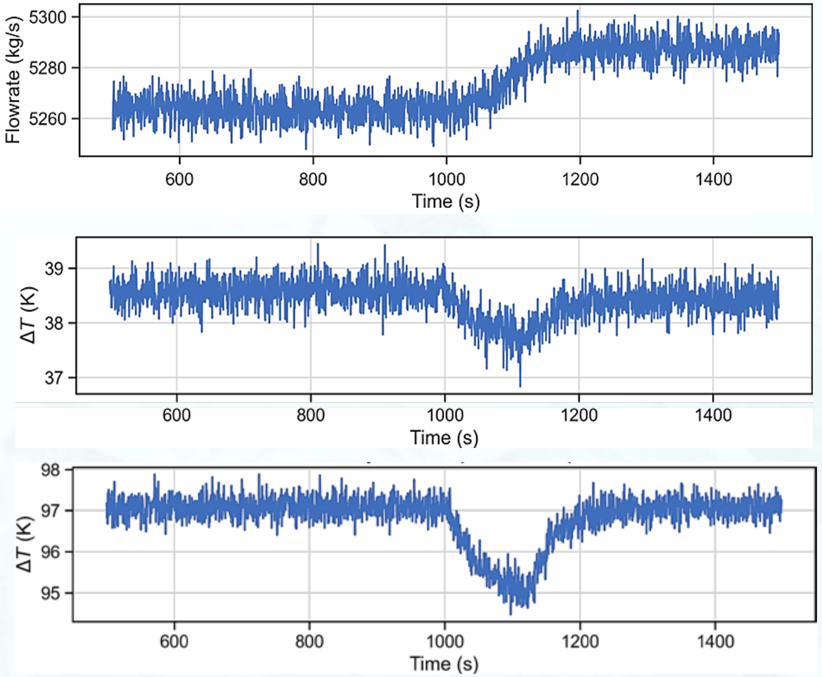
- Sensor uncertainties

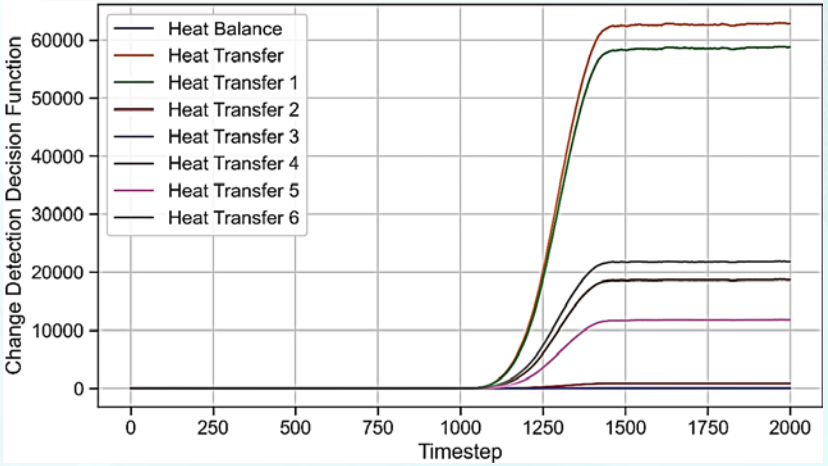
VARIABLE	3σ NOISE
Mass flowrate	15 kg/s
Temperature	0.5 ℃
Pressure	0.1 kPa



Results and Accomplishments: PRO-AID model for IHX (2/2)

- Ten sensors available, i.e., primary flowrate, secondary flowrate, inlet and outlet temperature on each side, inlet and outlet pressure on each side.
- Four component models, i.e., (1) Heat balance model, (2) Heat transfer model, (3) Pressure loss model on the primary side (i.e., Primary Circuit side), (4) Pressure loss model on the secondary side (i.e., Intermediate Circuit side). Component-level and sensor-level faults can be discriminated.
- Fouling test case: heat transfer coefficient on the secondary side reduced by 10% in 100 seconds.



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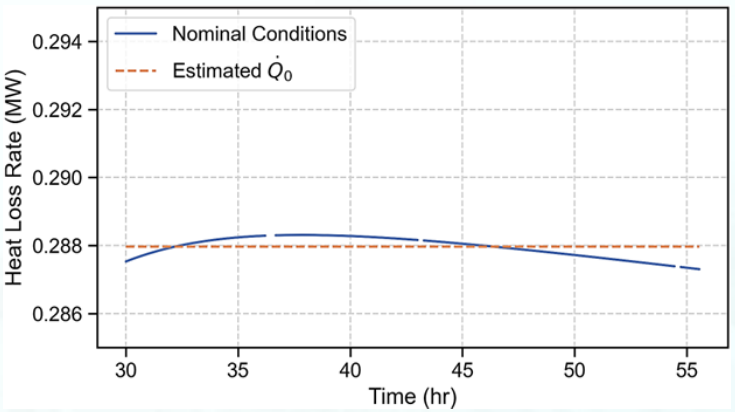
---------------------------------------------------------------
                      DIAGNOSTIC RESULT
---------------------------------------------------------------
Reasoning method: Probabilistic
Faults, ranked by posterior probability:
---------------------------------------------------------------
|Rank|Fault Name                                   |Probability|
---------------------------------------------------------------
|1   |Fouling-hx                                   |   0.99353 |
|2   |SensorFault-hx.tube:flow:in                  |   0.00219 |
|3   |SensorFault-hx.tube:temp:in                  |   0.00219 |
|4   |SensorFault-hx.tube:temp:out                 |   0.00219 |
|5   |SensorFault-hx.shell:flow:in                 |   0.00219 |
|6   |SensorFault-hx.shell:temp:out                |   0.00219 |
|7   |SensorFault-hx.shell:temp:in                 |   0.00219 |
|8   |Leakage-hx.tube                              |   0.00138 |
|9   |Leakage-hx.shell                             |   0.00138 |
---------------------------------------------------------------
Executed successfully
```

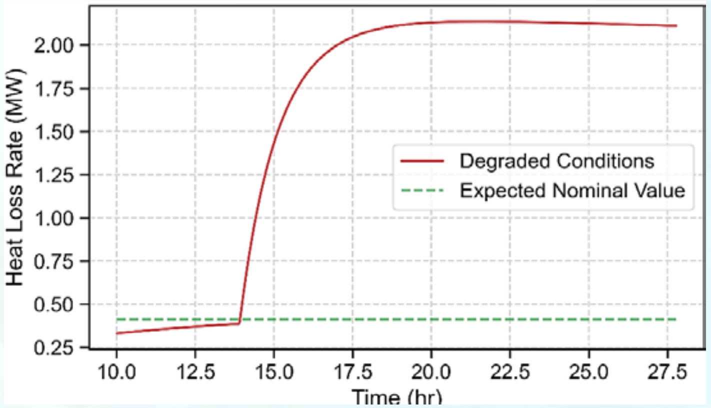
Results and Accomplishments: PRO-AID model for Tanks

- Monitoring tanks conditions and **tracking their efficiency** is crucial to estimate the profitability of the energy storing. Simple tank model with a **uniform cross-sectional area, single inlet/outlet ports**. The adopted sensor set for the tank consists of the following:
  - Tank level, l
  - Internal temperature, T
  - Inlet mass flowrate, $\dot{m}_i$
  - Inlet temperature (T_i)
  - Outlet mass flowrate ($\dot{m}_o$)

$$r_1 = \rho A \frac{\Delta l}{\Delta t} - (\dot{m}_i - \dot{m}_o)$$

$$r_2 = \rho A c_p \left(T \frac{\Delta l}{\Delta t} + l \frac{\Delta T}{\Delta t} \right) - \dot{m}_i c_p T_i - \dot{m}_o c_p T_o - \dot{Q}_o + \dot{Q}^{heat}$$





- Heat loss rate in reference and degraded operating conditions.

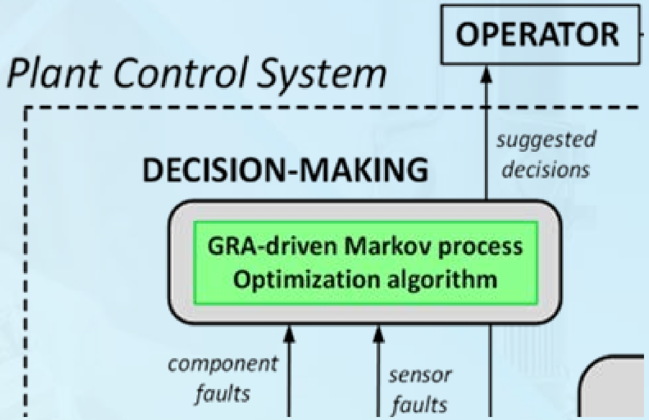
- **Non-zero energy balance residual and zero mass balance residual remains**: the possible diagnoses are either degraded thermal insulation or temperature sensor fault.

- Available residuals allow detecting **two component-level faults**, i.e., (1) leaks and (2) loss of thermal insulation.

Results and Accomplishments: GUI for the proposed architecture

- Developed a **Graphical User Interface (GUI)** of the proposed architecture ("CONTROL" and "DIAGNOSTICS" outputs are represented at the moment).
- In this demo, a **power transient in "Discharging" mode (Mode#1)** is simulated (RX in steady-state, load demand addressed by TES).
- **Primary and Intermediate circuit actuators** are shown.
- **Two faults** are simulated, (1) valve stuck (HT discharging) and (2) IHX fouling.
- **"Annunciator" section:** displays the outcomes of "DIAGNOSTICS" module (eventually also the actions suggested by "DECISION-MAKING" module)

Concluding Remarks



- Future Plans
  - (M3 milestone) “Implementation of the selected algorithms in the proposed framework, and demonstration of the developed architecture”
    - ➢ Design and implementation of “DECISION-MAKING” module, i.e., formulation of the MDP and PRA/GRA analysis of the Intermediate Circuit.
    - ➢ Coupling of different modules with the high-fidelity simulator and demonstration.
    - ➢ Identification of (1) possible actions to be taken and (2) constraints to be updated.
  - (M3 milestone) “Cost-benefit analysis”
    - ➢ Evaluation of the enhanced profitability due to more efficient use of human resources through automation of monitoring and control tasks.

Roberto Ponciroli
Principal Nuclear Engineer,
Plant Analysis & Control & NDE Sensors
Argonne National Laboratory
rponciroli@anl.gov
W (630)-252-3455
LinkedIn

Thank You