U.S. DEPARTMENT OF ENERGY | Office of NUCLEAR ENERGY

ASI 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

October 30 – November 1, 2023

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Argonne National Laboratory

Project Overview

Project Goal: Improve economic competitiveness of advanced reactors through

- Enhanced 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

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Schedule: FY21 - FY23 (FY24 through No Cost Extension)

Project Overview

- Schedule

FY21

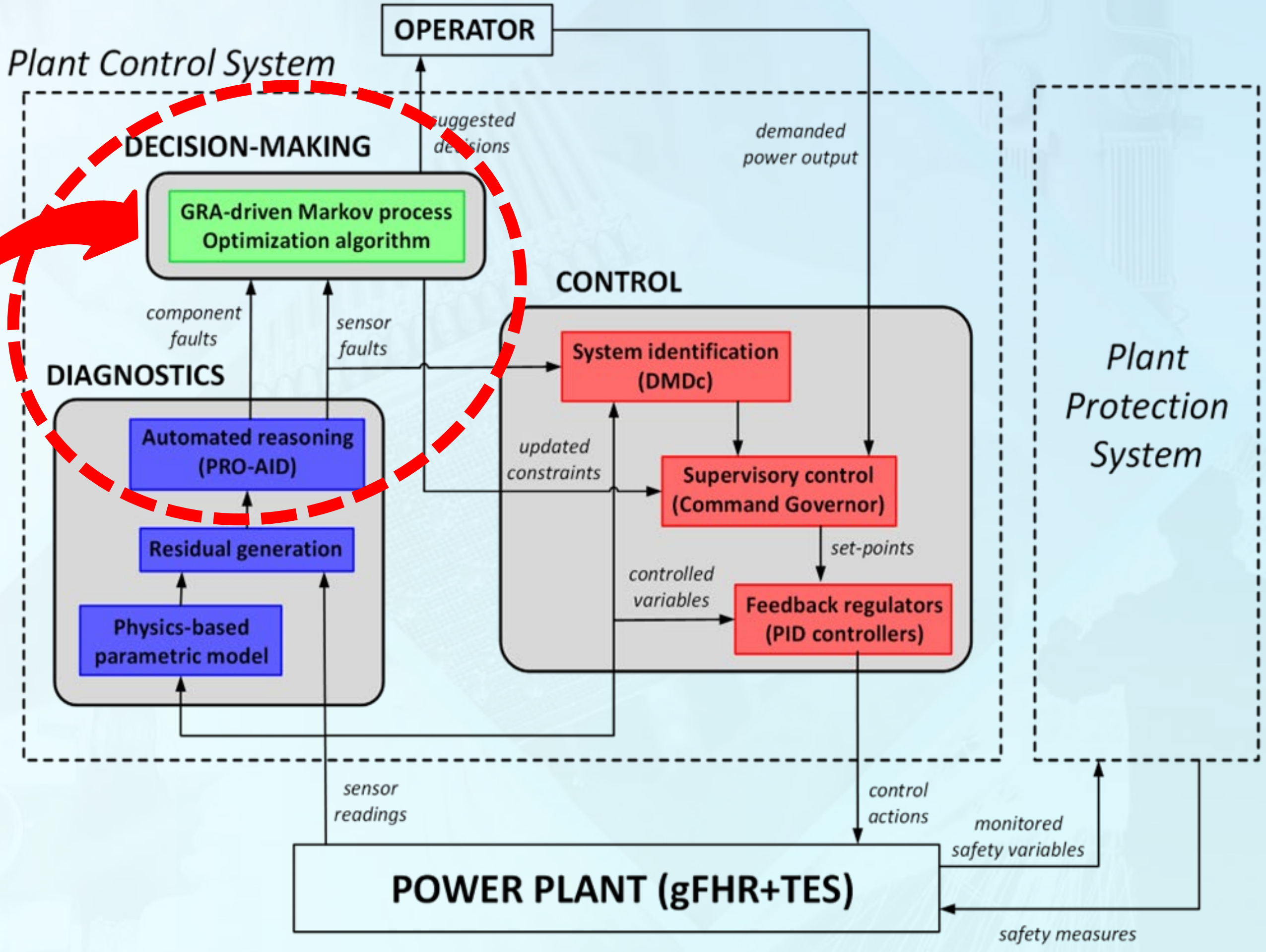
- Definition of the IES system reference configuration
- Development of the high-fidelity simulator

FY22

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

FY23

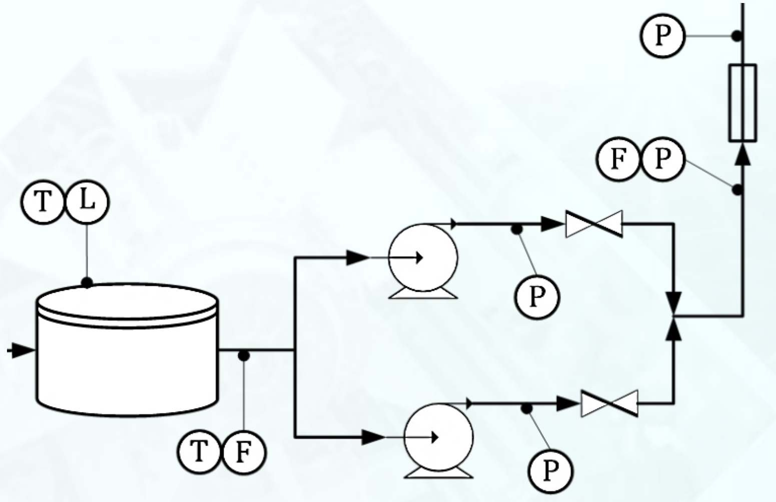
- Implementation of the selected algorithms in the proposed architecture
- Cost-benefit analysis

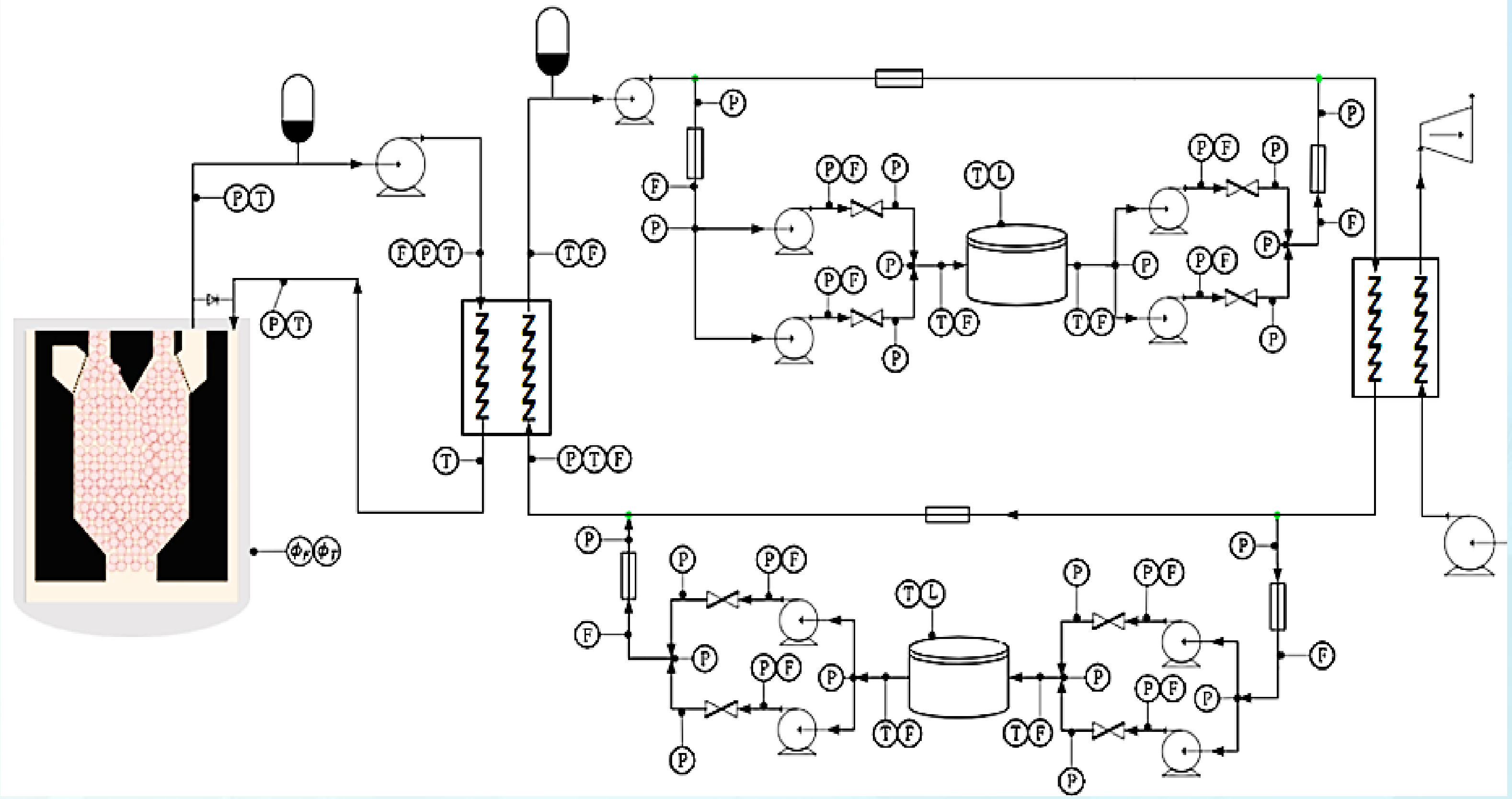


Results and Accomplishments: Finalization of the SAM simulator

Modifications to the P&ID of the Intermediate Circuit

- For demonstration purposes, we will focus on the **monitoring/diagnostics of the Intermediate Circuit**.
- Redundancy elements were included
- Advantages: (1) more realistic configurations, (2) enhanced system availability in case of faults





- Adjusted the corresponding sensor set
- Modifications performed to both the high-fidelity simulator (SAM model) and diagnostics algorithm (PRO-AID model)

Results and Accomplishments: “DECISION-MAKING” module design

Goal of the Integrated System (Reactor + Thermal Energy Storage): ensuring the continuity of service by meeting the load demand at any time without violating constraints.

Two sets of decisions to be made when operating the unit

SHORT-TERM DECISIONS

They concern the asset management (operational procedure)

- *Transitions to different Operational Modes*

ADOPTED ALGORITHM
Demand level compared with expected power production capabilities, i.e., outcome of the Generation Risk Assessment (GRA) analysis.

LONG-TERM DECISIONS

They concern the asset management (maintenance interventions)

- *“Do nothing”*
- *“Replace” faulted component*
- *“Fix” faulted component*

ADOPTED ALGORITHM
Decisions are made by solving a Partially Observable Markov Decision Process (POMDP).

Results and Accomplishments: “DECISION-MAKING” module design

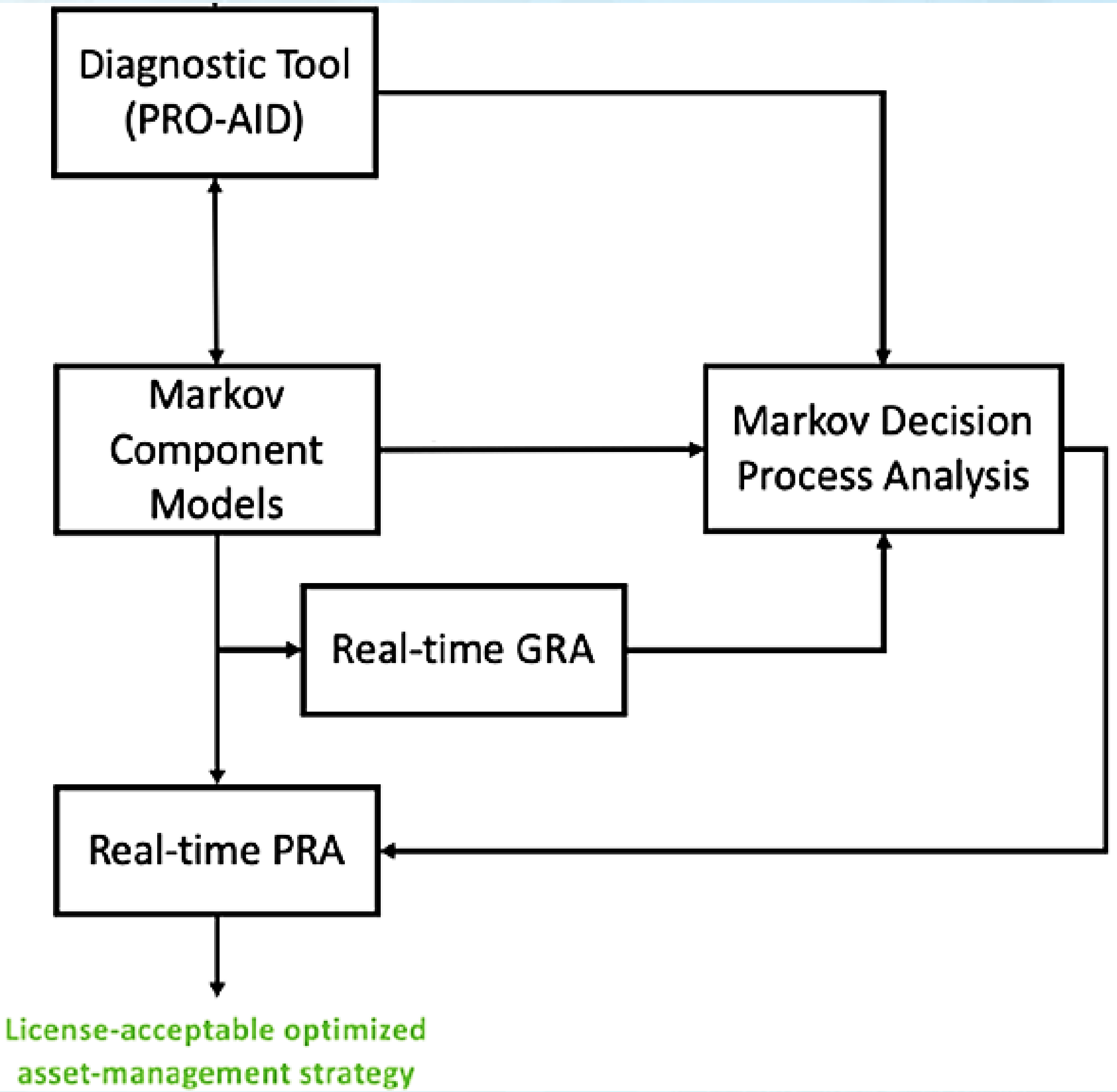
Methodology for making long-term decisions: Integrated Markov Decision Problem (MDP) Analysis Approach

- Adopted the approach developed in the NEUP Project 19-17045, “Cost-Benefit Analyses through Integrated Online Monitoring and Diagnostics”.

Key role played by the Generation Risk Assessment (GRA) analysis

Automatically accounts for the “compensation” that can be provided by the other actuators and/or components.

Estimate the impact that individual component faults have on the power production capabilities of the whole system.



Results and Accomplishments: PRO-AID and Markov models

Development of the Markov models for single components

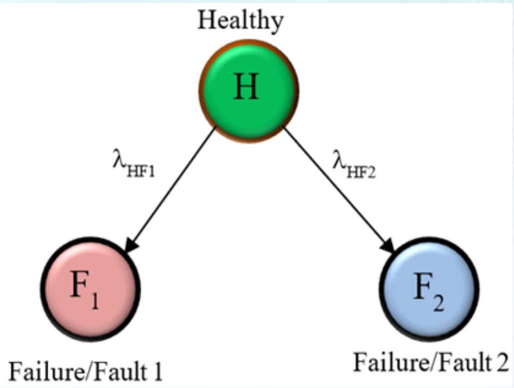
- Starting from PRO-AID diagnostics capabilities, the faults affecting the Intermediate Circuit components were identified.
- Markov models used to project components failure probability ahead in time. Components could either be in perfectly operating conditions or to have 2 or 4 failure modes (faults).

Component	Markov Model	Markov state	Component Fault
Valve	3-state	F_1	Stuck
		F_2	External Leak
Pipe	3-state	F_1	Blockage
		F_2	External leak
Tank	3-state	F_1	Leak
		F_2	Degradation of thermal insulation
IHX/SG	5-state	F_1	Fouling
		F_2	Blockage
		F_3	Shell side leak
		F_4	Tube side leak
Pump	3-state	F_1	Degradation
		F_2	External Leak

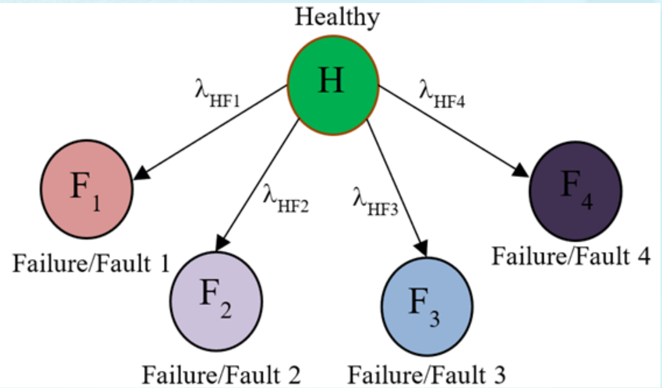
Markov model **PRO-AID model**

$$p^*(t^{n-1}) \quad p(t^n) \quad p^*(t^n)$$

Posterior **Prior** **Posterior**



3-State Markov Model diagram



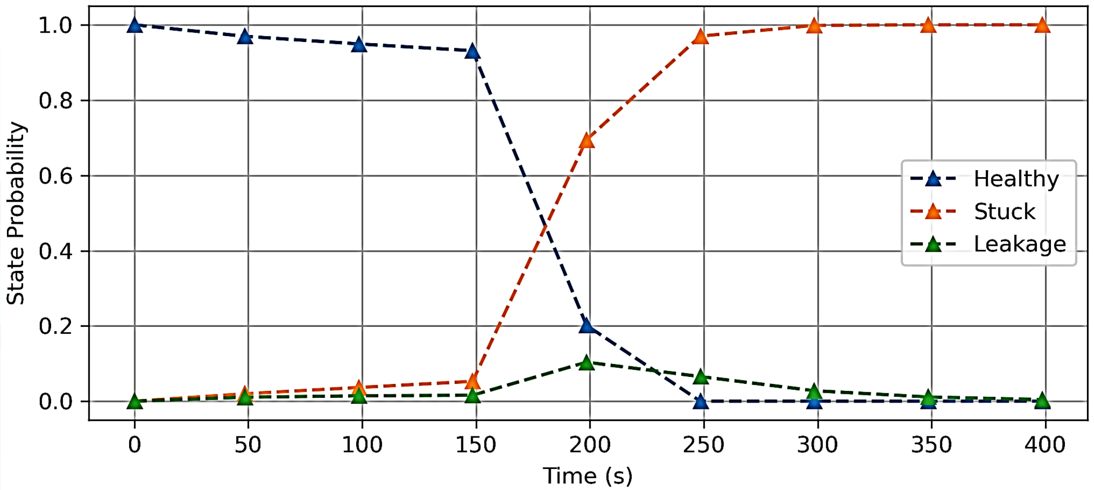
5-State Markov Model diagram

Results and Accomplishments: PRO-AID and Markov models

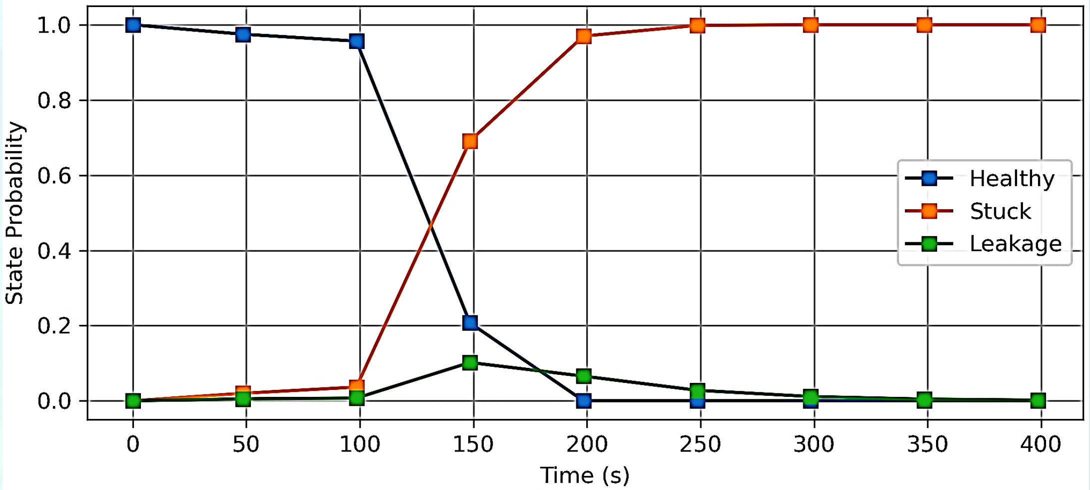
Coupling PRO-AID with Markov component models

- Results from coupling PRO-AID with Markov component models are component fault probabilities at each discrete time step ΔT
- Results used to estimate system output (GRA) and check safety limits (PRA)

1. **Initialize the Markov models for all components**
2. **Repeat for each macro time step ($n \geq 1$):**
   a. Use the Markov models to compute the state probabilities at time $t = n \cdot \Delta T$ using the known state probabilities at $t = (n-1) \cdot \Delta T$
   b. Use PRO-AID with the data collected between $t = (n-1) \cdot \Delta T$ and $t = n \cdot \Delta T$ to update the posteriors probabilities.



Prior probabilities (computed by Markov models)

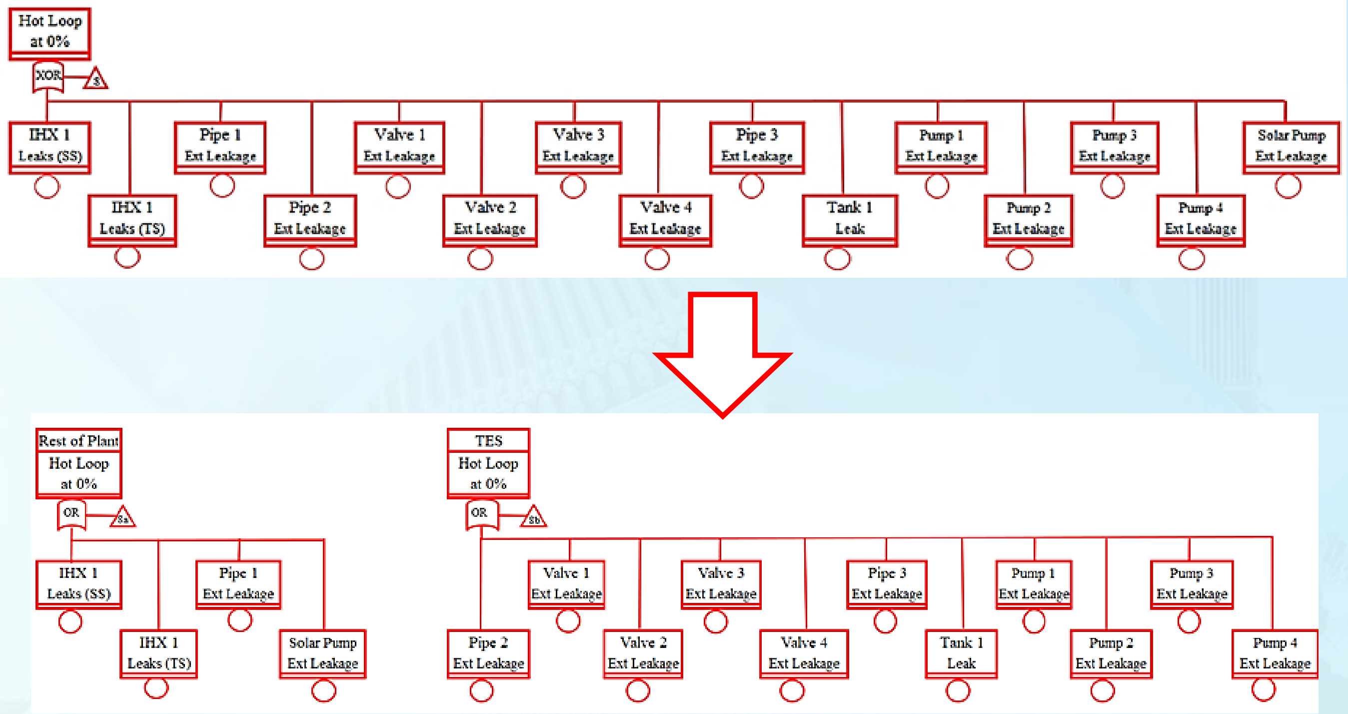


Posterior probabilities (computed by PRO-AID)

Results and Accomplishments: Development of the GRA model

Problem: along with abrupt failures, the performance of all the components progressively degrade → <u>multiple faults overlap during operation</u>.

- Analytical approach attempted first. Fault Tree method (FT) adopted to calculate the probability of system trip or derate. Rare Event Approximation (REA) could not be applied.
- FT approach needed to be abandoned (too many output levels deriving from simultaneous failures scenarios)
- Truncation to probability calculation series



Primary Circuit and Intermediate Circuit separately addressed

$$P_i = P(F_i, \text{no other faults}) = P(F_i) - \sum_{j \neq i} P(F_i)P(F_j) + O(p^3) \qquad P_{ij} = P(F_i, F_j, \text{no other faults}) = P(F_i)P(F_j) + O(p^3)$$

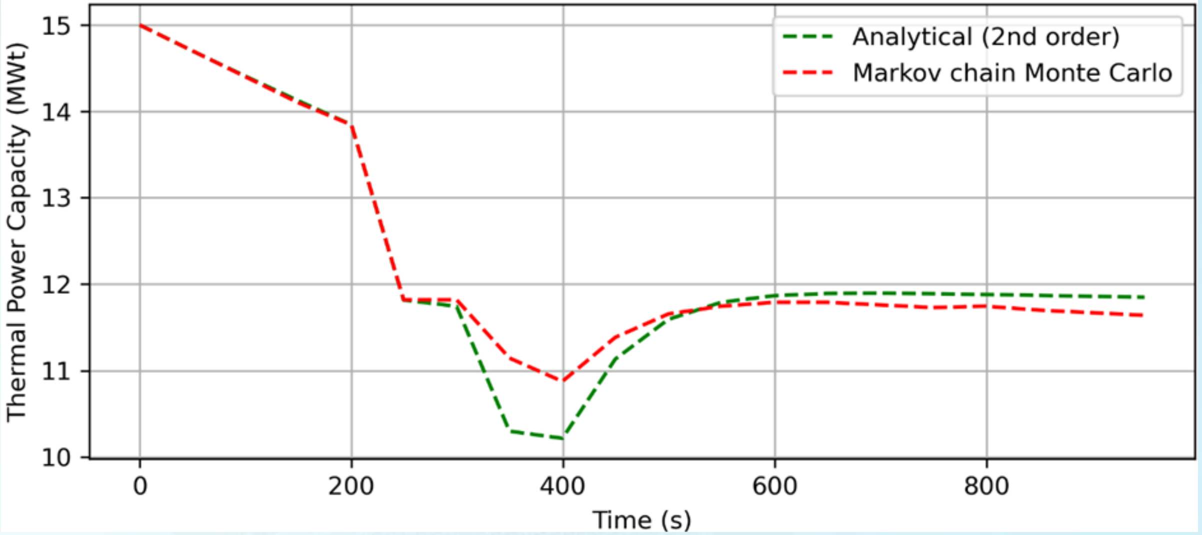
$$\text{System output} = 1 - R = \sum_i P_i R_i + \sum_i \sum_{j>i} P_{ij} R_{ij}$$

Results and Accomplishments: Finalization of GRA & PRA models

Solution: Probability distribution of the system output calculated with Markov Chain Monte Carlo (MCMC). Each fault sampled according to their probability distribution.

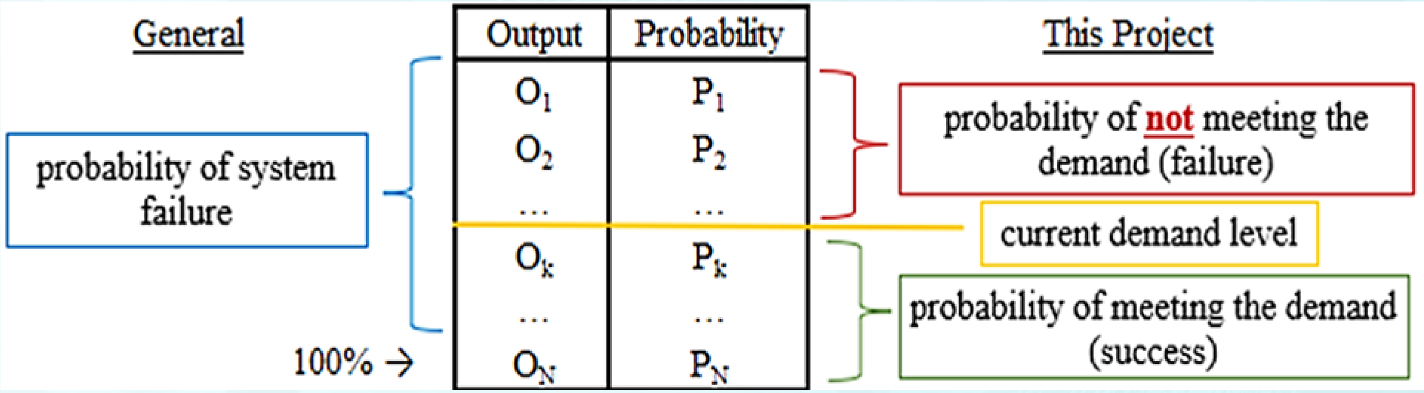
$$\text{System Output} = \prod_{i=1}^{N} (1 - R_i f_i)$$

- f_i → binary variable equal to 1 with probability p_i when fault is present.
- R_i → reduction of the system output



MCMC-calculated power production capability of the Intermediate Circuit

- PRA model evaluates the risk of not meeting the demand (new definitions of "success" and "failure").
- Probability distribution of the whole system equal to the combined probability of the independent events



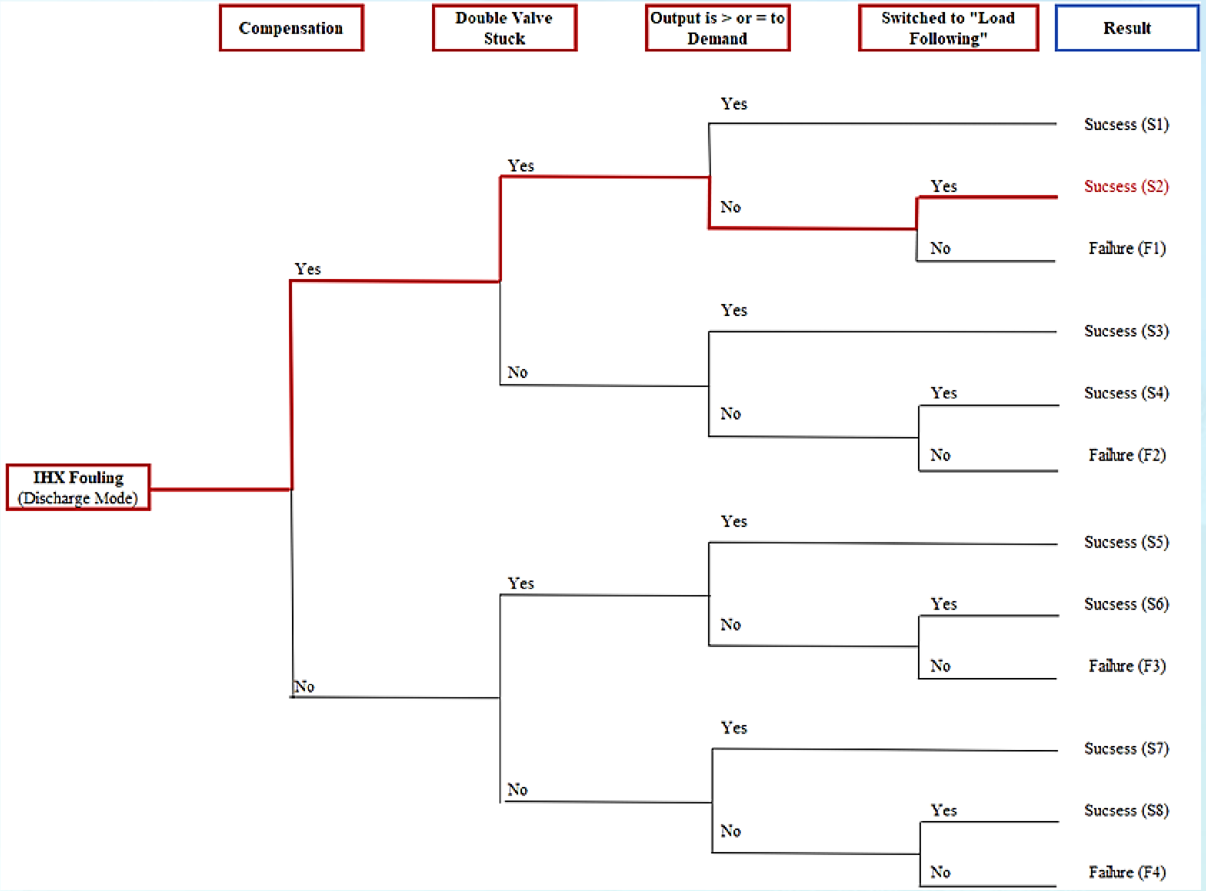
$$P\left(O = O_i^{(p)} + O_j^{(TES)}\right) = P\left(O^{(p)} = O_i^{(p)}\right) \cdot P\left(O^{(TES)} = O_j^{(TES)}\right)$$

Comparison of demand level with current power production capabilities

Results and Accomplishments: Definition of the test-case scenario

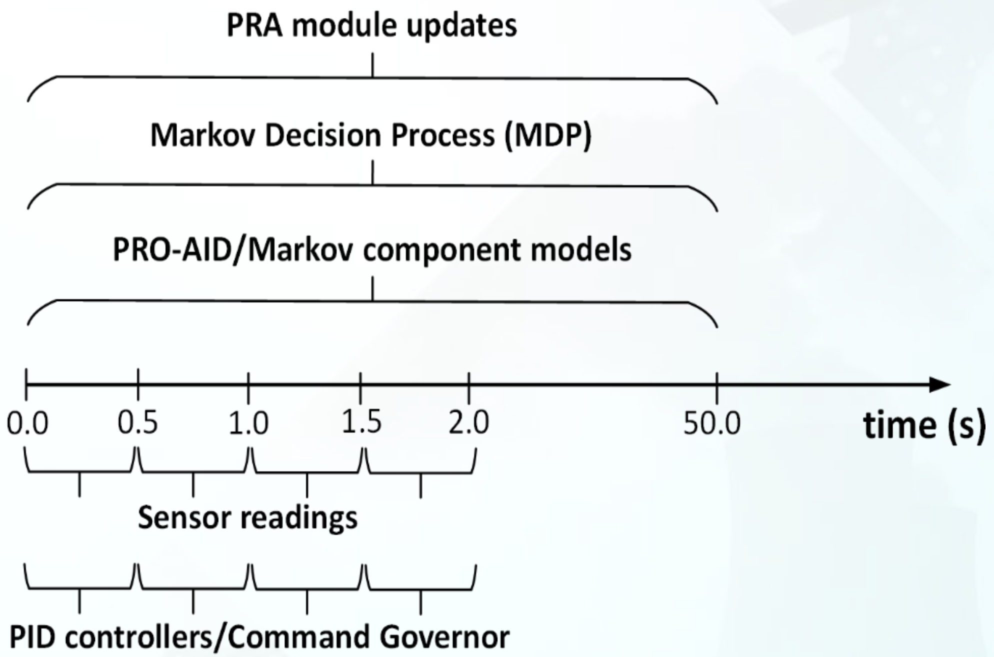
- **Not Severe failures:** performance degradation failures (e.g., fouling). Consequences mitigated by dedicated control actions (“compensation”).
- **Severe failures:** consequences are so severe that a transition to a different Mode is required, in case the failed component can be isolated; otherwise, prompt maintenance is required.

Stage #	Stage Description
1	System operated in “Load-Following” mode
2	“IHX Fouling” detected
3	Compensation through Actuators
4	Demand increase
5	Switch to “Discharging” mode
6	“Double valve stuck” detected
7	Switch to “Load-Following” mode



Visualization event-tree path for the test-case

Results and Accomplishments: Literature review (failure rates & costs)



Timescales ruling the algorithms performing control, diagnostics and Decision-making tasks.

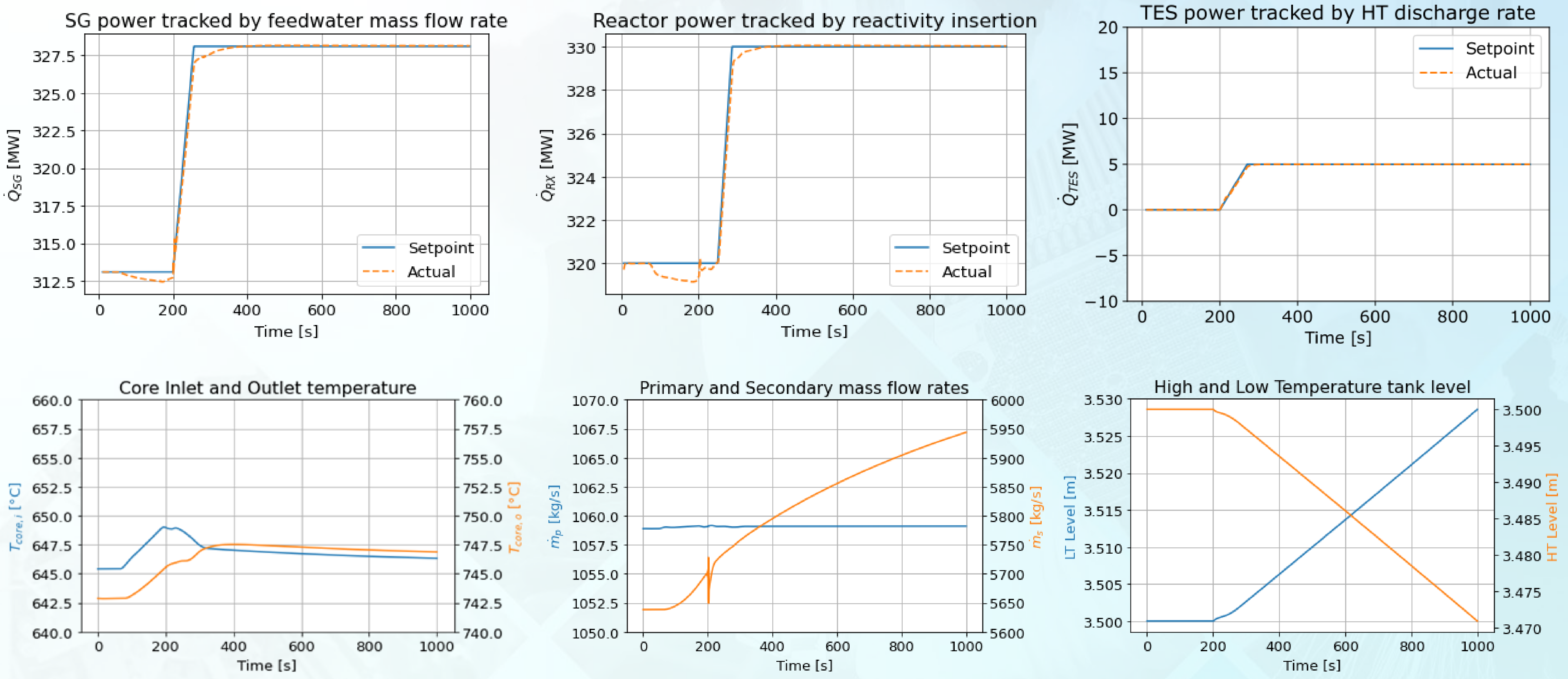
Component	Failure/Fault		Failure Rate (1/s)	Output Reduction (%)
Valve	1	Stuck	3.47E-04	10
	2	External Leakage	1.88E-04	100
Pipe	1	Blockage	8.20E-05	2
	2	External Leakage	6.89E-08	100
Tank	1	Leakage	1.98E-05	100
	2	Degradation of Thermal Insulation	4.18E-05	20
IHX/SG	1	Fouling	3.39E-05	2
	2	Blockage	3.39E-05	2
	3	Shell Side Leak	1.90E-05	100
	4	Tube Side Leak	2.76E-05	100
Pump	1	Degradation	9.13E-05	5
	2	External Leakage	1.98E-05	100

Failure rates for Intermediate Circuit components faults and impact on system power production capabilities.

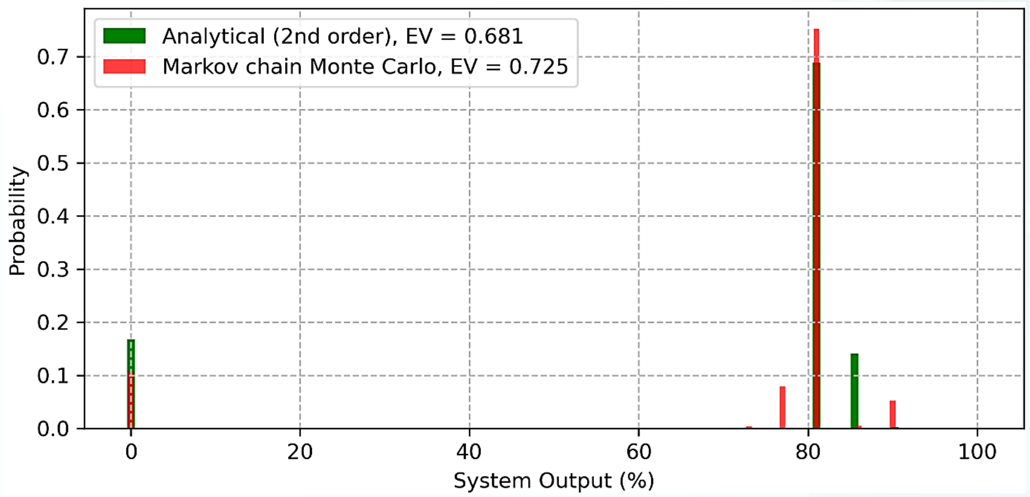
Component	Failure Mode	Policy Durations and Costs					
		Do nothing		Repair		Replace	
		Duration (h)	Cost ($)	Duration (h)	Cost ($)	Duration (h)	Cost ($)
IHX	Fouling	N/A	4350	60	50,000	1440	5,000,000
Valve	Stuck	N/A	N/A	72	5,400	168	37,600

Cost and duration of the policies to address selected failures.

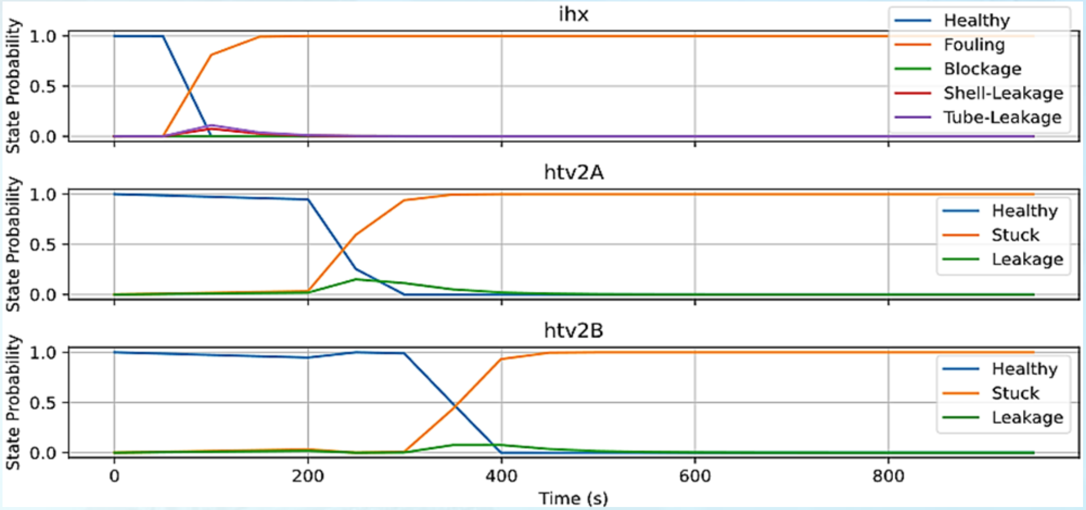
Results and Accomplishments: Simulation of the test-case scenario



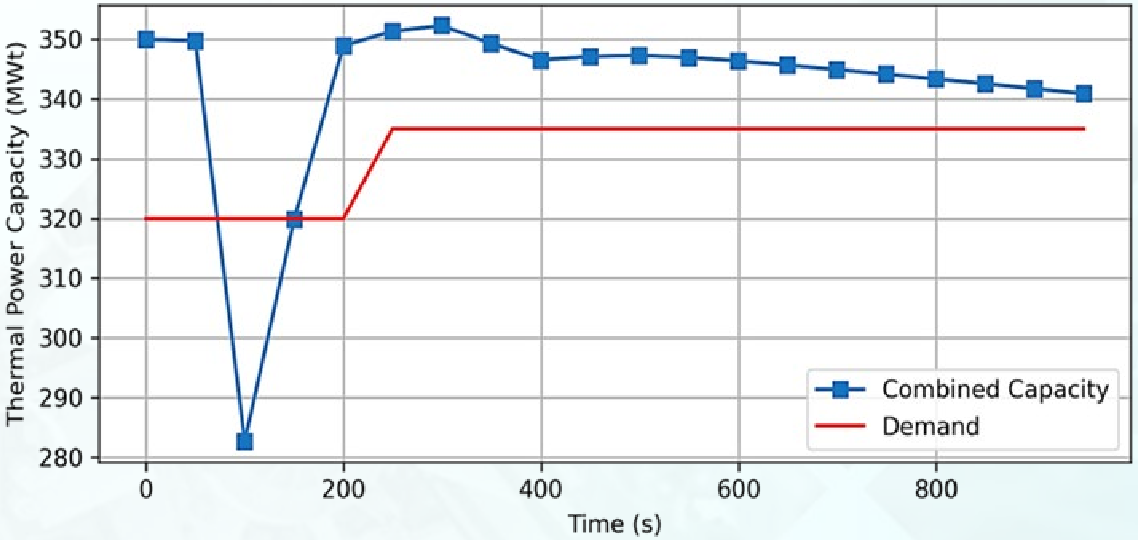
Results and Accomplishments: Outcomes of GRA/PRA analysis



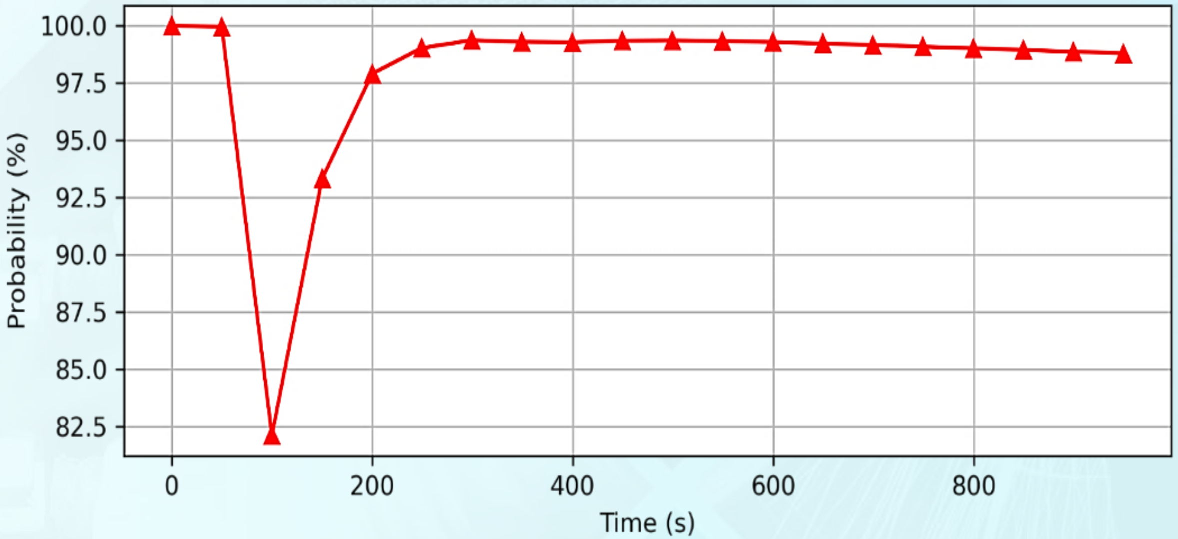
Distributions of the Intermediate Circuit output levels (t = 400s)



Probabilities of the different faults



Expected power production capabilities of Intermediate Circuit



Probability of meeting the demand

Results and Accomplishments: “DECISION-MAKING” finalization

- We can claim “Success” only if the demand is met over the next hour.

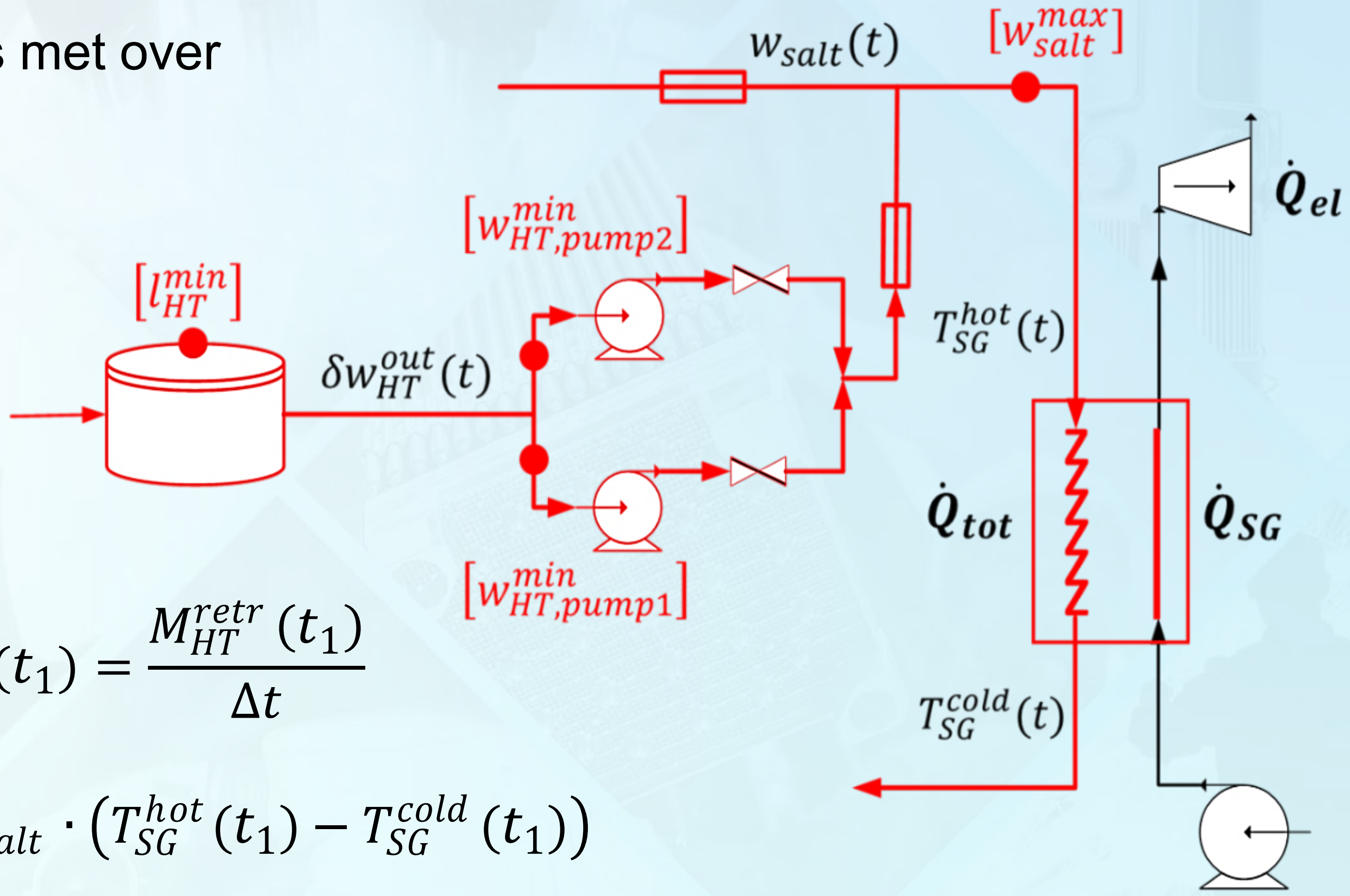
$$\Delta t = \text{mission time} = 3600\ s$$

- Only a portion of stored energy can be retrieved without violating the constraints.

- Definition of the “Retrievable Energy” ($\dot{Q}_{TES}^{retr}$)

$$M_{HT}^{retr}(t) = A_{HT}\rho_{salt} \cdot \left(l_{HT}(t) - l_{HT}^{min}\right) \qquad \delta w_{HT}^{retr}(t_1) = \frac{M_{HT}^{retr}(t_1)}{\Delta t}$$

$$\dot{Q}_{tot}^{retr}(t_1) = min(w_{salt}^{max}, w_{salt} + \delta w_{HT}^{retr}(t_1))c_{p,salt} \cdot \left(T_{SG}^{hot}(t_1) - T_{SG}^{cold}(t_1)\right)$$



$$\boxed{D(t_1) \leq \frac{\left(w_{salt} + min\left(\delta w_{HT}^{retr}(t_1), w_{HT,pump\,1}^{SP}(t_1) + w_{HT,pump\,2}^{SP}(t_1)\right)\right)c_{p,salt} \cdot \left(T_{SG}^{hot}(t_1) - T_{SG}^{cold}(t_1)\right)}{\Delta h_{SG}} \Delta h_{turbine}\,\eta_{is}\eta_{mech}}$$

Concluding Remarks

- Future Plans
  - Finalization of the "DECISION-MAKING" module by considering the estimate of the retrievable energy when deciding Operation Mode transitions
  - (M2 milestone) "Final Report for (Project 20-19321) Design and Prototyping of Advanced Control Systems for Advanced Reactors Operating in the Future Electric Grid - ANL

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Concluding Remarks

- FY23 Publications
  - **Presentation:** R. Ponciroli et al., “A Path to Semi-Autonomous Operation”, Workshop on Advanced reactors and the need for advanced control systems, Argonne National Laboratory, July 12-14 (2023).
  - **Conference paper:** T.N. Nguyen, A.J. Dave, R. Ponciroli, “Design and Prototyping of Diagnostic Methods to Support Autonomous Operations of Advanced Reactors”, 13th Nuclear Plant Instrumentation, Control & Human-Machine Interface Technologies (NPIC&HMIT 2023), Knoxville (TN), July 15-20 (2023).

- FY24 Publications
  - **Journal paper:** A.J. Dave et al., "Design and Simulation of a Molten Salt Thermal Energy Storage System Coupled to a Small Modular Nuclear Reactor“, Nuclear Technology, “SAM Code Development, Validation, and Applications” special issue, (to be submitted) (2024).
  - **Journal paper:** R. Ponciroli et al., "Design of a Semi-Autonomous Operation architecture for the operation of a Molten Salt Thermal Energy Storage System Coupled to a Small Modular Nuclear Reactor“, Nuclear Engineering and Design (2024).
  - **Journal paper:** T.N. Nguyen et al., "A Probabilistic Decision Making and Predictive Maintenance Framework for Integrated Energy Systems“, Annals of Nuclear Energy (2024).

Thank You