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
November 4, 6-7, 2024

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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 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

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

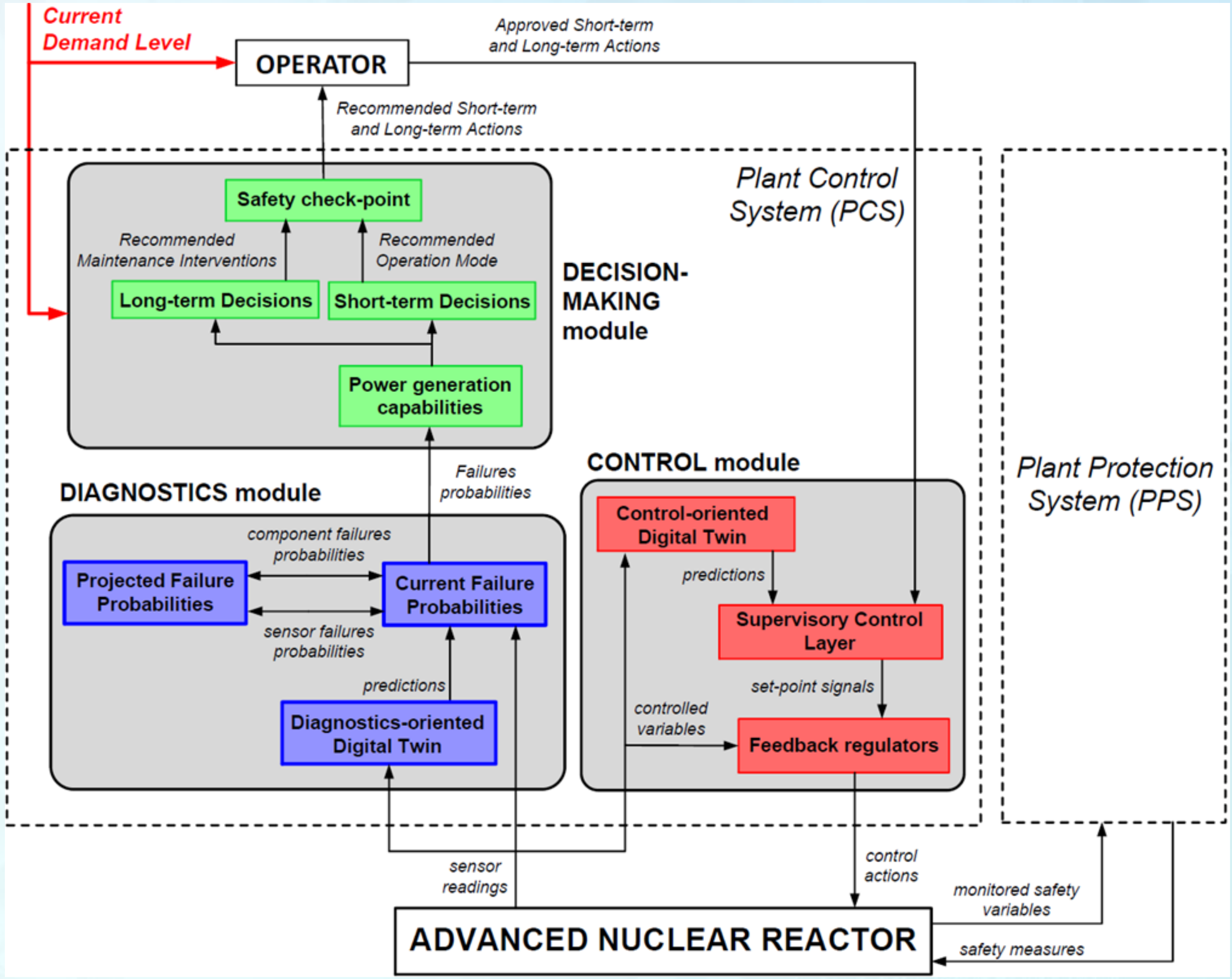
Project Overview

- 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



Project Overview: Why changing things in Nuclear Industry?

- Nuclear Units are struggling to stay competitive in U.S. deregulated markets (premature shutdowns in the last years). Production Tax Credits and Negative prices are an issue.
- Renewable penetration affects grid stability and continuity of service

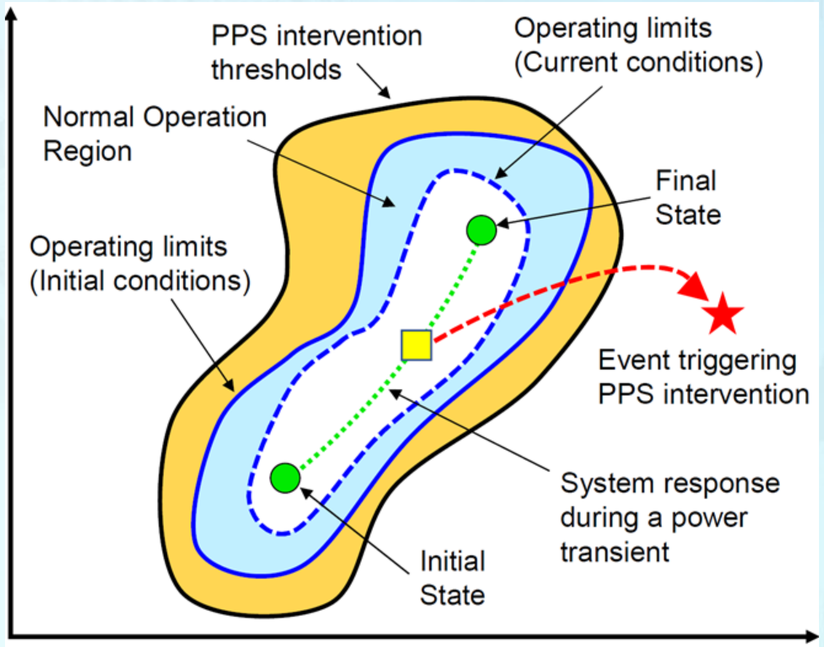
Identified Solution: ENHANCING FLEXIBLE OPERATION CAPABILITIES

Q. Any issues related to this operational paradigm?

- Frequent power variations might accelerate component wear and tear and increase failure rate.

Q. What capabilities/performance are expected from the control system?

- Meet the grid demand;
- Maximize the profitability of the unit;
- Meet the operational limits on temperatures, pressures and flowrates, i.e., keep the system within *Normal Operation Region (NOR)*;



Qualitative representation of NOR (Adapted from *Supervisory Control System for Multi-Modular Advanced Reactors* by S.M. Cetiner et al., ORNL/TM-2016/693, 2016).

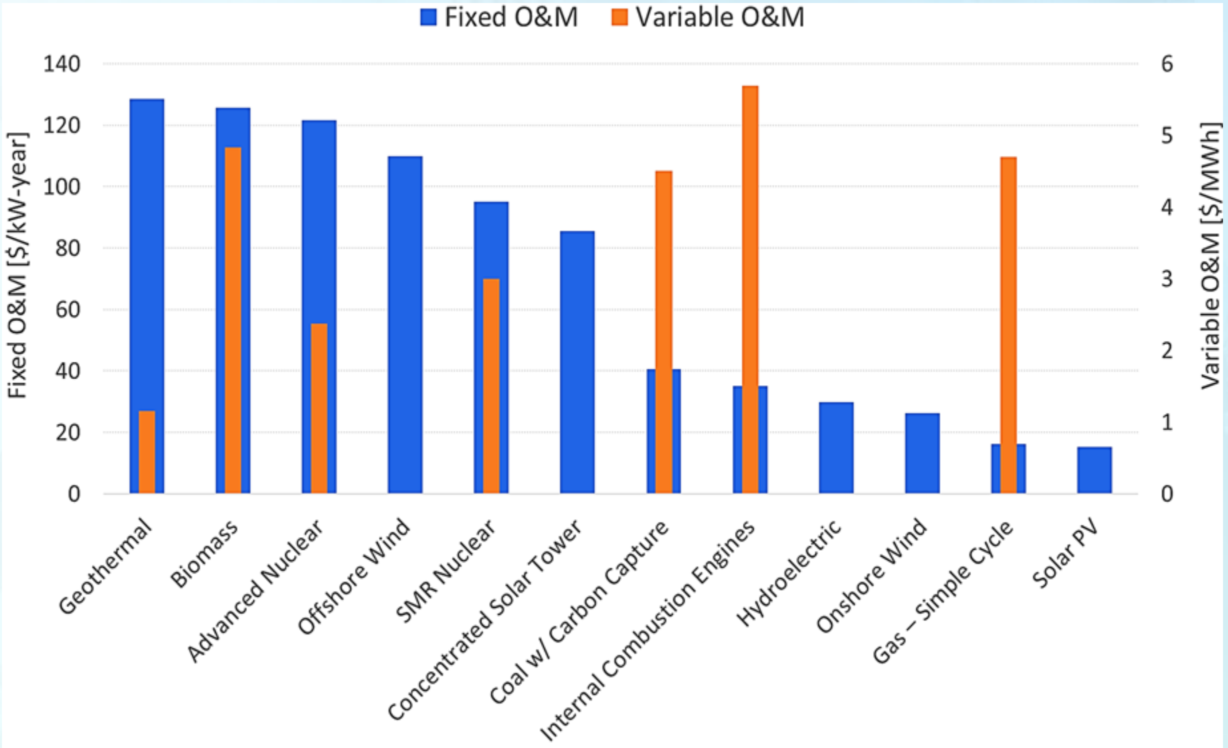
Project Overview: Autonomous Operation and Nuclear Profitability

- Economics is the main driver for implementing an innovative control system architecture. With respect to other power generation technologies, nuclear units have higher fixed O&M costs.

Q. How exactly can Autonomous Operation help be saving? What are the critical items?

- Reducing the number of in the *Main Control Room* does not significantly reduce the payroll for staffing.

- Most of the savings can be accomplished by optimizing the Maintenance Schedule (less time-consuming interventions, reduced number of on-site technicians).



Identified solution: enhancing the Monitoring and Diagnostics capabilities informing the Decision-making process.

Project Overview: How can AI/ML algorithms be helpful?

- **Idea**: using AI/ML algorithms to perform repetitive, time-consuming tasks performed by human operators.
- **Goal**: selecting the best way to perform power transients, taking feasible control actions and scheduling maintenance interventions.
- Interesting question is not "*Can we operate the unit in Load-following mode?*", but …

"Is Load following mode the most profitable way of operating the unit?"

(Keep unit within the bounds of Normal Operation Region)

"Can plant components withstand thermal stress from Load-following?"

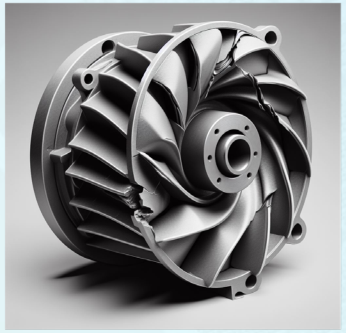
(Costs/benefits trade-off, given diagnostics results)

Results and Accomplishments: Importance of teamwork in a crew

- When collaboration is correctly applied, it is one of the best ways for nuclear units to produce power with fewer errors, events and improved performance.
- U.S. NRC organized a team of researchers to review literature in psychology, cognition, behavioral science and apply it to human performance in NPP operation (NUREG-2114).

Alert pops on the monitor indicating a problem with a pump

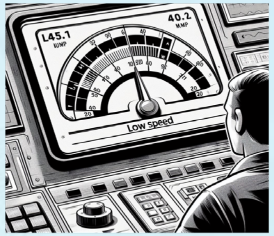
DIAGNOSTICS
(Evaluation of component health conditions)



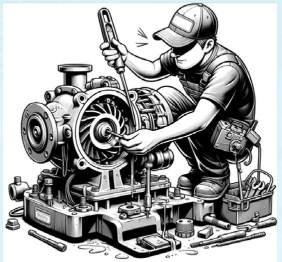
Would operating at current conditions damage the impeller?

RISK EVALUATION
(Estimate of current performance and failure probability)

SHORT-TERM DECISIONS
(Operation Mode)



Keep using the pump, but at lower speed



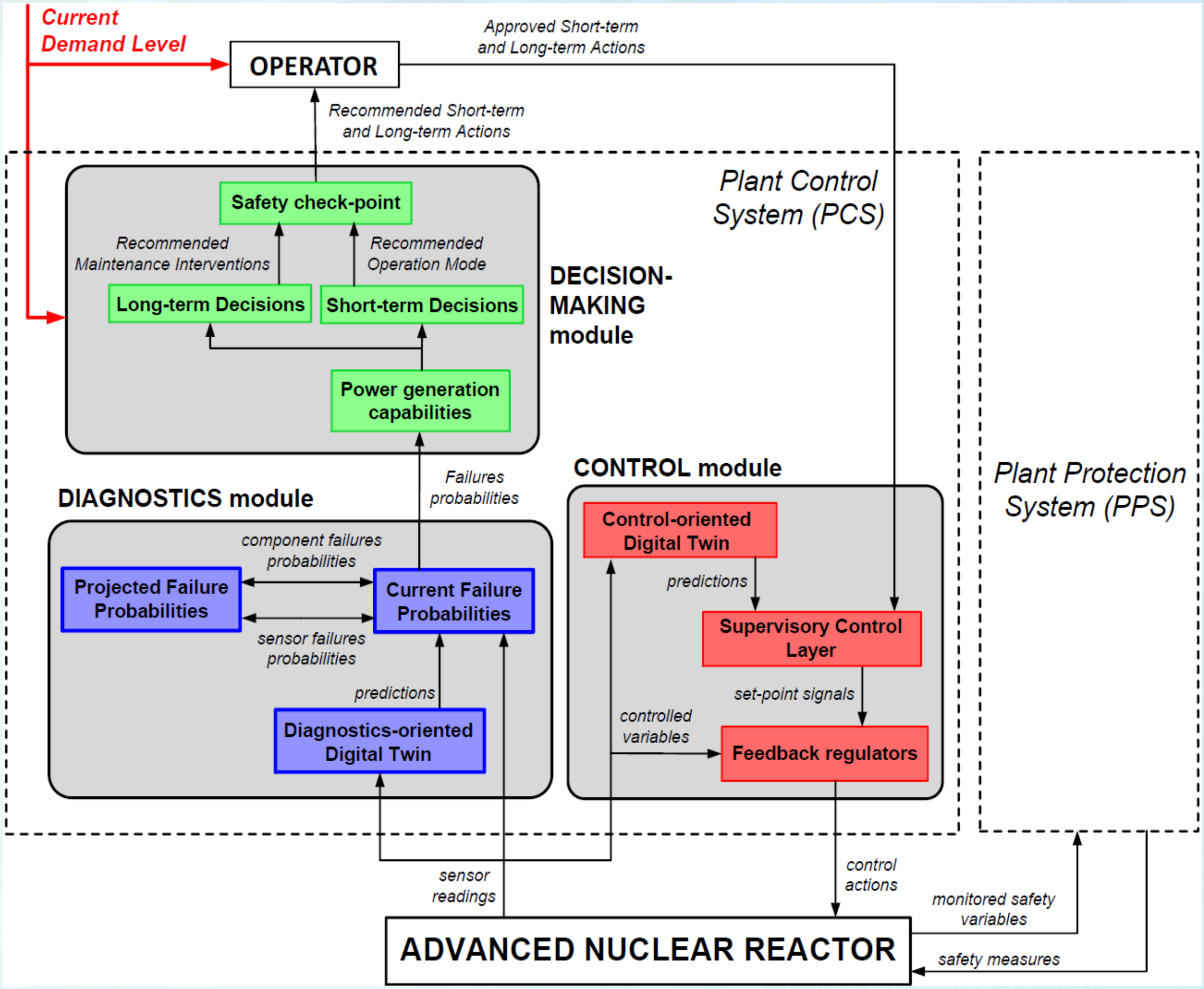
Opening the case and fixing the pump

Installing a brand new pump

LONG-TERM DECISIONS
(Asset-management)

Results and Accomplishments: Key concepts

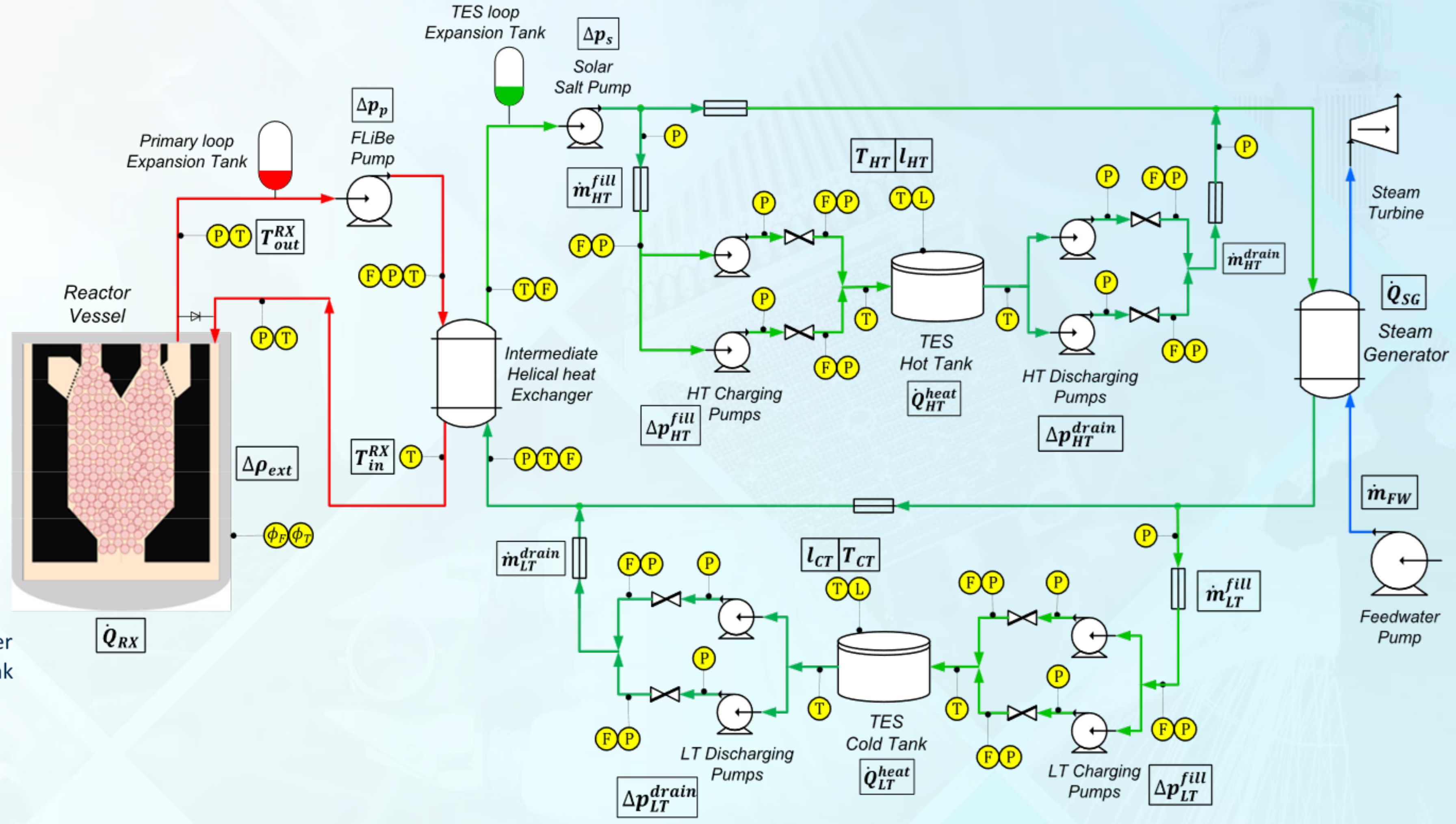
- Algorithms applied to Normal Operation only. The goal is to assist operators in making the best decisions, given the system's current capabilities and the health of its components.
- Algorithms fulfilling Control, Diagnostics and Decision-making tasks need to “talk” to each other.
- PPS must be independent of PCS. In case of violation of limits on safety variables, PPS must be allowed to take over.
- Operators must be given the possibility to override the Supervisory Control system.

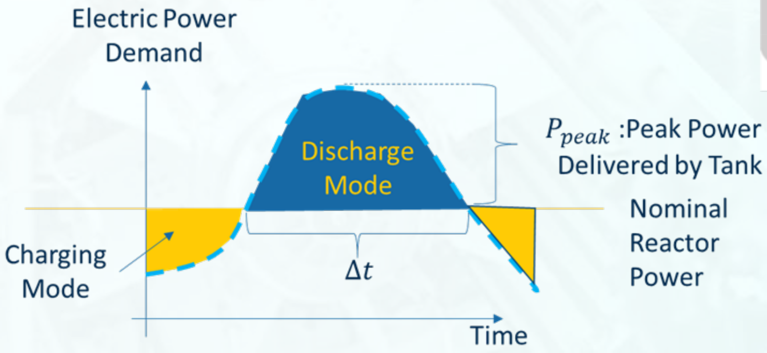


Results and Accomplishments: System description

- Fluoride-cooled High-Temperature pebble-bed Reactor (gFHR design selected by Kairos Power) coupled with Thermal Energy Storage (TES) system. The designed architecture was applied to the Intermediate circuit operation.

- System can be operated in multiple Operation Modes to supply the grid demand:
  - *Load-following*
  - *Charging*
  - *Discharging*
  - *Prolonged Charging*
  - *Prolonged Discharging*



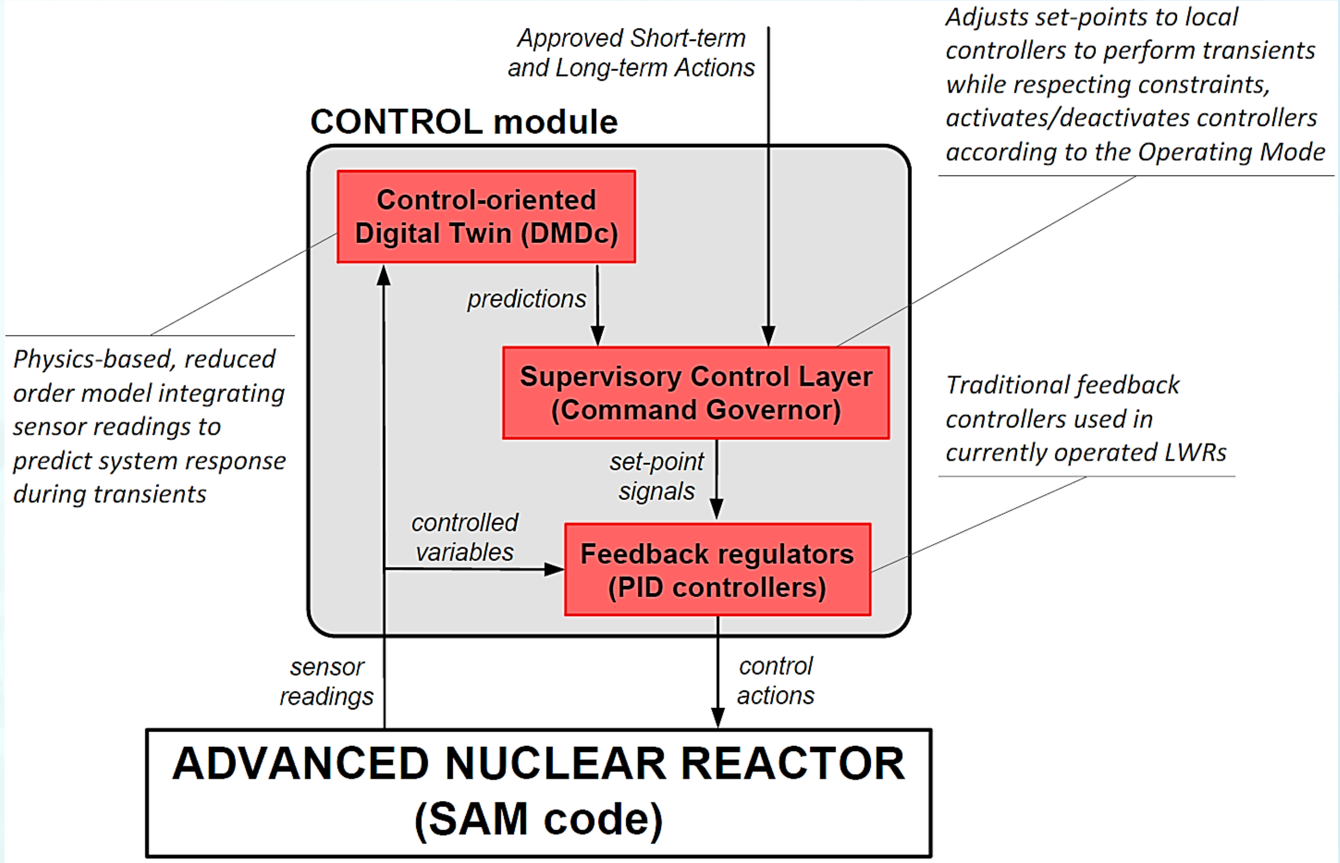


Results and Accomplishments: "CONTROL" module

- **Task**: ensuring the system components do not experience operating conditions that might affect their integrity or accelerating the wear and tear.

Identified Algorithms: Reference Governor (RG) and Feedback Regulators

- Control-oriented DT derived by tracking main process variables
- RG in the "Supervisory Control Layer" enforces the constraints via adjusting set-point trajectories, not the control actions (PID-based configuration is preserved).
- Embedded algorithms coupled with a diagnostics and a decision-making algorithms

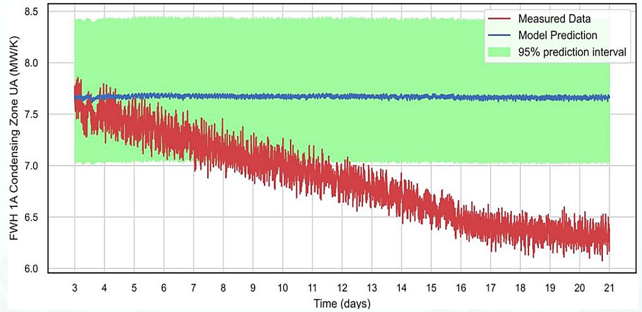


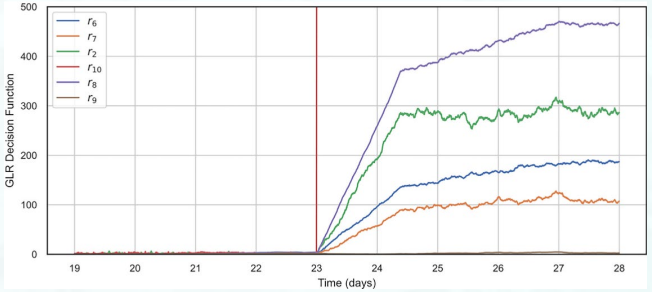
Results and Accomplishments: “DIAGNOSTICS” module

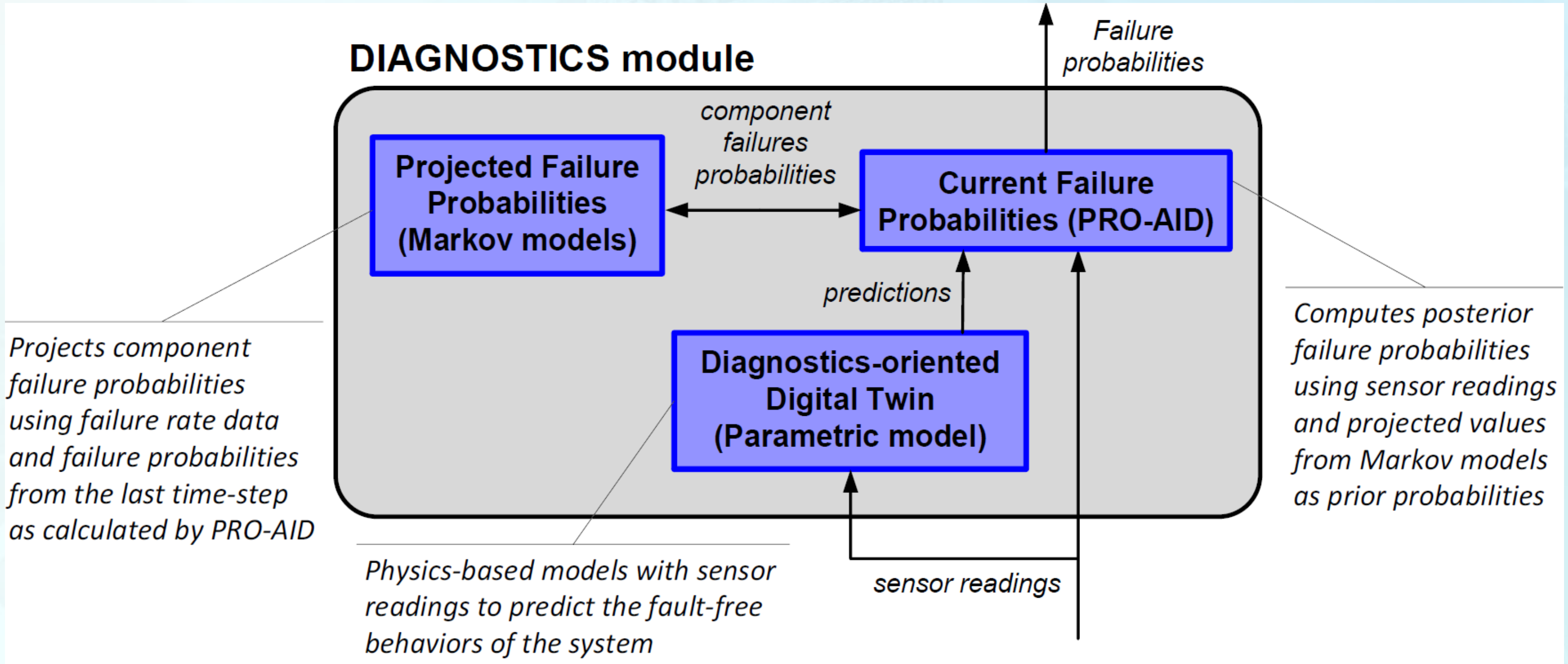
- **Task:** A Diagnostics algorithm discriminating component and sensor failures
- Data-driven diagnostic methods reconstruct the relationship between the input/output variables
  - **Not physics-based** (unreliable for detecting equipment/sensor anomalies, off-training conditions).
  - **Large datasets needed**

Identified Algorithms: PRO-AID for real-time diagnostics, Markov models for projecting failure probabilities of single components.

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

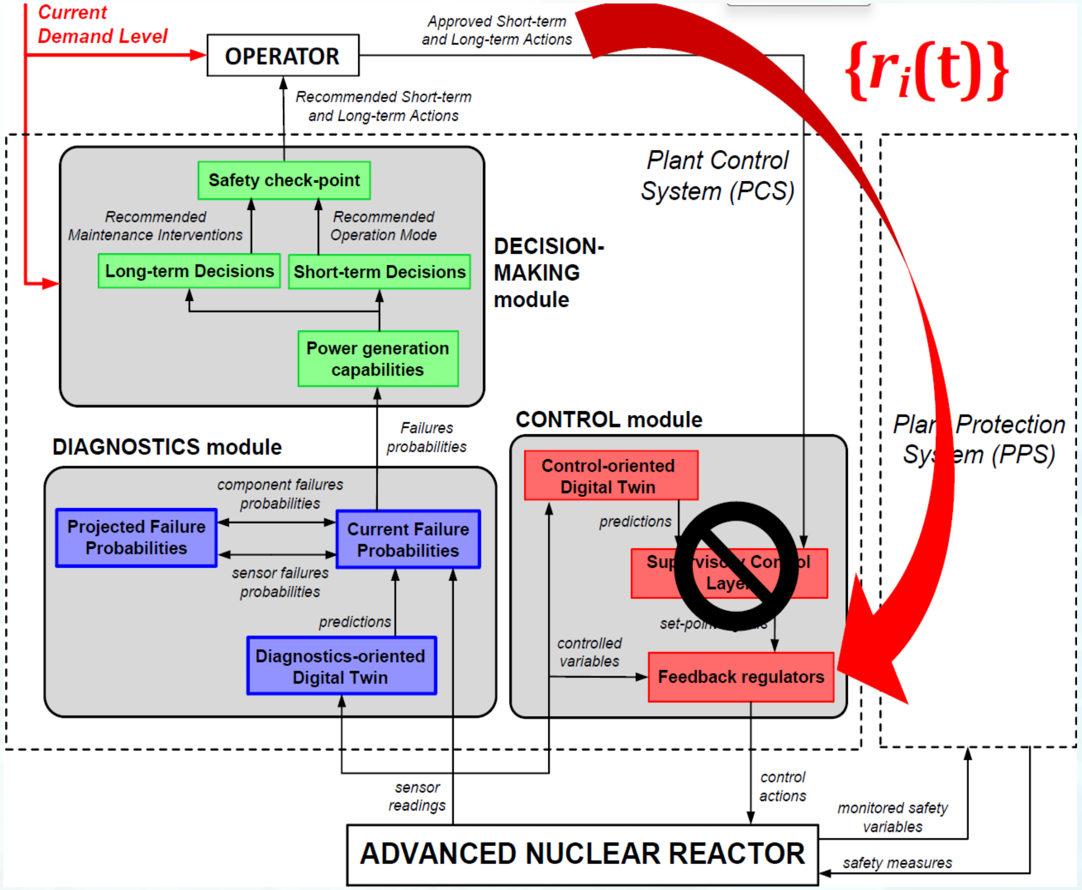




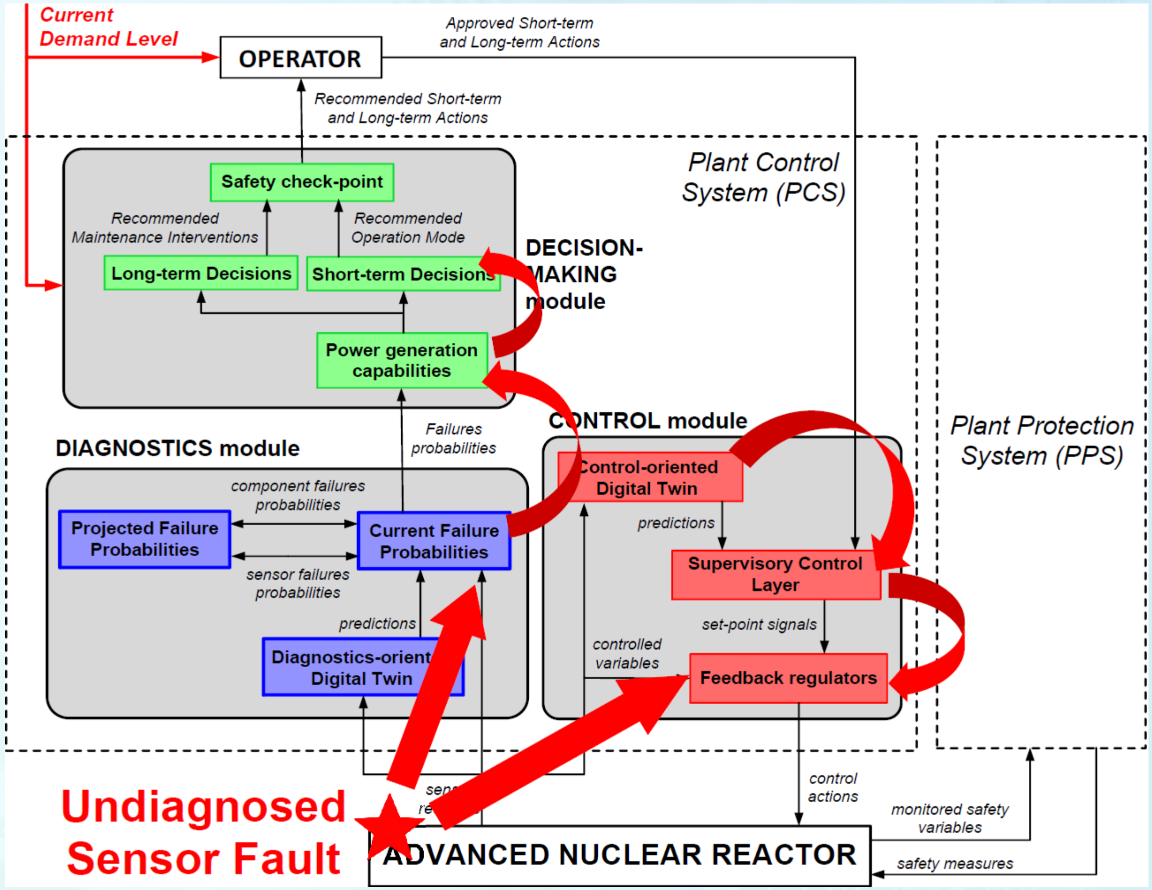


Results and Accomplishments: Advantages of proposed solutions

- Operator can bypass Supervisory control layer, and supply set-points to PIDs ("keeping the hands on the wheel").



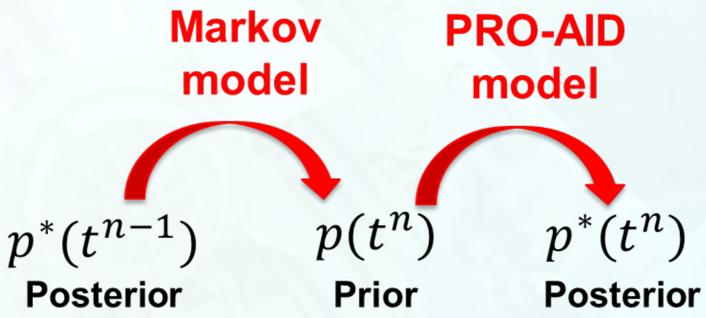
- In an architecture of data-driven algorithms, what happens if sensor failures are not promptly diagnosed?



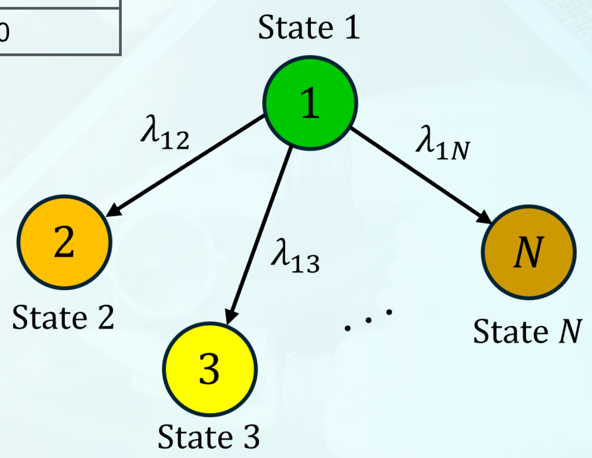
Results and Accomplishments: PRO-AID and Markov models (1/2)

FMEA Table for Intermediate Circuit components.

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



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



$$P_s(t) = A_s \cdot e^{-at} + B_s$$

$$\begin{cases} \dfrac{dP_1(t)}{dt} = -\sum\limits_{n=2}^{N} \lambda_{1n} \cdot P_1(t) & P_1(t=0) = 1 \\ \dfrac{dP_2(t)}{dt} = \lambda_{12} \cdot P_1(t) & P_2(t=0) = 0 \\ & \vdots \\ \dfrac{dP_N(t)}{dt} = \lambda_{1N} \cdot P_1(t) & P_N(t=0) = 0 \end{cases}$$

Results and Accomplishments: PRO-AID and Markov models (2/2)

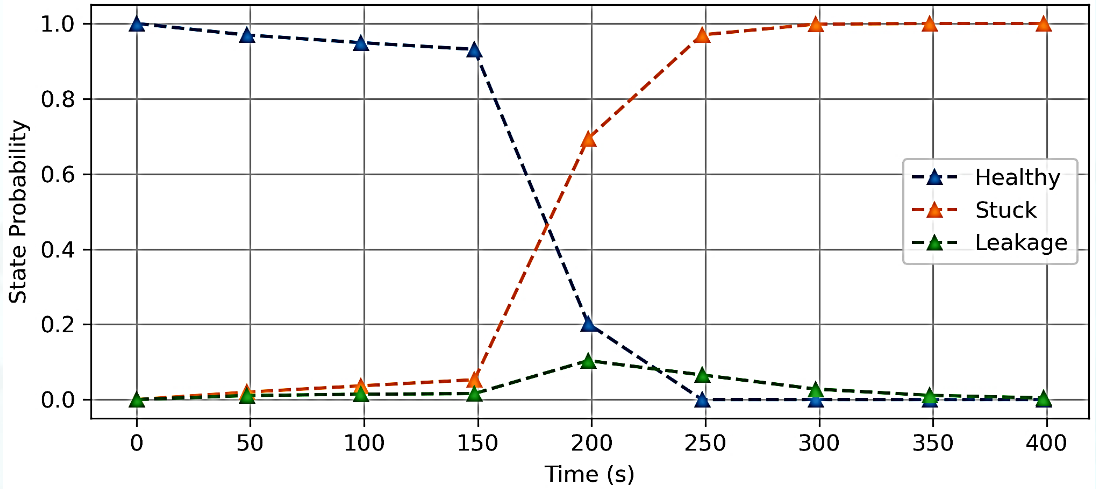
- Results from coupling PRO-AID with Markov component models are fault probabilities at each discrete time-step ΔT
- Results used to estimate system output (GRA) and check safety limits (PRA)

1. Initialize the Markov models for all components

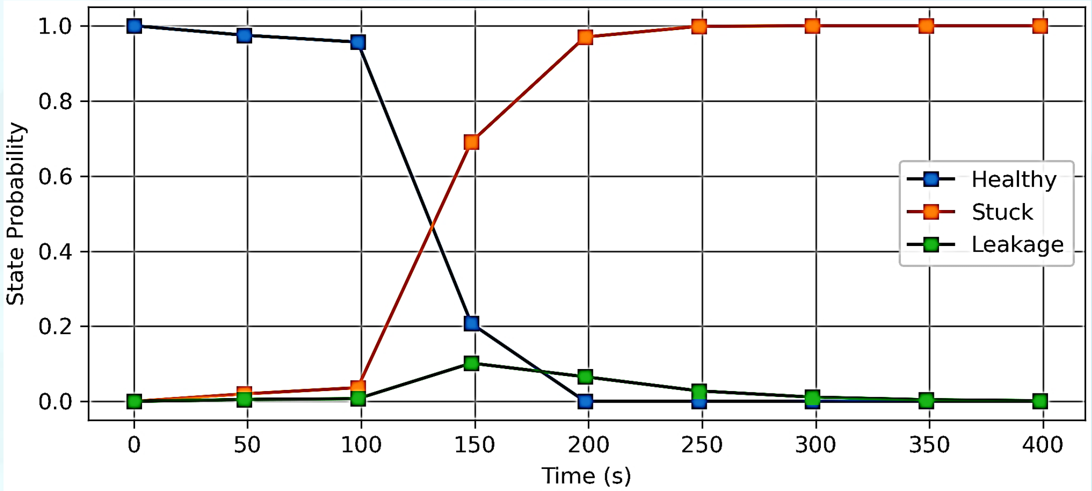
2. Repeat for each macro time step ($n \geq 1$):

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: “DECISION-MAKING” module (1/2)

- **Objective:** ensuring the continuity of service by meeting the demand at any time without violating operational limits.

Two sets of Decisions need to be made during Unit Operation

SHORT-TERM DECISIONS (operational procedures)

- *Transitions to different Operation Modes*

LONG-TERM DECISIONS (maintenance interventions)

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

Identified Algorithm:

Demand level compared with expected power production capabilities (outcome of the Generation Risk Assessment (GRA) analysis).

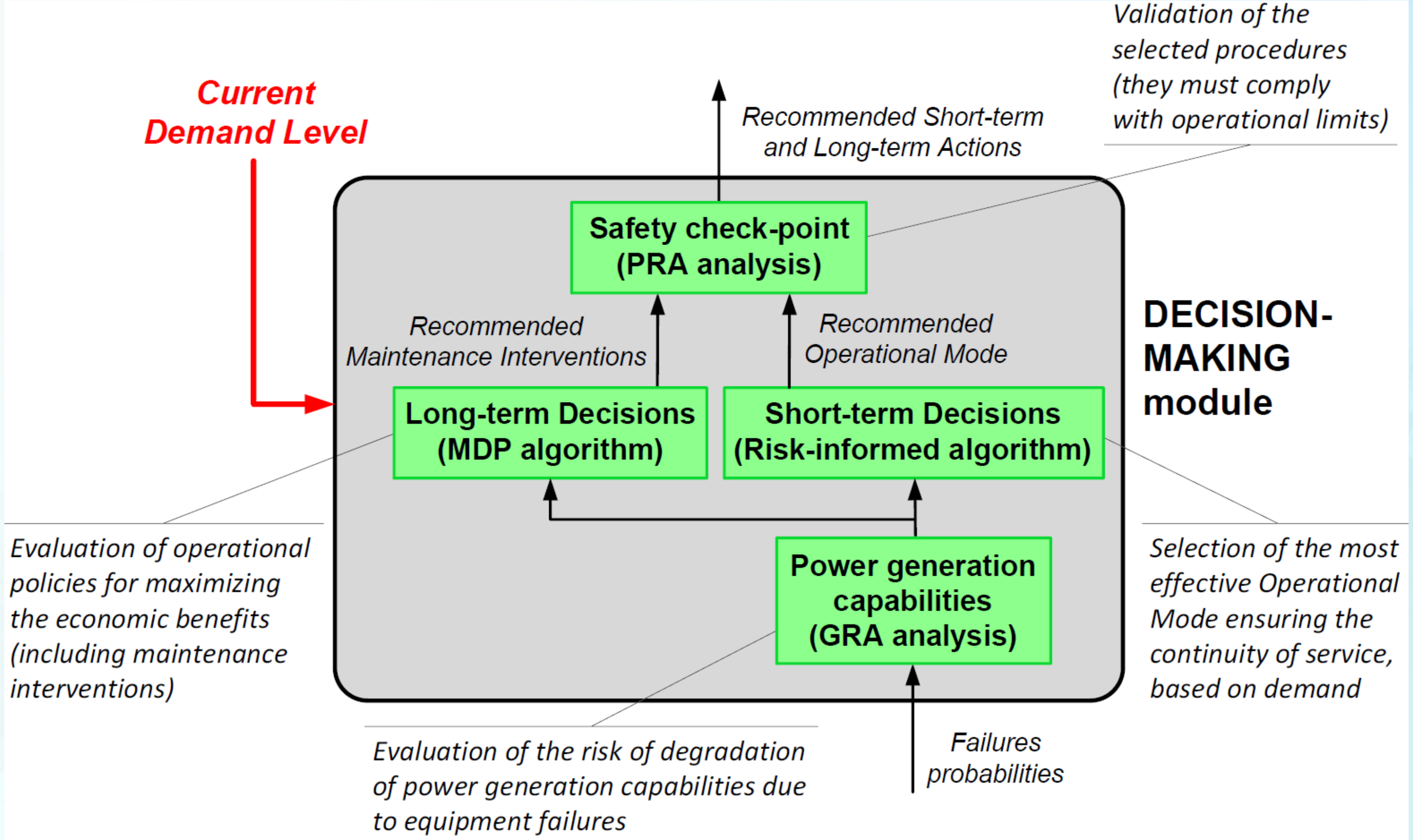
Identified Algorithm:

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

Results and Accomplishments: “DECISION-MAKING” module (2/2)

Key role played by the GRA analysis:

- In addition to abrupt failures, multiple slow performance degradation phenomena affect components. Multiple failures overlap during operation.
- Automatically accounts for the “compensation” that can be provided by the other actuators and/or components in case of degraded performance.
- Estimates the impact that individual component faults have on the system power production capabilities.

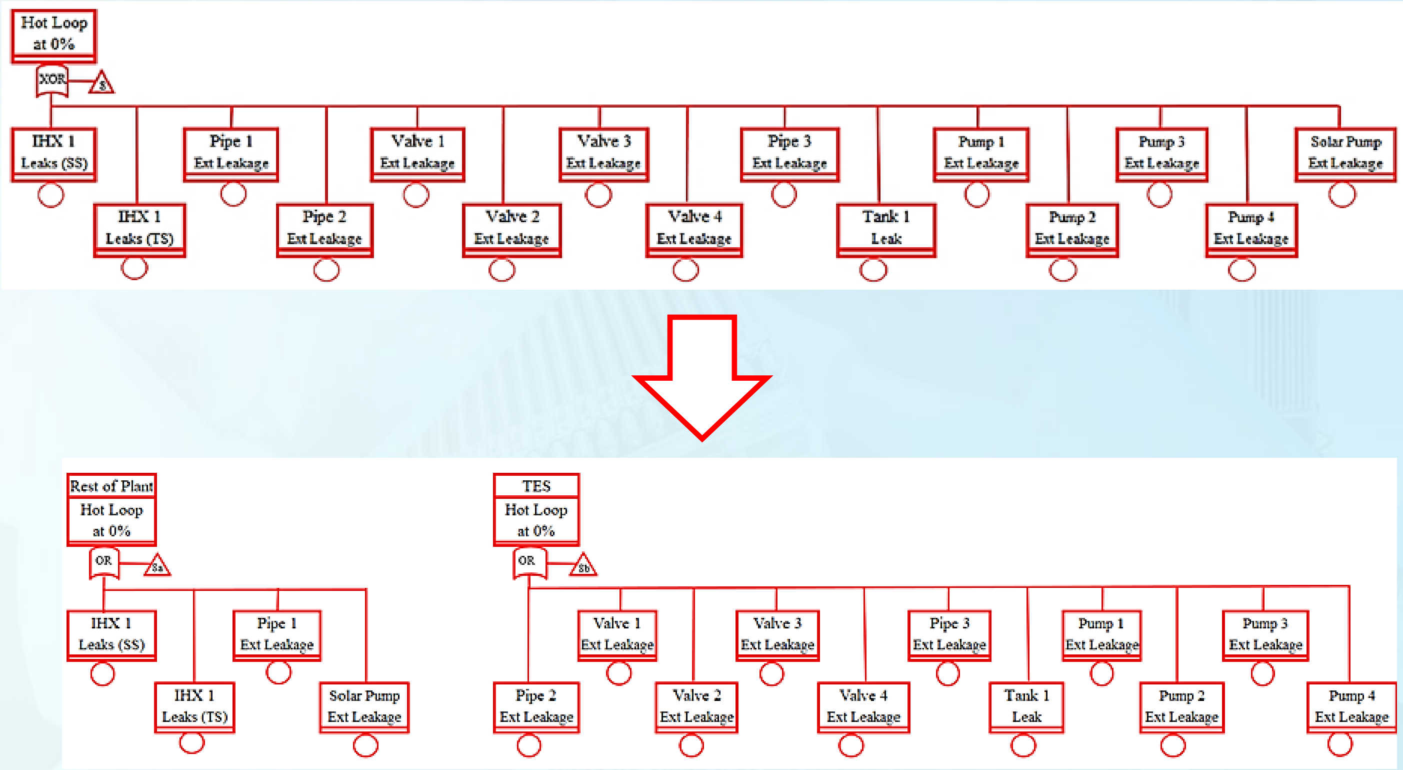


Results and Accomplishments: Development of GRA model

- Analytical approach: Fault Tree method to calculate the probability of system trip or derate. Rare Event Approximation could not be applied.

- Abandoned FT approach (too many output levels deriving from simultaneous failures scenarios)

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



Primary and Intermediate Circuit separately addressed

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

- $f_i \rightarrow$ binary variable equal to 1 with probability p_i when a failure occurs
- $R_i \rightarrow$ reduction of the system output

Results and Accomplishments: Development of PRA model

- Generated a probabilistic model of the system from which the system output (O_j) is sampled according to their probability distributions (MCMC).

- At each time step, the probability that system power capacity is higher than the current demand level is calculated.

$$p(O_j > D) = \frac{|O_j \in \{O_1, O_2, \dots, O_N\}: O_j > D|}{N}$$

- **Modified PRA:** new definitions of "success" and "failure". System "failure" is defined as the event when the system cannot meet the demand.

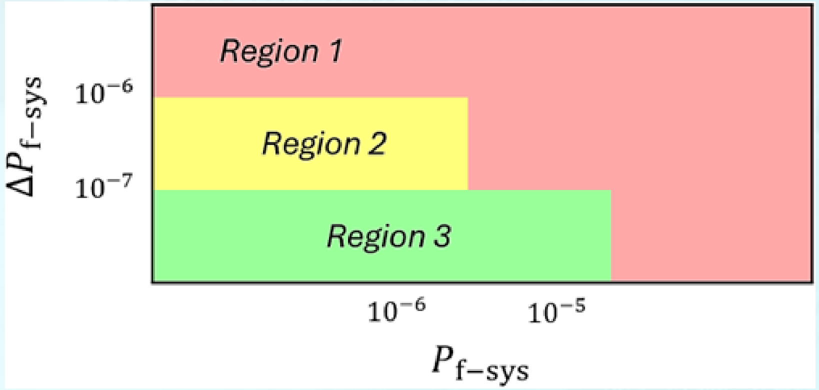
Power Output (%)	Probability
$O_1 = 10\%$	P_1
$O_2 = 20\%$	P_2
…	…
$O_k = 60\%$	P_k
…	…
$O_N = 100\%$	P_N

Current Demand level ($D(t)$)

Probability of not meeting the demand ("FAILURE")

Probability of meeting the demand ("SUCCESS")

Comparison of expected power production capabilities with current demand level.

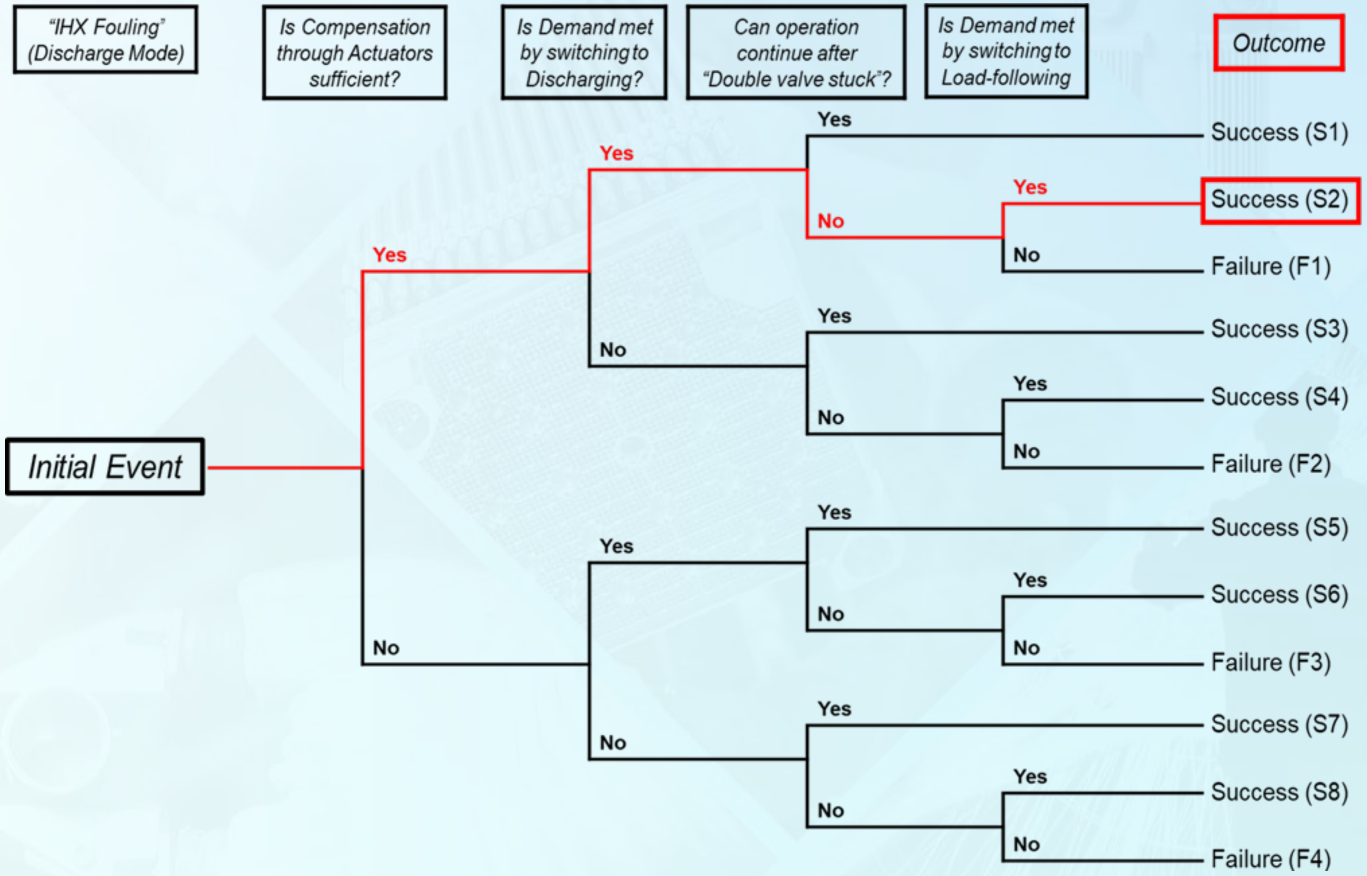


Acceptance Guidance for system failure probability.

Results and Accomplishments: Definition of test scenario

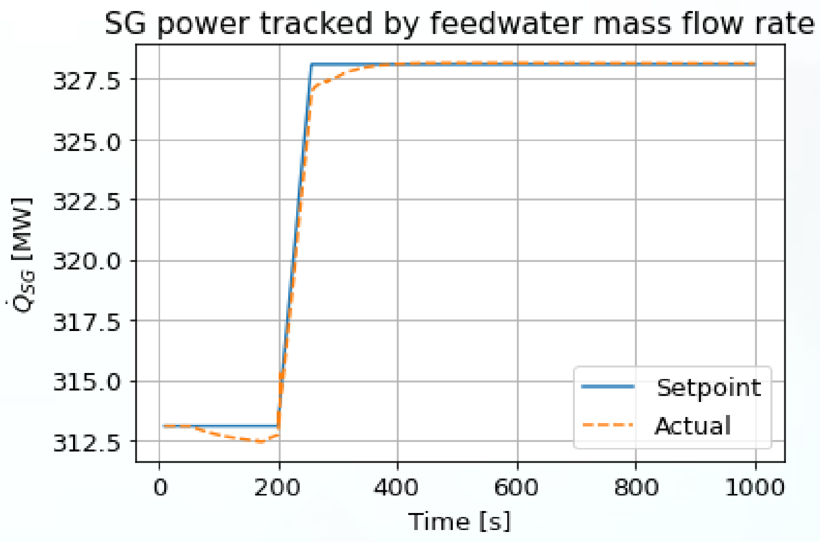
- **Not Severe failures:** Performance degradation failures (e.g., fouling). Consequences can be mitigated by dedicated control actions ("compensation").
- **Severe failures:** Consequences are so severe that a transition to a different mode is required, in case failed component can be isolated; otherwise, maintenance intervention is required.

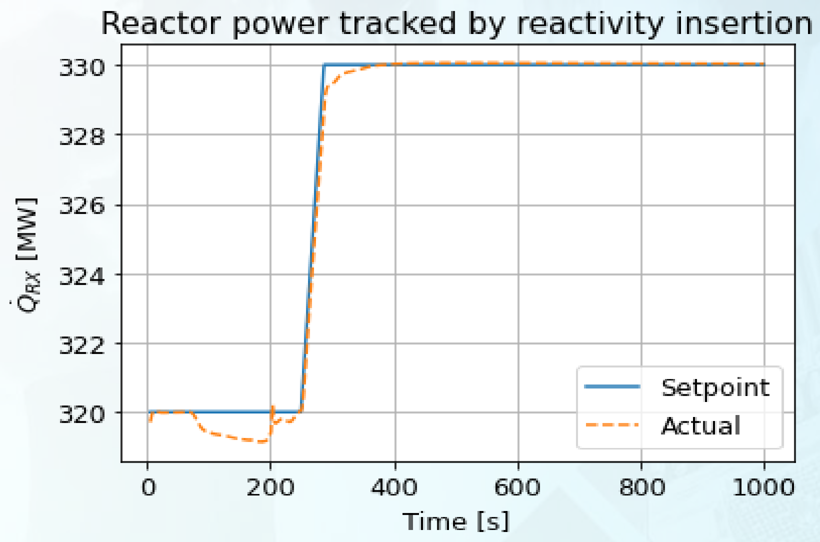
Stage #	Time (s)	Stage Description
1	0.0	System operated in *Load-Following* mode
2	100.0	IHX fouling detected
3	Automated	Compensation through Actuators
4	200.0	Demand increase
5	200.0	Transition to *Discharging* mode
6	249.0 (first valve) 349.0 (second valve)	Double-valve stuck detected
7	249.0	Transition to *Load-Following* mode

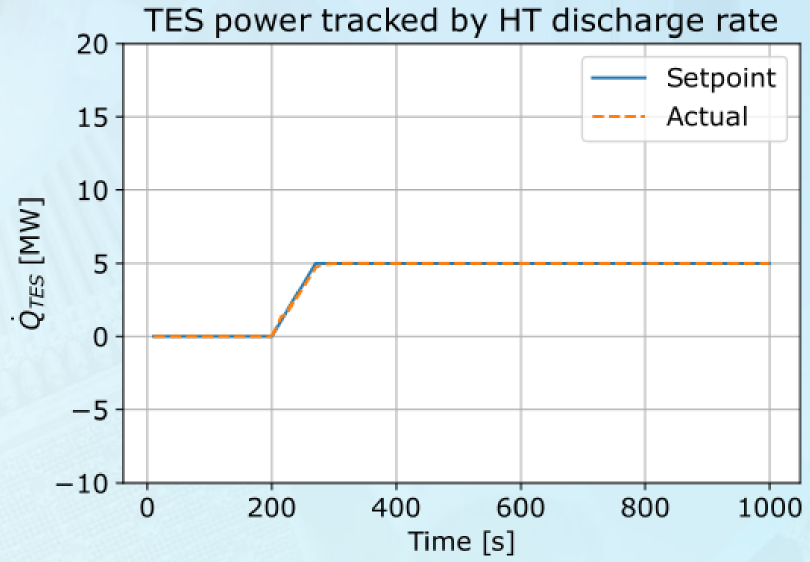


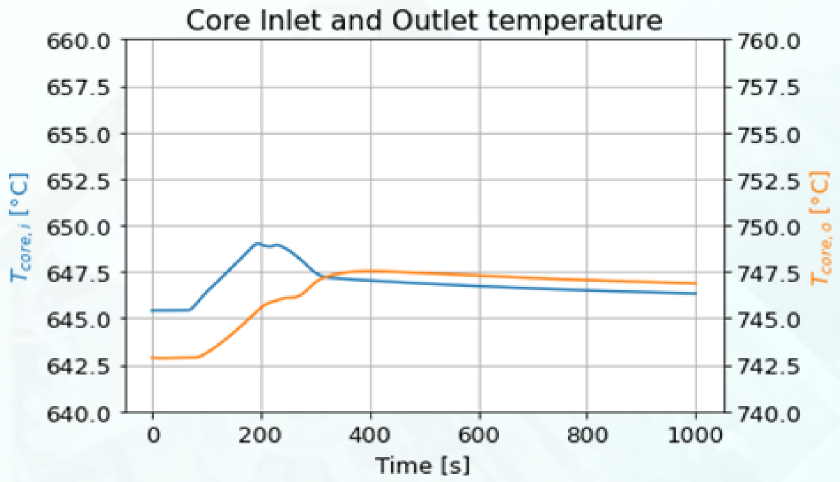
Visualization Event Tree (ET) path for the test-case sequence.

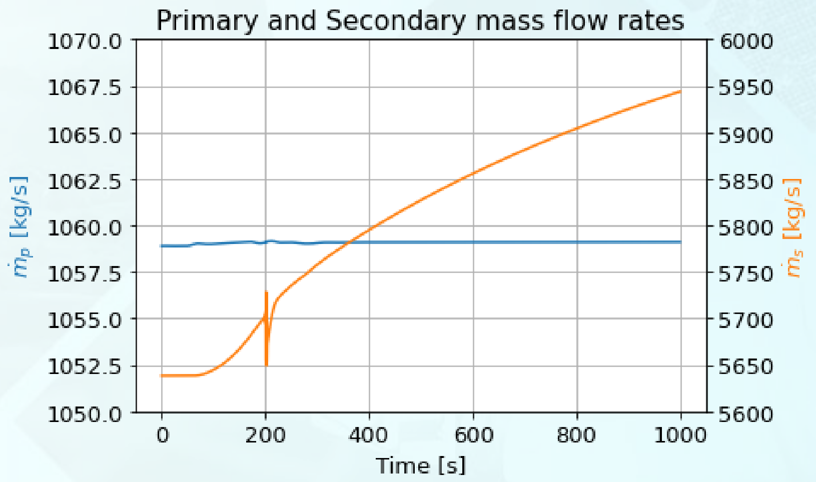
Results and Accomplishments: Simulation of test scenario (1/2)

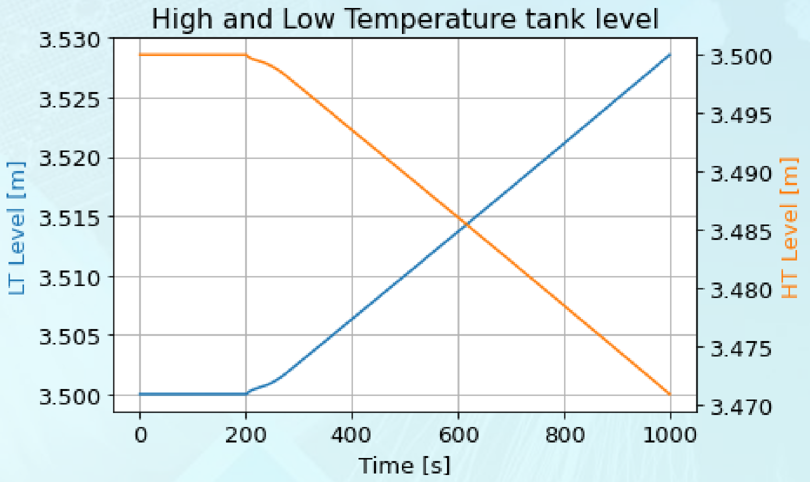




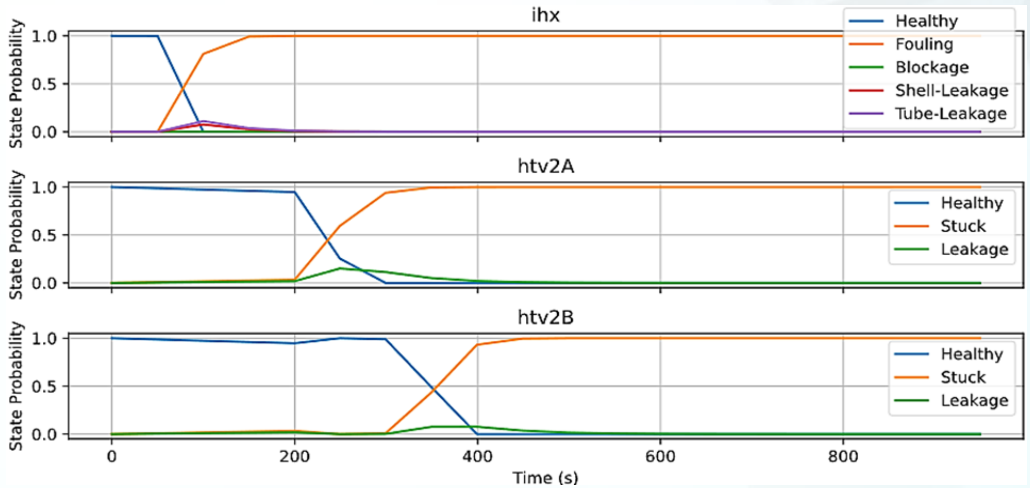




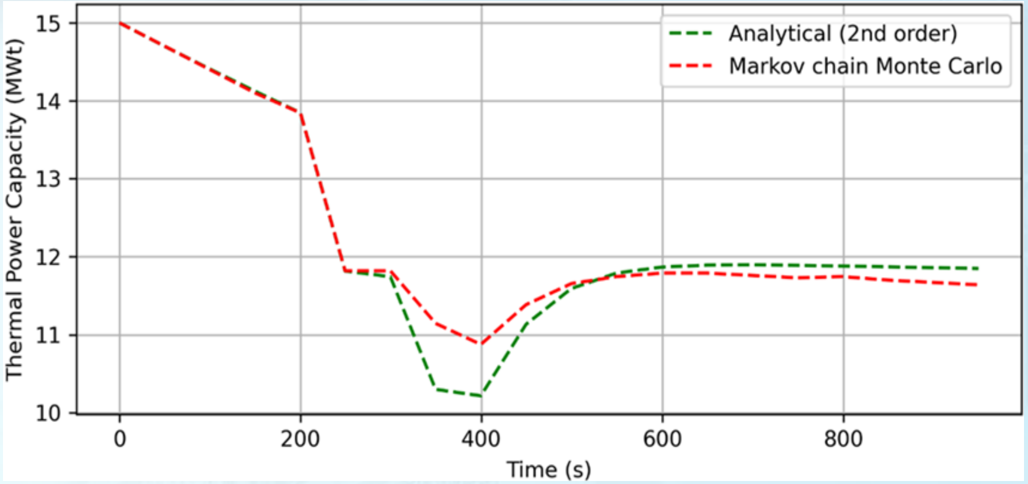




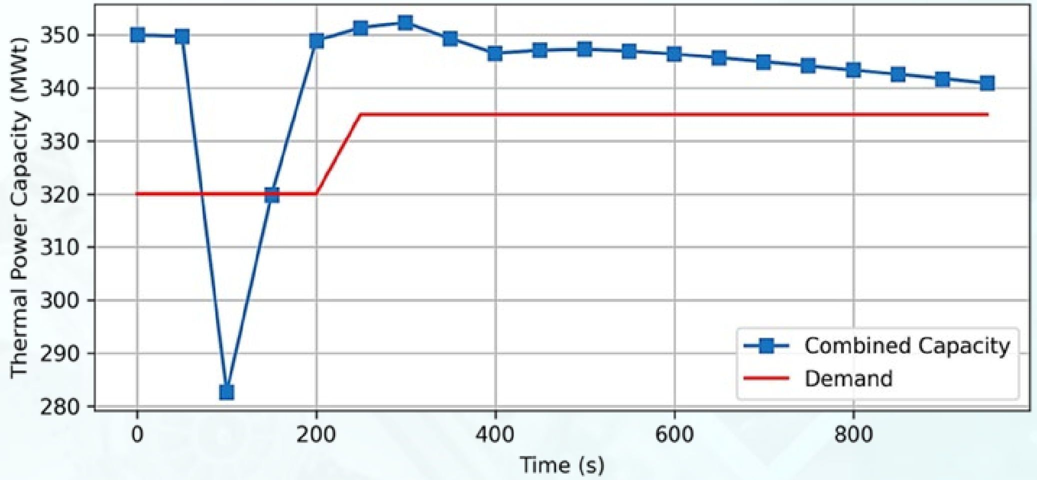
Results and Accomplishments: Simulation of test scenario (2/2)



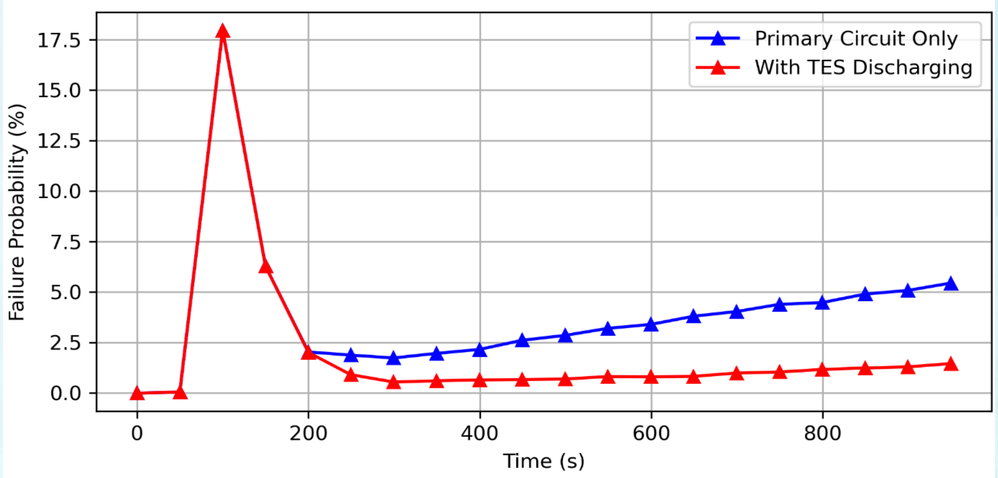
PRO-AID model outcomes - Time evolution of failure probabilities.



GRA analysis outcome - Time evolution of the expected thermal power capacity of the TES system.



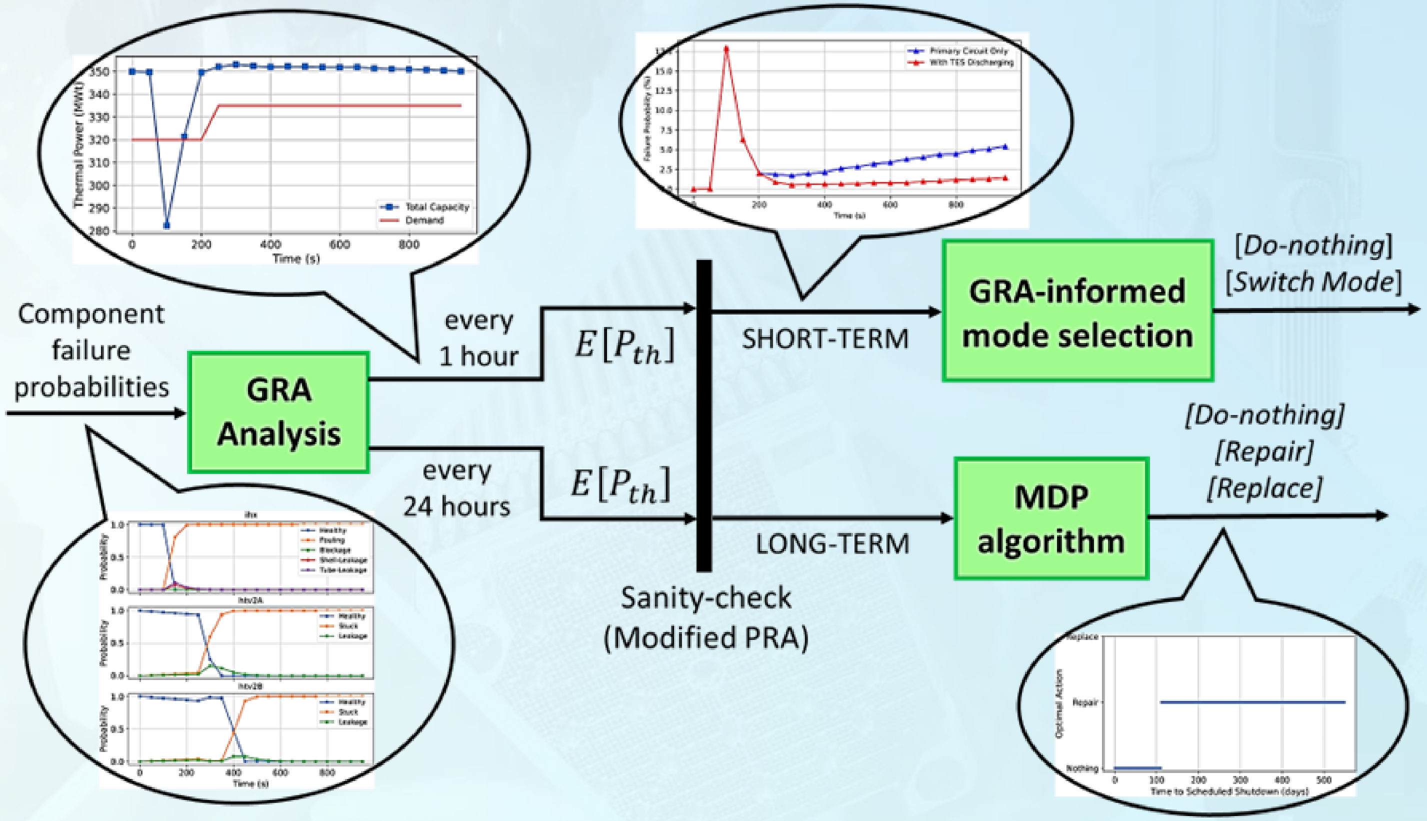
GRA analysis outcome - Time evolution of the expected power production capabilities of the whole system.



PRA analysis outcome - Failure probability trends corresponding to "Do nothing" and "Transition to *Discharging* mode" (t=200 s).

Concluding Remarks

- Future Plans
  - Real-time adjustment of operational constraints
  - Implementation of an additional PRA sanity check based on safety criteria
  - Final Report for Project 20-19321 “Design and Prototyping of Advanced Control Systems for Advanced Reactors Operating in the Future Electric Grid”



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Thank You