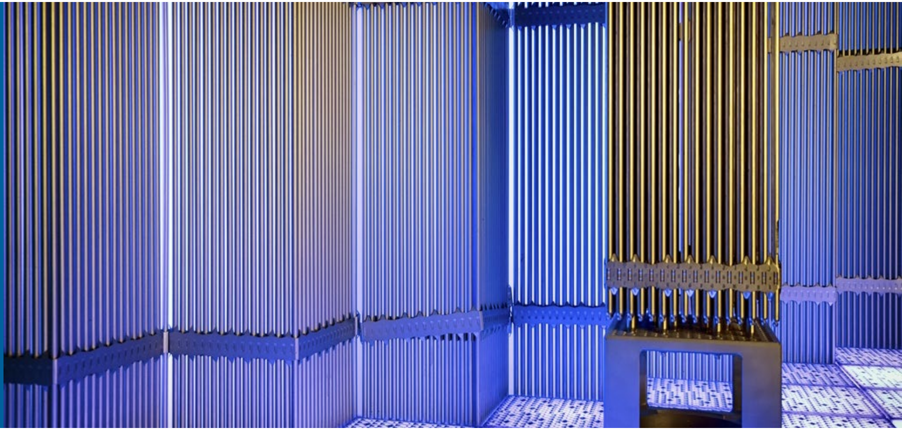
ADVANCED REACTORS AND THE NEED FOR ADVANCED CONTROL SYSTEMS – ARGONNE NATIONAL LABORATORY – JULY 12-14, 2023

Argonne NATIONAL LABORATORY

A PATH TO SEMI-AUTONOMOUS OPERATION



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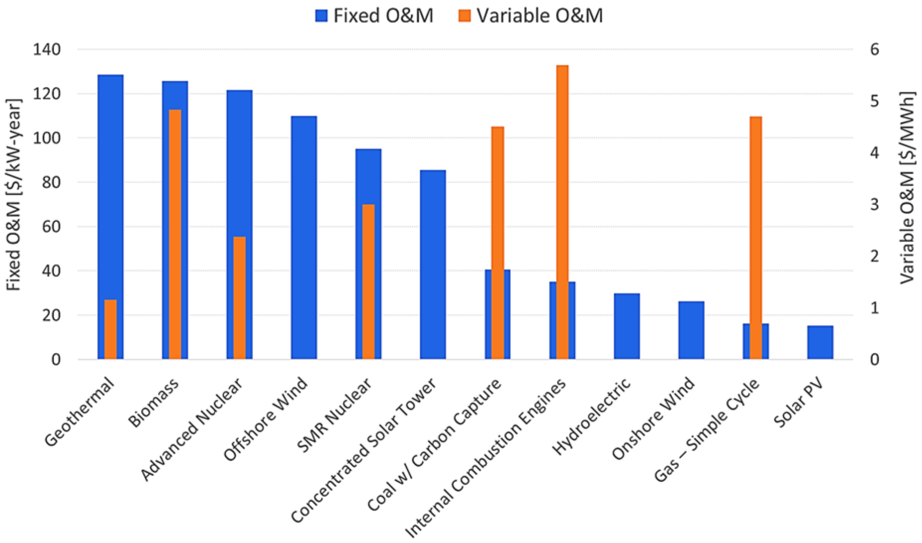
ROLE OF AUTONOMOUS OPERATION IN IMPROVING NUCLEAR UNITS' PROFITABILITY

Impact of O&M costs on the economy of Nuclear Units

- Currently operated units are struggling to stay competitive in U.S. Deregulated markets. Significant impact of fixed O&M costs (largest portion goes to payroll for staffing).

How can Autonomous Operation help saving on O&M costs?

- Limiting the number of operators in the MCR (Main Control Room) does not significantly reduce costs
- Most of the savings can be accomplished by optimizing the maintenance schedule
- Maintenance interventions can be less time-consuming, number of on-site technicians reduced



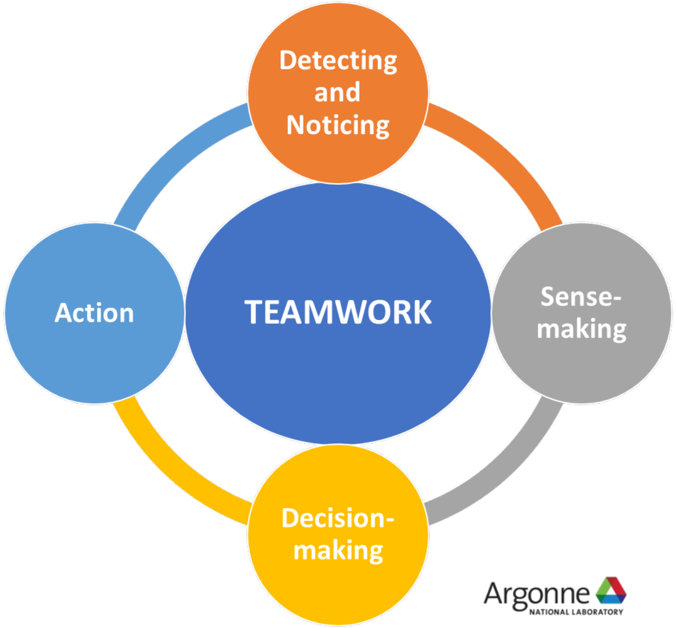
AUTONOMOUS OPERATION AS A TEAMWORK PROCESS (1/2)

Teams without teamwork defeat the purpose of teams

- 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 Nuclear Power Plant operation (NUREG-2114, January 2016).

- Cognitive framework focuses on the nature of human performance "in the field" where decisions must be made quickly, in risky or high-stake situations. If one of five cognitive functions is missing, errors might occur.

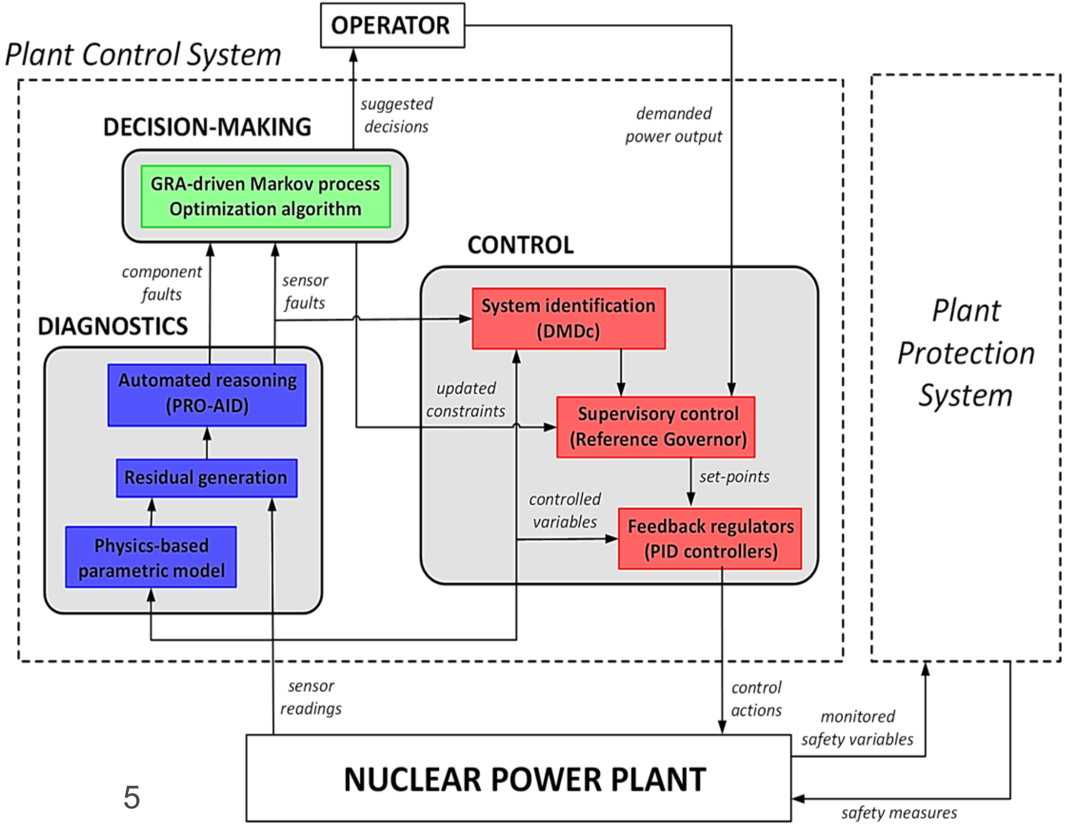


AUTONOMOUS OPERATION AS A TEAMWORK PROCESS (2/2)

HOW AI ALGORITHMS CAN ENABLE AUTONOMOUS OPERATION

List of key concepts

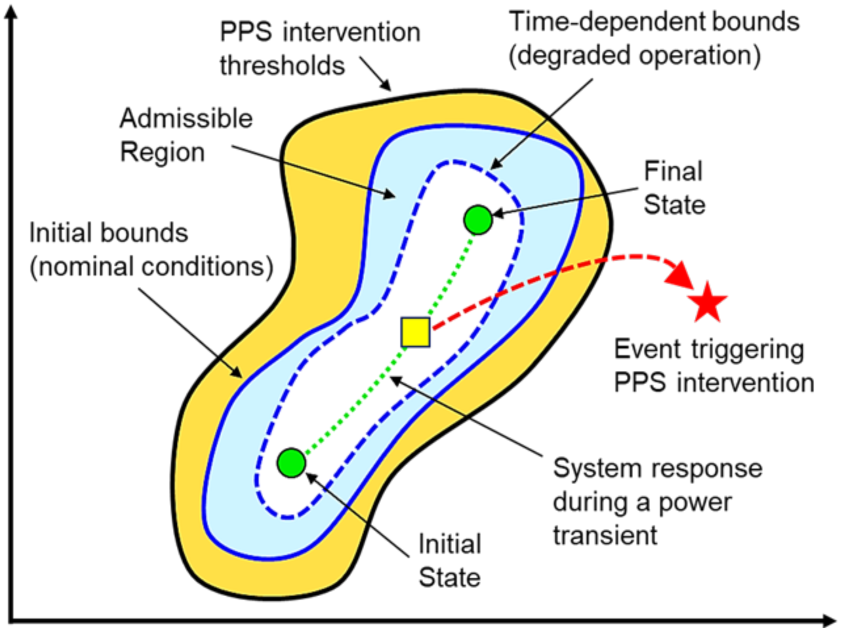
- Application of AI/ML algorithms to Normal Operation only
- Algorithms fulfilling Control, Diagnostics and Decision-making tasks need to “talk” to each other
- Plant Protection System (PPS) must be allowed to take over in case of violation of limits on safety variables
- Ensure to Operators the opportunity to override the Supervisory Control layer



AUTONOMOUS OPERATION-ORIENTED ARCHITECTURE: NEEDS AND SOLUTIONS (1/4)

Need to monitor the Normal Operation Envelope

- To improve the profitability, flexible operation must be exploited to full extent
- Component conditions and performance evolve in time. "Admissible Region" evolves accordingly.
- Need of a control algorithm confirming compliance of plant trajectories with safety bounds (necessary condition).



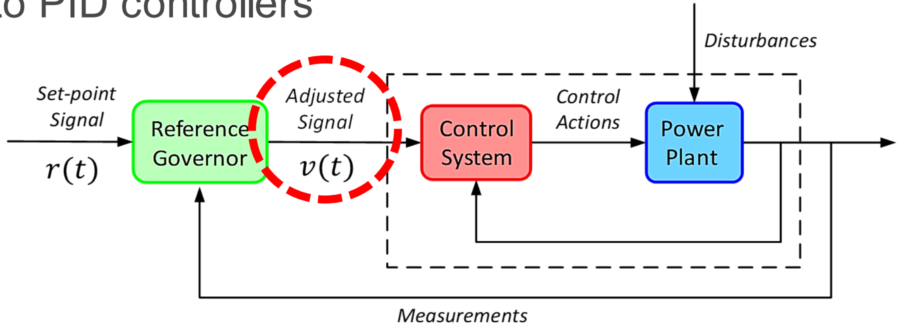
Identified SOLUTION: Reference Governor

- Optimizes the set-points to meet load demand by respecting the constraints

AUTONOMOUS OPERATION-ORIENTED ARCHITECTURE: NEEDS AND SOLUTIONS (2/4)

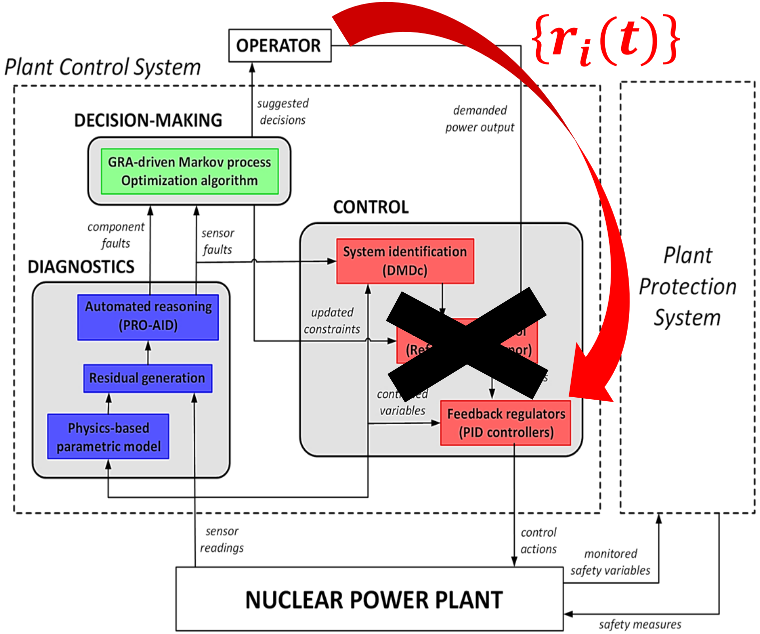
Transferability of control tasks to Operator

- Modular design ensures the Operator the possibility of manually providing set-points signals to PID controllers



- **Reference Governor** adjusts the set-points, not the control actions
- Currently-adopted, PID-based structure is preserved

Supervisory control layer can be bypassed, and set-points directly fed to PIDs

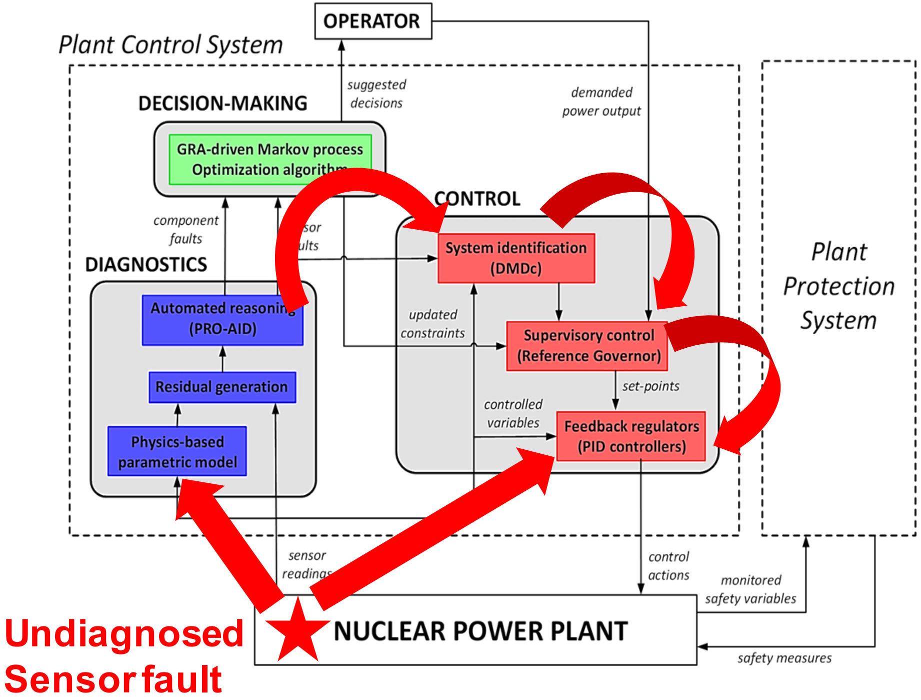


AUTONOMOUS OPERATION-ORIENTED ARCHITECTURE: NEEDS AND SOLUTIONS (3/4)

Unexplored levels of integration means unprecedented failure modes

Q. In an architecture made of data-driven algorithms, what happens if sensor faults are not promptly diagnosed?

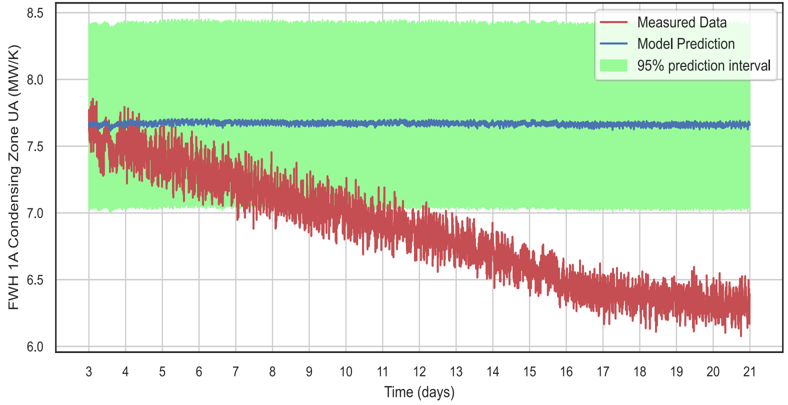
- Poor performance of PID controllers
- Wrong diagnoses (sensor faults might be interpreted as component-level faults)
- Wrong decisions (ineffective procedures are selected)
- Damages to components and PPS intervention



AUTONOMOUS OPERATION-ORIENTED ARCHITECTURE: NEEDS AND SOLUTIONS (4/4)

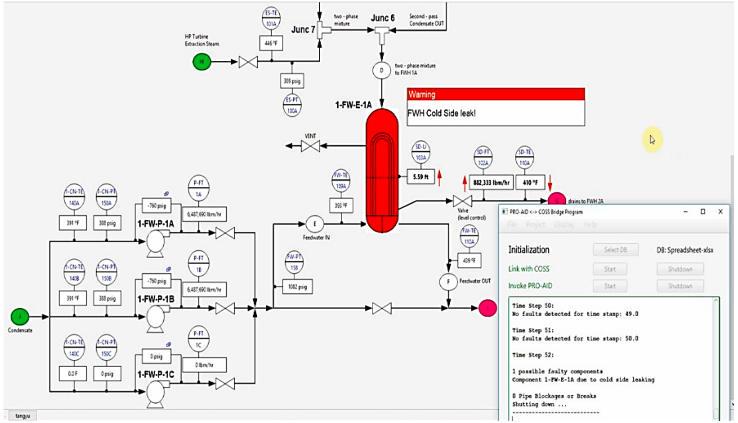
"Redundancy" might not be an option

Using multiple, independent sensors to monitor hundreds of process variables is too expensive



Identified SOLUTION: PRO-AID

- PRO-AID can discriminate between Sensor-level and Component-level faults
- Given the P&ID, a physics-based model of the system is automatically assembled from a library of components;
- Immune to plant operating point changes;
- Ranks component faults by probability;
- Auto reconfigures on dropped sensor.

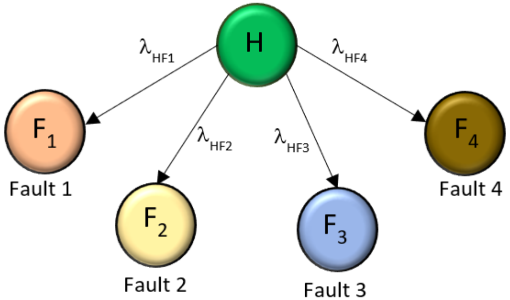


AUTONOMOUS OPERATION-ORIENTED ARCHITECTURE: NEEDS AND SOLUTIONS (5/5)

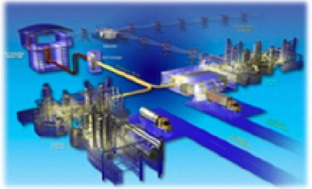
Decisions should aim at maximizing profits by limiting the risk for failures

Identified SOLUTION: Diagnostics-informed Markov Decision Process (MDP)

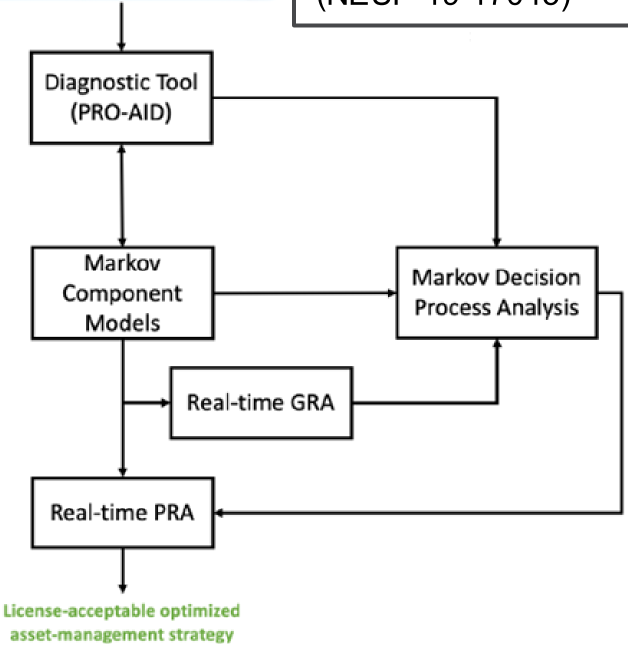
- Generation Risk Assessment (GRA) evaluates the current system capacity capabilities, Probability Risk Assessment (PRA) evaluates the risk of not meeting the demand.
- Markov models developed for each component of the Intermediate Circuit.



Operating Plant



“Cost-Benefit Analyses through Integrated Online Monitoring and Diagnostics”
(NEUP 19-17045)

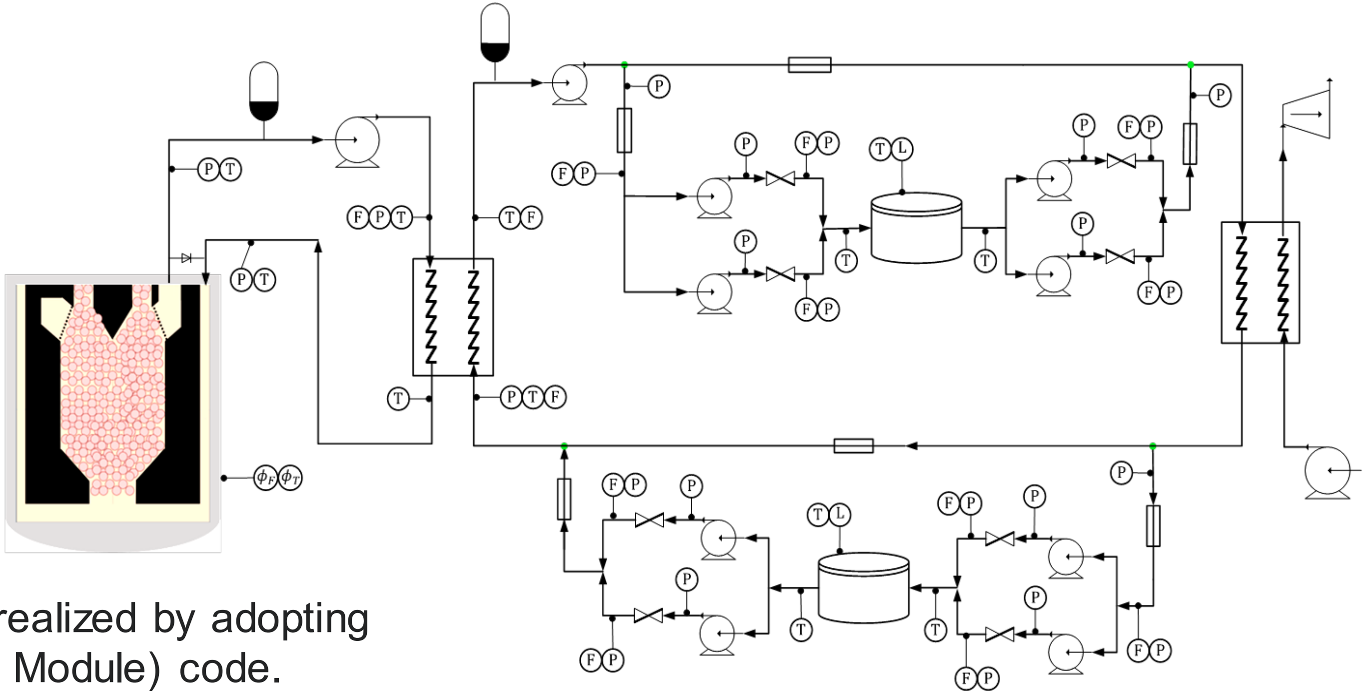


APPLICATION OF PROPOSED ARCHITECTURE TO AN ADVANCED REACTOR DESIGN (1/4)

NEUP 20-19321 (ANL/UM/Kairos Power, 3 years, 1 M$)

Selected system:

- Integrated energy system, i.e., a pebble-bed fluoride salt-cooled, high temperature reactor (KP-FHR) coupled with molten-salt thermal energy storage.



- High-fidelity simulator realized by adopting SAM (System Analysis Module) code.

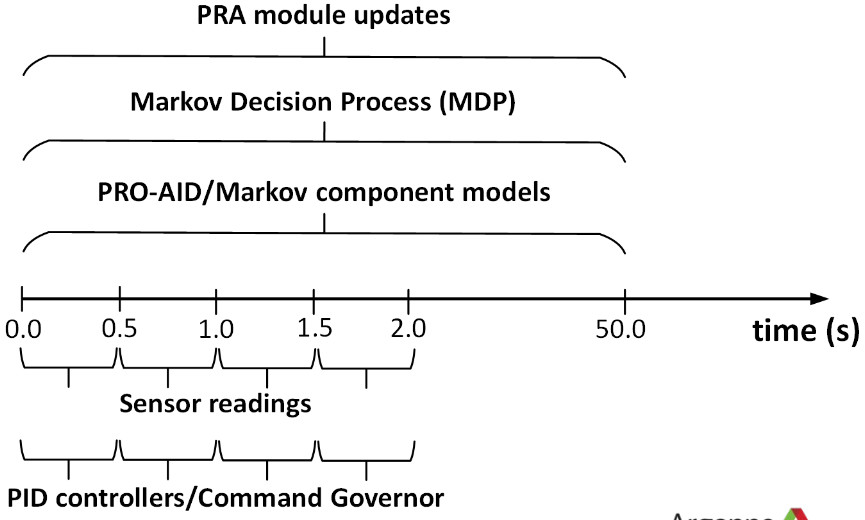
APPLICATION OF PROPOSED ARCHITECTURE TO AN ADVANCED REACTOR DESIGN (3/4)

Definition of the Test-case scenario

- Performance degradation fault addressed via "compensation"
- Severe fault addressed via Operation Modes transition

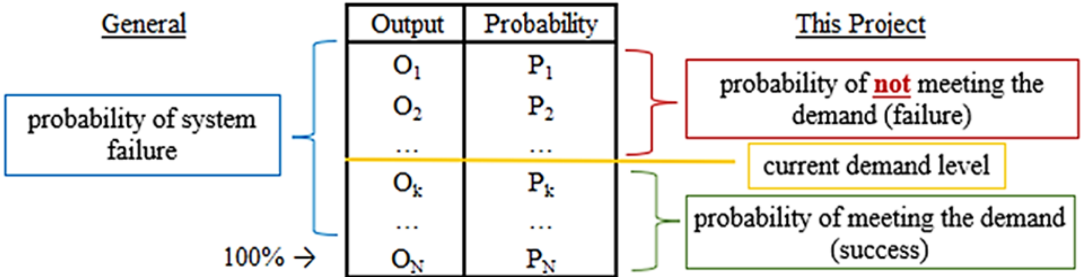
Stage #	Stage Description
1	System is in "Load-Following" mode (constant reactor power, TES bypassed, constant load demand)
2	"IHX Fouling" detected
3	Compensation through Actuators
4	Load demand increase
5	MDP suggests switching to "Discharging" mode
6	"Double valve stuck" detected
7	MDP suggests transition to "Load-following" mode

- Control, diagnostics and decision-making algorithms characterized by characteristic time-scale.

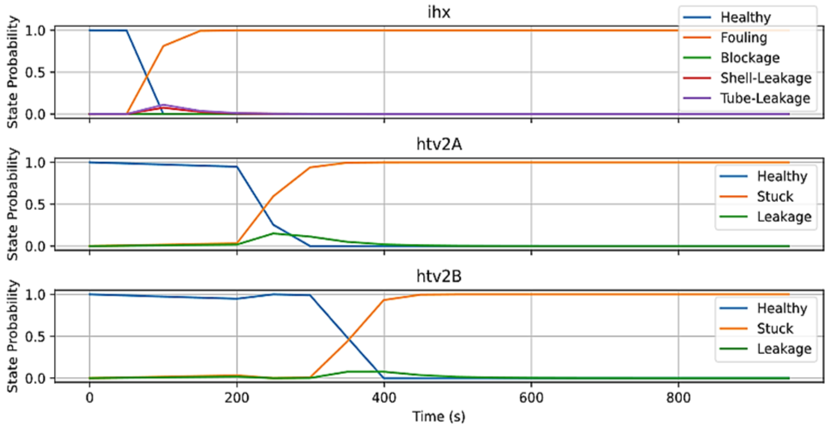


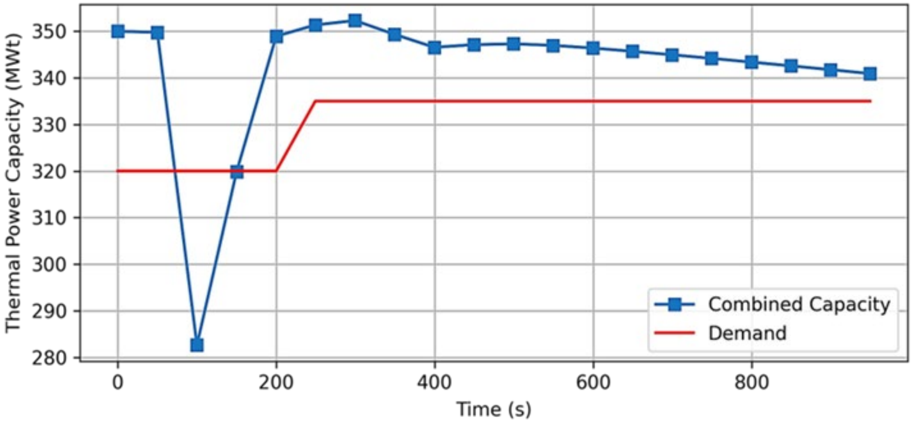
APPLICATION OF PROPOSED ARCHITECTURE TO AN ADVANCED REACTOR DESIGN (3/4)

Test-case simulation results: Diagnostics, GRA and PRA analysis



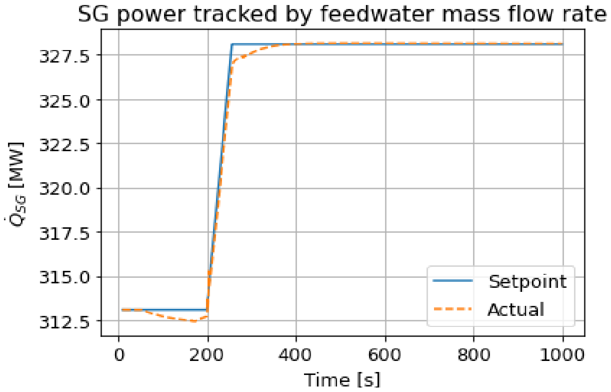
- Addressing load fluctuations through "compensation" and/or transitions to different Operation Modes.
- Ensuring continuity of service while meeting constraints.

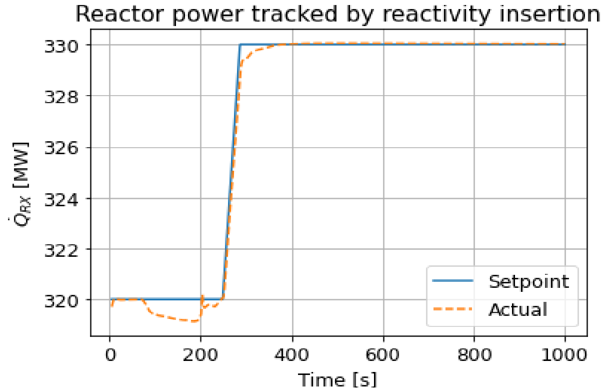


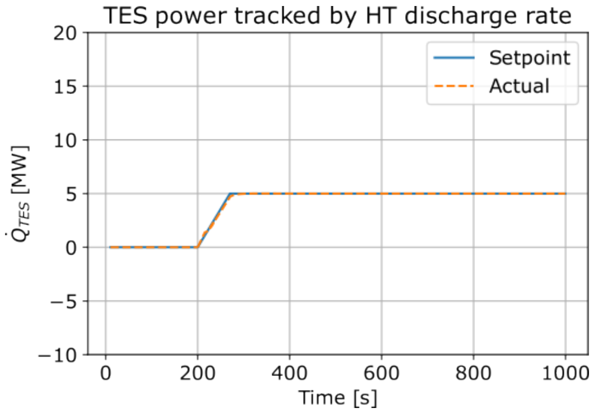


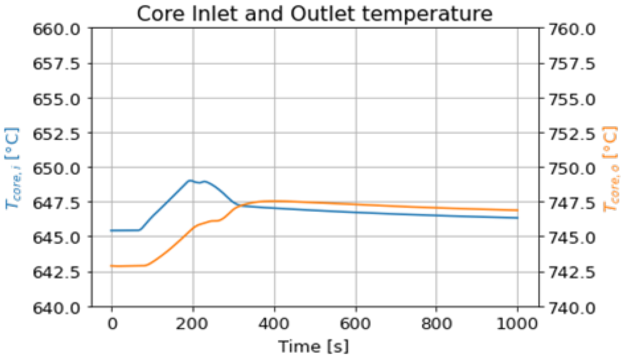
APPLICATION OF PROPOSED ARCHITECTURE TO AN ADVANCED REACTOR DESIGN (4/4)

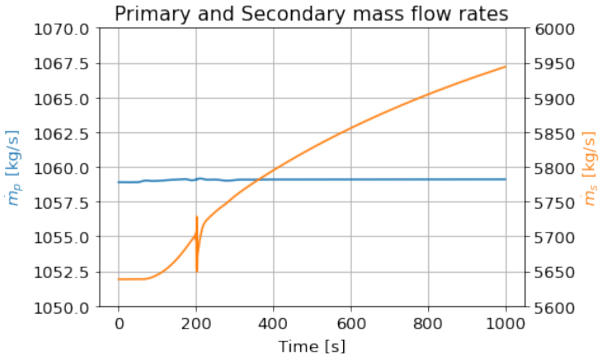
Test-case simulation results: system dynamic response

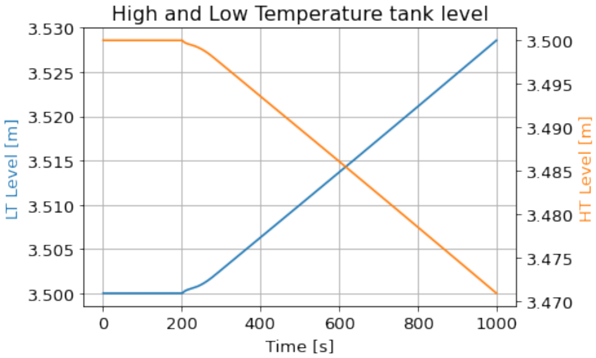












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