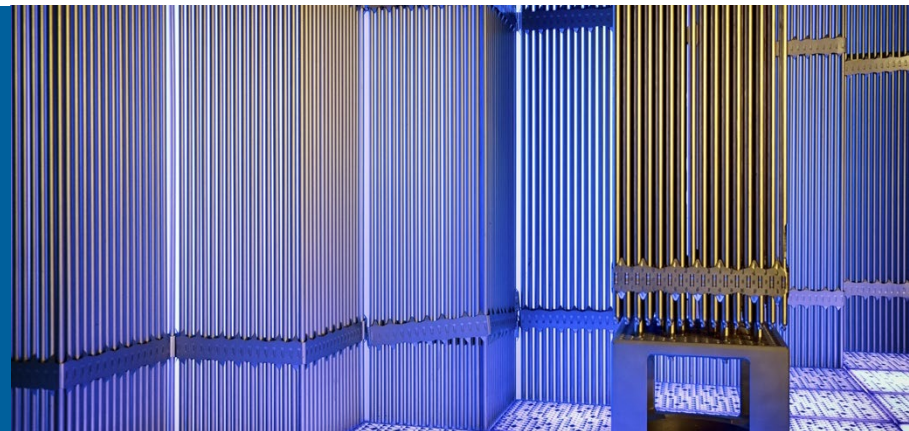


GIF INDUSTRY FORUM – OCTOBER 3-6, TORONTO (CANADA)  
TS02 - ARTIFICIAL INTELLIGENCE FOR NUCLEAR



# THE CHALLENGE OF AUTONOMOUS OPERATION AND AUTOMATED REASONING AS AN AI ENABLER



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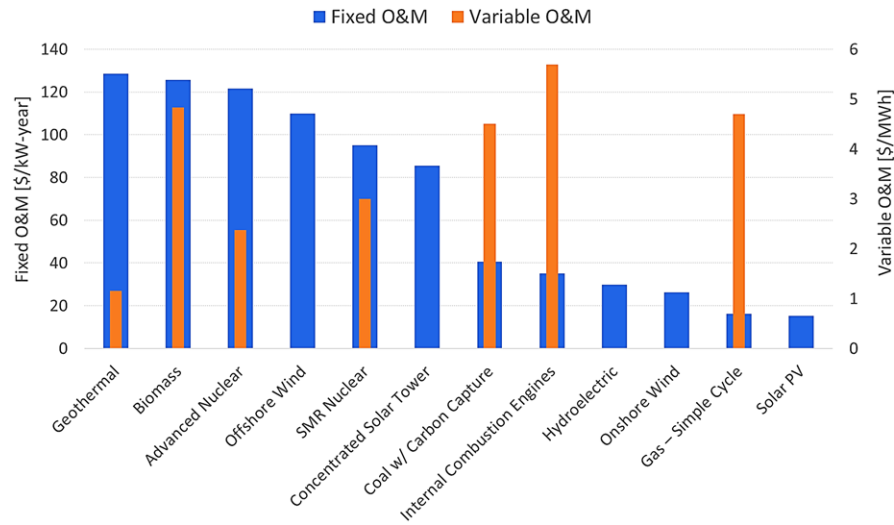
# ROLE OF AUTONOMOUS OPERATION IN IMPROVING NUCLEAR UNITS PROFITABILITY

## 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 MCR (Main Control Room) operators 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



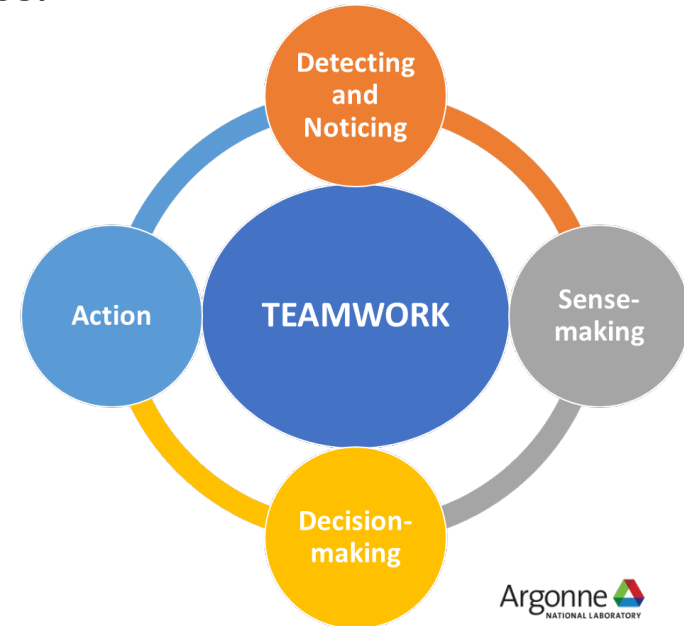
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# AUTONOMOUS OPERATION AS TEAMWORK PROCESS (1/2)

## 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 TEAMWORK PROCESS (2/2)



**SENSORS**



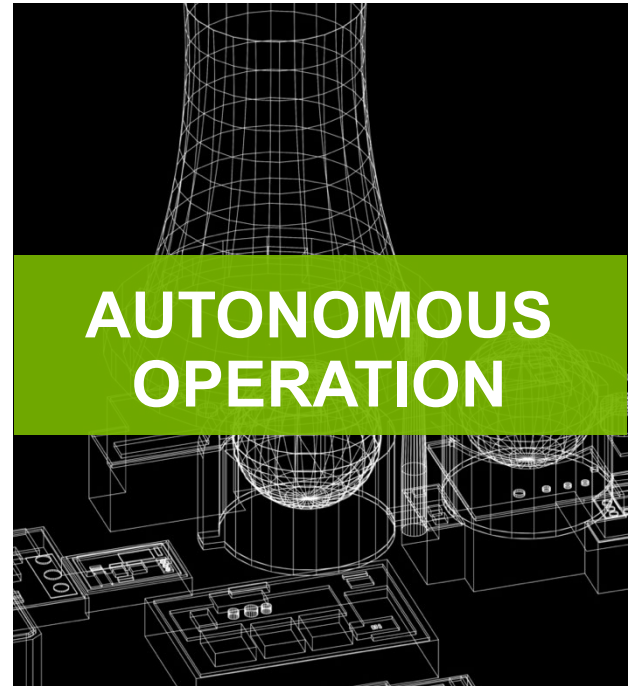
**MONITORING**



**CONTROL**



**DECISION MAKING**

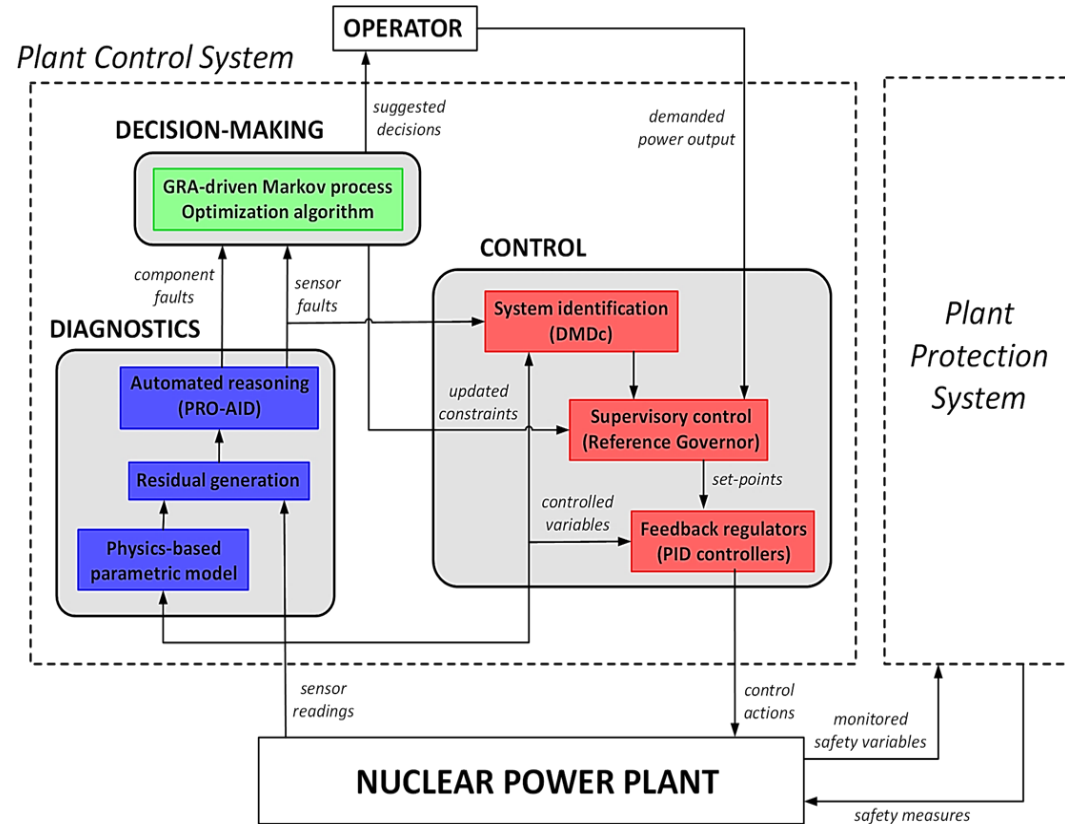




# HOW AI ALGORITHMS CAN ENABLE AUTONOMOUS OPERATION

## List of key concepts:

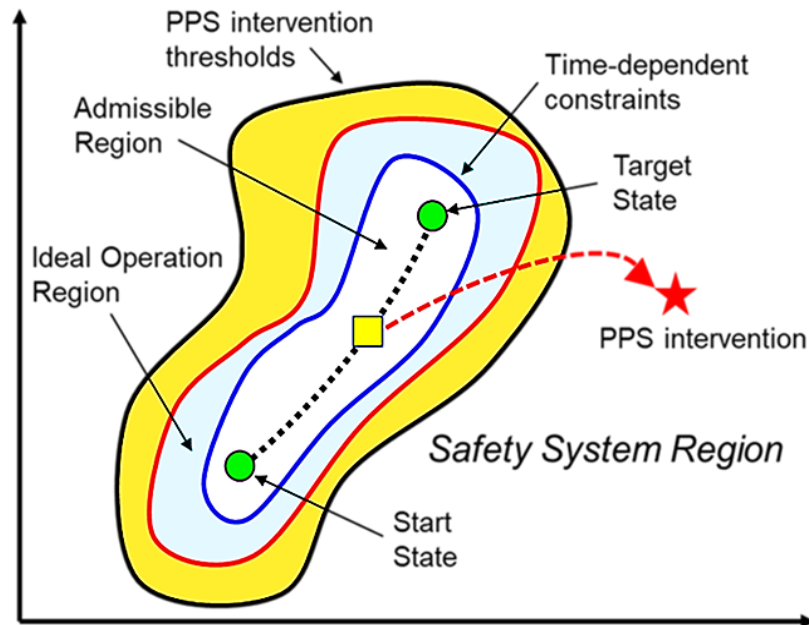
- Application of AI/ML algorithms to Normal Operation only
- Algorithms fulfilling Control, Diagnostics and Decision-making tasks need to “talk” to each other
- Plant Protection System (PPS) must be allowed to take over in case of violation of limits on safety variables
- Ensure to Operators the opportunity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



# AUTONOMOUS OPERATION-ORIENTED ARCHITECTURE: NEEDS AND SOLUTIONS (1/5)

## Need to monitor the Normal Operation Envelope

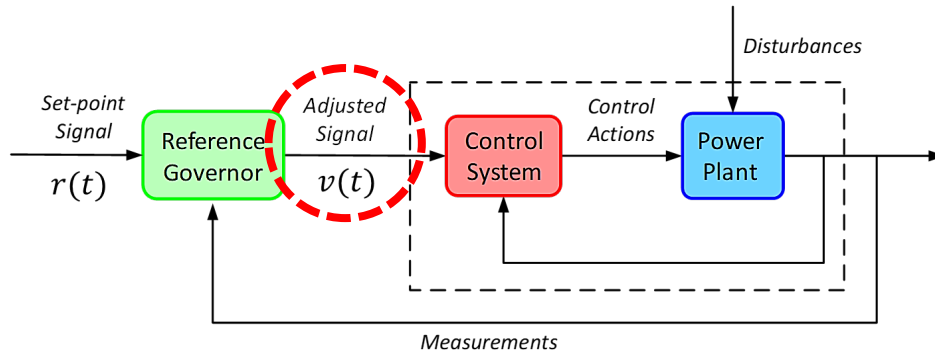
- To improve the profitability through Autonomous Operation, performance must be exploited to the full extent
- Plants can be operated as long as safety-imposed bounds are not violated (NOT subject to changes)
- Conditions and performance of plant components evolve in time. Normal Operation Envelope evolves accordingly
- A control algorithm confirming compliance of plant trajectories is necessary



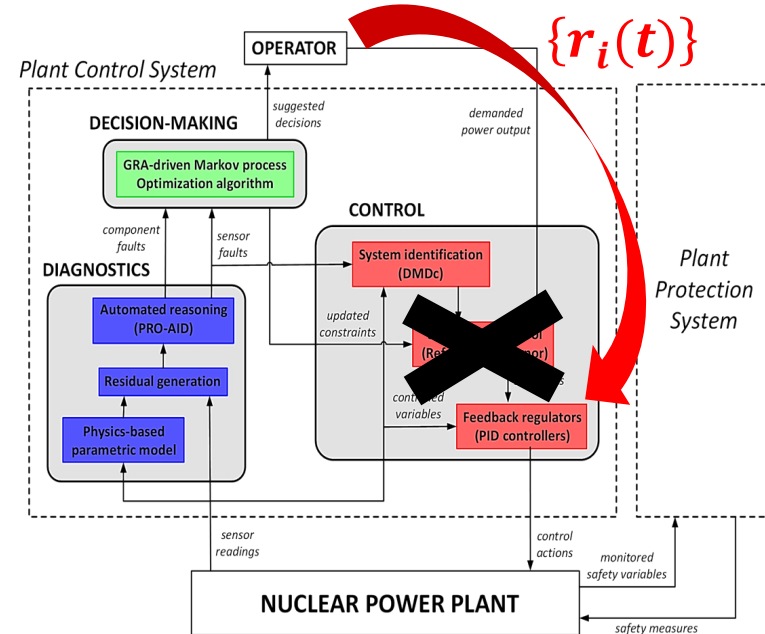
# AUTONOMOUS OPERATION-ORIENTED ARCHITECTURE: NEEDS AND SOLUTIONS (2/5)

## Transferability of Control tasks to Operator

- Currently-adopted, PID-based structure is preserved
- Reference Governor adjusts set-points, not control actions
- If needed, operator can directly provide set-points signals to PID controllers (*modular configuration*)



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

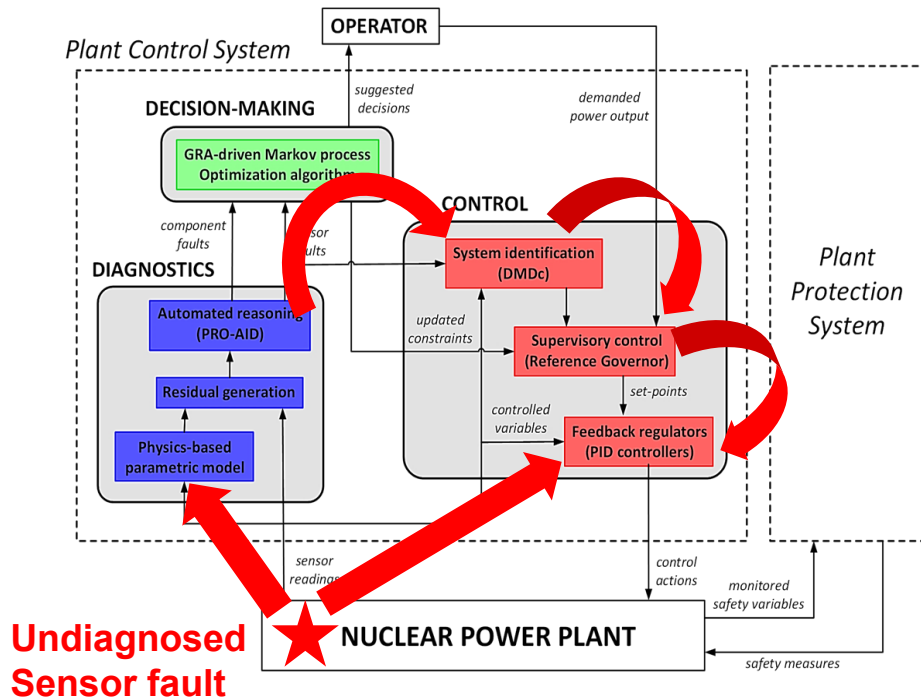


# AUTONOMOUS OPERATION-ORIENTED ARCHITECTURE: NEEDS AND SOLUTIONS (3/5)

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 (4/5)

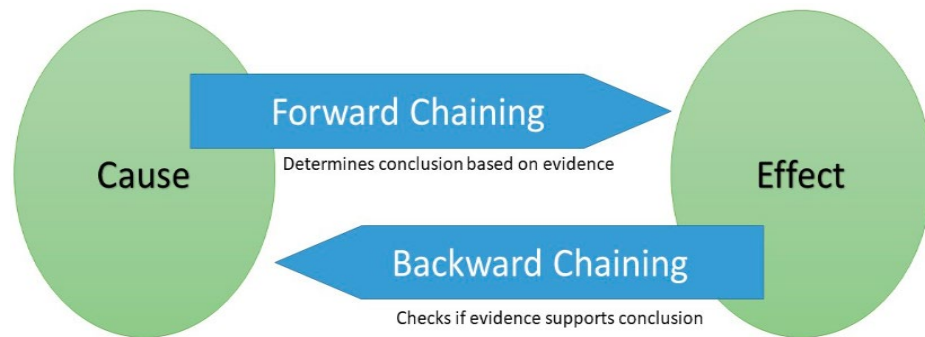
## “Redundancy” is not be an option

Digital Twins for Control, Diagnostics and Decision-making tasks require hundreds of process variables to be monitored. Multiple, independent sensors might be too expensive.

## A Diagnostics algorithm that can discriminate between Sensor-level and Component-level Faults is needed

## Automated Reasoning is the key

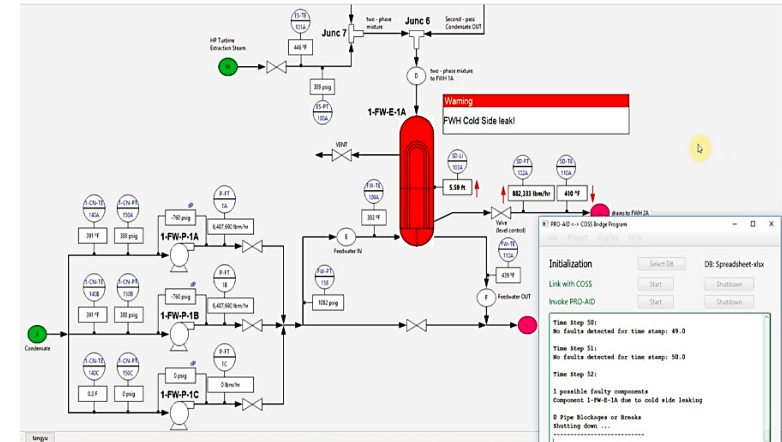
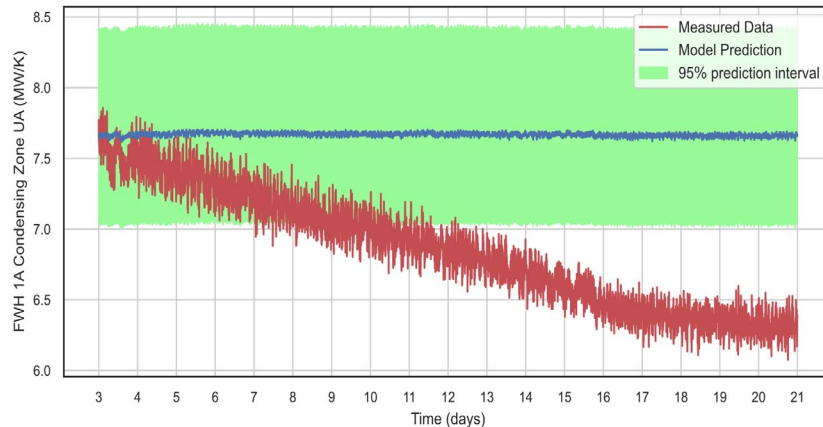
- Forward chaining procedure to diagnose component faults and sensors that are out of calibration or failed
- A generalized likelihood ratio test to include the effects of model/measurement uncertainties on diagnosis is incorporated



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

## PRO-AID (Parameter-Free Reasoning Operator for Automated, Identification and Diagnosis)

- Given the P&ID, a physics-based model of the system from a library of components is automatically assembled
- Differentiates between component and sensors faults
- Immune to plant operating point changes
- Rank orders likelihood of component faults by probability
- Auto reconfigures on dropped sensor

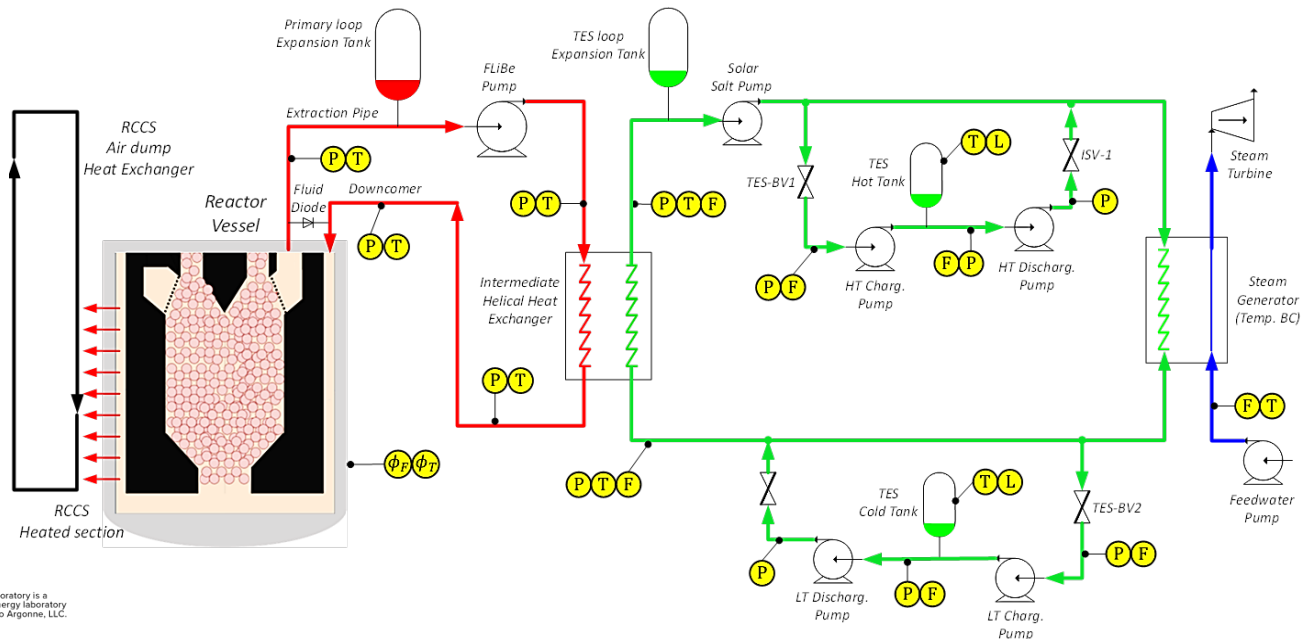




# APPLICATION OF PROPOSED ARCHITECTURE TO AN ADVANCED REACTOR DESIGN (1/2)

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

- The proposed architecture is currently tested on a pebble-bed fluoride salt-cooled, high temperature reactor (KP-FHR) coupled with a molten-salt thermal energy storage.



# APPLICATION OF PROPOSED ARCHITECTURE TO AN ADVANCED REACTOR DESIGN (2/2)

- Simulation of a power variation. Supervisory control layer intervenes to limit the set-point variation (“First RG intervention”).
- Tracking performance of PID controllers, constraint enforcement and Admissible Region evolution are displayed.
- Enforcement of time-dependent constraints (crucial capability when “Diagnostics” and “Decision-making” modules are coupled).

