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Supervisory Control of Multi-Modular Advanced Reactor Plants (AT-17OR230201)

DOE NE
Advanced Sensors and Instrumentation
Program Review Webinar
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Oak Ridge National Laboratory

Acknowledgement

Project participants (FY16)

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- **ANL (Subcontract)**
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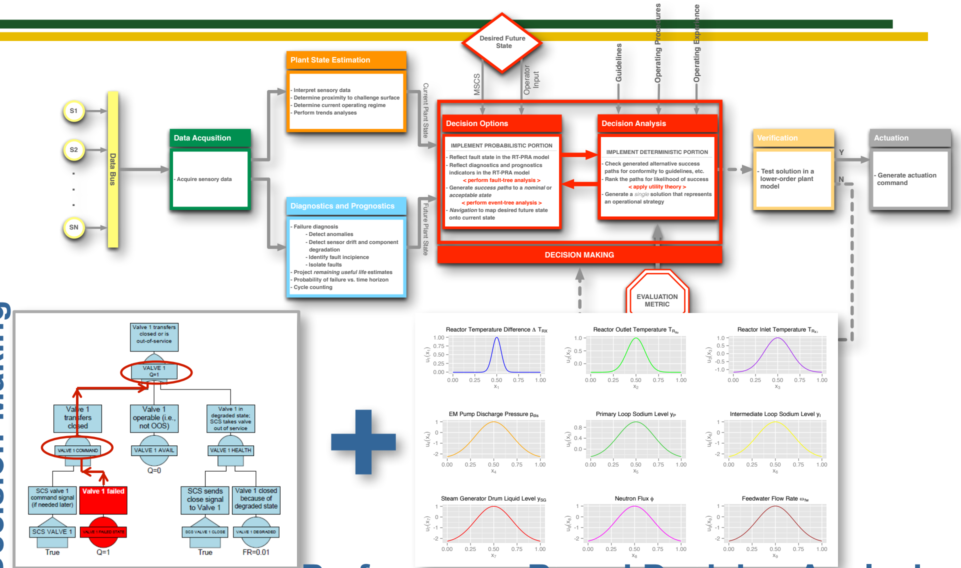
AT-17OR230201 — Supervisory Control of Multi-Modular Advanced Reactor Plants

Mission Relevance

- **Benefits of a supervisory control system (SCS)**
  - optimization of plant staffing
  - significant reduction in operations and maintenance (O&M) costs through integrated enhanced risk monitors (ERMs)
  - design and performance optimization through risk-informed operations framework
  - increase in plant availability, reliability, and safety

Probabilistic Decision-Making



Performance-Based Decision Analysis

Technical Approach, Accomplishments/Results

- **A control decision is made based on actual plant status in real time**
  - probabilistic models rank control options based on the health and operational status of components
  - system models evaluate performance implications of probabilistically identified control actions
  - integrated control decision re-ranks the probabilistically-identified control options using weighted utility functions
    - The utility functions are determined based on the trip set points and other constraints that define the operational space

Expected Deliverables & Schedule

- **Developed and demonstrated the *probabilistic* and *deterministic* parts of decision-making for ALMR PRISM (FY16)**
- **Incorporated PNNL's enhanced risk monitors (ERMs) module into the SCS framework (FY16)**
- **Demonstration of full supervisory control capabilities in an end-to-end ALMR PRISM plant (FY17)**
  - Level 2 Milestone due Nov. 30 (on target)

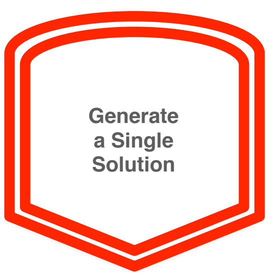
Presentation Outline

- **Background on Supervisory Control Project**
- **Work performed during FY16**
- **Summary and Conclusions**

The process of decision-making is to identify and choose among alternatives that will move from a degraded state to a desired state or condition

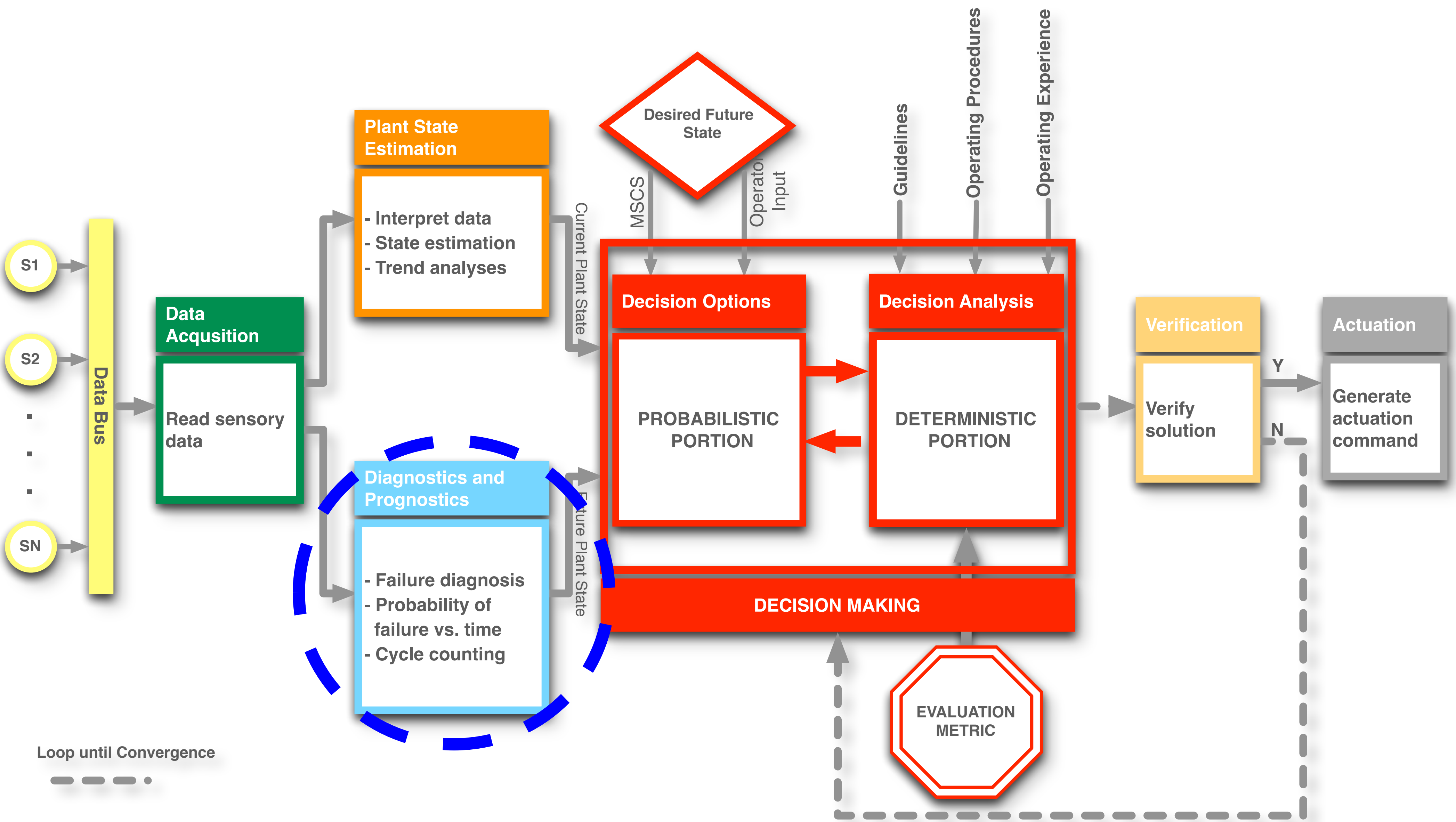
- **Probabilistically identify decision alternatives**
  - reflect the change of state in any component,
  - reconfigure the probabilistic models to reflect the change,
  - execute the probabilistic tools, and
  - identify and transmit the operational alternatives ranked by probability of successfully avoiding the actuation of a safety system setpoint

- **Deterministically evaluate alternative decisions using system models**
  - reflect the change of state in any component,
  - reconfigure the system models to reflect the change,
  - execute the probabilistically selected control options,
  - provide profiles of variables of interest that show selected metrics over time, rate of approaching a safety system setting, and how close the system is to the safety system setting



- **Generate a single solution**
  - identify the optimal control option based on utility theory analysis of the probabilistic/system analyses (i.e., makes a decision),
  - transmit an actuation signal to the component(s) of interest, and
  - inform the operator of action taken or requests permission to take action

SCS decision-making framework



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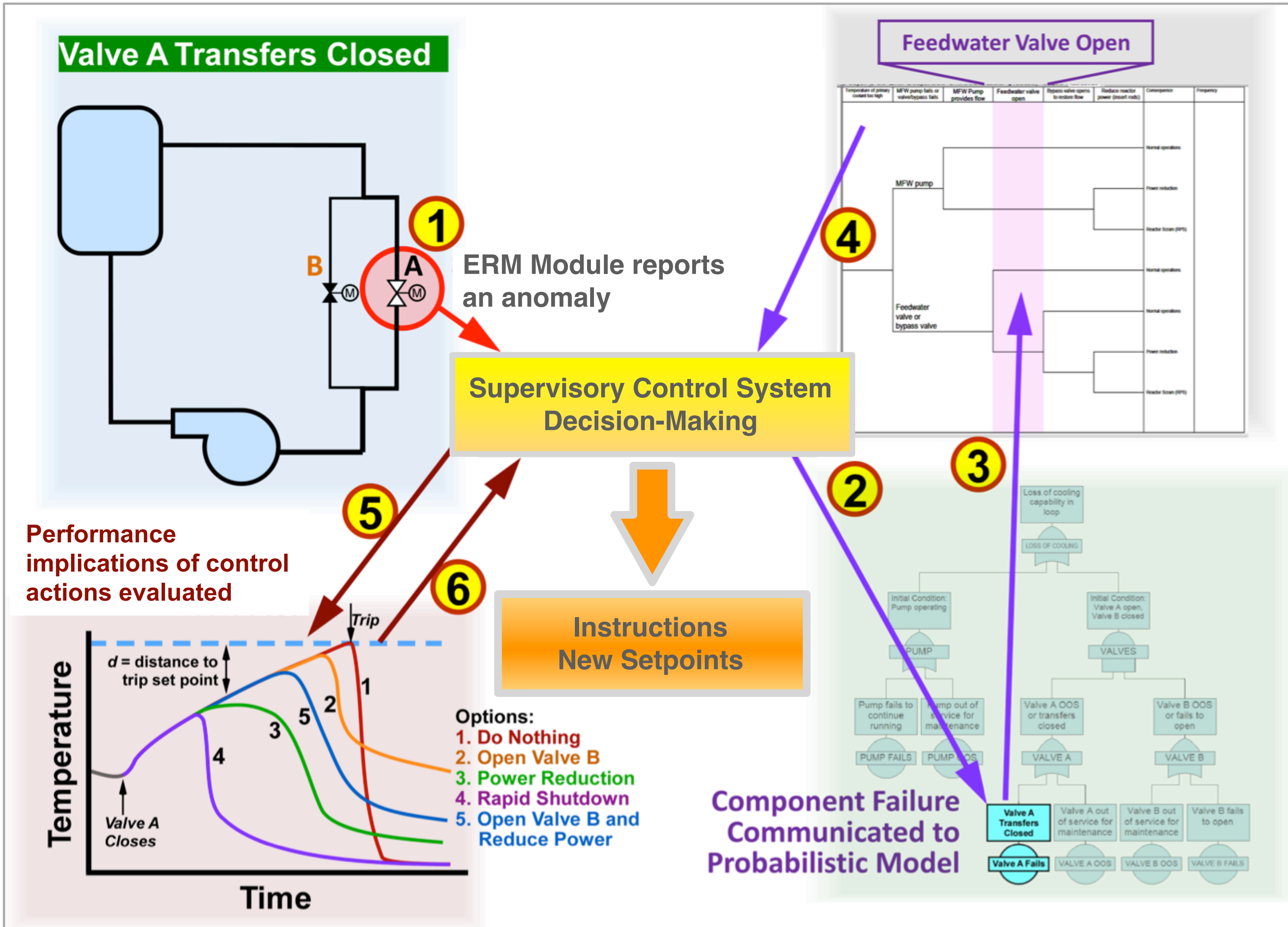
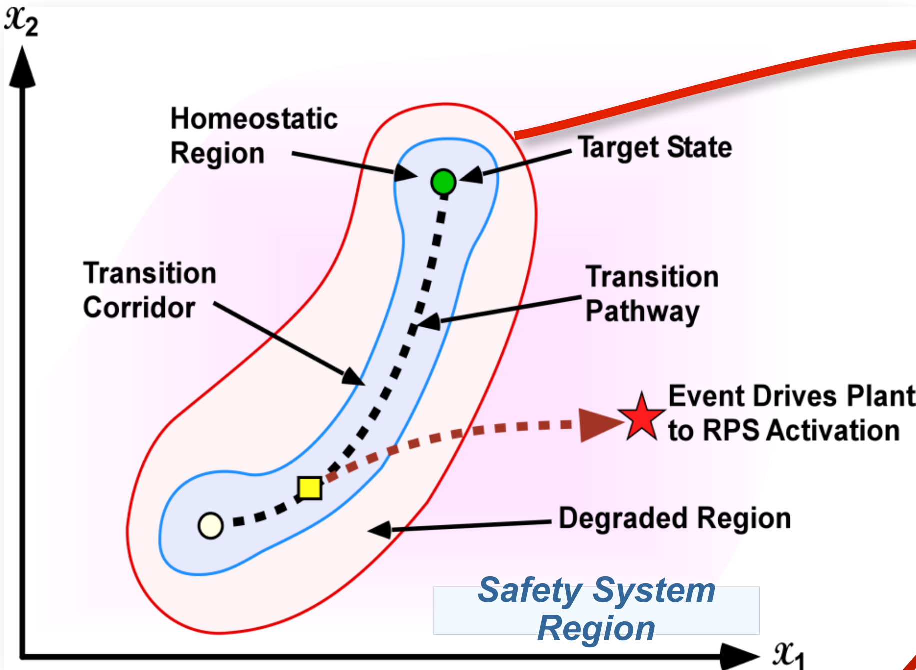
Embedded decision-making enables proactive operations rather than simply reactive control



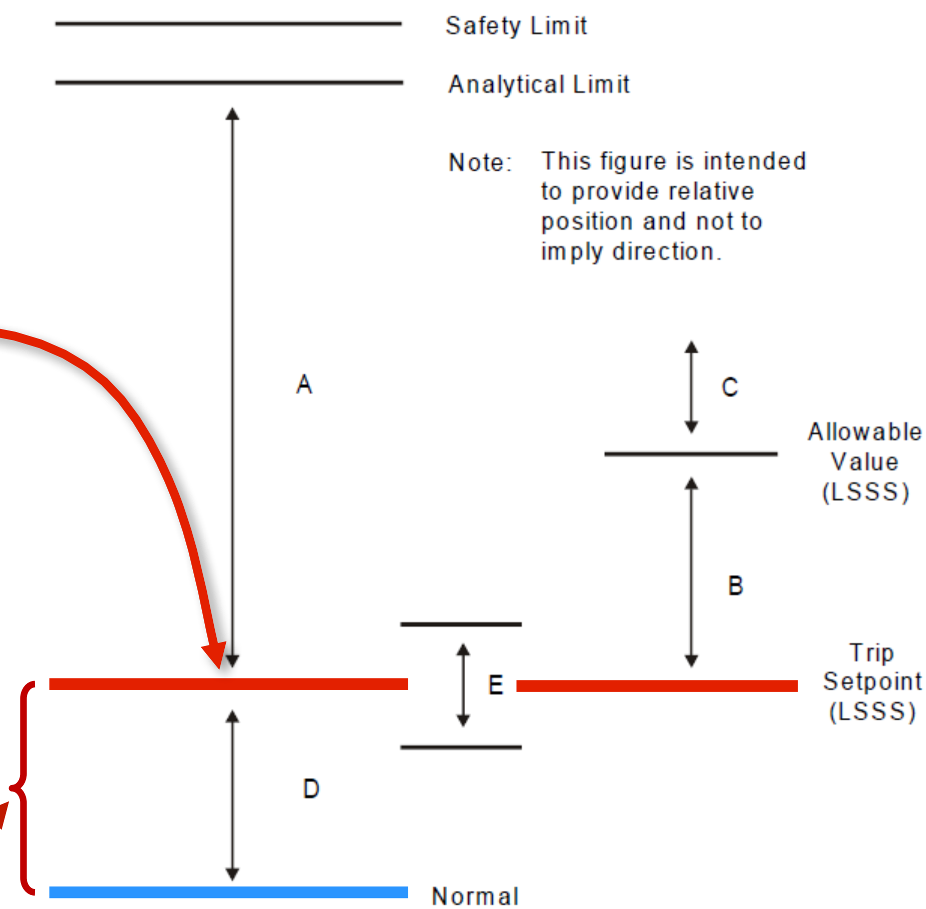
The metric of interest for the SCS is the *likelihood of avoiding an unplanned trip*

The SCS is
- **Implemented as a non-safety system**
- **completely independent of and isolated from the reactor protection system (RPS) (GDC 22, 24)**
- **functional domain is bounded by the safety system (e.g., RPS) trip setpoints**



State space spanned by two arbitrary state variables, x_1 and x_2

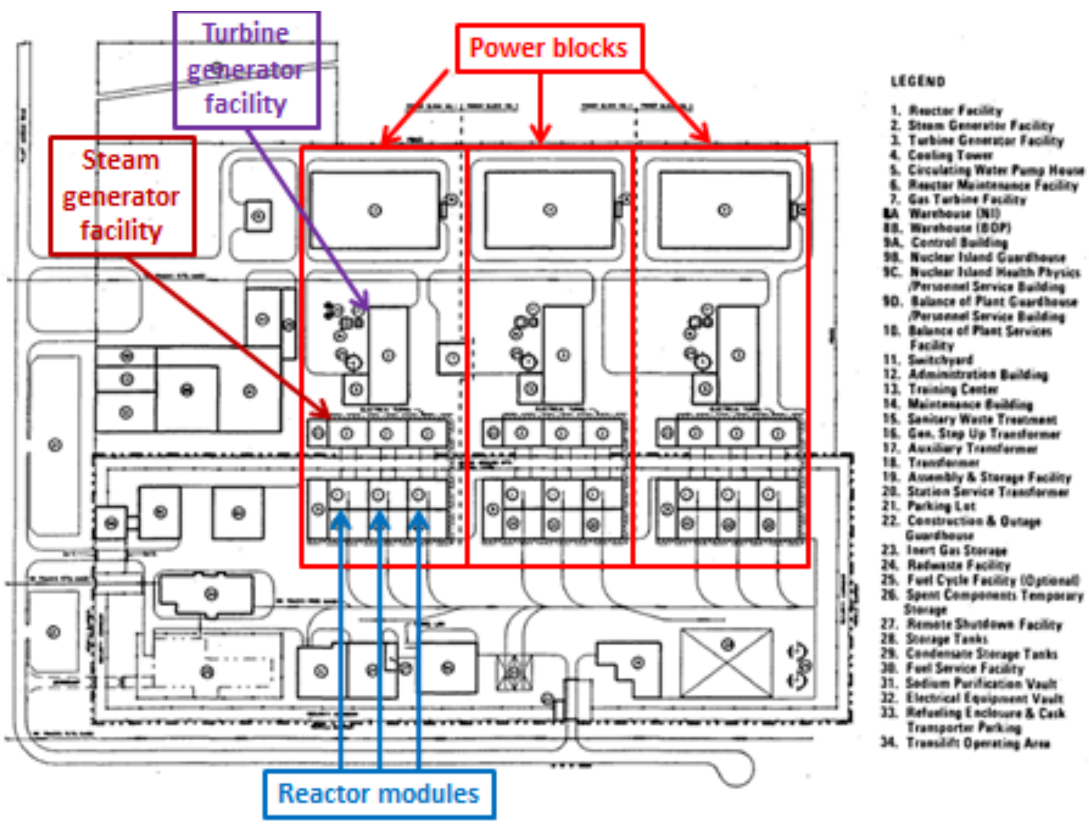
Operation anywhere within the homeostatic region is considered normal



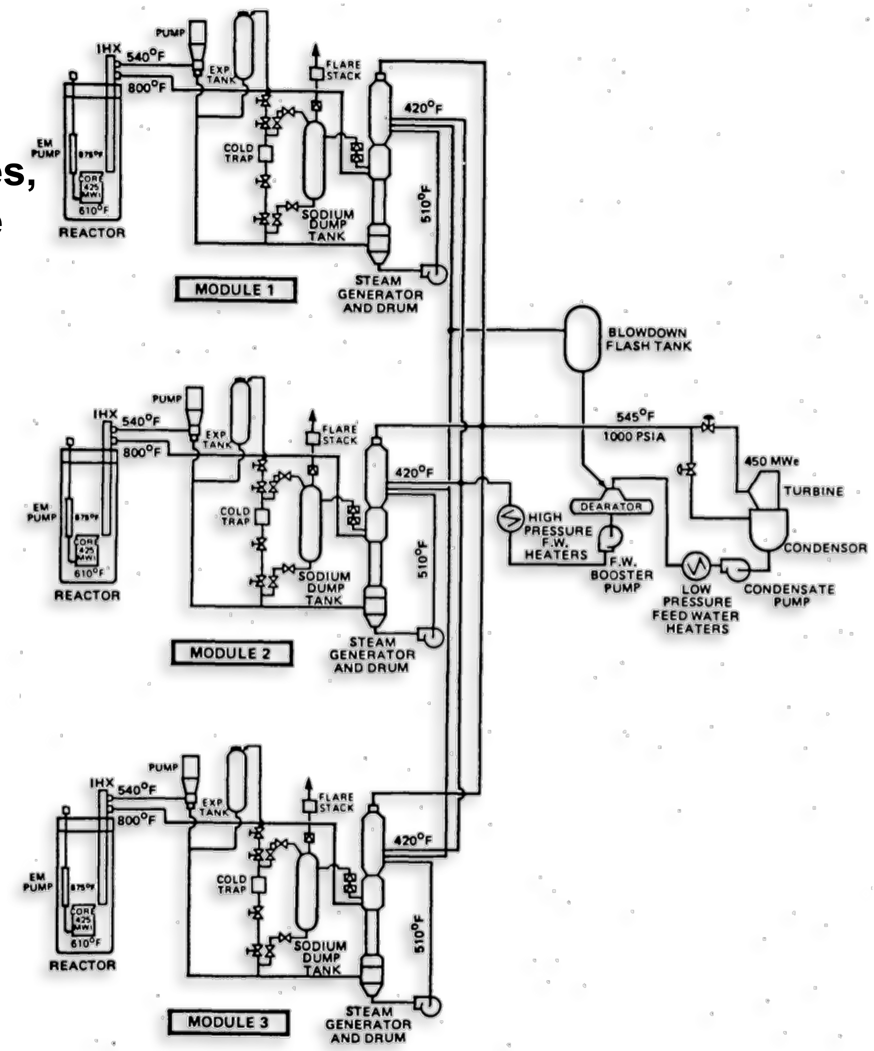
A. Allowance
B. Allowance
C. Region where channel may be determined inoperable
D. Plant operating margin
E. Region of calibration tolerance (acceptable as left condition)
(Source ISA-S67.04-1994)

Probabilistic and deterministic models capture the operational characteristics of the ALMR PRISM

- Reference: *PRISM Preliminary Safety Information Document*
- Nine reactor modules arranged in three identical power blocks
- Each power block features three identical reactor modules, each with its own SG that jointly supply power to a single turbine-generator

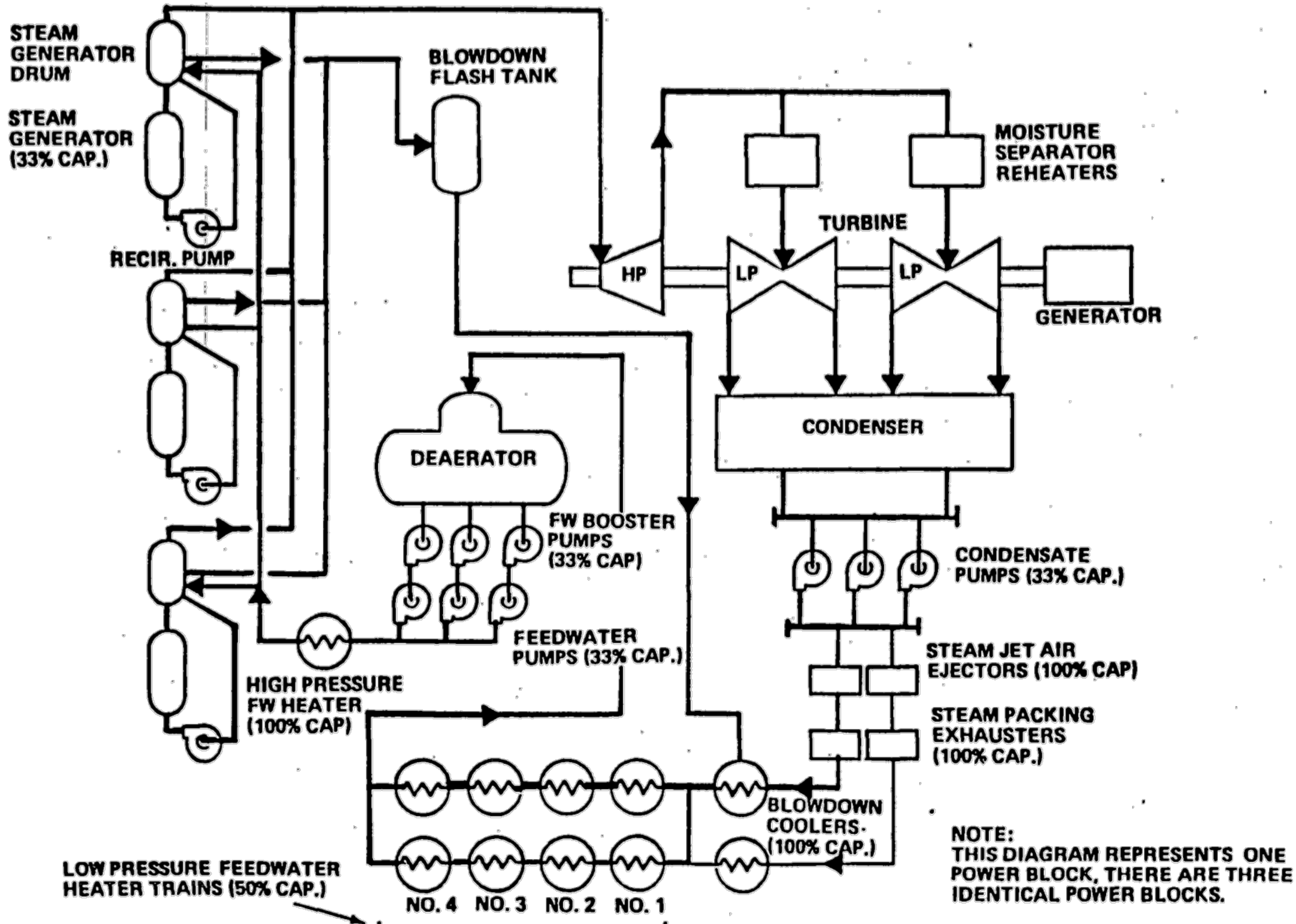


ALMR PRISM power plant



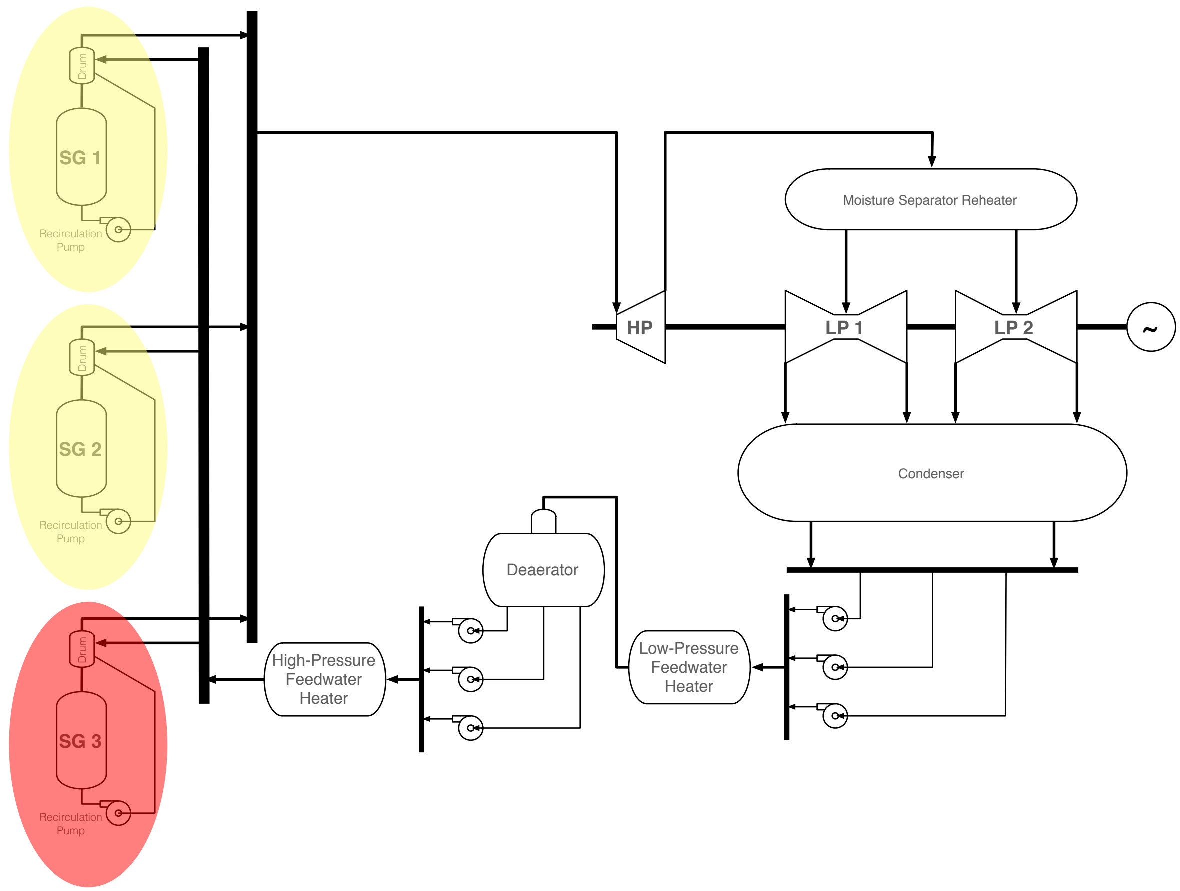
ALMR PRISM Power Block End-to-End System Configuration

ORNL started with the reference BOP design provided in the ALMR PRISM Preliminary Safety Information Document (PSID)

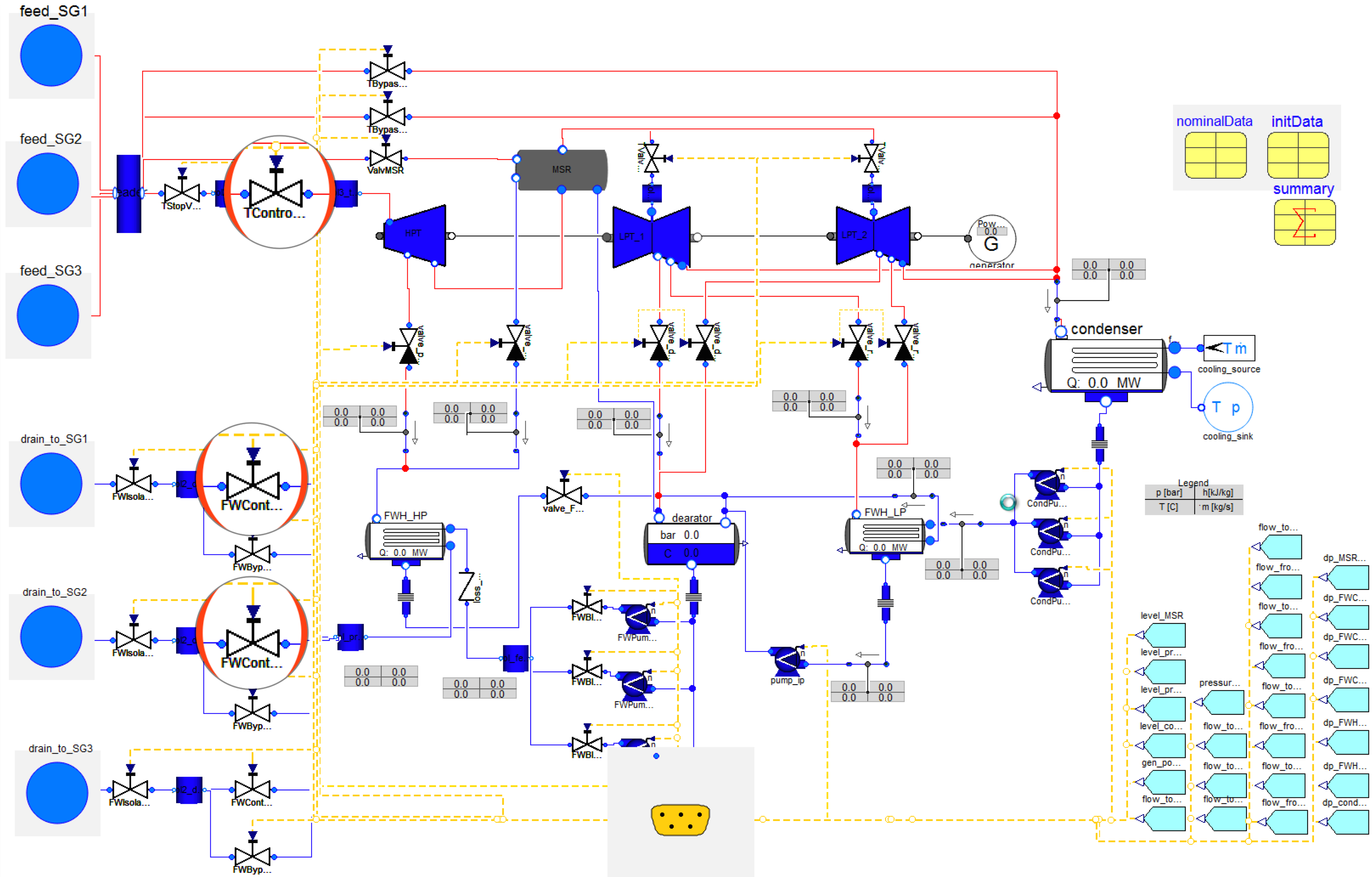


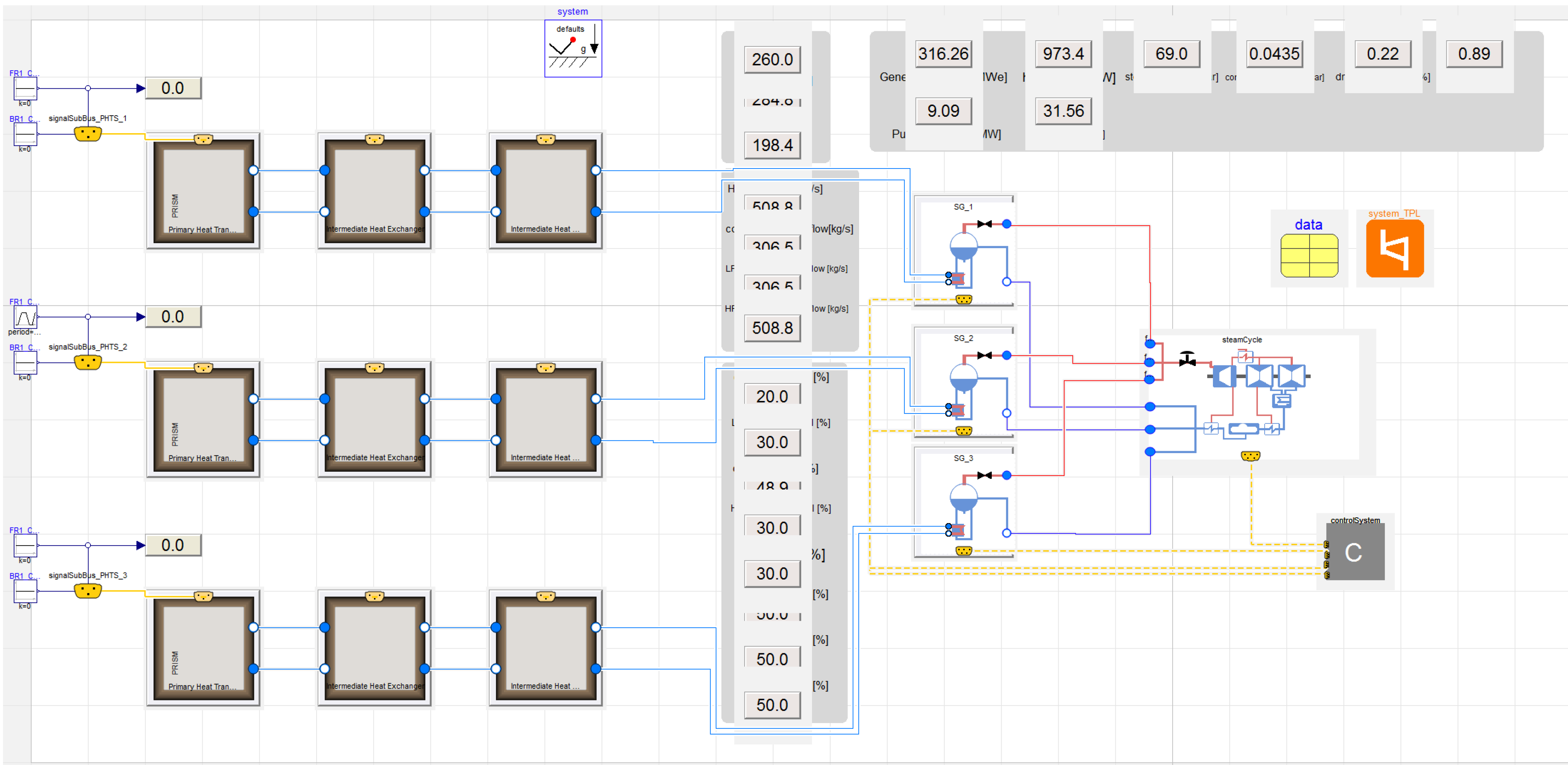
ALMR PRISM BOP system is simplified for SCS modeling

- **Three steam generators**
  - Only SG1 and SG2 participate in autonomous control;
    SG3 is a base-load generator
- **One high-pressure turbine (HPT)**
- **One low-pressure turbine (LPT)**
- **One moisture separator and reheater stage (between HPT and LPTs)**
- **Condenser**
- **One low-pressure feedwater heater (FWH)**
- **One high-pressure FWH**
- **One deaerator**
- **Pumps, valves**



Probabilistic and system models were constructed based on this flow layout


feed_SG1
feed_SG2
feed_SG3
drain_to_SG1
drain_to_SG2
drain_to_SG3
TBypas...
ValvMSR
MSR
TStopV...
TContro...
HPT
LPT_1
LPT_2
generator
condenser
Q: 0.0 MW
cooling_source
cooling_sink
nominalData
initData
summary
FWIsola...
FWCont...
FWByp...
FWH_HP
FWH_LP
dearator
valve_F...
FWBl...
FWPum...
pump_lp
CondPu...
Legend
p [bar]
h[kJ/kg]
T [C]
m [kg/s]
level_MSR
level_pr...
level_co...
gen_po...
flow_to...
flow_fro...
pressur...
dp_MSR...
dp_FWC...
dp_FWH...
dp_cond...


system
defaults
signalSubBus_PHTS_1
signalSubBus_PHTS_2
signalSubBus_PHTS_3
0.0
0.0
0.0
Primary Heat Tran...
Intermediate Heat Exchanger
Intermediate Heat ...
260.0
198.4
508.8
316.26
973.4
69.0
0.0435
0.22
0.89
9.09
31.56
20.0
30.0
30.0
30.0
50.0
50.0
SG_1
SG_2
SG_3
steamCycle
data
system_TPL
controlSystem
C

PNNL's Enhanced Risk Monitors (ERM) module was incorporated into the SCS Decision-Making Framework

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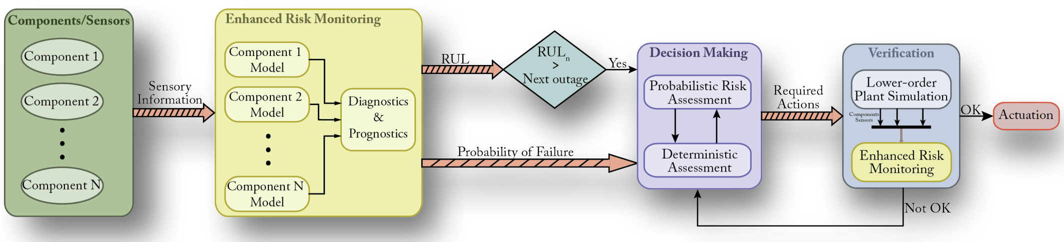
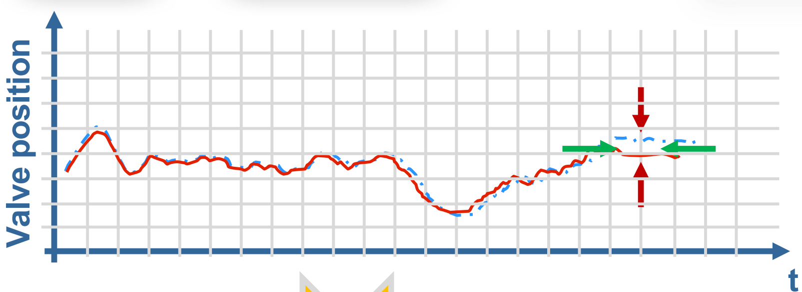
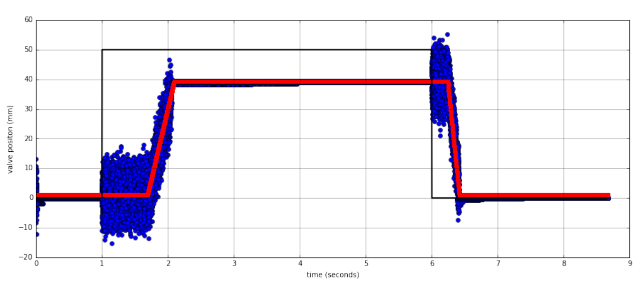
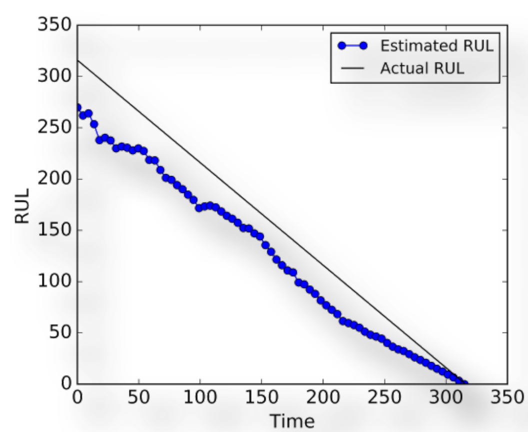
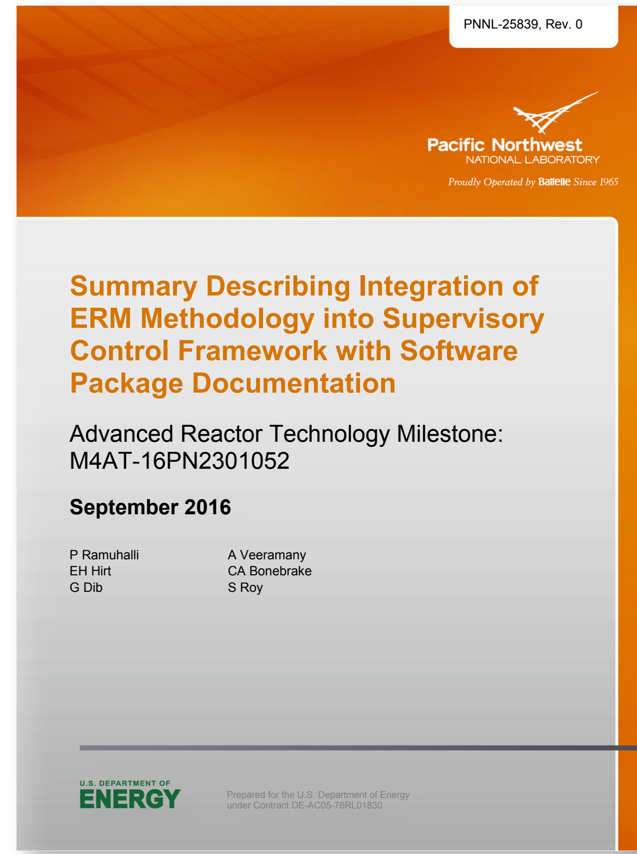
- Overview of ERMs
- ERM Framework
- Integration of ERM Module with Supervisory Control Framework



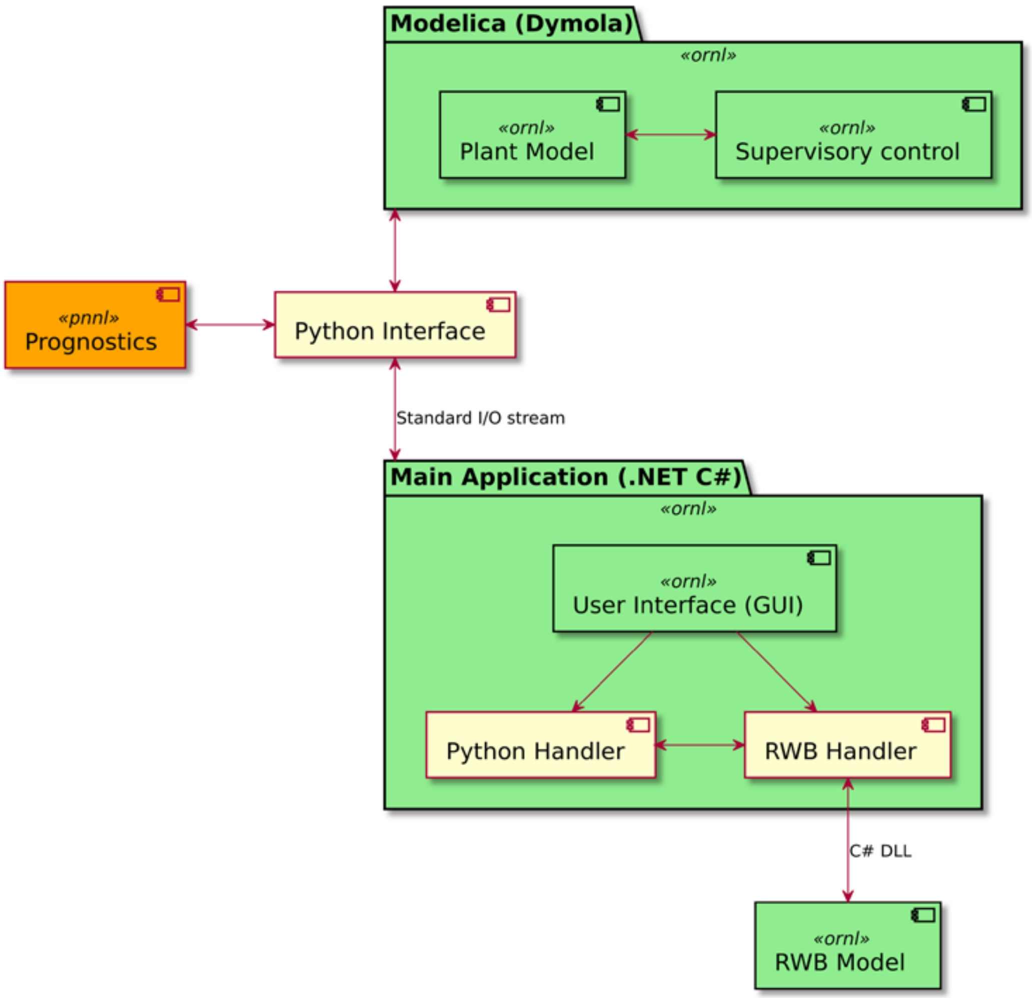








The ERM module is integrated into the SCS framework



Failure modes and reliability data for the BOP components were provided by ANL

- **BOP components failure modes and reliability data**
  - Turbines
  - Reheaters
  - Generator
  - Condenser
  - Pumps
  - Deaerator
  - Valves
    - *Air-operated valves (AOV)*
    - *Motor-operated valves (MOV)*
    - *Hydraulically operated valves (HOV)*
    - *Turbine bypass valve (TBV)*
    - *Main steam isolation valve (MSIV)*
    - *Check valve (CKV)*
    - *Manual valve (XVM)*

Argonne NATIONAL LABORATORY

PRISM Balance-of-Plant Analysis

Failure Modes and Reliability Data

Nuclear Engineering Division

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August, 2016

ORNL modeled three scenarios to demonstrate and validate the SCS

- Scenario 1: Turbine Control Valve (TCV) drifts in closed direction
- Scenario 2: SG #1 feedwater flow control valve (FCV) drifts in closed direction
- Scenario 3: SG #1 feedwater FCV drifts in open direction

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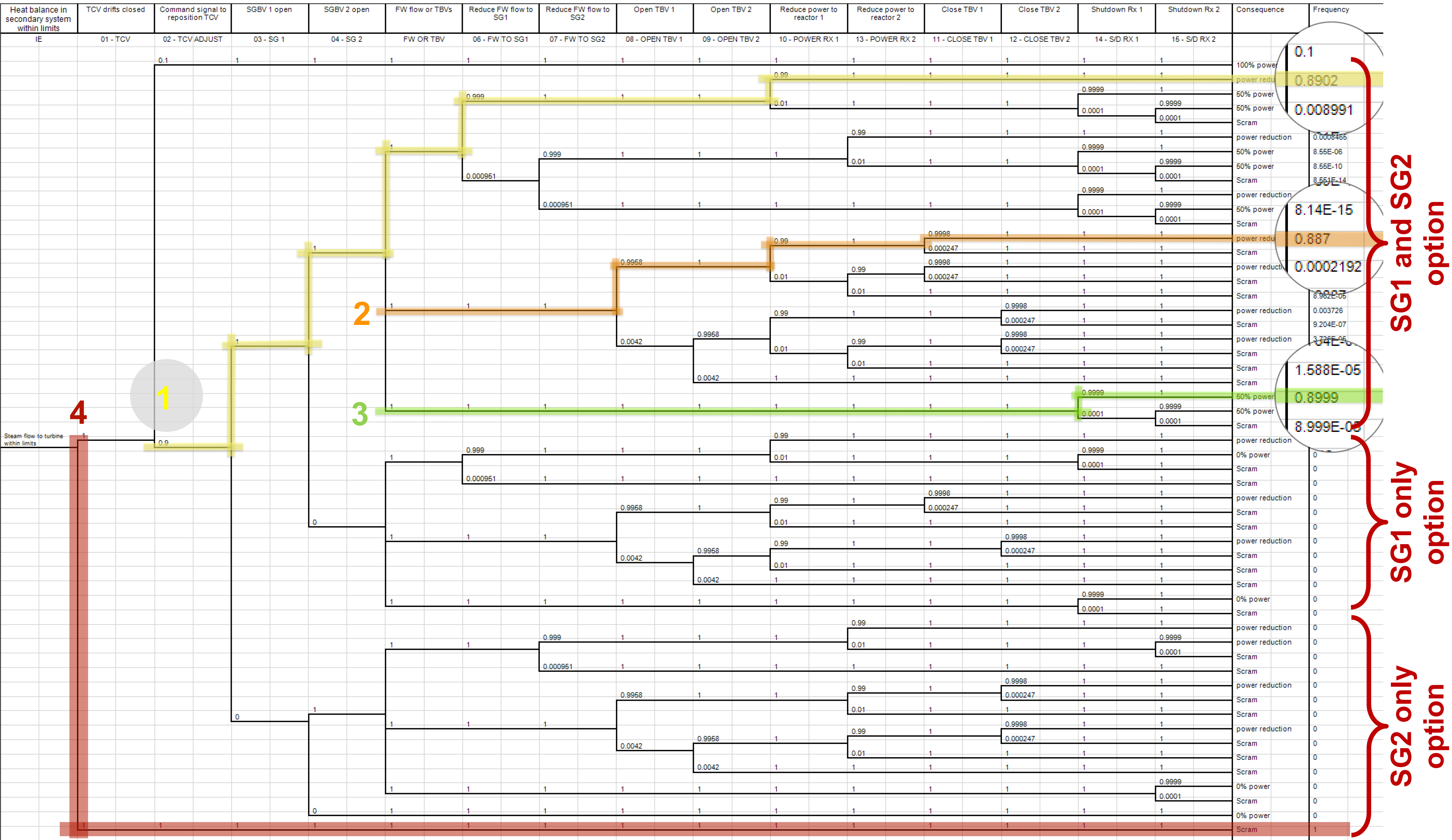
Reactor Module 1 and Reactor Module 2 in operation; *turbine control valve (TCV) drifts close*: four control options are identified probabilistically



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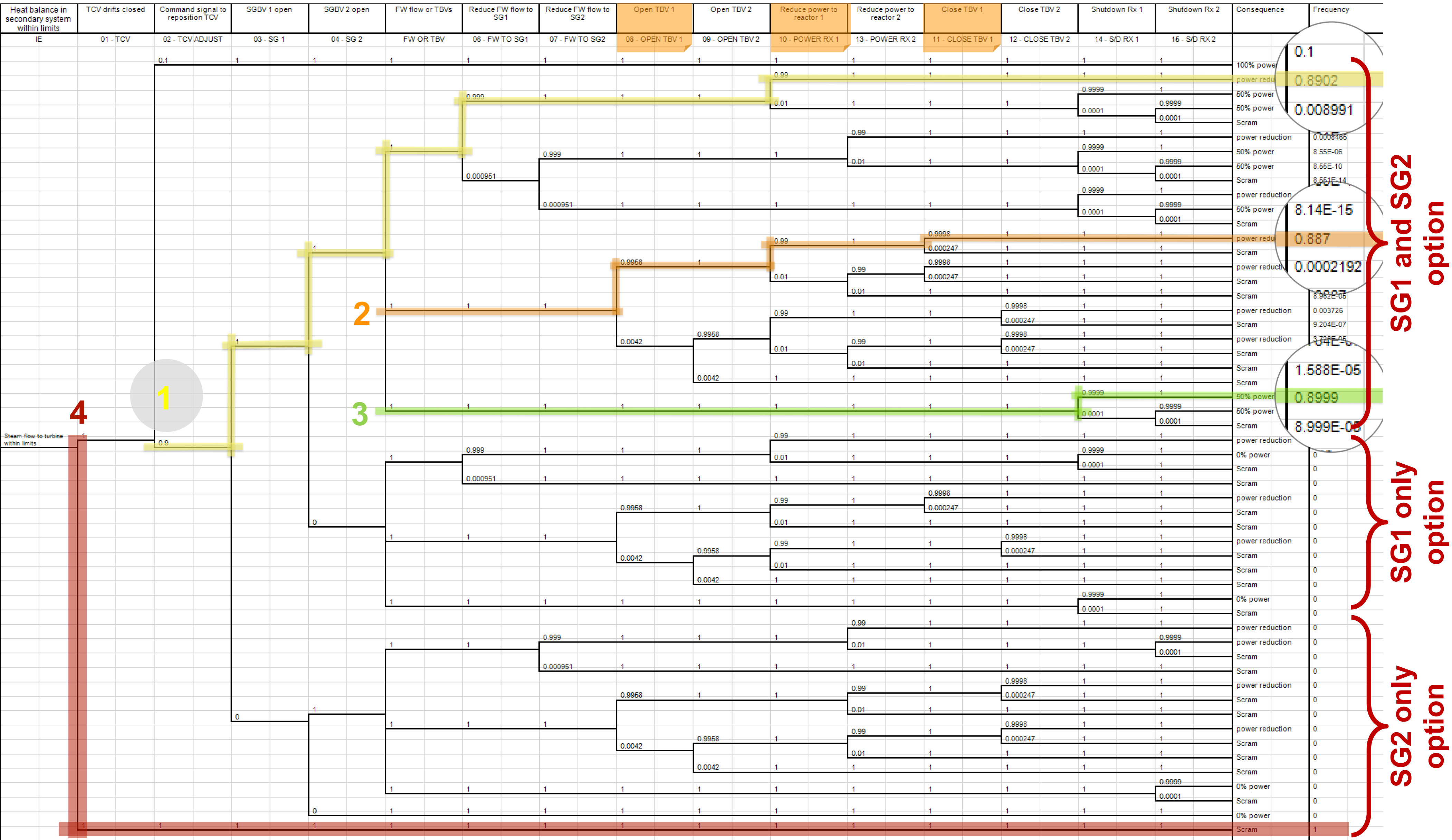
Reactor Module 1 and Reactor Module 2 in operation; *turbine control valve (TCV) drifts close*: four control options are identified probabilistically



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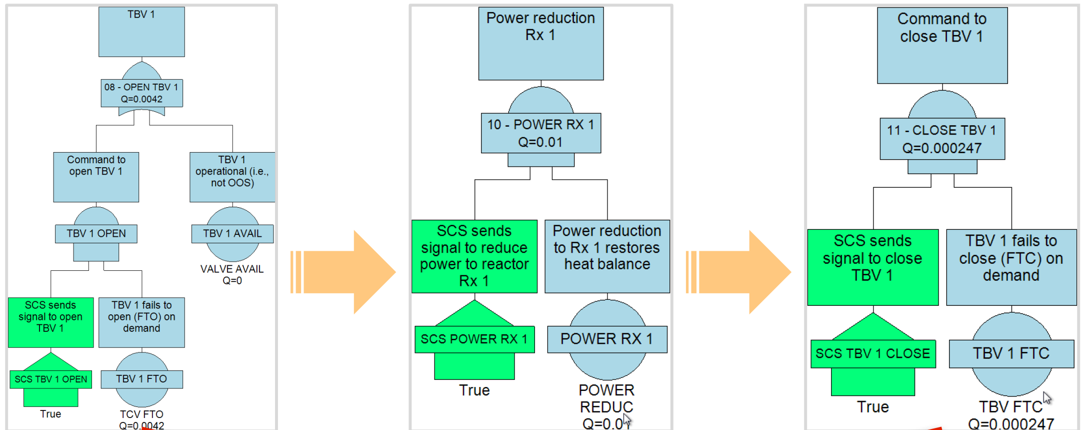
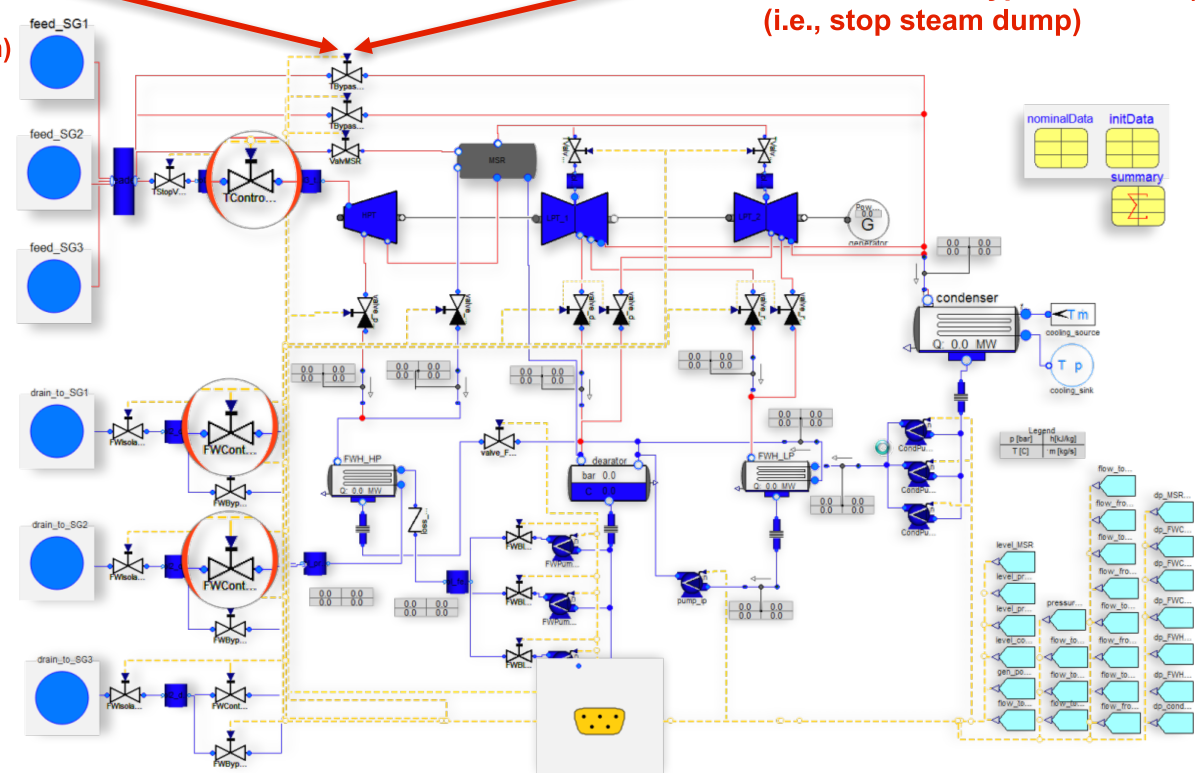
Based on the decision trajectory, SCS generates actuation instructions for lower level controllers

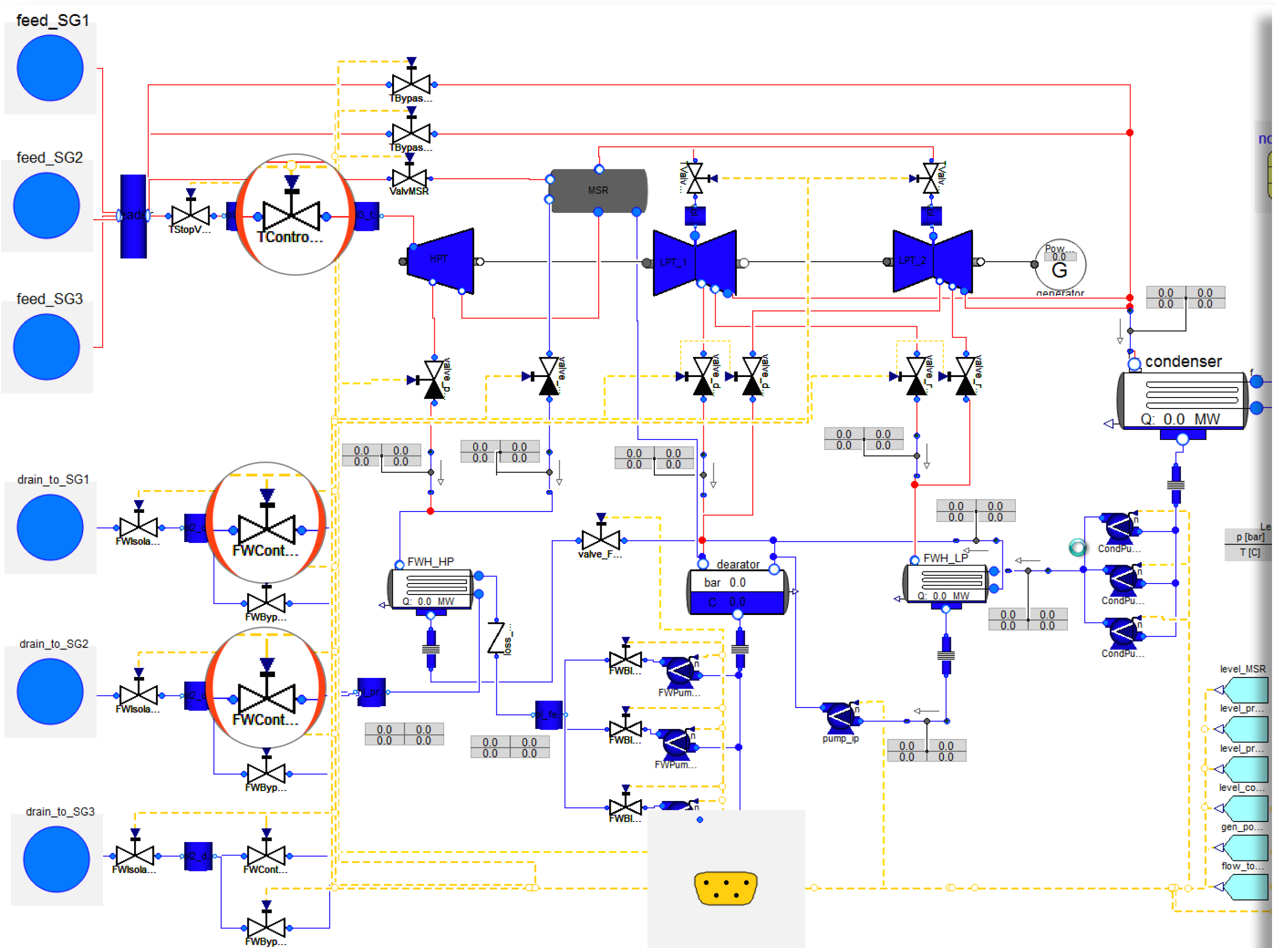


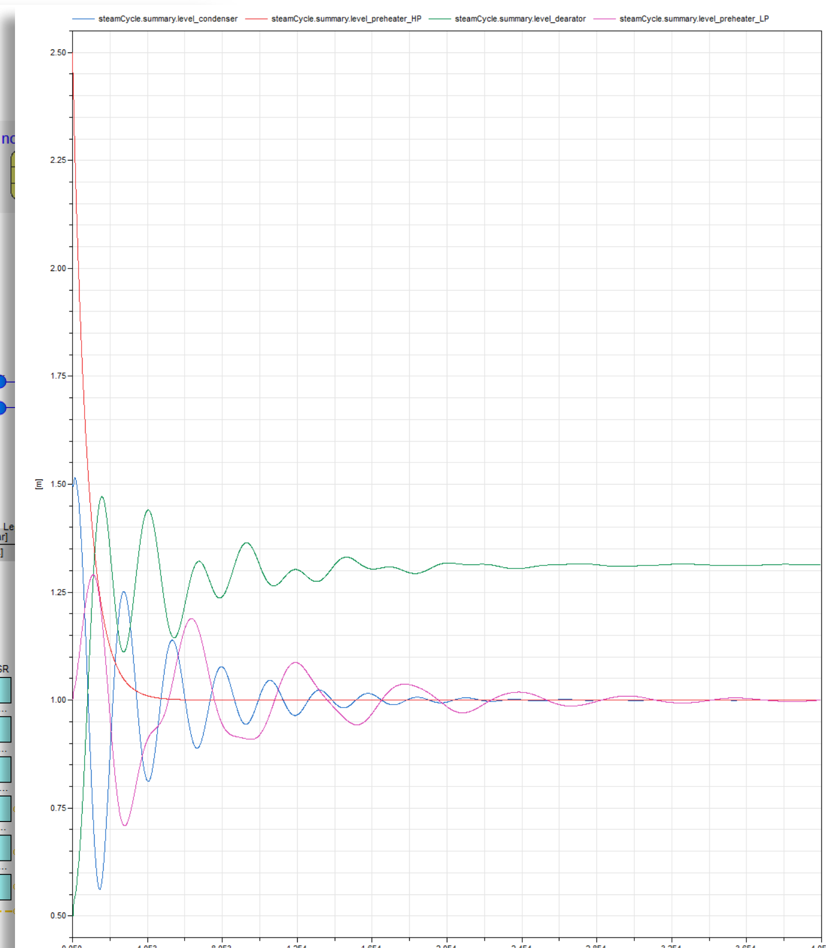
Open Turbine Bypass Valve 1 (TBV 1)
(i.e., partial steam dump into the condenser—accomplished via a new setpoint on the control system)

Close Turbine Bypass Valve 1 (TBV 1)
(i.e., stop steam dump)

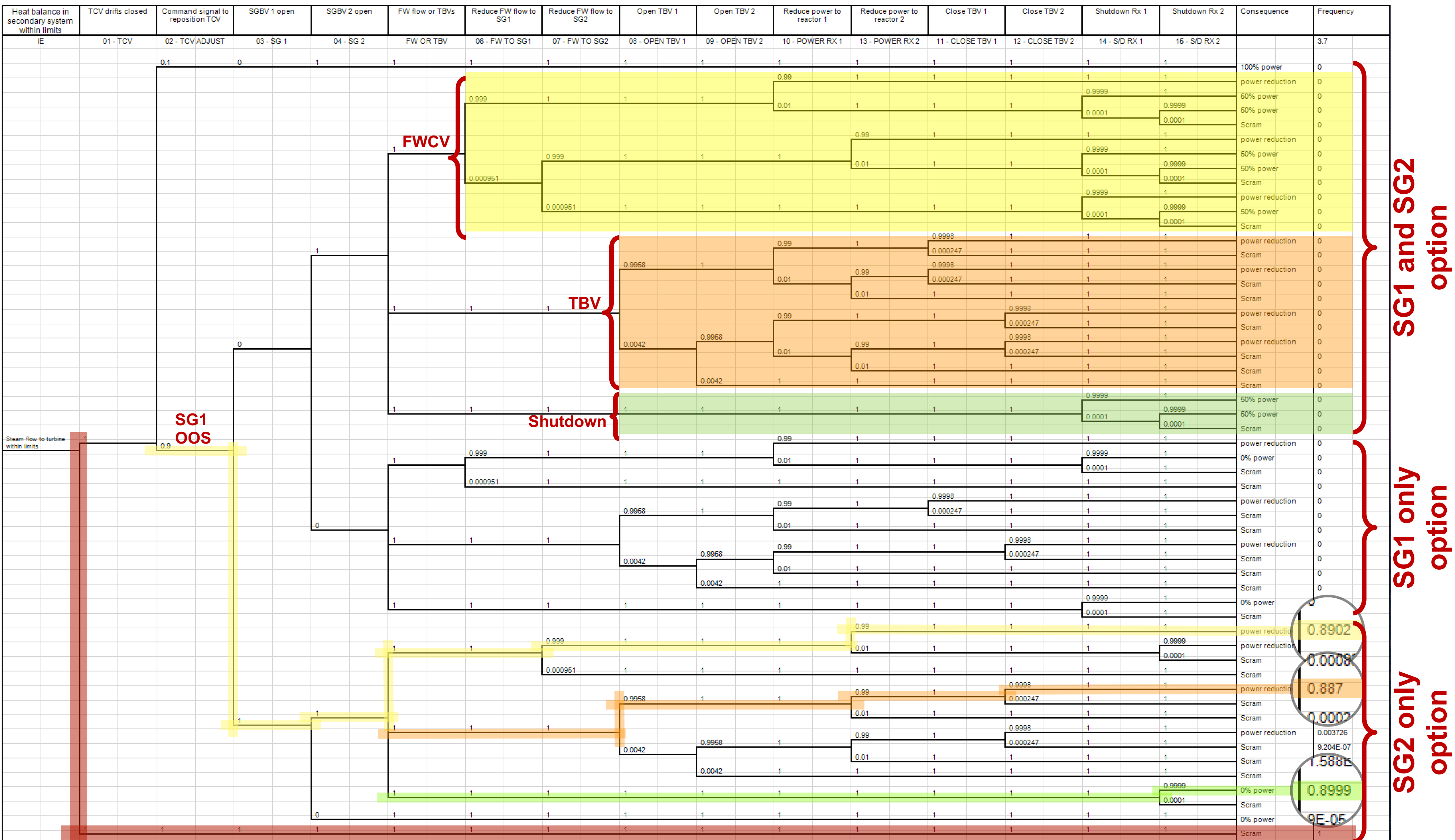


The BOP model matches the ALMR PRISM BOP technical specification at steady state—benchmarking needed for transient response





Based on the previous decision path “shutdown Rx 1”, the models are automatically updated to capture the actual system and component status



Monitoring component health via the ERM results in re-ranking of probabilistic options – Example: feedwater FCV degraded

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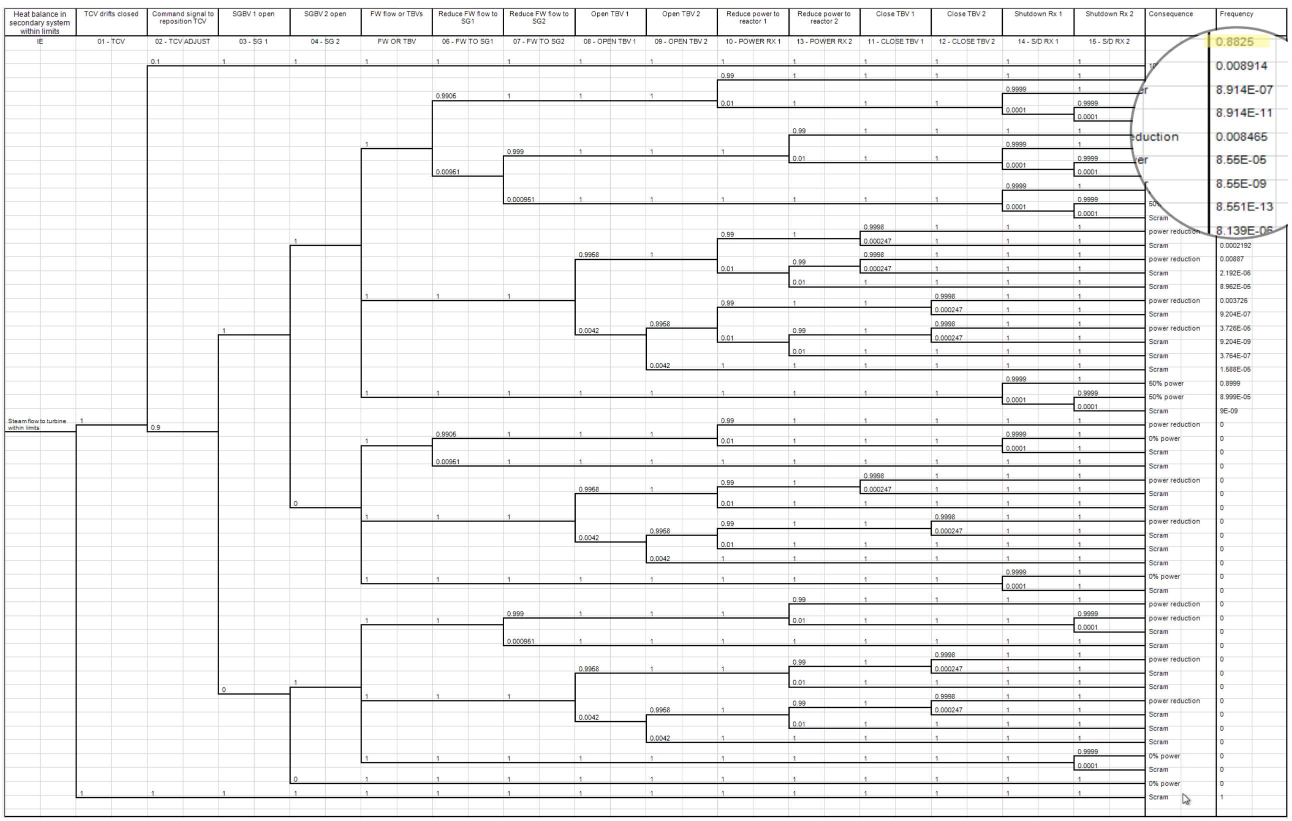
Before:

1. Do nothing
2. Controlled shutdown of Rx 1
3. Reduce FW flow—reduce power
4. Open TBV—reduce power—close TBV

Degraded FW FCV:

1. Do nothing
2. Controlled shutdown of Rx 1
3. Open TBV—reduce power—close TBV
4. Reduce FW flow—reduce power



Summary

- **ORNL developed a supervisory control (semi-autonomous control) concept that uses a multi-tiered decision-making approach**
- **The approach employs well-known tools for decision-making, and implements a novel way to integrate individual results into a single operational decision**
  - FT/ET for probabilistic models
- **ALMR PRISM concept was selected as the demonstration platform**
- **Probabilistic and systems models were created for ALMR PRISM BOP**
  - The ERM monitors component health, and via the SCS, updates the probabilistic models
  - Probabilistic models successfully identify and rank available control actions
  - The system model matches the probabilistic model, recognizes and simulates the SCS instructions
  - The integrated model makes a decision
- **Decision-making capabilities were demonstrated for a number of operational scenarios**
  - Level 2 Milestone due Nov. 30 (on target)

Technology Impact

- **SCS can help reduce control room staffing size**
  - an autonomous control capability can reduce demand on human resources
  - the proposed operator staffing for the ALMR PRISM design is a minimum of eight licensed operators for nine reactor modules
  - Under current regulatory requirements, this same nine reactor module facility would require at least 24–30 operators
- **Increase plant availability by scheduling maintenance outages**
  - The SCS accounts for all combinations of equipment conditions, such as out-of-service for maintenance, failed state, or degraded state to accurately reflect system/component status and operating conditions
  - There are three basic approaches taken to plant maintenance:
    - *Reactive – failure based (i.e., repair or replace components after they have failed)*
    - *Preventive – interval based (i.e., use failure data to establish a maintenance interval)*
    - *Predictive – condition based (i.e., track remaining useful lifetime(RUL) of components)*
- **Minimize plant transients; increase plant safety**
  - probabilistic techniques are used to determine those control actions that have the greatest likelihood of avoiding a trip setpoint based on actual plant status and component health
- **Higher operational performance**
  - expanding the scope of PRAs to the nuclear I&C system will lead to architectures that deliver higher operational performance, similar to how PRAs helped in the design of NPPs

Questions?