Investigation of Cycling Coal-Fired Power Plants Using High-Fidelity Models

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This material is based upon work supported by the Department of Energy under Award Number DE-FE0031822.

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Background

Changing market

- Increased competition with lower cost generation
- Renewables: increased penetration & intermittent generation

Resulting in increased cyclic plant mission

- Load following (with higher ramp rate)

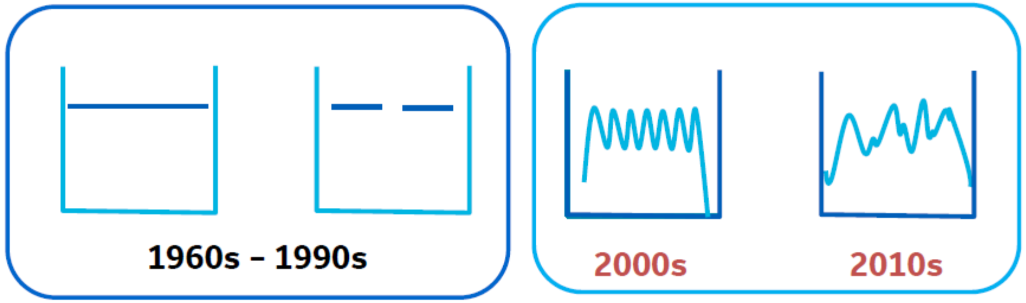
Impact on flexibility

- A higher ramp rate allows a power plant operator to adjust net power more rapidly to meet changes in power demand.

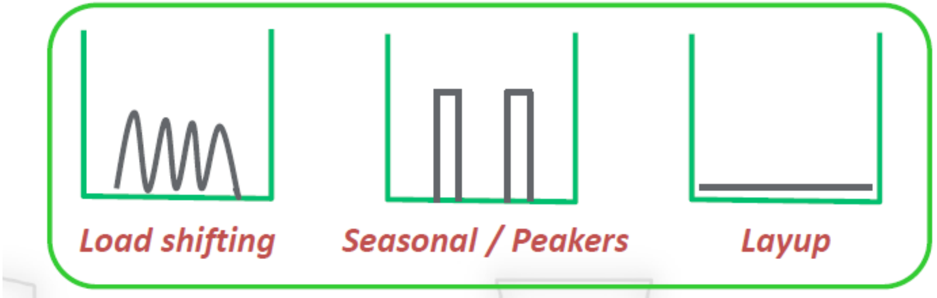
Disadvantages of higher ramp rate

- A rapid change in firing temperature results in thermal stress for plant components

How plants were running when commissioned



How plants are running today



*Dramatic shift in Coal Plant Missions over last decade from traditional base load to **daily loading shifting**, seasonal operation and on/off cycling for peaking duty*

Project Description and Objectives

NATIONAL ENERGY TECHNOLOGY LABORATORY

Program Team

GE Research

Coal Fired Power Plant Modeling and Model Calibration, Model Integration and Optimization, Model-Based Analysis

GE Steam Power

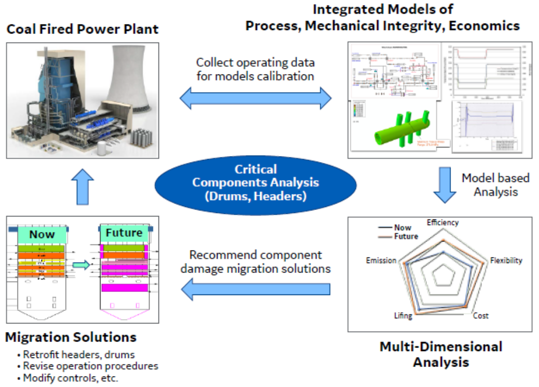
Coal-Fired Power Plant Design, Manufacturing and Building, Commissioning, Operation Optimization; Coal-Fired Power Plant Modeling and Simulation Analysis

Relevant Prior Work

- Coal power plant transient models
- Steady state thermal performance calculations
- Component mechanical integrity models
- GE's Efficiency Optimizer and Flexibility Suite

1.5 Year, $ 0.9MM Program to Develop New Methods for Calibration and Integration of High-Fidelity Models and Model-Based Analysis of Critical Components in Coal-Fired Power Plants Impacted by Cycling Operations

Project Objectives: Deliver critical components analysis results with insight into existing coal plant challenges impacted by cycling operations and recommend mitigation solutions



Technical Approach

- Integrate multiple models of process, mechanical integrity and economics into high-fidelity dynamic simulation platform
- Multi-dimensional analysis of flexibility, efficiency, emission compliance, component damages and financial impacts

Technical Challenges

- Cohesive integration of multiple types of models
- Lack of measurement for accurate model calibrations in wide range operating conditions

Program Deliverables

- Integrated high-fidelity simulation platform for investigation of cycling coal power plant
- Analytical results on coal power plant challenges impacted by cycling operations
- Recommendations on how to cycle coal power plant safely and cost-effectively and potential component damage migration solutions

Anticipated Benefits of the Proposed Technology

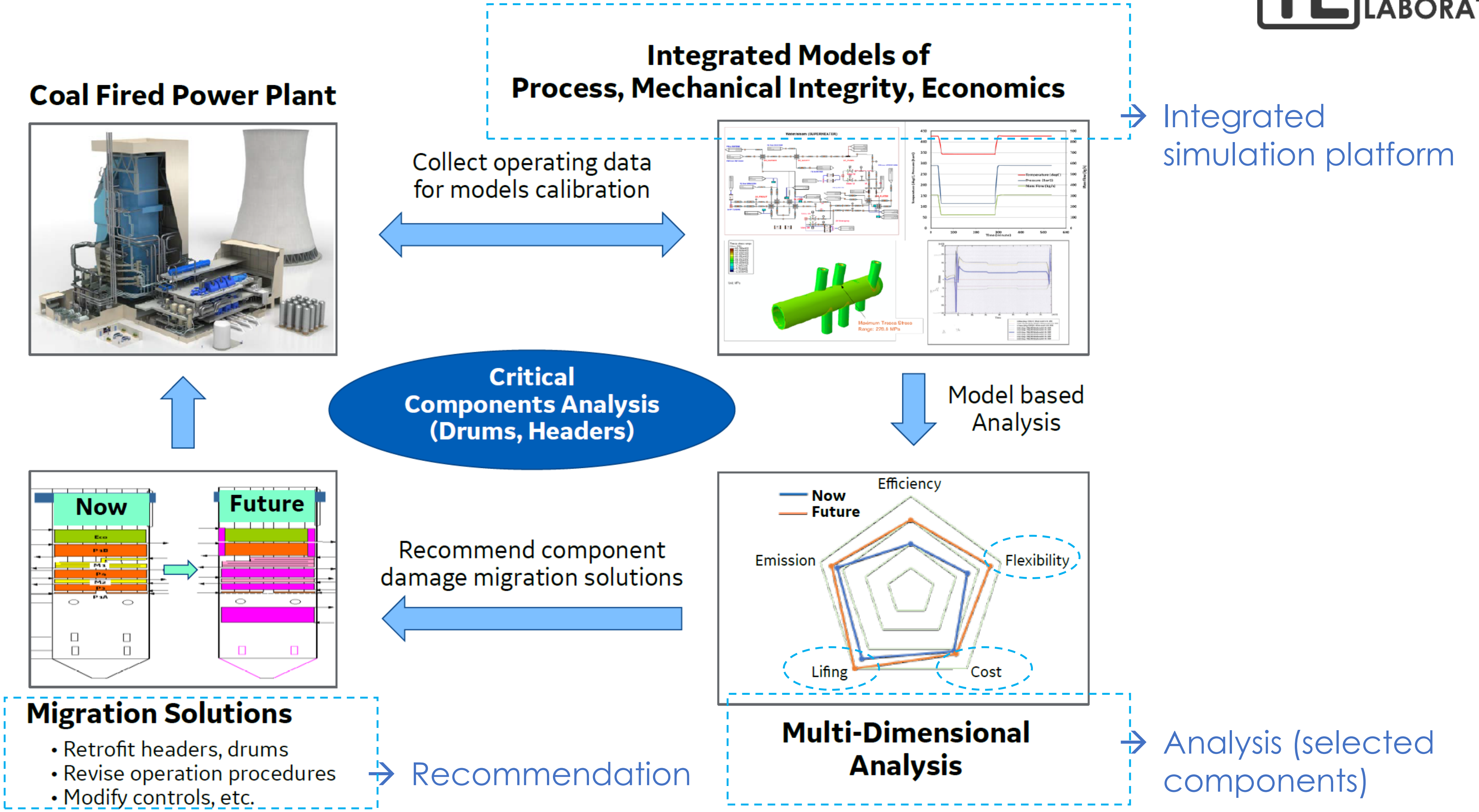
- Generate practical and cost-effective solutions to cycle coal power plants to reduce plant failures (60%~80% caused by cycling operations) and extend plant lifing

	2019 Q4	2020 Q1	2020 Q2	2020 Q3	2020 Q4	2021 Q1
Task 1 Project Management and Planning *Deliverable: Updated Project Management Plan* *Deliverable: Final Project Report*						
Task 2 Define Specification for Critical Component Analysis *Deliverable: Report on requirements for critical component analysis of existing coal plant challenges and mitigation solutions with focus on steam cycle impacted by cycling operations*						
Task 3 Reconfigure and Integrate Models for High-Fidelity Simulation Environment 3.1 Reconfigure process dynamic models 3.2 Reconfigure mechanical integrity models 3.3 Develop economic models to evaluate financial impacts of cycling challenges and mitigation solutions 3.4 Integrate multiple types of models into one simulation platform *Deliverable: Report on the multiple model integration methodology and integrated simulation environment description* *Milestone: An integrated simulation platform for critical components analysis*						
Task 4 Collect and Process Reference Plant Operating Data *Deliverables: Report on operating datasets that represent a) cycling operations from reference unit; b) steady states at both low and high load conditions; c) typical faulted operating scenarios*						
Task 5 Calibrate and Validate the Integrated Models using Operating Data *Deliverable: Report on the automated data processing and model calibration tool and descriptions of the calibrated and integrated models* *Milestone: A well calibrated and integrated models for reference coal power plant*						
Task 6 Investigate Cycling Operations based on Integrated Models *Deliverable: Report on analytical results of cycling simulations of the reference coal power plant and recommendations for migration solutions* *Milestone: Report critical components analysis results using the reference coal power plant model*						

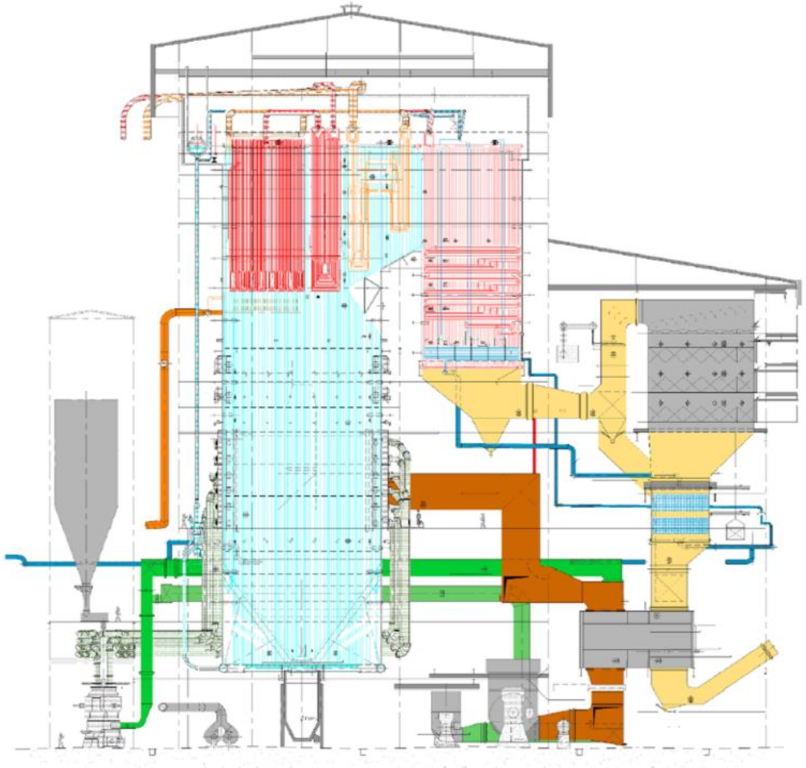
Legend: ▽ Deliverable ◆ Milestone

→ Integrated simulation platform
→ Analysis (selected components)
→ Recommendation

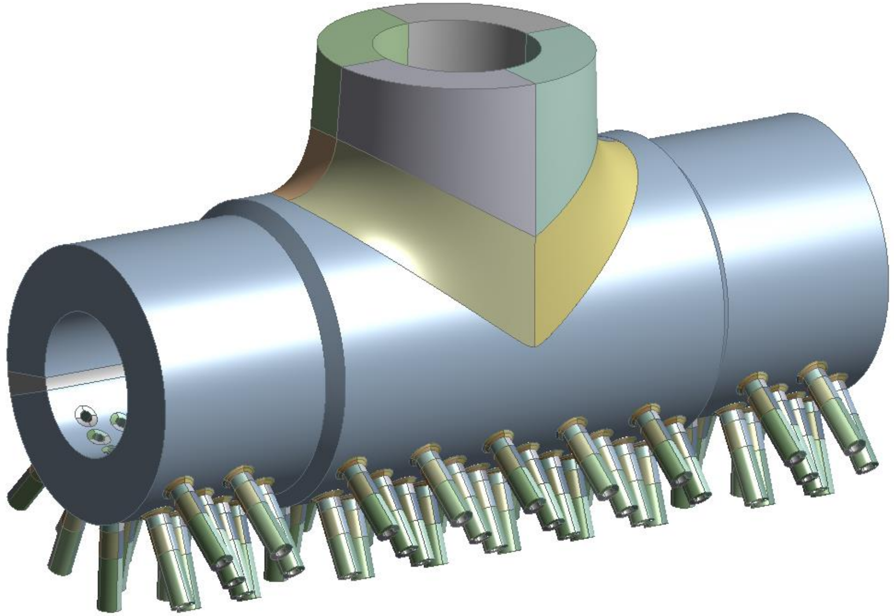
Technology Overview



Plant Information



A 750MW subcritical coal fired power plant was selected for this analysis.



Selected Critical Components

- Super Heater Outlet Header
- Dissimilar Metal Welds in Super Heater Section

Process Dynamic Modeling

- **APROS*** software package used for modeling
- Graphical (schematic) configuration of the plant model through predefined process component models.
- Process **component properties** were configured through definition of properties; both material and thermodynamic.
- **Data** for steam and gas conditions came from "in-house" Reheat Boiler Program Code (based on internal standards and ASME Steam Tables).
- **Calibration**: A mixture of manual adjustment and automated tuning
- **Limits:** Focused on boiler. Simplified firing system through the economizer outlet. Turbine, air-preheater, and ECS equipment omitted.

** Apros is a high-fidelity dynamic simulation product for integrated thermal power plant process and automation design and engineering, and for creating highly realistic plant-specific operator training simulators. It includes complete model libraries to build plant-specific dynamic models of thermal power plants for high-fidelity engineering and training simulation needs.*

Process Dynamic Modeling

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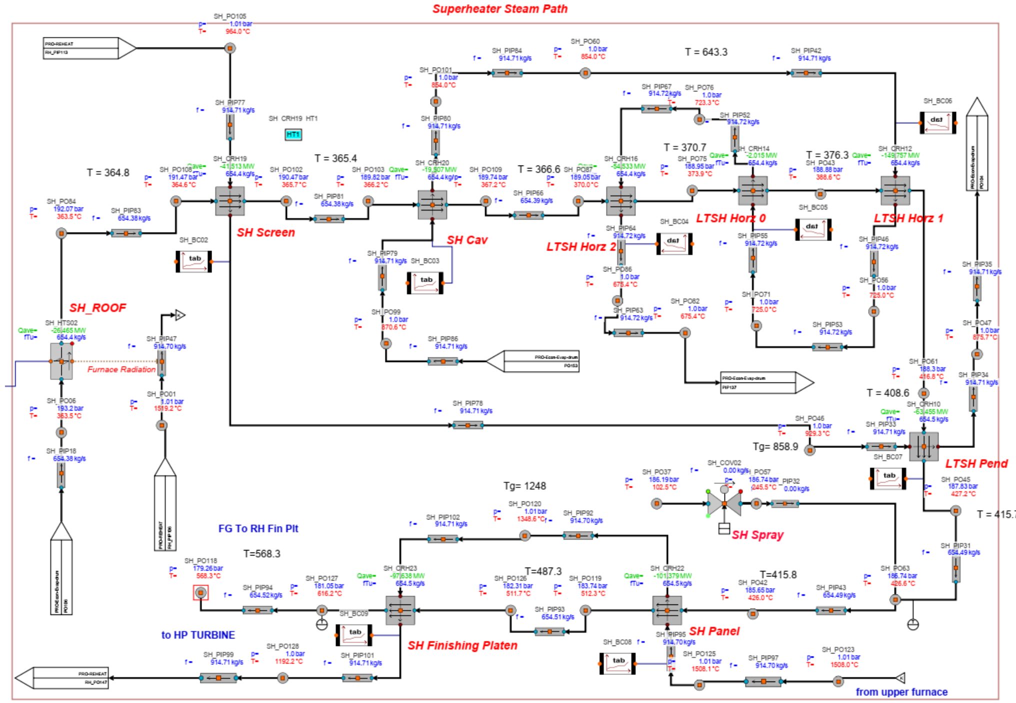
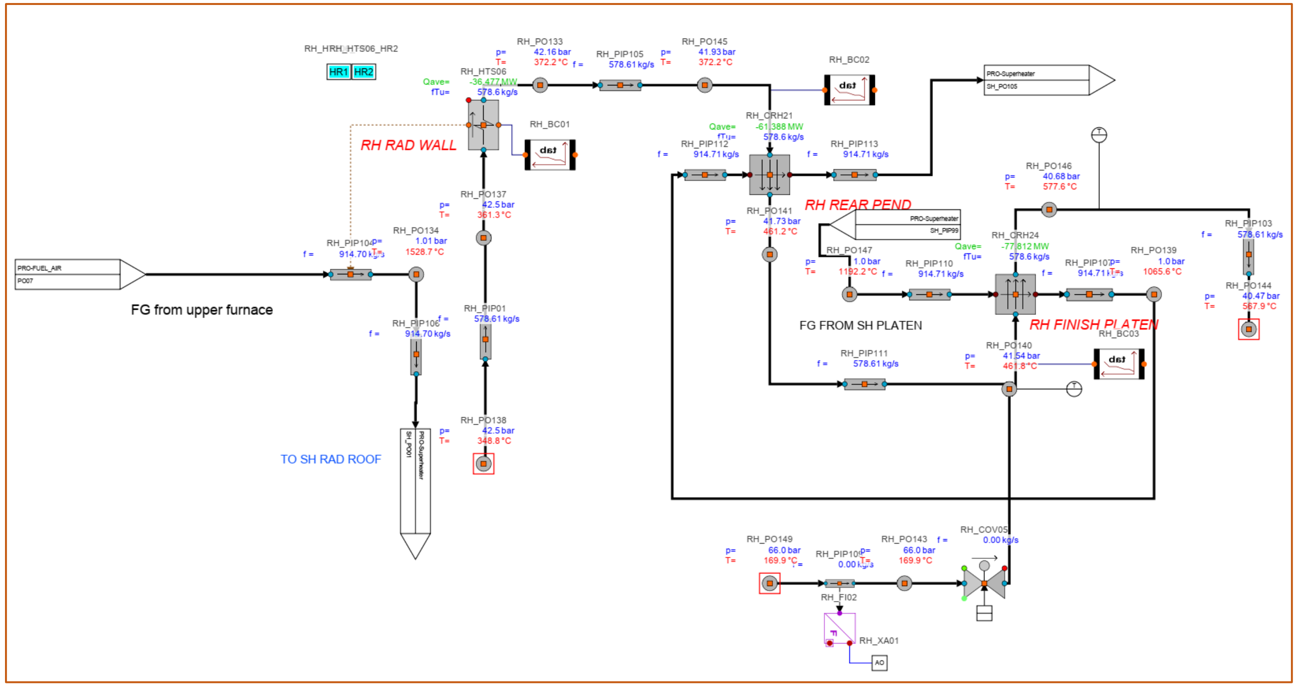
- Configured the steam circuit of the boiler (excluding the turbine)
- Calibrated TMCR condition, more operational conditions ongoing
- Implemented control logic for drum level and pressure
- Implemented control logic for de-superheat sprays

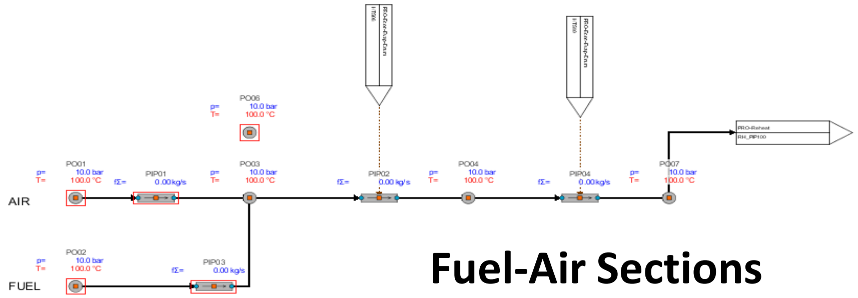


Superheater Sections

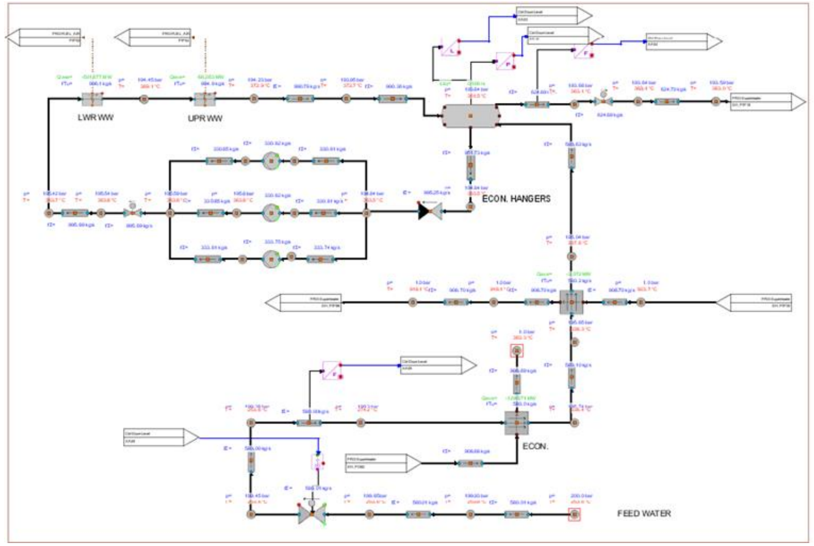


Reheater Sections

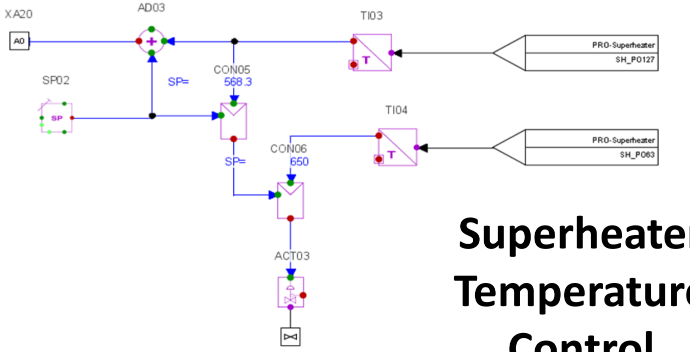
Process Dynamic Modeling



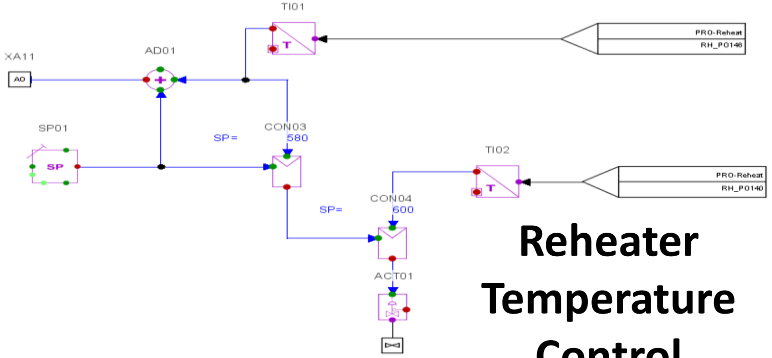
Fuel-Air Sections



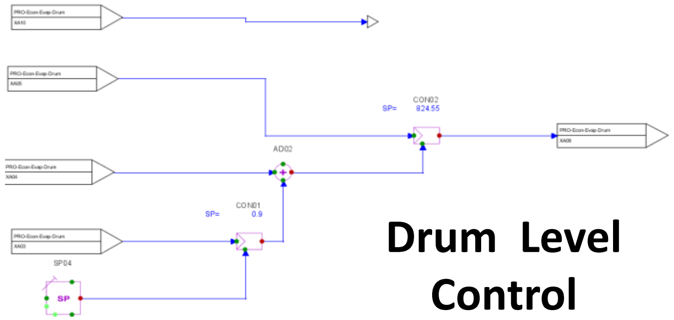
Economizer-Evaporator-Drum



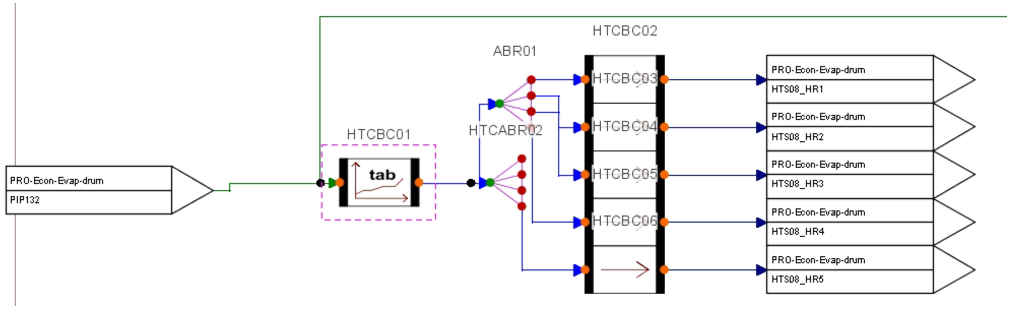
Superheater Temperature Control



Reheater Temperature Control



Drum Level Control



Load Dependency Table

Automated Model Calibration

Current Manual Calibration Process (Weeks)

RHBP output files → *Manually copy parameters into excel* → Excel parameters summarized files (for easy operation) → *Manually copy Excel parameters into Apros* → Apros model with fixed parameters configured → *Run Apros and manually tune several parameters* → Apros model with well-tuned parameters.
The model should make sure the concerned variables are behaving as expected

Automated Model Calibration Tool (Days)

Automated Model Calibration Tool

Collect fixed parameters into Apros with minimal manual intervene

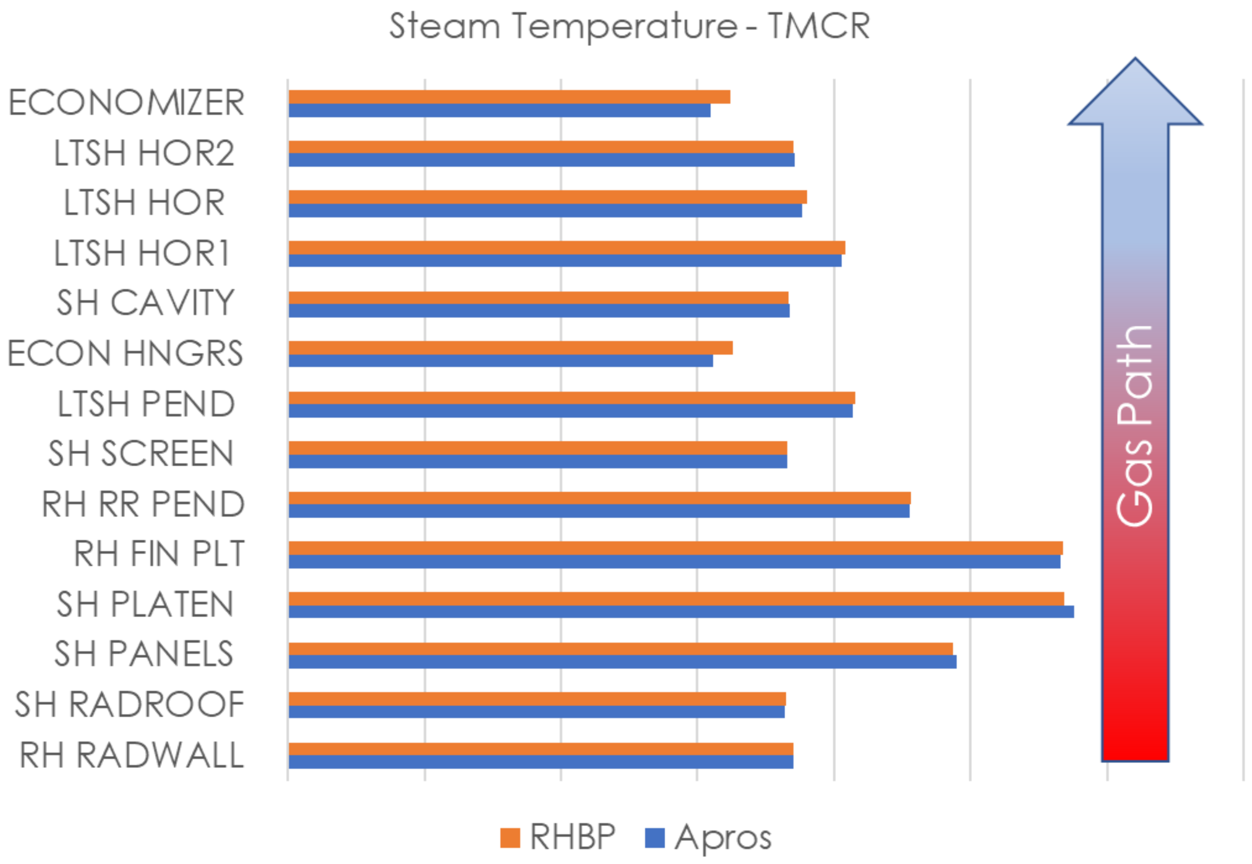
1. Parse the format of the RHBP output files
2. Functions to read the parameters from the RHBP out files
3. Functions to save the values into excel (optional)
4. Functions to save the values into text file that Apros will accept and send them to Apros through OPC communication

Use Optimization algorithms to search the optimal tunable parameters

1. Configure the OPC sever in Apros
2. Functions for communication between Matlab and Apros through OPC
3. Functions to control Apros start/stop to generate data for parameter tuning
4. Functions for cost function and PSO-based parameter tuning (PSO: Particle Swarm Optimization)

Process Dynamic Modeling Status

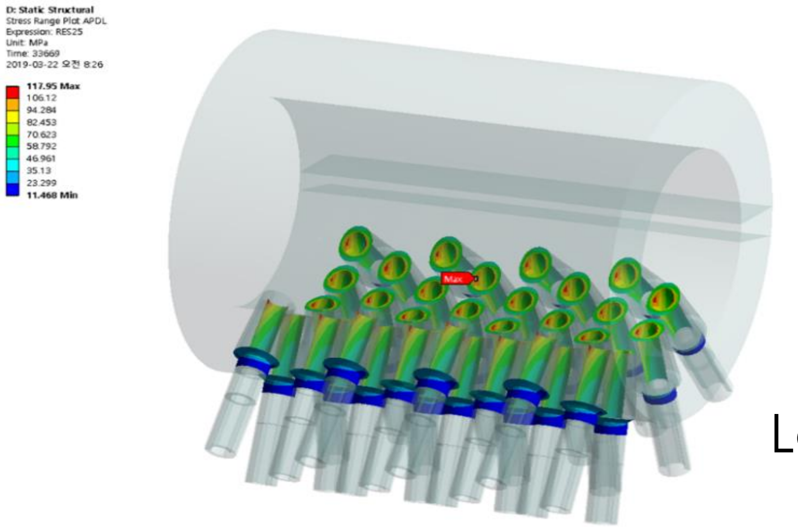
- For steam conditions, tuned within 3-5 °C/K of references from the RHBP runs.



Mechanical Integrity (MI) Modeling

The generalized mechanical integrity framework has three main modules:

- Fatigue damage module
  - Fatigue damage is the result of cyclic <u>transient</u> steam conditions during start-up/shut-down and load change cycles.
- Creep damage module
  - Creep damage is the result of <u>steady-state</u> steam conditions at various load levels.
- Mission-mix module
  - Assess the combined effects fatigue and creep damage

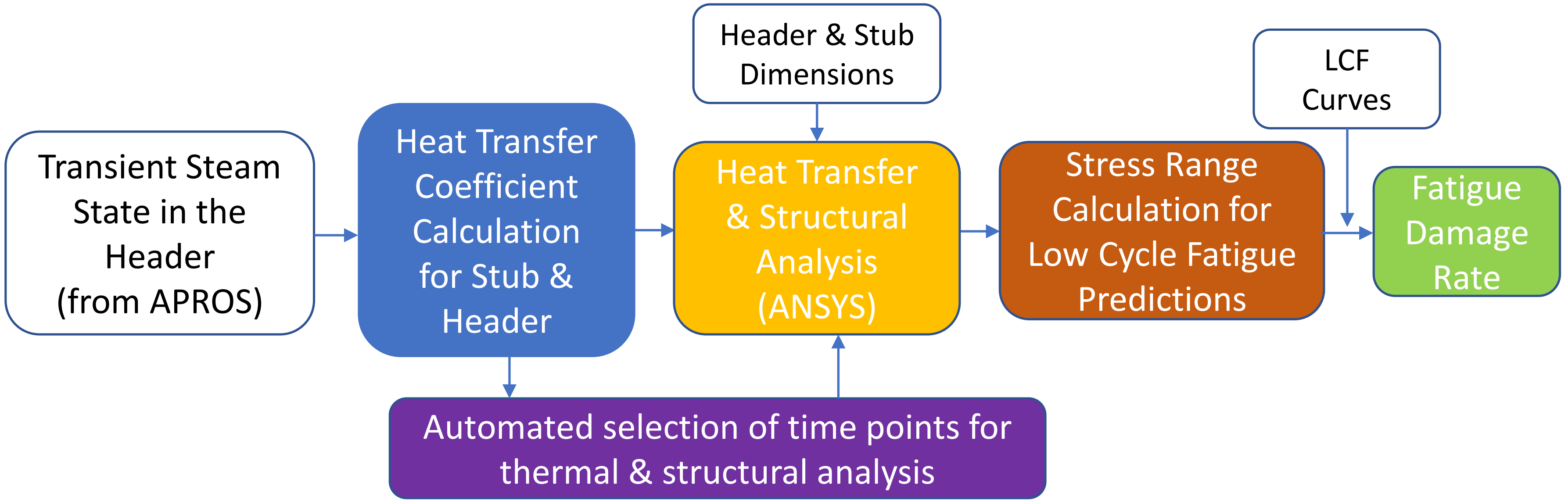


Local hot spots around stub penetrations

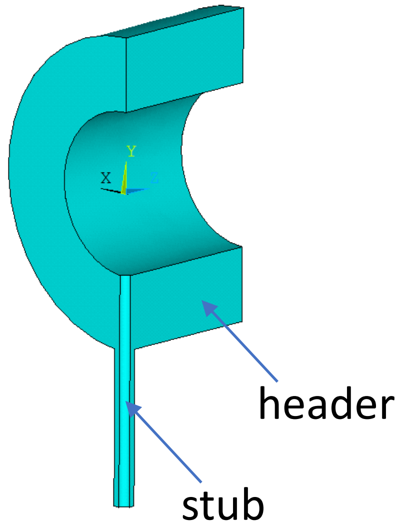
Fatigue Damage Module

- Finite element assessment procedure requires transient heat transfer and structural analysis

Elements of Fatigue Damage Module (for Headers)



Reduced Header model (symmetry model)



- Closed-form solutions are used for Heat Transfer Coefficient calculations
- A representative reduced order (single penetration) model is used for computation efficiency
- Stress range calculation methodology is based on European Union Unified Pressure Vessels Code EN-12445-3

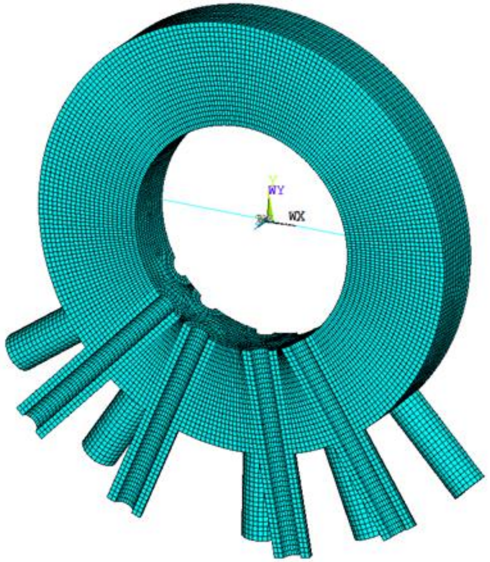
Creep Damage Module

Elements of Creep Damage Module (for Headers)

Header & Stub Dimensions + Repeating stub configuration → Finite Element Limit Load Analysis (ANSYS) → Ligament Efficiency + Steady State Metal Temperature & steam pressure @ steady state condition → Creep Damage Rate

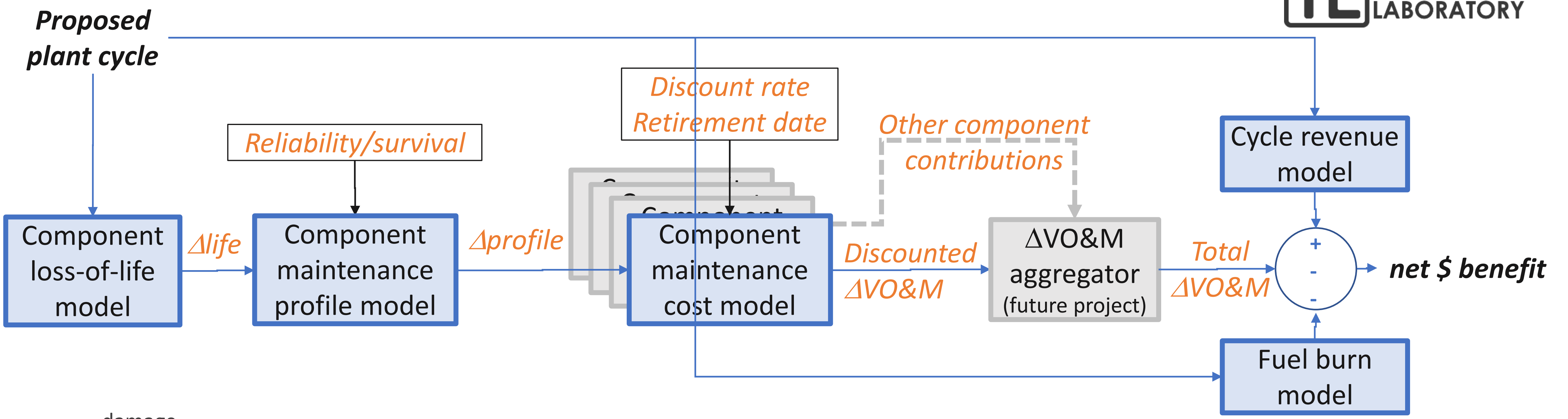
Creep Rupture Curves → Creep Damage Rate

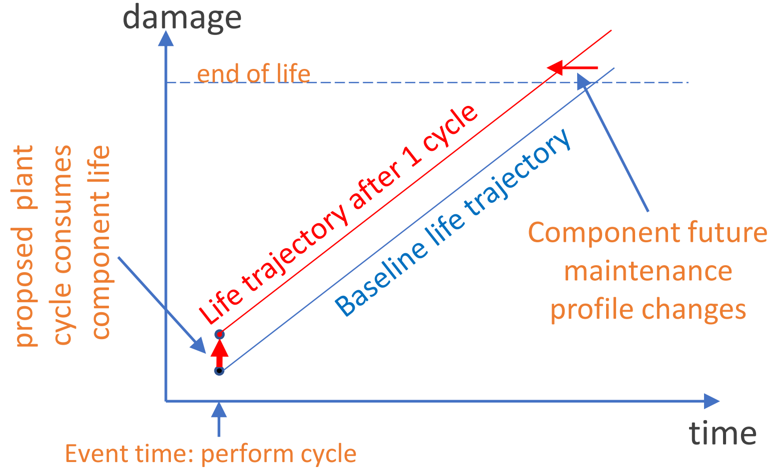
Reduced Header model (symmetry model)

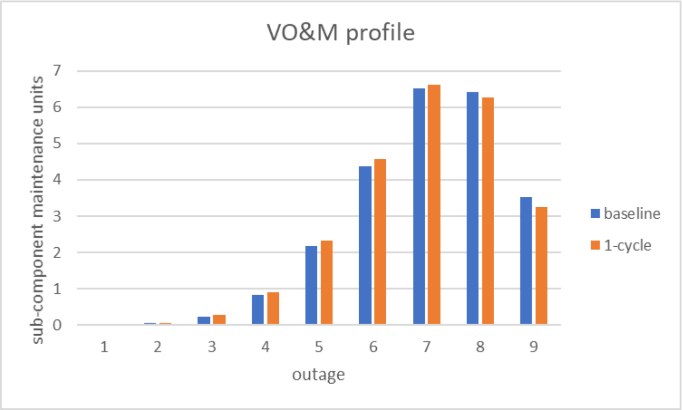


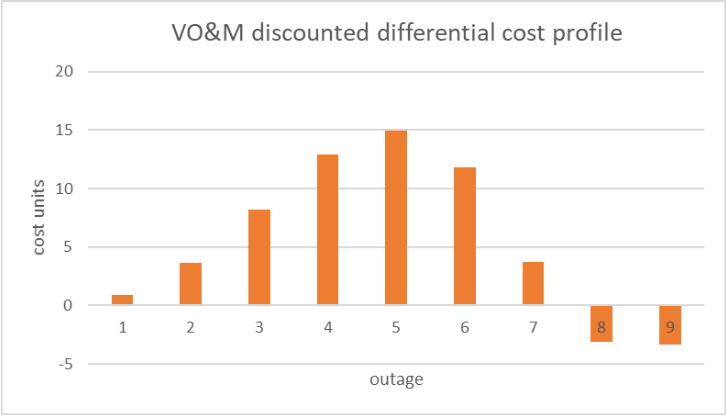
- Creep life calculation is based on reference stress methodology enhanced with ligament efficiency modification (per recommendation in EN Pressure Vessel Design Code)
- Creep properties are obtained from published European Creep Collaborative Committee data sheets
- A representative reduced order model (two adjacent stub penetrations) is used for computation efficiency

Economic Model: VO&M, fuel and revenue









Design of Experiment

S. NO.	CL REFERENCE	SPECIFICATION PROVISION
1	1.04.00 SUB SECTION A-01 OPERATING CAPABILITY OF PLANT	The plant shall be designed to operate as a base load station. However, continuous operation under two shift and cyclic modes during certain periods is also envisaged. The design would cover adequate provision for quick startup and loading of the units to full load at a fast rate. The unit shall have minimum rate of loading or unloading of 5% per minute above the control load (i.e. 50% MCR). Plant shall be capable of minimum 5 (five) number of daily load cycles, i.e. load variation from 100% to 50 % (and vice versa) of MCR. In addidtion, the plant shall also be capable of minimum (2) two number of daily load cycling from 50% to 30% (and vice versa) of MCR with a minimum ramp rate of 3% per minute. The main plant and its auxiliaries with their controls would be designed to permit operation of the units on house load without there being any necessity to shut down the units in the event of sudden loss of total load due to tripping of transmission lines or any other grid disturbances. The design of the plant equipments and control system would permit participation of the plant in automatic load frequency control.

Cold Startups = **455**
Warm Startups = **910**
Hot Startups = **4550**

Cycle: 100%→50%→100% = 2 ramps/cycle x 5 cycles/day x 350 days/yr x 25 years = **87,500** 5% ramps/lifetime; **43,750** 5% cycles/lifetime

Cycle: 50%→30%→50% = 2 ramps/cycle x 2 cycles/day x 350 days/yr x 25 years = **35,000** 3% ramps/lifetime; **17,500** 3% cycles/lifetime

A regular customer requirement. This project is investigating more aggressive flexible operations.

Integrated Simulation

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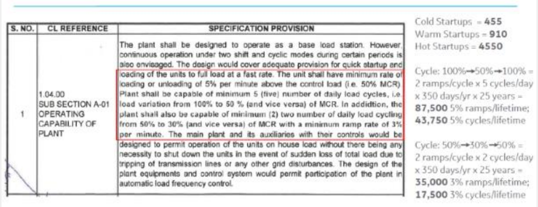
Design a standard set of simulation scenarios

Design of experiment

Baseline
- Today's operations



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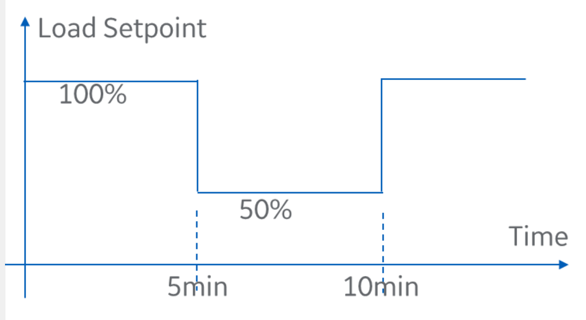
New Analysis
- Faster ramping
- More runs

Save to Excel as input to Apros model

Excel Table (example)

Count	Load Change	Ramp Rate	time to change load 1	time to change load 2
1	100-25-100	3%	5min	10min
2	100-25-100	5%	5min	10min
2	100-25-100	7%	5min	10min

Load Profile (example)



Integrated Analysis Tool: (Apros, Ansys, and Matlab Scripts to glue all together

Integrated platform using Matlab

1. Functions to read configurations from excel, one case per run till to complete all cases
2. Functions to control Apros (model) through OPC to run the case and save time series data (w/ pre-defined variables) into file
3. Functions to call Ansys (e.g. system) in Matlab to run the FEA analysis and save result to file
4. Functions (Algorithms) to do analysis of life/damage
5. Functions (Algorithms) to do economic analysis
6. Functions to write the analysis results into a Report

OPC

Mechanism to control Ansys running

Apros Model

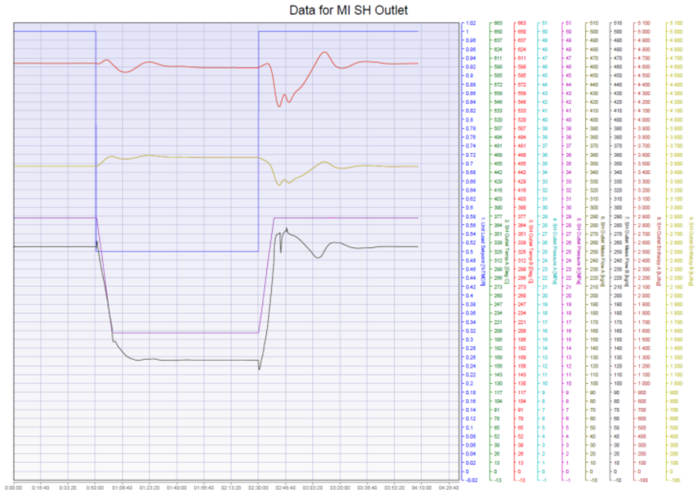
Ansys Model

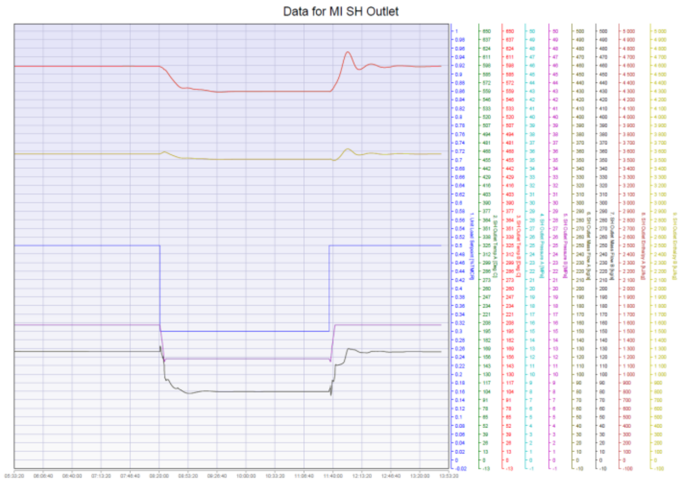
Apros model required parameters

Ansys model required parameters

Preliminary Analysis Results

- Load change operation data





- Fatigue assessment of two load change scenarios with different ramp rates using fatigue damage module

Not final conclusions

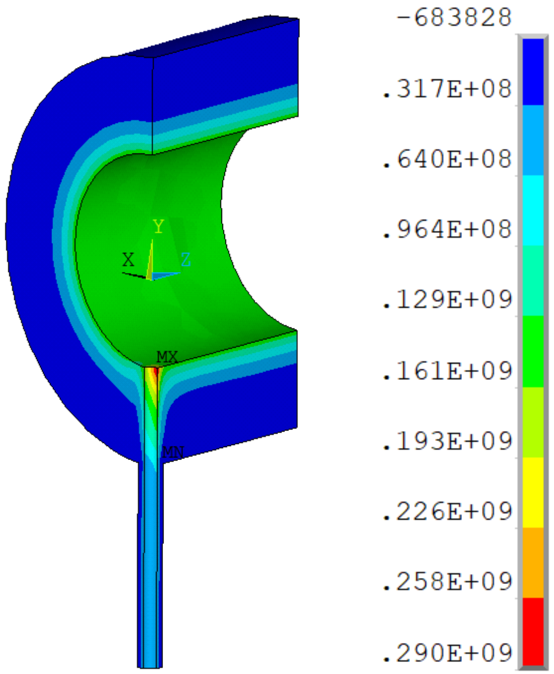
Load Change Type	Load Change Rate	Stress Range (MPa)	Allowed # of Load Change Cycles	Fatigue Damage Rate (per cycle)
50%-25%-50%	7%	256	39,834	2.51E-05
50%-25%-50%	5%	246	52,089	1.92E-05
50%-25%-50%	3%	254	41,994	2.38E-05
75%-25%-75%	7%	301	13,392	7.47E-05
75%-25%-75%	5%	293	16,054	6.23E-05
75%-25%-75%	3%	282	20,771	4.81E-05

- Creep calculation summary of a select manifold using creep damage module

Not final conclusions

Header OD (mm)	Minimum Wall Thickness (mm)	Ligament Efficiency	Operating Pressure (MPa)	Reference Stress in Ligament (MPa)	Operating Temperature (^{0}C)	Creep Life (hrs)	Creep Damage Rate (per hr)
508	105.88	0.76	28.83	70.3	603	167,227	5.98E-06

Stress state of a select time point in the transient history



Summary and Next Steps

Summary

- Built an integrated tool to help Engineering and Customer quickly quantify the benefits/loss of doing flexibility operations.
- Multiple types of models were configured, calibrated, and integrated
- Preliminary analysis results successfully demonstrated the whole simulation and analysis process

Next Steps

- Remaining technology challenges: *quantify the benefit in a plant-level using component-level results*
- Identify potential new research
  - *Extend component-level analysis with more use cases as well as to plant-level analysis*
  - *Extend the platform application from subcritical power plant to supercritical power plant*
- Industry collaborators
  - *Power plant was identified. Will involve power plant owner and discuss the opportunity to deploy the analysis results into the operating power plant*

Thank you!

Who contribute to this presentation slides:

- Braun, Timothy (GE Power)
- Ozkan, Umit (GE Research)
- Salasoo, Lembit (GE Research)
- Lou, Xinsheng (GE Power)
- Kunkel, Robert (GE Power)
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- Sargent, Benjamin (GE Power)
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