Integrated Dynamics, Control, and Health Modeling of a Supercritical Pulverized Coal Power Plant under Flexible Operation

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NATIONAL ENERGY TECHNOLOGY LABORATORY

U.S. DEPARTMENT OF ENERGY

Presentation Overview

- **Key Challenge Facing the Energy Industry**
- **Fossil Energy Generation Flexibility**
  - R&D Objectives and Technical Approach
- **Dynamic Performance Baseline**
- **Results and Accomplishments**
  - Sliding- vs. Fixed-Pressure Operation
  - Regulatory, Coordinated, and Advanced Process Control
  - Boiler Health Modeling
- **Concluding Remarks and Future Work**

Key Challenge Facing the Energy Industry

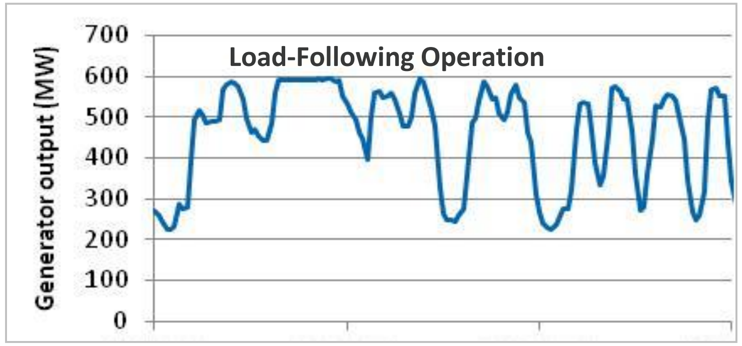
Variability/Uncertainty vs. System Flexibility

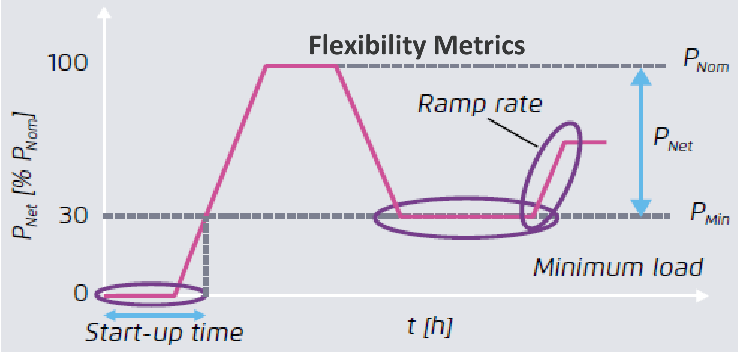
- **Factors Driving Variability and Uncertainty**
  - Fluctuating residual load
    - Variations in total load demand
    - Intermittent renewable generation
  - Grid faults and conventional generation outages

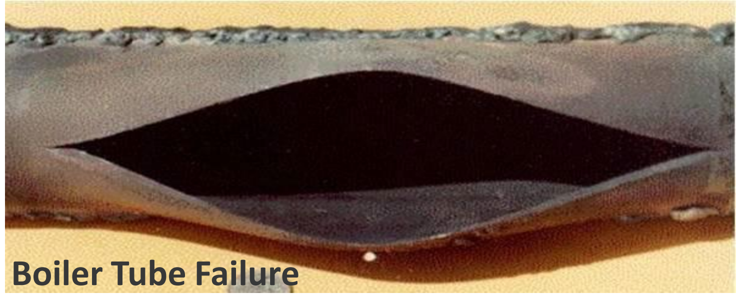
- **Key Priorities for Improving Flexibility**
  - Grid-friendly renewable generation
  - Energy storage and demand side management
  - Fossil energy generation flexibility

Key Challenge Facing the Energy Industry
Fossil Energy Generation Flexibility

- **Improve load-following operations**
  - Performance and efficiency
  - Faster startup and ramp rates
  - Lower minimum loads
- **Minimize negative impacts**
  - Equipment/plant health and life expectancy
  - Plant downtime and operations & maintenance (O&M) costs
  - Environmental emissions
- **Lack of measurements due to harsh operating conditions**







Fossil Energy Generation Flexibility
R&D Objectives and Technical Approach

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- **R&D Objectives**
  - Improve fossil energy plant **performance** and **reliability** under **flexible operations**
- **Technical Approach**
  - Develop **dynamic performance baselines** for existing fossil energy power plants
    - High-fidelity, plant-wide **dynamic process and control models**
    - **Health models** for key equipment items
  - Quantitatively assess **plant operation and control approaches** to improve performance and reliability
  - **Minimize negative impacts** on plant/equipment health

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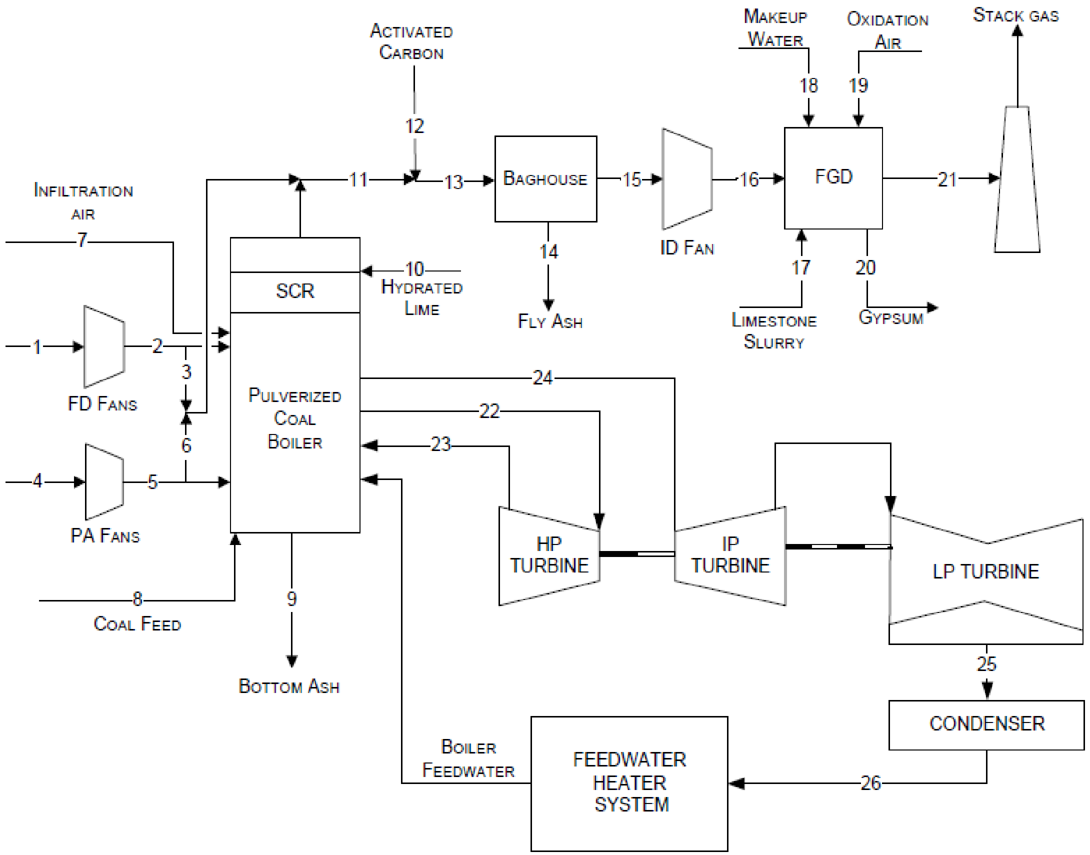
Dynamic Performance Baseline
Supercritical Pulverized Coal (SCPC)



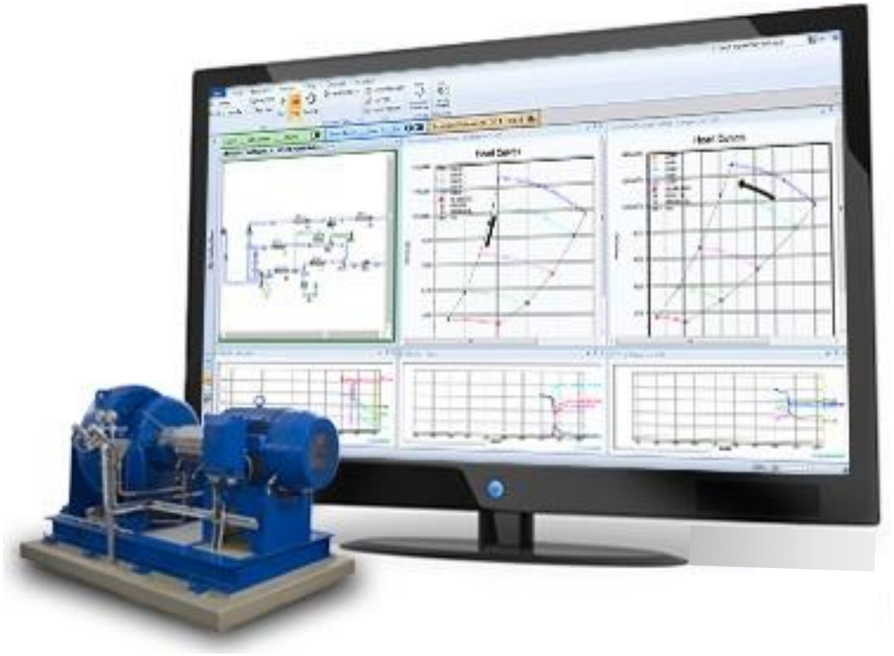
SCPC Plant Configuration – Major Equipment

- **Case B12A, Fossil energy cost and performance baseline, Vol. 1a, Rev. 3, DOE/NETL-2015/1723***
- **Nominal output of 550 MWe (net)**
- **Illinois #6 coal**
- **Steam Generator**
  - Supercritical, once-through
  - Superheaters, reheater, economizer, air preheater
- **Single-reheat steam conditions**
  - 24.1 MPa/593°C/593°C
- **Air Quality Control**
  - Selective Catalytic Reduction (NOx)
  - Flue Gas Desulfurization (SO_2)
- **Regulatory and supervisory controls**

* Case B12A, Cost and Performance Baseline for Fossil Energy Power Plants Study, Volume 1a: Bituminous Coal (PC) and Natural Gas to Electricity, Revision 3, National Energy Technology Laboratory, www.netl.doe.gov, DOE/NETL-2015/1723, July 6, 2015.

SCPC Dynamic Performance Baseline
Modeling Software and Physical Properties

- **Modeling Software**
  - Aspen Plus Dynamics®
    - Plant-wide model and controls
    - Equation-oriented, pressure-driven
  - Aspen Custom Modeler® (ACM)
    - Equipment models
    - 1D Partial Differential Equations (PDEs)

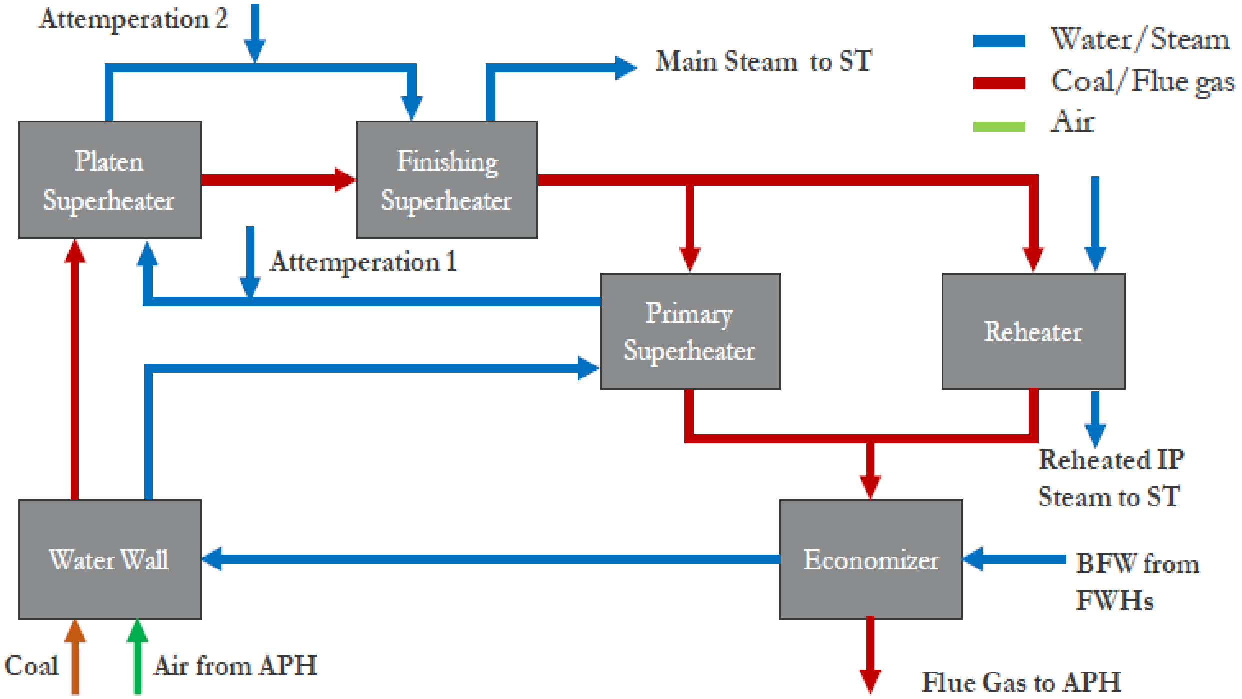


- **Physical Properties**
  - Flue Gas: PENG-ROB (Peng-Robinson Equation-of-State*)
  - Water/Steam: IAPWS-95 Steam Tables**

* D.-Y. Peng and D. B. Robinson, "A New Two-Constant Equation-of-state," Ind. Eng. Chem. Fundam., Vol. 15, (1976), pp. 59–64.
** Wagner , W. and A. Pruß, "The IAPWS Formation 1995 for the Thermodynamic Properties of Ordinary Water Substance for General and Scientific Use," J.Phys. Chem. Ref. Data, 31(2), 387- 535, 2002.

SCPC Dynamic Performance Baseline
Dynamic Custom Equipment Models

- **Boiler**
  - **First-principles dynamic model**
    - Steam side and flue gas side
    - Mass and energy balances
    - Pressure drop correlations
    - 1D temperature and pressure profiles
  - **Heat exchanger models**
    - Economizer, water wall
    - Superheaters, reheater
    - Modular for customization
  - **Flue-gas side models**
    - Convective heat transfer (around tubes)
    - Combustion model (water wall)
    - Radiation (water wall, platen superheater)



- **Tube/header thermal dynamics and health models**
  - Temperature profiles along and through tube walls/headers
  - Thermal and mechanical stresses: tri-directional (tangential)
  - Creep and fatigue damage, as well as synergistic effects

* D. Yang, J. Pan, C. Q. Zhou, X. Zhu, B. Qincheng, and T. Chen, "Experimental investigation on heat transfer and frictional characteristics of vertical upward rifled tube in supercritical CFB boiler," Exp. Therm. Fluid Sci., vol. 35, pp. 291–300, 2010.
** VDI Heat Atlas, Second Edition. Berlin Heidelburg: Springer-Verlag, 2010.
*** A. Taklifi, M. A. Akhavan-Behabadi, P. Hanafizadeh, and A. Aliabadi, "Experimental investigation of inclination effect on subcritical and supercritical water flows heat transfer in an internally ribbed tube," Heat Mass Transf., 53(2), 635–647, 2016.

SCPC Dynamic Performance Baseline
Dynamic Custom Equipment Models

- **Steam Turbine**
  - Full- and partial-arc admission
  - Fixed- and sliding-pressure operation
  - Moisture detection on all stages
  - Liese (2014), Sarda et al. (2018)
- **Condenser**
  - 1D cross-flow model
  - ε-NTU heat transfer method
- **Feedwater Heaters**
  - 1D cross-flow shell & tube
  - Shell-side: ε-NTU method
    - Heat transfer correlations for desuperheating, condensation, and subcooling
- **Pulverizers**
  - Four Zones: Bowl, Grinder, Separator, Classifier
- **Selective Catalytic Reduction**
  - 1D heterogeneous plug flow reactor model with detailed kinetics

- Liese, E. "Modeling of a Steam Turbine Including Partial Arc Admission for Use in a Process Simulation Software Environment.", *Journal of Engineering for Gas Turbines and Power*, vol. 136, no. 11, pp. 112 605-1 - 112605-7, 2014. doi: 10.1115/1.4027255.
- Sarda, P., E. Hedrick, K. Reynolds, D. Bhattacharyya, S.E. Zitney, and B. Omell, "Development of a Dynamic Model and Control System for Load-Following Studies of Supercritical Pulverized Coal Power Plants," *Processes*, 6(11), 226, Nov. 2018.

SCPC Dynamic Performance Baseline
Model Validation at Full-Load

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- **SCPC dynamic baseline validated against steady-state results from the Fossil Energy baseline study (NETL, 2015)**
  - SCPC plant-wide dynamic model at full-load was shown to be in good agreement (Sarda et al., 2018)
  - Detailed PDE-based boiler dynamic model was also shown to be in good agreement in terms of LHV efficiency (Reynolds et al., 2019)

$$\eta = \frac{m_{steam}\Delta H}{m_{coal}LHV_{coal}}$$

Parameter	Unit	NETL Baseline Study*	SCPC Dynamic Model	Error
Coal Flow Rate	tonne/h	225	228	1.53%
Gross Power	MW	641	620	-3.28%
Net Power	MW	550	532	-3.21%
Heat Rate	kJ/kWh	11,086	11,629	4.90%
Main Steam Pressure	MPa	24.2	24.1	-0.37%
Main Steam Temperature	°C	593	593	0.00%
Main Steam Flow Rate	tonne/h	2,003	2,027	1.19%

	NETL Baseline	Model
LHV Efficiency	92.4%	92.5%

- Sarda, P., E. Hedrick, K. Reynolds, D. Bhattacharyya, S.E. Zitney, and B. Omell, "Development of a Dynamic Model and Control System for Load-Following Studies of Supercritical Pulverized Coal Power Plants," *Processes*, 6(11), 226, Nov. 2018.
- Reynolds, K., E. Hedrick, P. Sarda, S.E. Zitney, B. Omell, and D. Bhattacharyya, "Dynamic Modeling and Simulation of a Supercritical Pulverized Coal-Fired Boiler under Load-Following Operation," *EPRI Flexible Operations Conference: Conventional and Combined Cycle Power Plant Cycling Damage and Management*, Pittsburgh, PA, June 5-7 (2019).

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SCPC Dynamic Simulation Results
Sliding- vs. Fixed-Pressure for 100% to 50% Load

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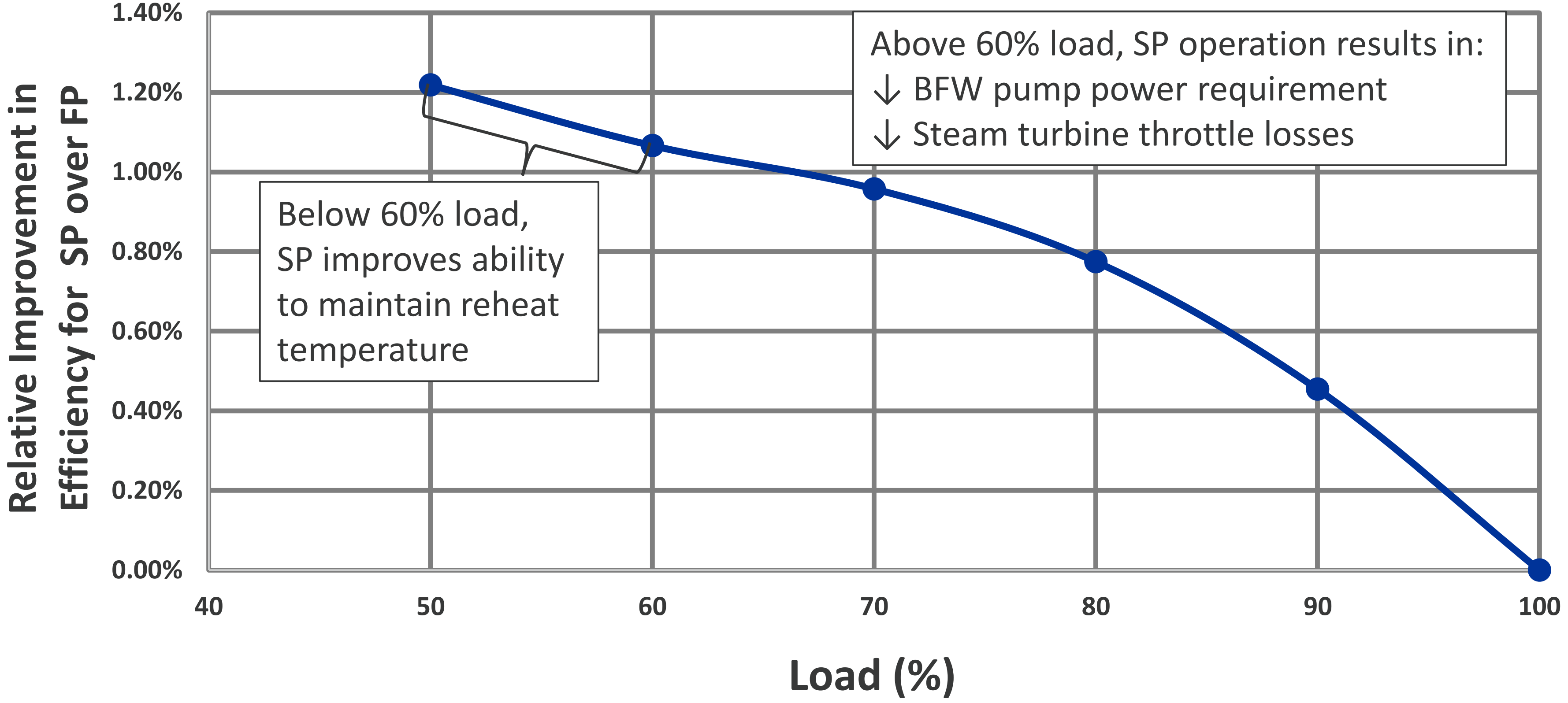
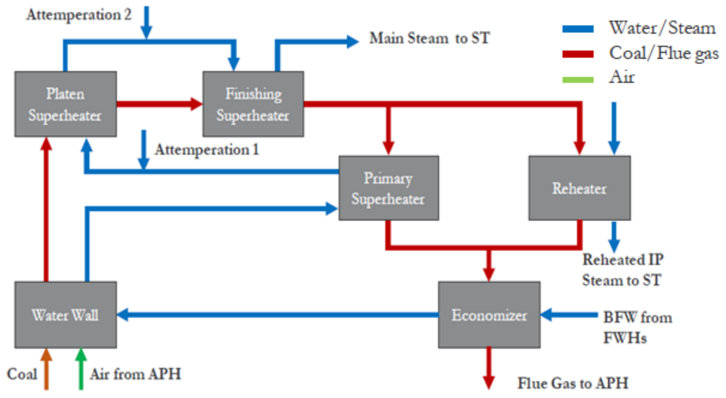
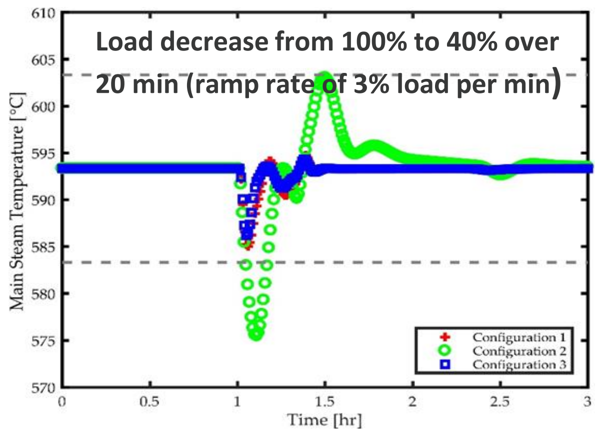


Improved efficiency for sliding-pressure (SP) over fixed-pressure (FP) at part-load operation

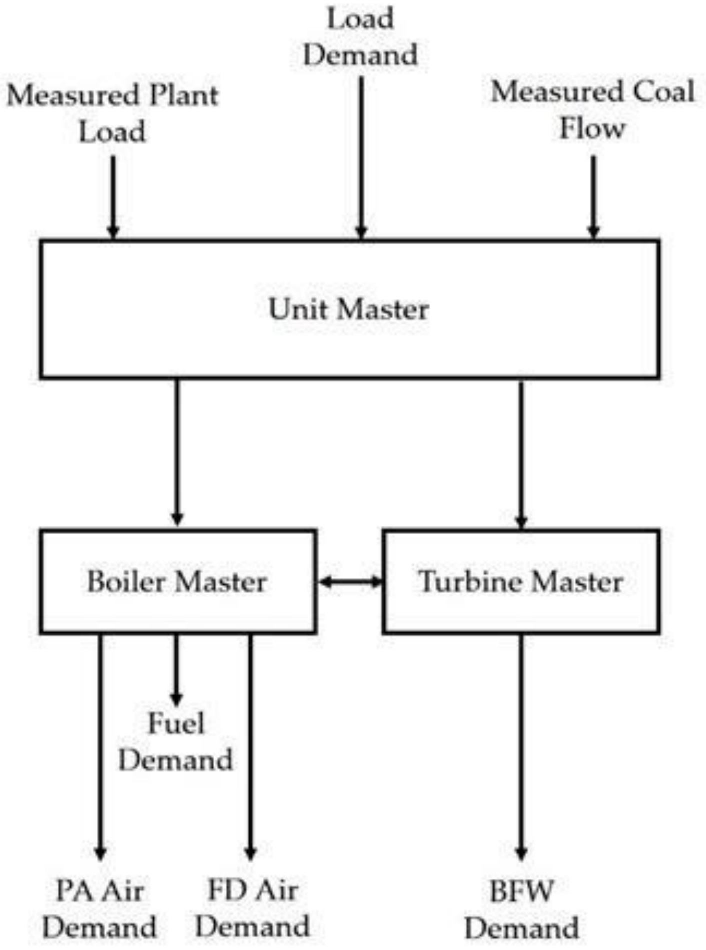
SCPC Dynamic Performance Baseline
Regulatory and Supervisory Control Layers

- **Regulatory PID Control Layer**
  - **16 single-loop feedback loops and 13 cascade loops**
  - **Main Steam Temperature Control**
    - Two-stage attemperation
    - Feedforward correction based on BFW flow
    - Smith predictor accounts for time delay (Configuration 3)





- **Coordinated Control System**



Sarda, P., E. Hedrick, K. Reynolds, D. Bhattacharyya, S.E. Zitney, and B. Omell, "Development of a Dynamic Model and Control System for Load-Following Studies of Supercritical Pulverized Coal Power Plants," *Processes*, 6(11), 226, Nov. 2018.

Main Steam Temperature Control
Reinforcement Learning (RL)

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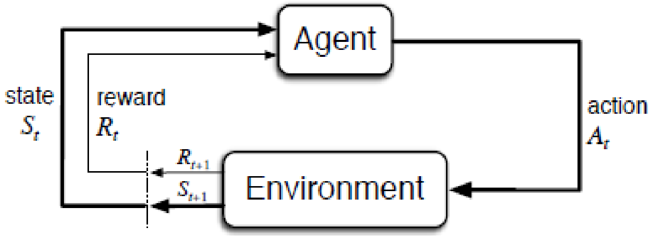
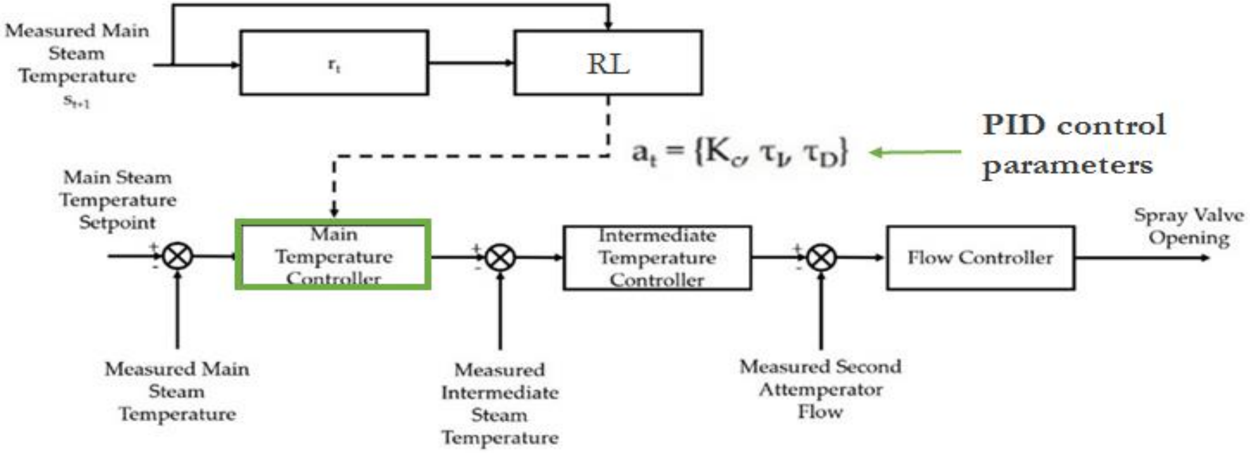
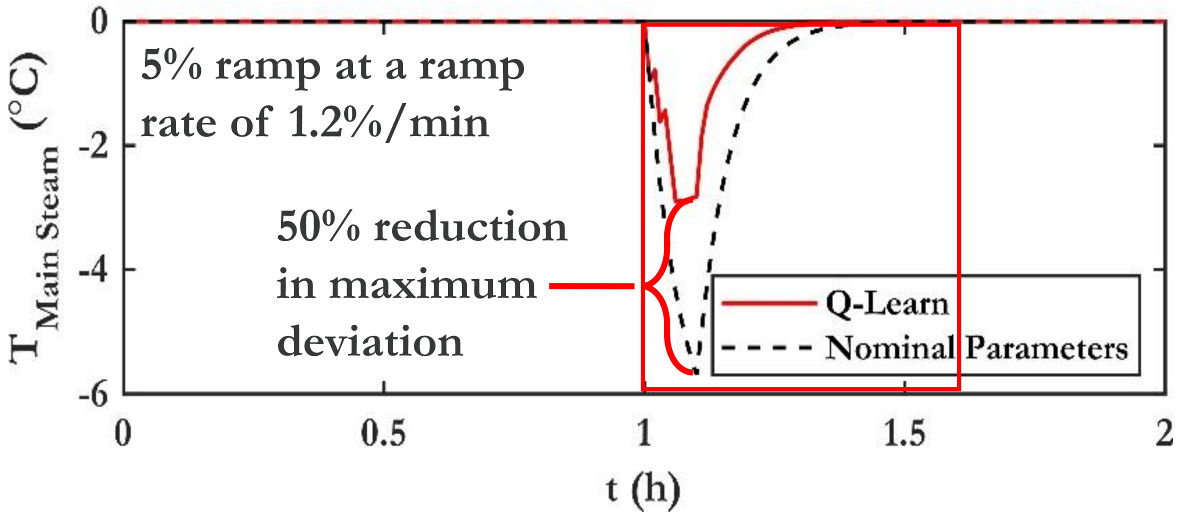
- **Adaptive and retentive learning**



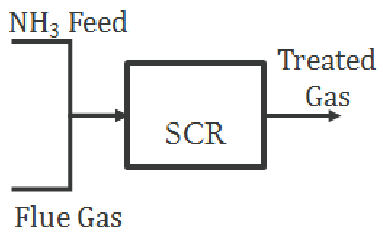
- **RL-augmented PID control**
  - Q-learning for PID control parameters
- **Episodic learning**
  - Disturbance: Random ramped load changes
  - Input: BFW flow to Attemperator before FSH
  - Output: Main Steam Temperature
- **State-action clustering**
  - Retentive learning
  - Reduces computation time





Selective Catalytic Reduction (SCR) Control
LMPC with RL and State-Action Clustering

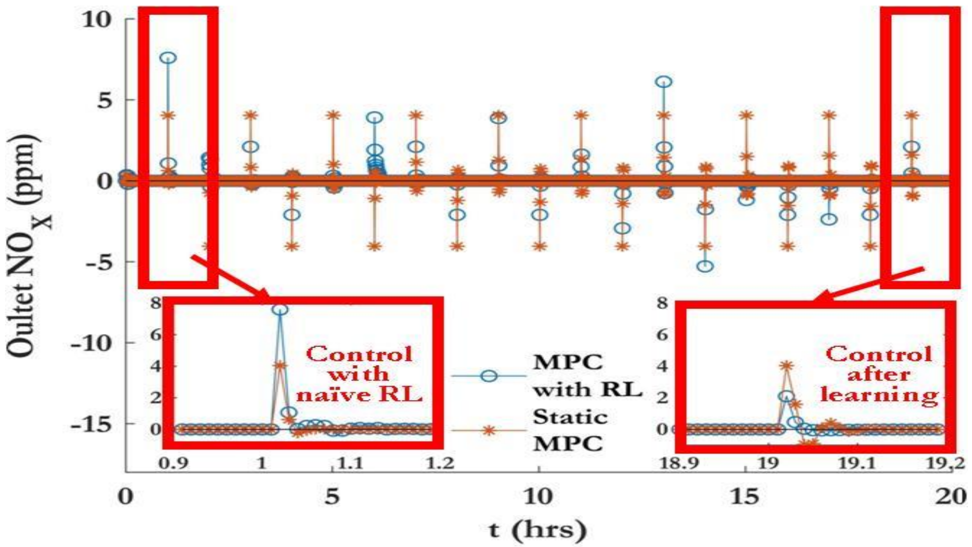
- **SCR for NOx control is highly nonlinear time-varying system with time-delay**
- **Reduced model is identified from dynamic SCR model of the form:**



Model Variable	System Variable
u_1	NH_3 Flow (kmol/h)
d_1	Flue Gas Flow (kmol/h)
d_2	Flue Gas NO_x Flow (kmol/h)
d_3	Flue Gas Temperature (˚C)
y	Outlet NO_x (ppm)

- **Identified model is used in a Linear Model Predictive Control (LMPC)**

- **RL-augmented LMPC**
  - Temporal-difference learning
  - Learned parameters are the LMPC prediction and control horizons
  - State-action clustering



Comparison of Static MPC and RL-based MPC for SCR Outlet NOx Control with Disturbances in Flue Gas Temperature

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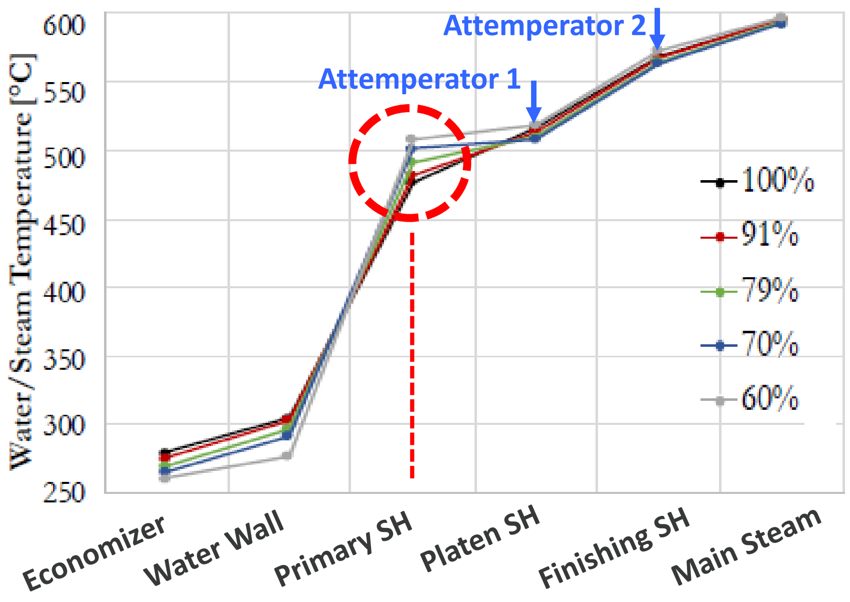
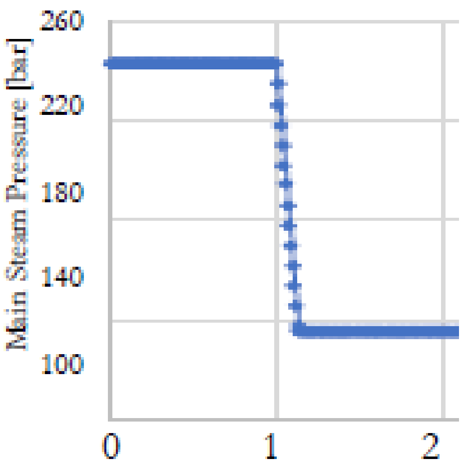
Impact of Load-Following on Boiler Health
Primary Superheater - Tubes

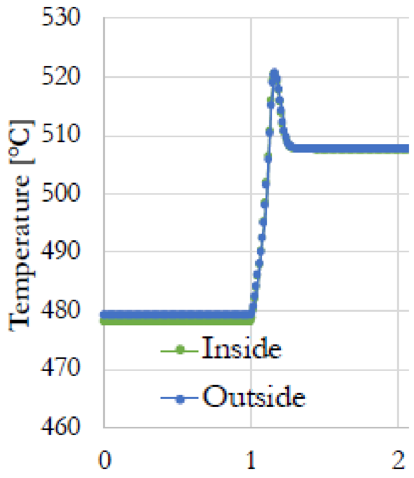
- Load ramped from 100% to 60% (5%/min)
- Boiler thermal profile depends on plant design and controls
- Temperature at inlet of Primary SH rises with reduction in load — possible location for damage



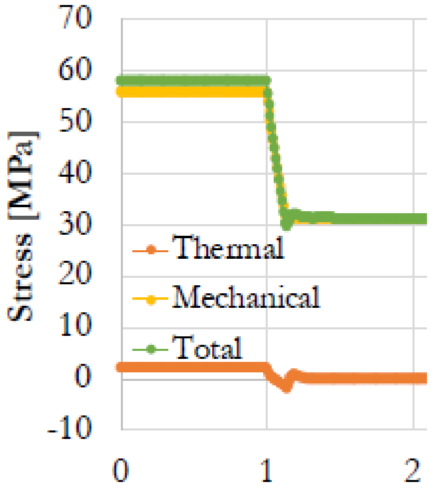
Boiler Thermal Profile



Sliding Pressure Operation



Tube Temperature at Primary SH Inlet



Stress at Primary SH Inlet

- ΔT between inner and outer tube wall is small
- Thermal stress does not add significantly to total stress (fatigue)
- However, higher temperature (+40°C) at 60% load increases **creep damage**
- **Relative rupture time** at 60% load reduced by 6X compared to full load

	PSH	
Load	100%	60%
Wall Surface Temperature [°C]	477.92	507.41
Equivalent Stress [MPa]	71.72	39.18
Relevant Rupture Time	1.00	0.16

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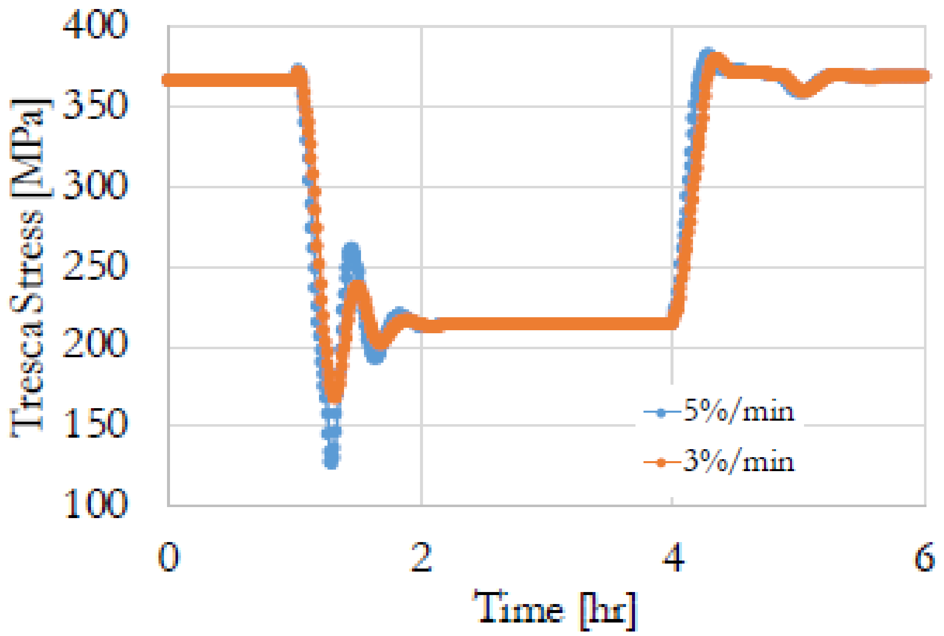
* - "Water-tube boilers and auxiliary installations - Part 3: Design and calculation of pressure parts," British Standards Institution, London, UK, BS EN 12952-3:2001, May 2002.

Impact of Load-Following on Boiler Health
Primary Superheater - Header

- Stresses in **superheater headers** are higher than in tubes due to thicker walls and larger through-wall temperature differences, so **fatigue damage** is of more concern
- Stress used in a fatigue cycle calculation **(rainflow counting using ASTM E1049)***
- **Ramp rate affects number of allowable cycles**



- Load ramped from 100% to 60% at Time=1 hr and then back up to 100% at Time = 3 hr
- Two different ramp rates: 3%/min, 5%/min

Ramp Rate [%/min]	3	5
$\Delta\sigma_{Tresca}$ [MPa]	212	256
Relative # of Cycles	1	0.14

* - "Water-tube boilers and auxiliary installations - Part 3: Design and calculation of pressure parts," British Standards Institution, London, UK, BS EN 12952-3:2001, May 2002.

Concluding Remarks and Future Work

- **Developed dynamic model of SCPC power plant with regulatory and coordinated controls**
  - Used to analyze sliding- vs. fixed-pressure operation for load-following
  - Sliding-pressure operation provides 1.2% efficiency improvement over fixed-pressure at 50% load
- **Developed reinforcement learning-augmented control approaches**
  - RL-augmented PID control improved main steam temperature control by reducing maximum temperature deviation by 50% during load ramp
  - RL-augmented MPC improved NOx control for highly nonlinear SCR process with time-delay
- **Developed first-principles dynamic model of SCPC boiler with stress sub-models**
  - Provides information about unmeasured and unmeasurable process variables in harsh conditions
  - Tube wall temperatures can vary significantly under sliding-pressure operation
  - For superheaters, stress magnitude is higher for inner tube surface and especially thick-walled headers
  - Number of allowable cycles due to fatigue damage is greatly affected by ramp rate
  - Tube rupture times due to creep damage in primary superheater are impacted by low load operation
- **Future work will focus on:**
  - Dynamic model validation using the plant operating data from industrial partner(s)
  - Control strategy development for load-following with due consideration of health/damage

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