APM Tutorial:

Improving load following capabilities of natural gas and coal-fired boilers

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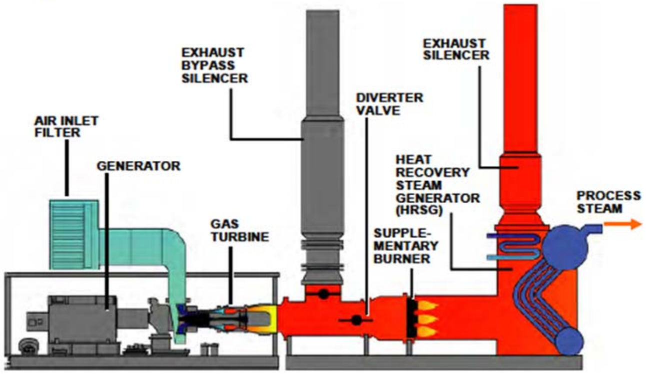
Discussion Objectives

- Cogeneration opportunities
  - UT Austin example
  - Challenges: Boiler fatigue
- Model forms
  - Empirical MPC
    - System identification
  - First Principles
    - Model development
- Comparisons of PID vs Non-linear MPC
- Future Work

Cogeneration

ExxonMobil

Typical Industrial Cogeneration System



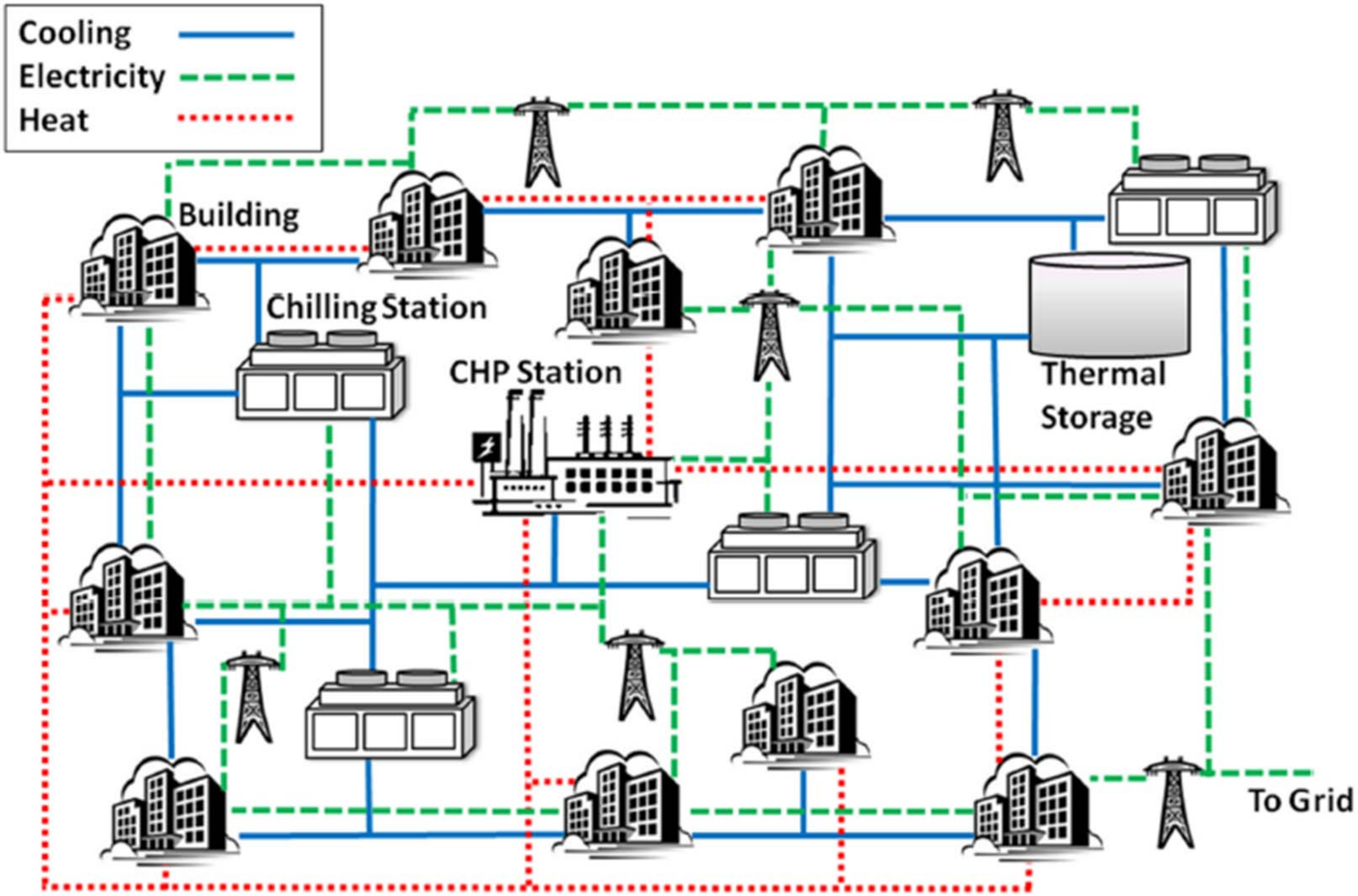
≅

3000 large onshore wind turbines

≈ half of **Belgium's annual residential electricity** demand

Source: Meidel, R.W. (2012) *Cogeneration, Challenges and Opportunities: Meeting Cogeneration TArgets in the Marketplace*.

University of Texas at Austin



Diagrams Courtesy Kody Powell, UT Austin

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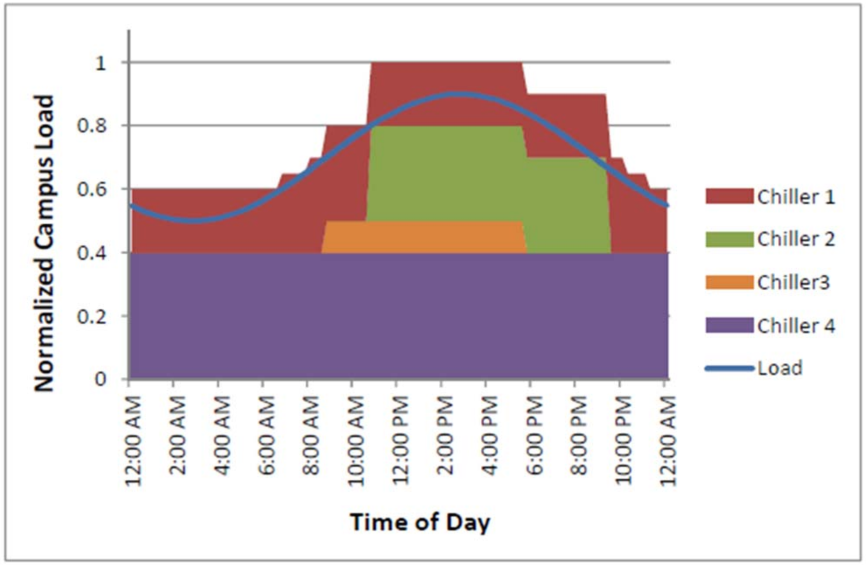
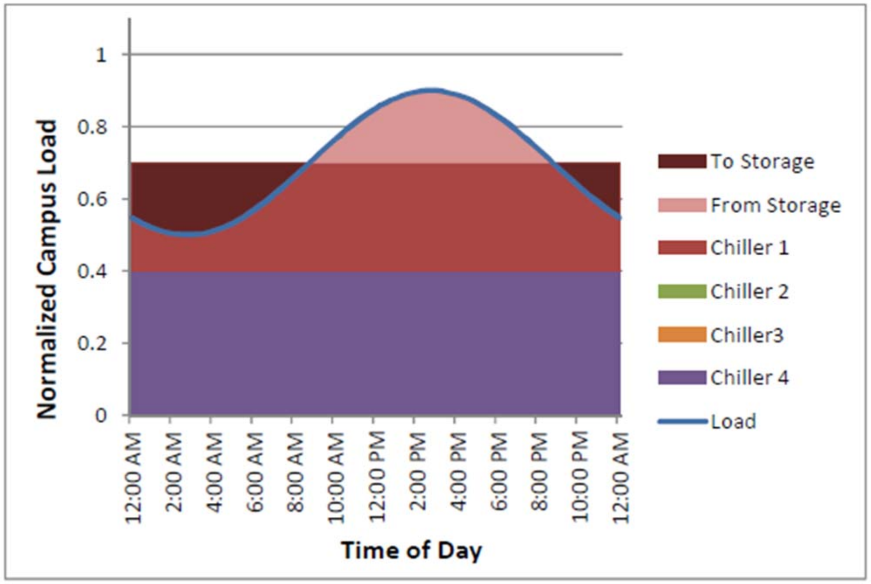
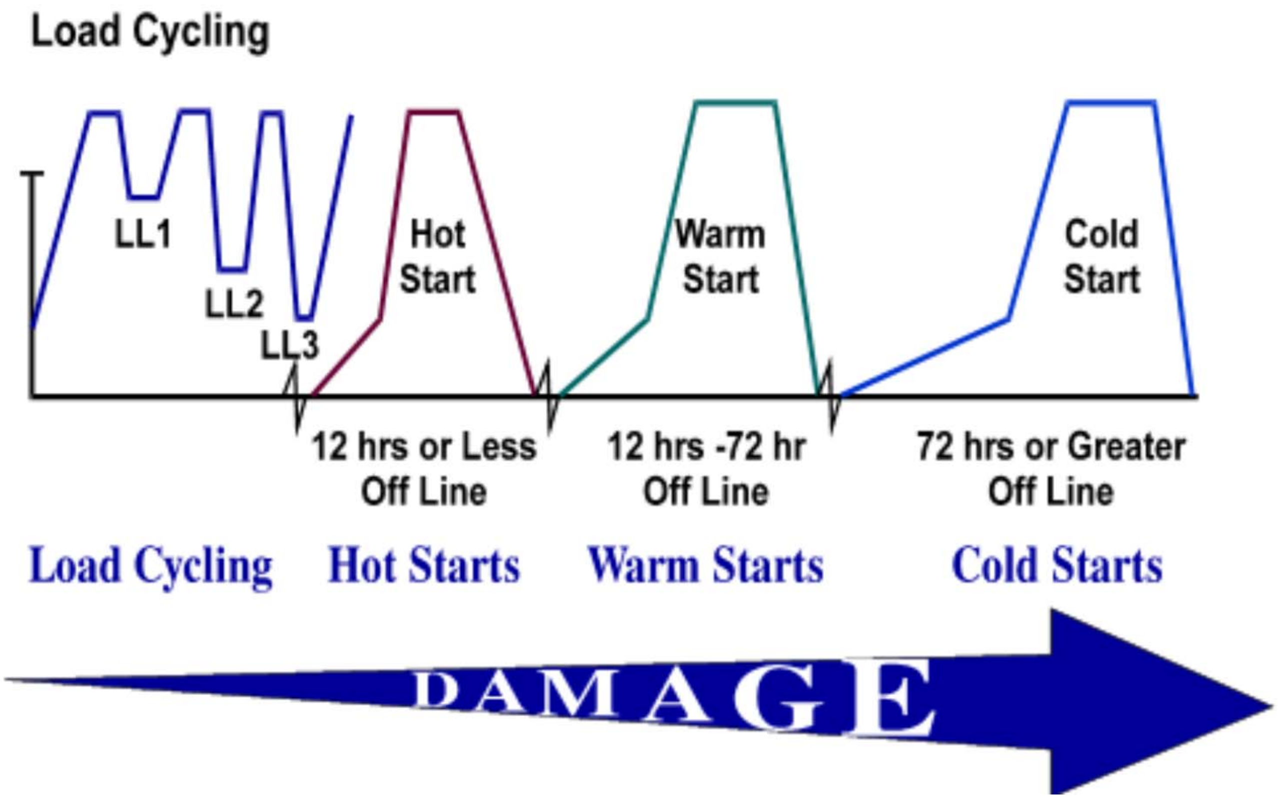




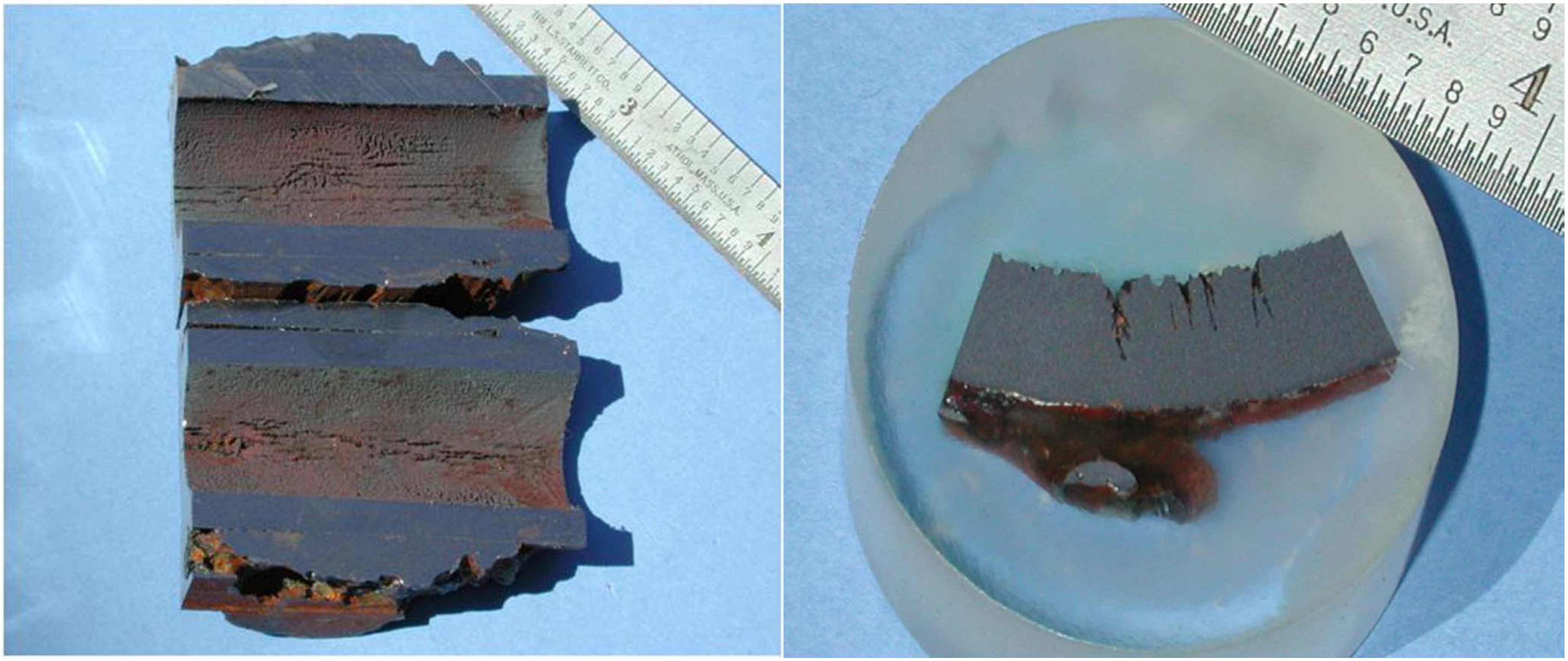
Diagrams Courtesy Kody Powell, UT Austin

Boiler Fatigue



Photos & Diagram Courtesy NREL http://www.nrel.gov/docs/fy11osti/51579.pdf

Boiler Fatigue



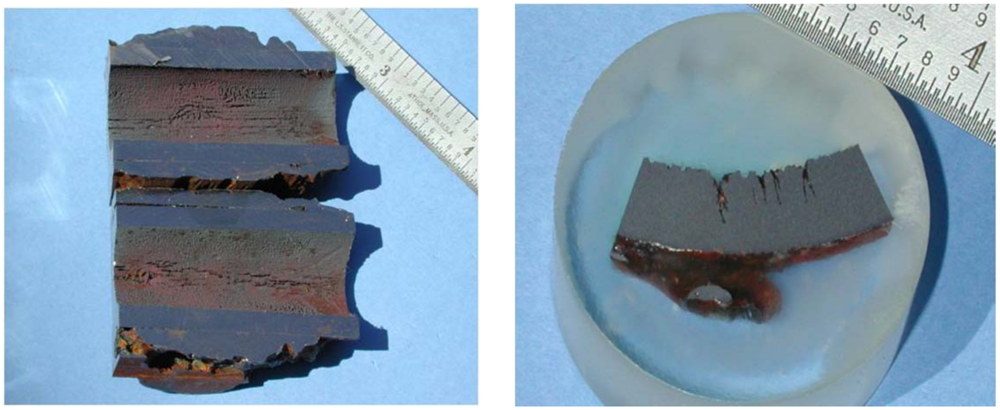
Photos & Diagram Courtesy NREL http://www.nrel.gov/docs/fy11osti/51579.pdf

Control System Developments

- Typically based on:
  - Operator Knowledge
    - Safe
    - Meet Requirements
    - Successful
  - Perceived Limitations
    - Challenge assumptions
    - Optimize everything

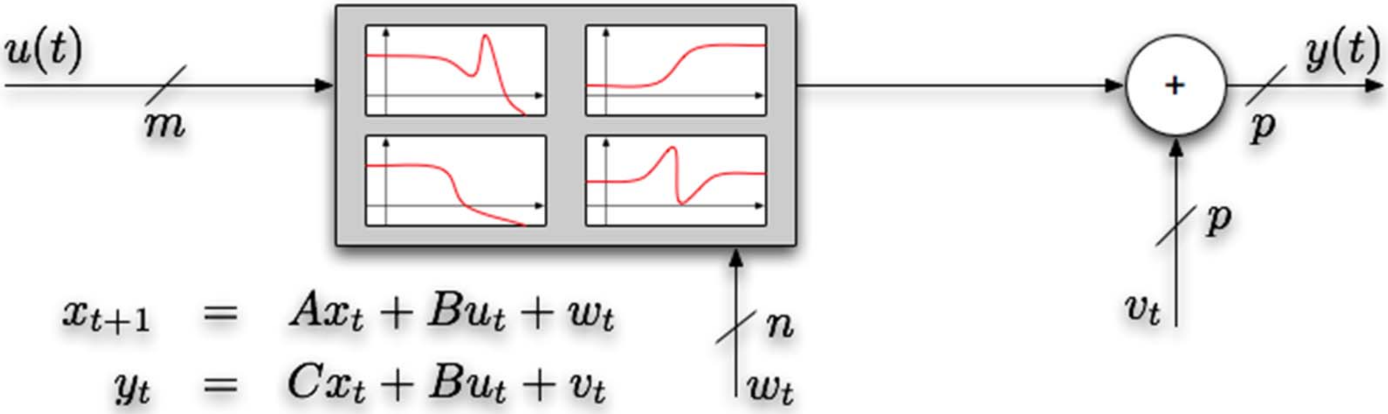
Special Controls

- Most processes have unique operating conditions and requirements
- Ex: Boiler for steam/energy production
  - Load change at specified rate
  - Wear and tear
  - Emissions

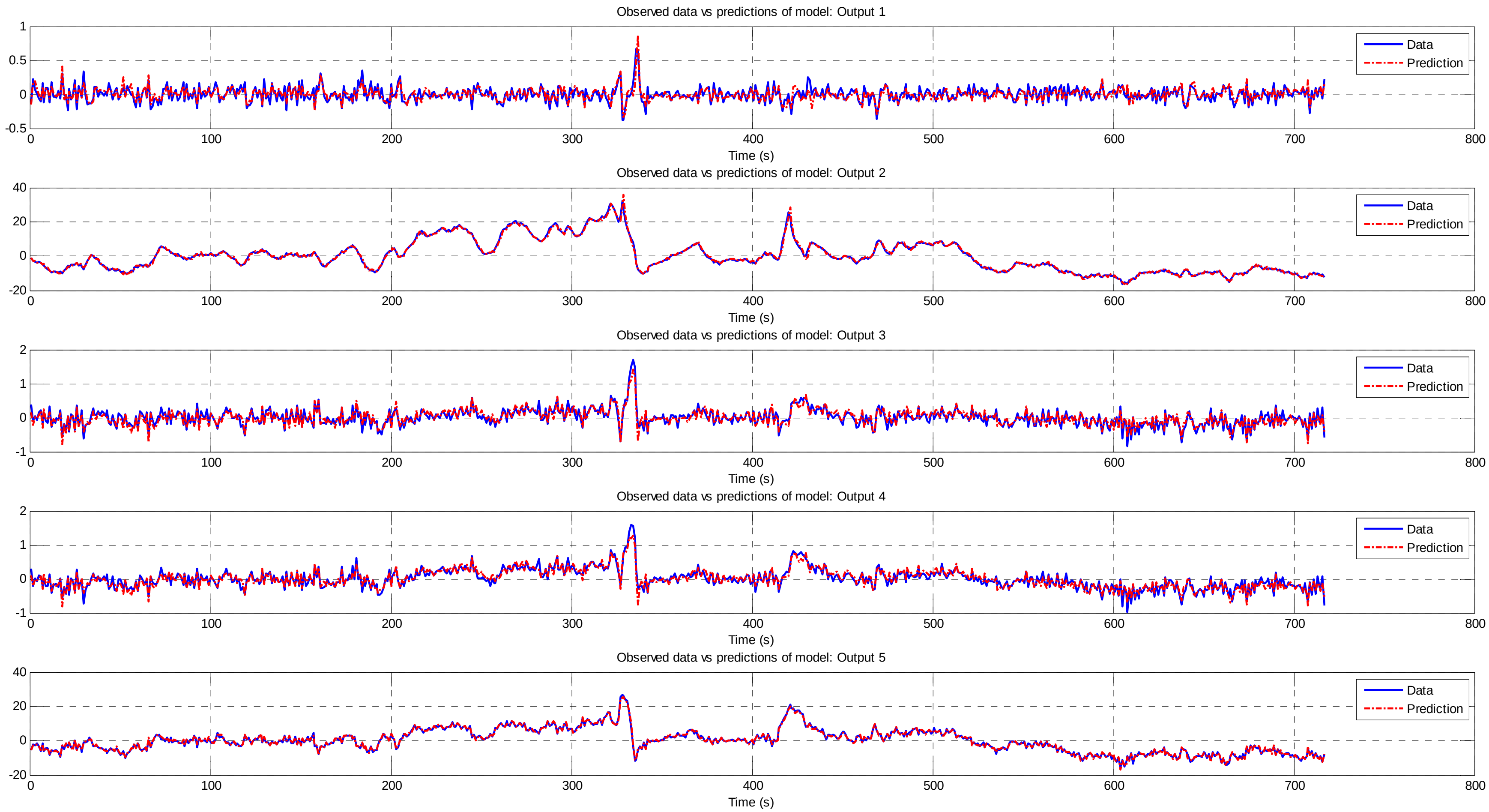


Empirical Models

- Can help in identifying cause and effect relationships within the boiler's MVs and CVs
- Information from empirical models can help develop better first principles models



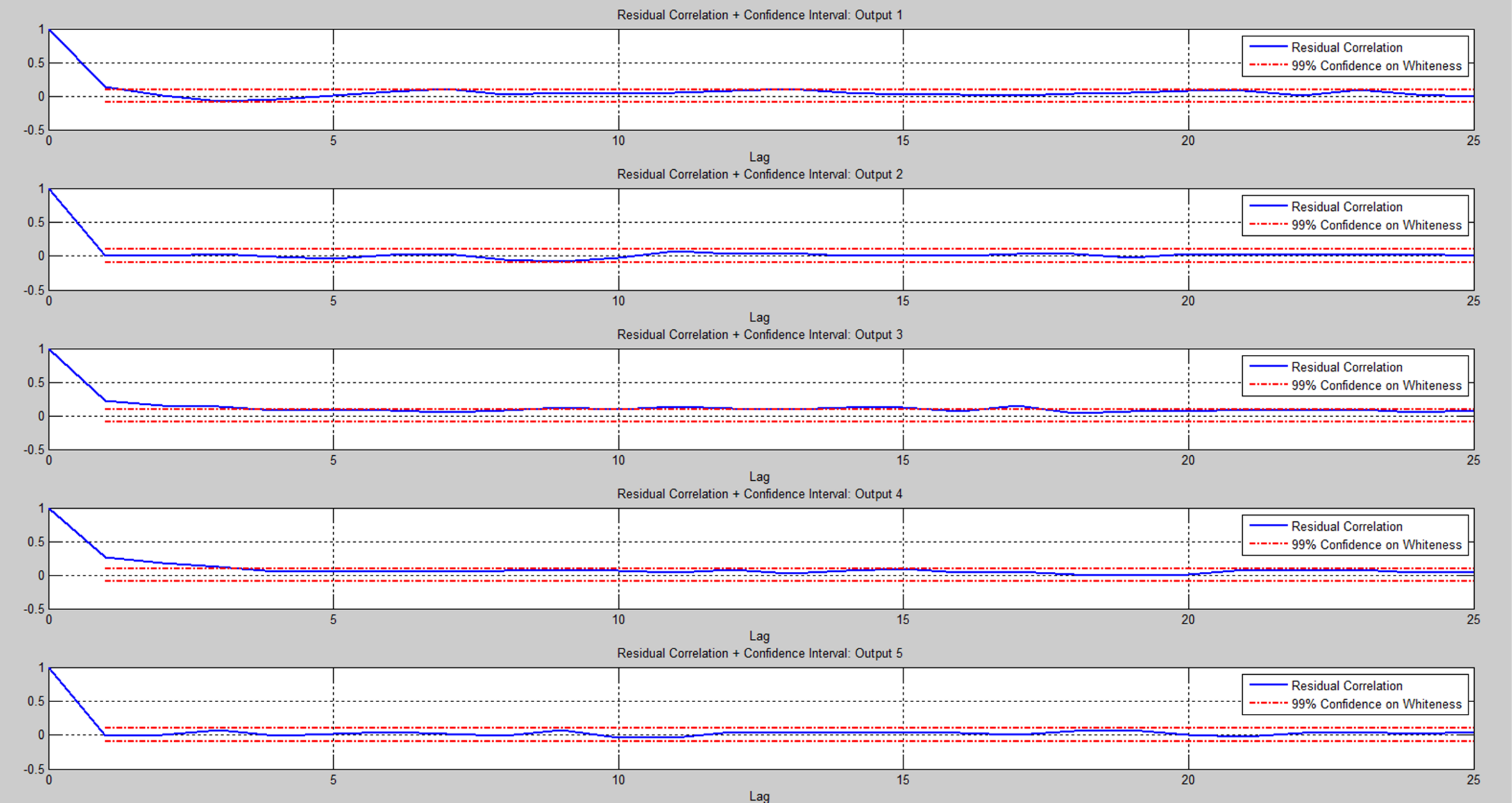
Model Identification



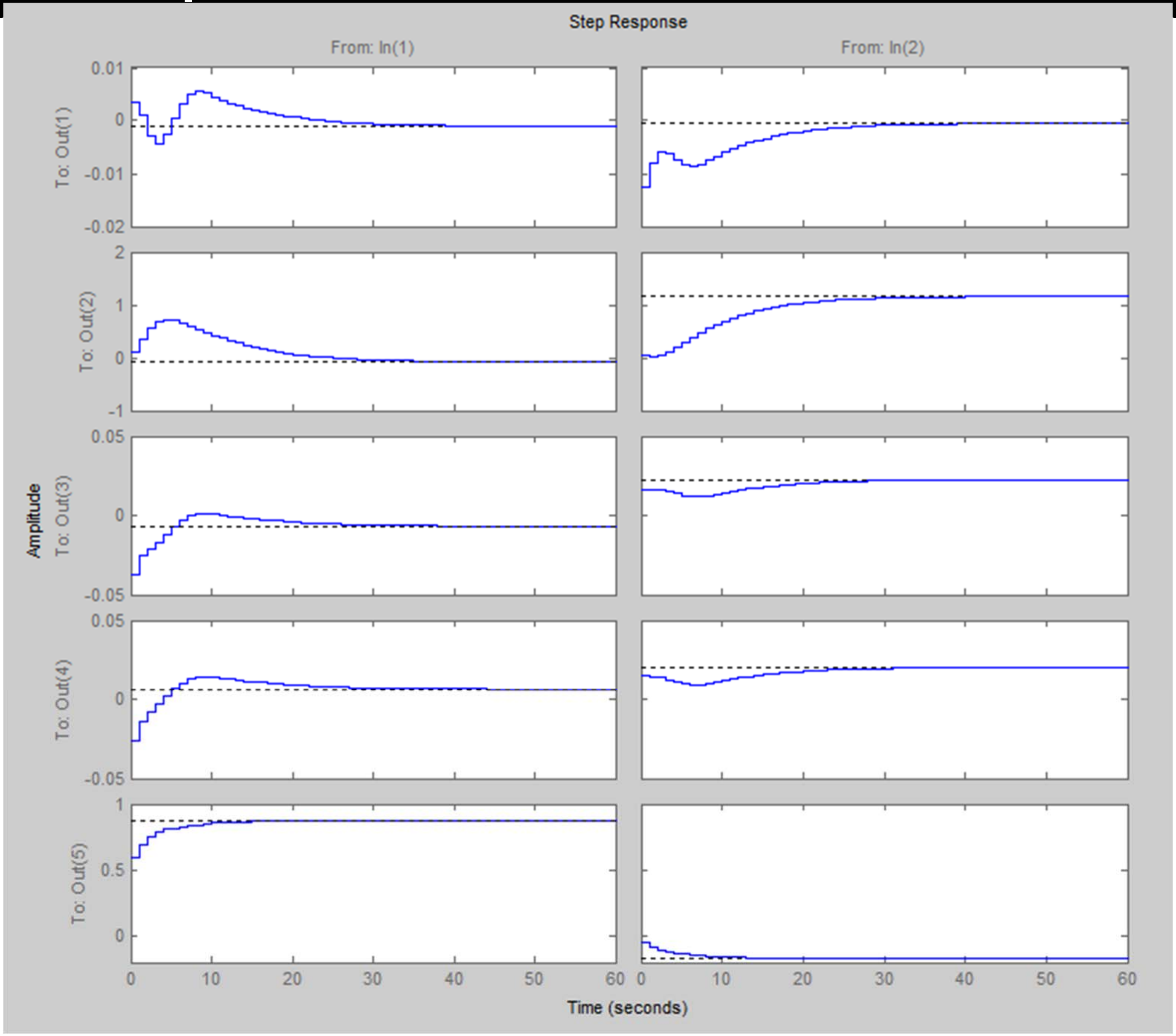
Inputs: gas flow , supply water flow

Outputs: (1) drum level (2) steam temp (3) steam pressure (4) drum pressure (5) steam flow

Confidence Intervals



Step Response

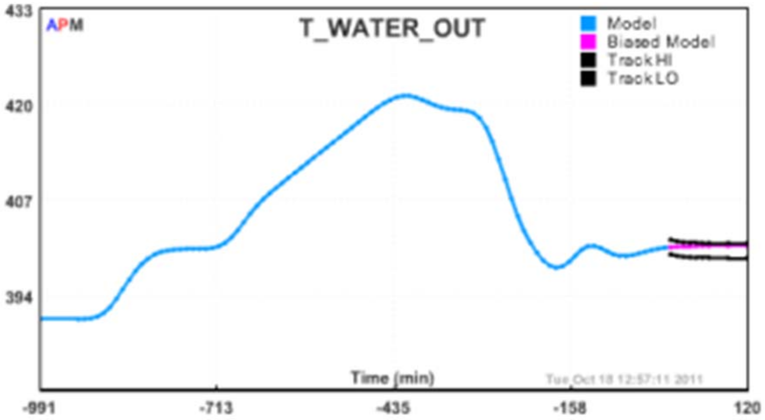


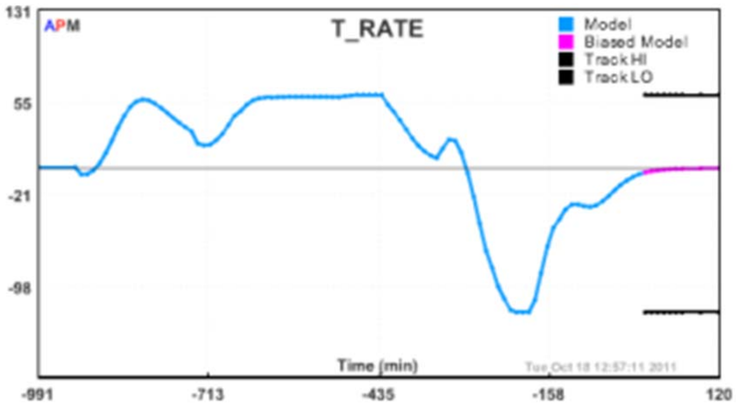
Model

- Model Source
  - Operational knowledge from
  - Literature values
  - Heat transfer equations
  - Material and energy balances
- Model Form
  - Differential and Algebraic Equations (DAEs)
  - Combined Empirical and First Principles forms

Nonlinear Model Predictive Control

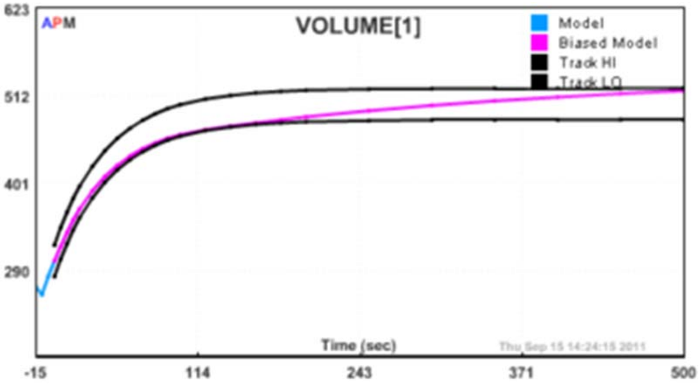
- Trajectory tracking
- Other constraints can be specified
  - Rate of Temperature Change
  - Emissions, Costs, Process unit life, etc.





Nonlinear Model Predictive Control

- Effective over entire range of interest
    - Load Following
    - Large Disturbances
    - Steady State
    - Transient
- Large-scale problems
    - Sparse NLP solvers
    - Simultaneous Solution Approach



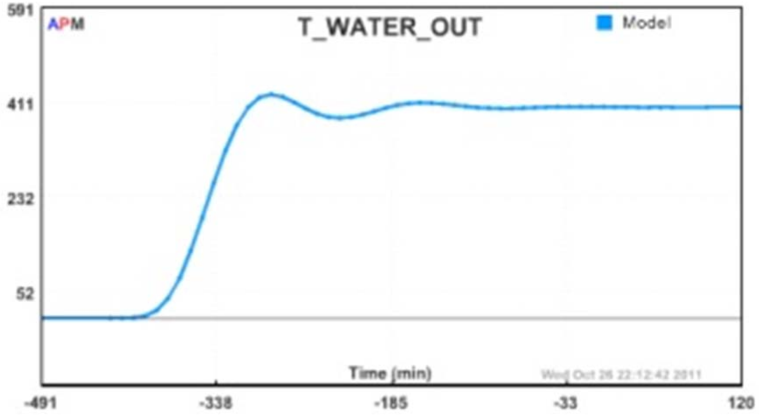
$$\min_{u} J(x,u,\Delta u)$$

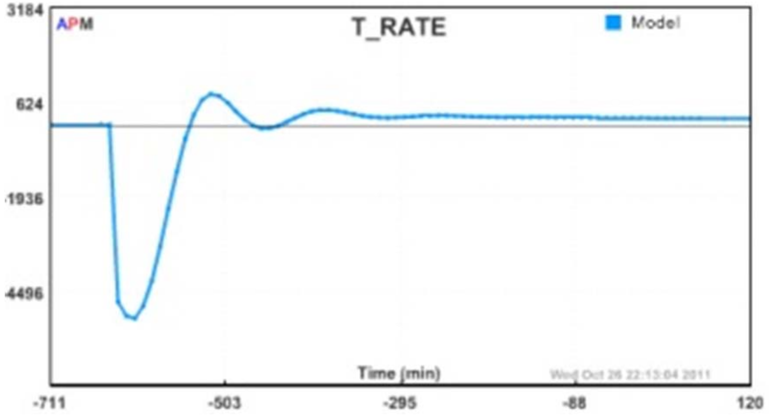
$$\begin{aligned} s.t.\ 0 &= f(\dot{x},x,u) \\ 0 &= g(x,u) \\ 0 &< h(x,u) \end{aligned}$$

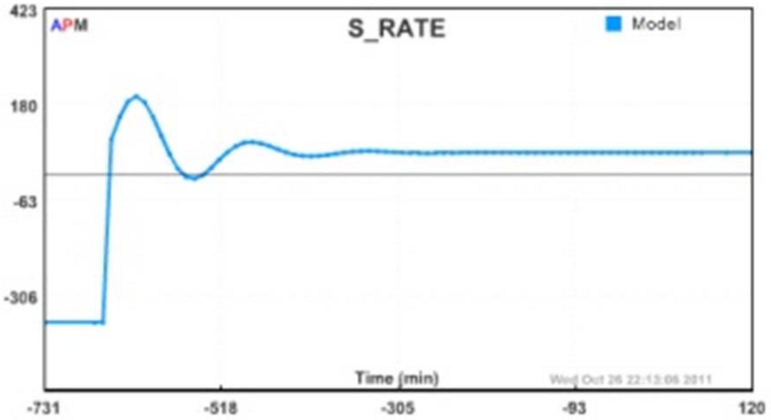
PID Controller

- SIMPLE
  - Easy to Use
- Effective for:
  - Steady state
  - Small Disturbances
- Ineffective
  - Load Cycling
    - Frequently Saturated
    - Violated Rate Constraints

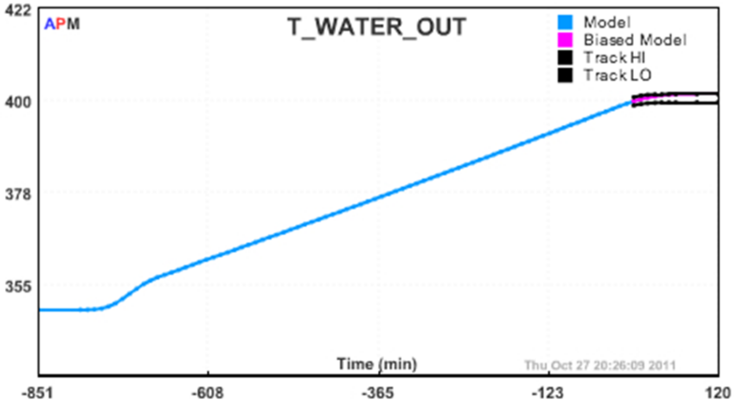
PID Start-Up

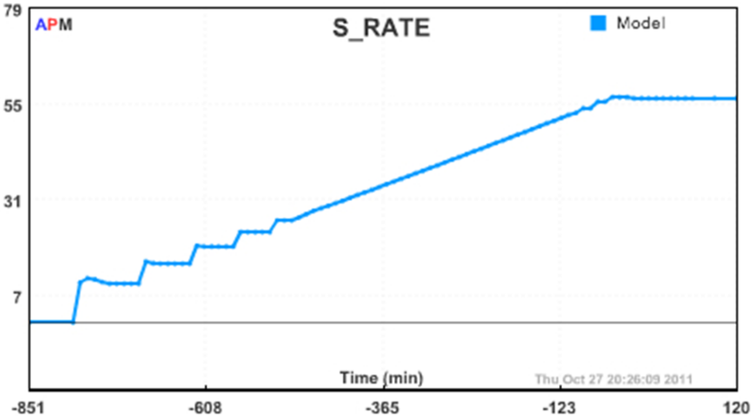

APM
T_WATER_OUT
Model
591
411
232
52
Time (min)
Wed Oct 26 22:12:42 2011
-491
-338
-185
-33
120

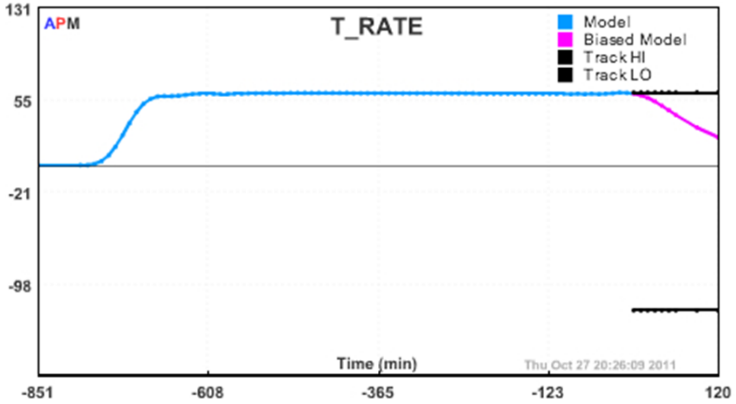

APM
T_RATE
Model
3184
624
-1936
-4496
Time (min)
Wed Oct 26 22:13:04 2011
-711
-503
-295
-88
120


APM
S_RATE
Model
423
180
-63
-306
Time (min)
Wed Oct 26 22:13:08 2011
-731
-518
-305
-93
120

NLC Start Up

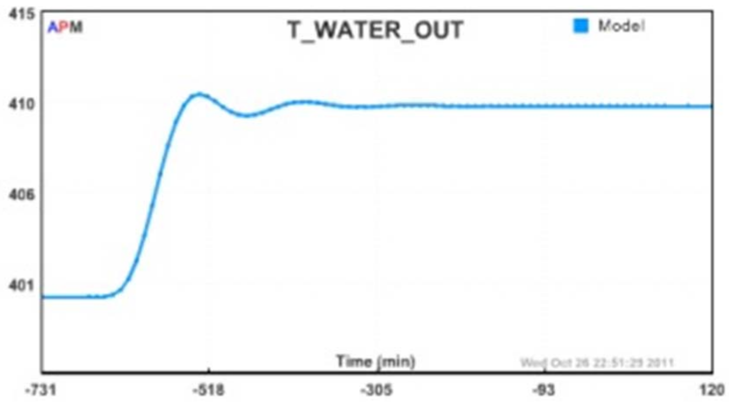

422
400
378
355
APM
T_WATER_OUT
Model
Biased Model
Track HI
Track LO
Time (min)
Thu Oct 27 20:26:09 2011
-851
-608
-365
-123
120

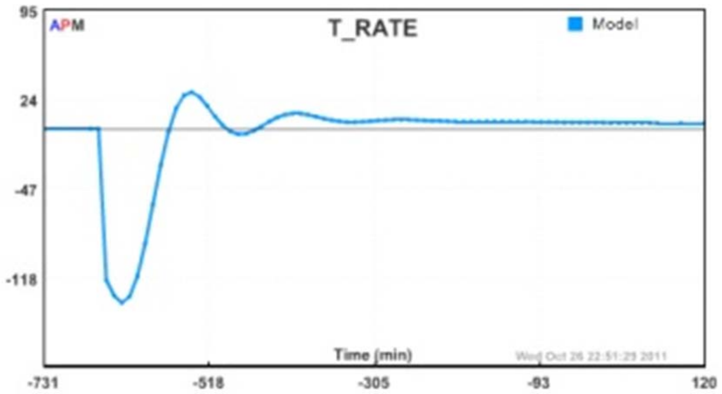

79
55
31
7
APM
S_RATE
Model
Time (min)
Thu Oct 27 20:26:09 2011
-851
-608
-365
-123
120


131
55
-21
-98
APM
T_RATE
Model
Biased Model
Track HI
Track LO
Time (min)
Thu Oct 27 20:26:09 2011
-851
-608
-365
-123
120

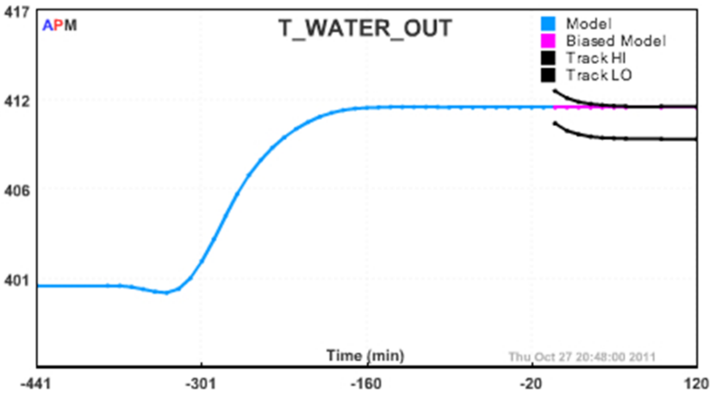
Comparison of Set Point Changes

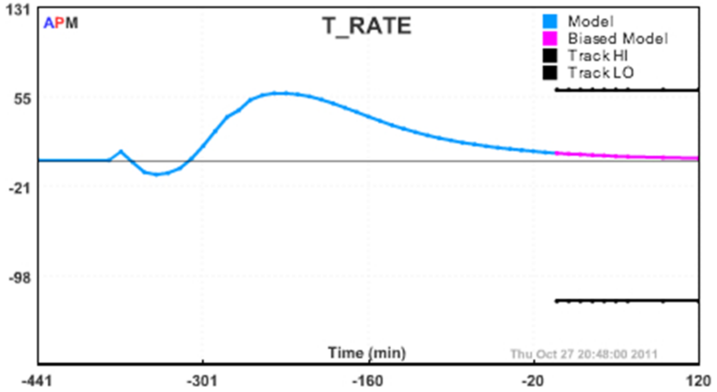
PID Control





Nonlinear Control





Model-Based Controller

- Challenges restrictions by driving to actual process constraints
  - Optimized load changes
    - i.e. Faster/slower, boiler life
- Explicitly Targeted Constraints

Future Work

- Empirical MPC
  - Model identification
  - cause and effect relationships within the boilers MVs and CVs
- Develop thermal stress model of thermal sensitive areas (super heated steam headers)
- Forecasting:
  - Energy availability
  - Time of day pricing
  - Peak power demands
- Energy storage
  - Optimize design and operation
  - Meet peak demand with lower base-load

Acknowledgements

- Kevin Jensen and Dr. John Hedengren
- University of Texas at Austin
  - Kody Powell and his team