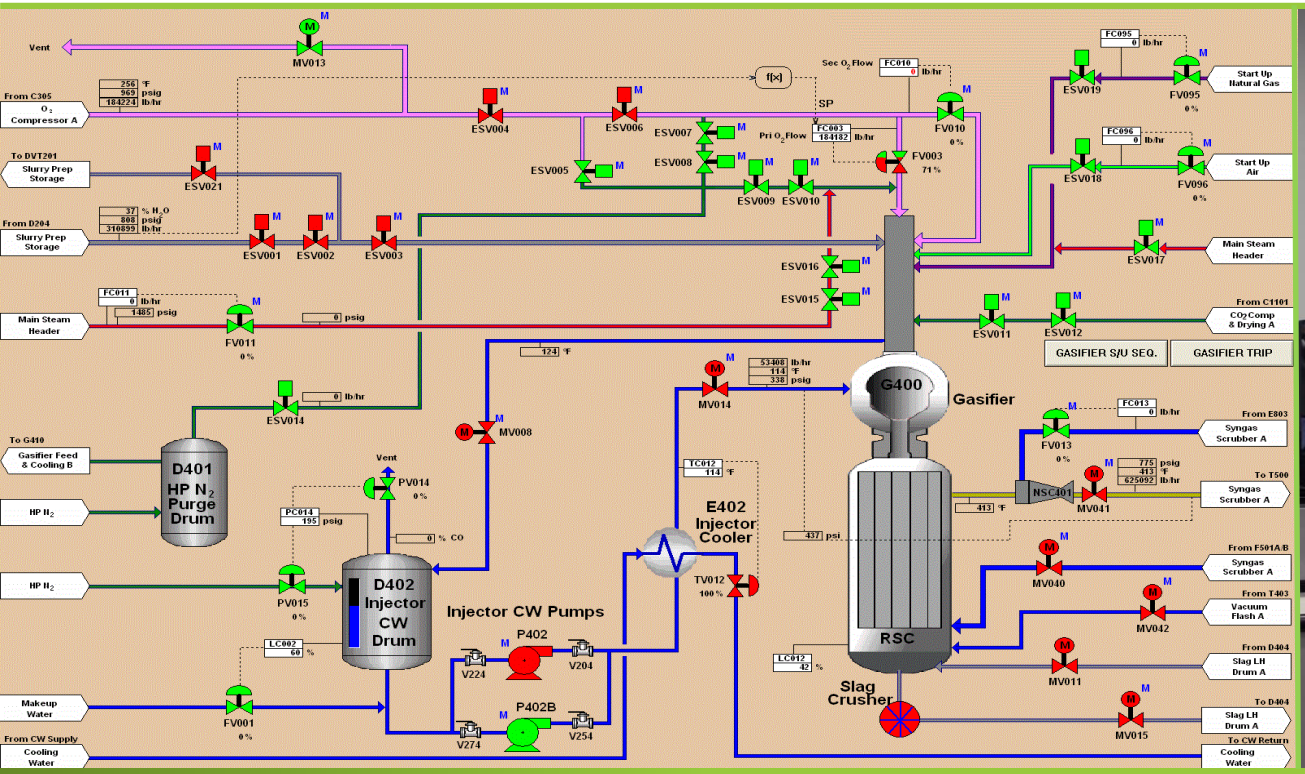
Clearwater Clean Energy Conference
June 16-21, Clearwater, FL

NATIONAL ENERGY TECHNOLOGY LABORATORY

Dynamic Model-Based Digital Twin Technology for Flexible Power Plant Operations and Control

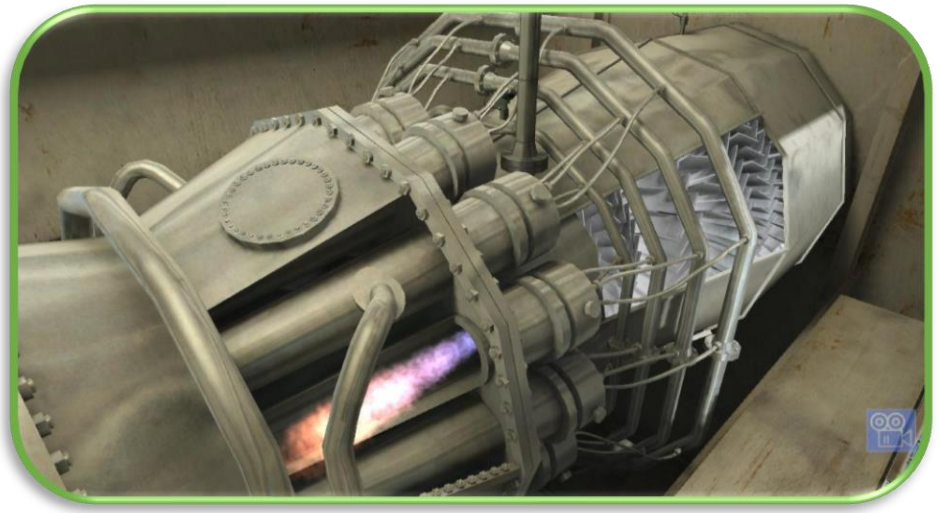
Stephen E. Zitney, NETL and Prof. Debangsu Bhattacharyya, West Virginia University, Morgantown, WV



U.S. DEPARTMENT OF ENERGY

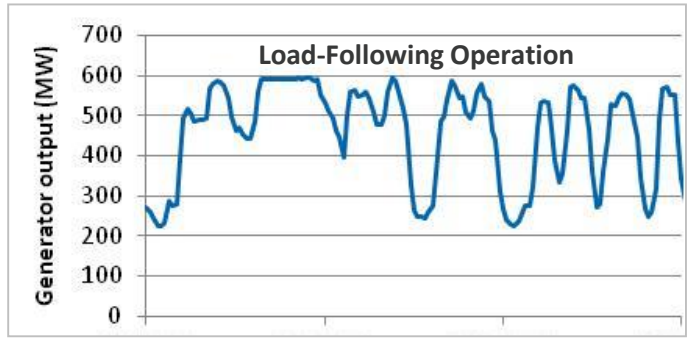
Presentation Overview

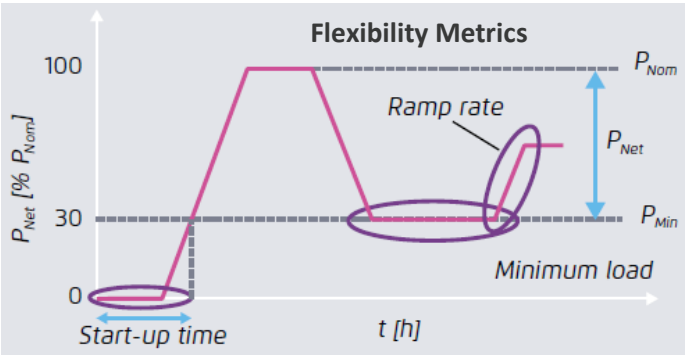
- Key Challenges Facing the Energy Industry
- Digitalization Technologies and Solutions
- Dynamic Model-based Digital Twins
- Application to Power Plant Operations and Control
- Conclusions and Future Work



Key Challenges Facing the Energy Industry
Rapid Transformation of Power Systems

- **Driving Factors**
  - Increasing variable renewable energy resources
  - Growing share of decentralized energy resources
  - Emerging demand side management
- **Key Priority**
  - Enhancing power systems flexibility, while reducing costs and strengthening grid resilience
- **Changing Role of Fossil Power Plants**
  - Increased load-following operation
  - Faster startup and ramp rates
  - Lower minimum loads

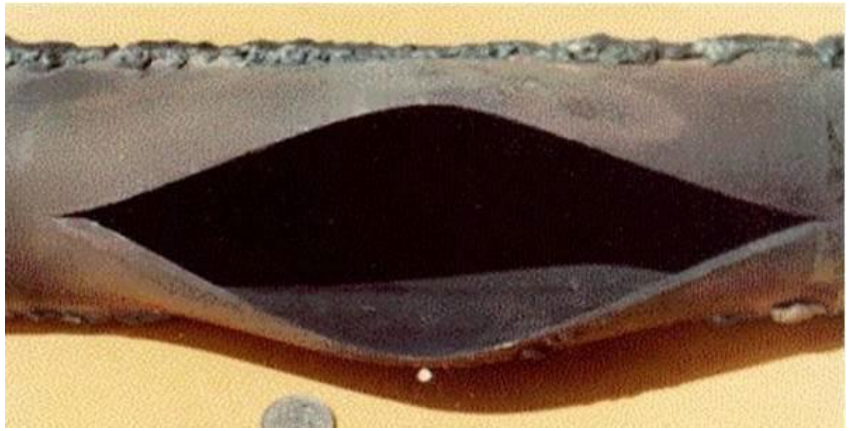




Key Challenges Facing the Energy Industry
Negative Impacts of Power Plant Cycling

- ↓ Plant performance, efficiency, and profitability
- ↓ Equipment health and life expectancy
- ↑ Plant downtime and operations & maintenance (O&M) costs
- ↑ Environmental emissions

Cracked Economizer Header*



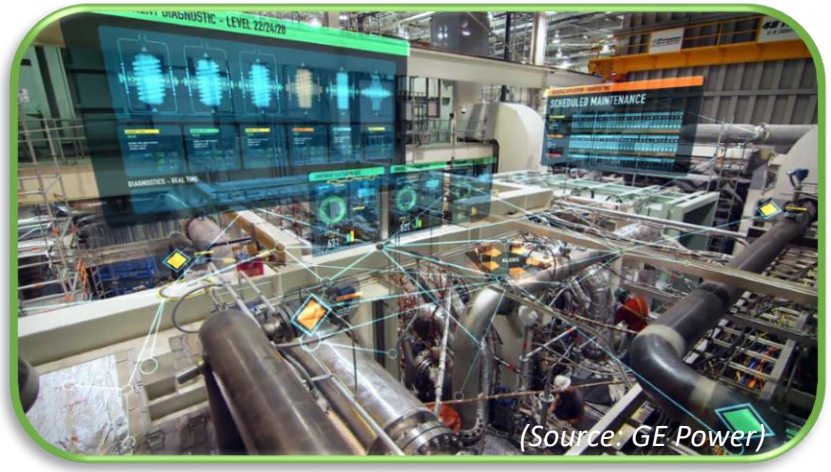
Failed Boiler Tube**

* Hesler, S., "Mitigating the Effects of Flexible Operation on Coal-Fired Power Plants," Power Magazine, August 1 (2011).

** Sakthivel, P., S. Kalaimani, and R. Sasikumar, "Analysis of Tube Failure in Water Tube boiler," International Journal of Innovative Research in Science, Engineering and Technology, Vol. 6, Issue 8, May (2017).

Improving Flexible Power Plant Operations
Digitalization Technologies

- **Advanced process control and optimization**
  - Model predictive control
  - Boiler optimization, intelligent soot blowing
- **Digital twins of physical plant assets**
  - Physics-based dynamic models
  - Data-driven models
  - Virtual/Augmented Reality (VR/AR) models
- **Data analytics, AI, and machine learning**
  - Condition-based monitoring and fault diagnosis
  - Predictive maintenance and asset performance management
- **Digital automation, intelligence, and interconnectivity across fleet-wide enterprise**

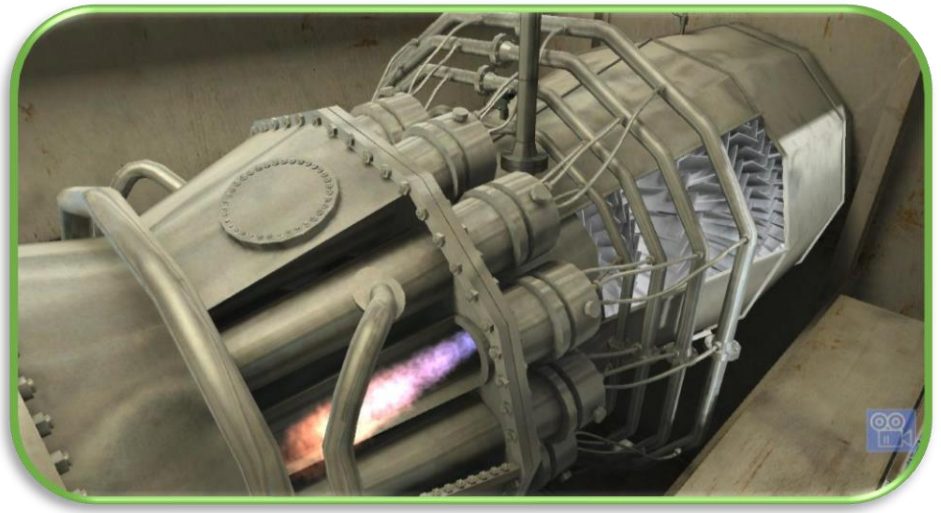


(Source: GE Power)


(Source: Siemens Global)

Presentation Overview

- Key Challenges Facing the Energy Industry
- Digitalization Technologies and Solutions
- Dynamic Model-based Digital Twins
- Application to Power Plant Operations and Control
- Conclusions and Future Work



Power Plant Digital Twin
Integrated Dynamic Simulation and VR Technologies

- High-fidelity, real-time dynamic simulator
- 3D immersive VR-based plant environment
- Real-time data connection
- Virtual digital test bed for power plant R&D
  - Optimal sensor network design
  - Advanced process control
  - Operational flexibility
    - Performance, Monitoring, Fault Diagnosis

Power Plant Digital Twin
Integrated Dynamic Simulation and VR Technologies

- High-fidelity, real-time dynamic simulator
- 3D immersive VR-based plant environment
- Real-time data connection
- Virtual digital test bed for power plant R&D
  - Advanced process control
  - Optimal sensor network design
  - Operational flexibility
    - Performance, Monitoring, Fault Diagnosis

Dynamic Simulator/Control Room

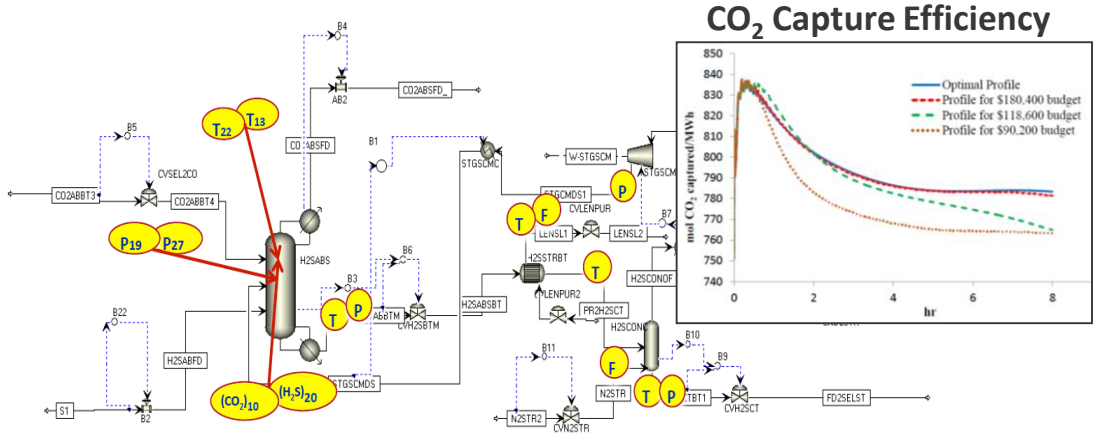
Virtual Power Plant

- **Integrated Gasification Combined Cycle (IGCC)**
  - Chemical Plant: Coal-Fired Gasification with CO_2 Capture (Syngas Production and Cleanup)
  - Power Plant: Combined Cycle (Power Generation)
  - Electrical System: Real-Time Grid Connection

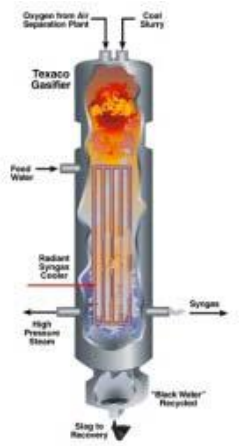
Zitney, S.E., D. Bhattacharyya and R. Turton, "17 - Dynamic IGCC system simulator," In T. Wang and G.J. Stiegel (Eds.), *Integrated Gasification Combined Cycle (IGCC) Technologies*, Woodhead Publishing, pp. 665-697, ISBN 9780081001677, http://dx.doi.org/10.1016/B978-0-08-100167-7.00015-9, (2017).

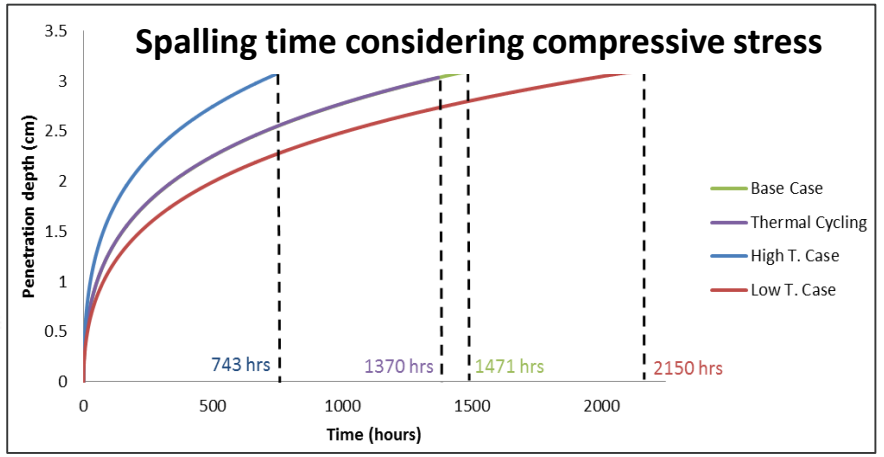
Power Plant Digital Twin
Optimal Sensor Network Design

- **Developed dynamic optimization-based approach to synthesize sensor networks**
  - Two-tier approach: Plant and component
  - Intentional data for various objectives: Performance, Disturbance rejection, State estimation, Condition monitoring, and Fault diagnosis
- **IGCC Applications**
  - Performance: Maximize CO_2 capture efficiency
  - Condition Monitoring: Minimize slag layer thickening and refractory degradation in the gasifier
    - Detailed mechanistic model – slag detachment, deposition, flow, penetration, and spallation
    - Model predictive control strategies to minimize damage



Optimal sensor placement for IGCC CO_2 capture process*





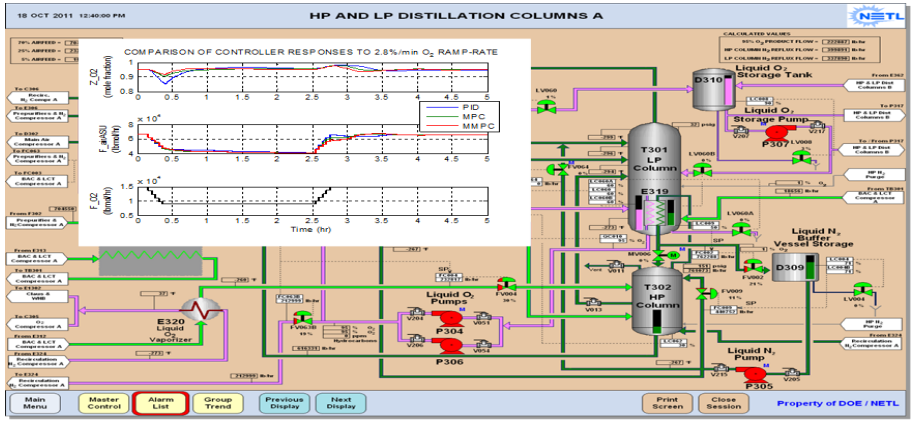
Gasifier refractory degradation**

* Paul, P., D. Bhattacharyya, R. Turton, and S.E. Zitney, "Nonlinear Dynamic Model-Based Multi-Objective Sensor Network Design Algorithm for a Plant with an Estimator-Based Control System," *Ind. Eng. Chem. Res.*, http://dx.doi.org/10.1021/acs.iecr.6b04020 (2017).

** Pednekar, P, "Modeling and Simulation of Components in an Integrated Gasification Combined Cycle Plant for Developing Sensor Networks to Detect Faults," PhD Thesis, Advised by Prof. D. Bhattacharyya, Department of Chemical Engineering, West Virginia University (2016).

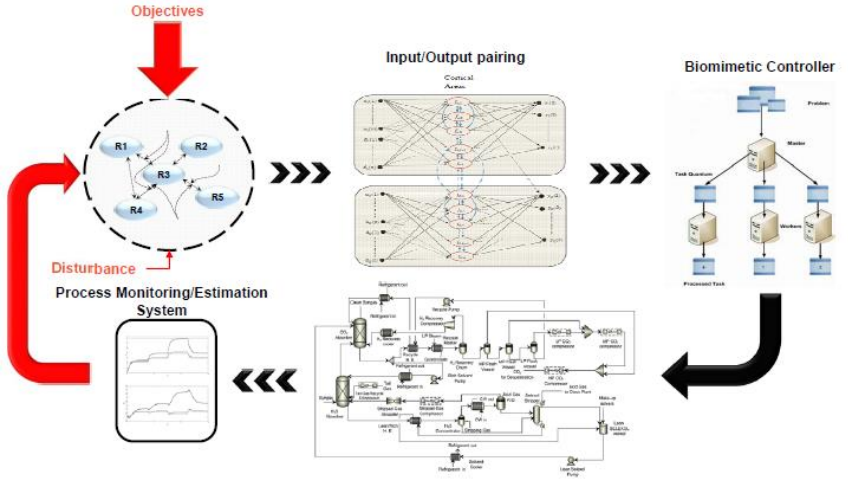
Power Plant Digital Twin
Advanced Process Control for Flexible Operations

- **Multiple Model Predictive Control (MMPC)**
  - Improved ramp rate of Air Separation Unit (ASU) during IGCC load-following operation
  - Provided better dynamic response to disturbances compared to conventional control approaches*



MMPC for improving IGCC-ASU ramp rates

- **Biomimetic Adaptive Control**
  - Demonstrated adaptive, biologically-inspired, distributed multi-agent approach
    - Optimal selection of controlled variables**
    - Biologically-Inspired Optimal Control Strategy (BIO-CS)***
  - Provided better setpoint tracking for control of CO_2 capture rate during IGCC transients



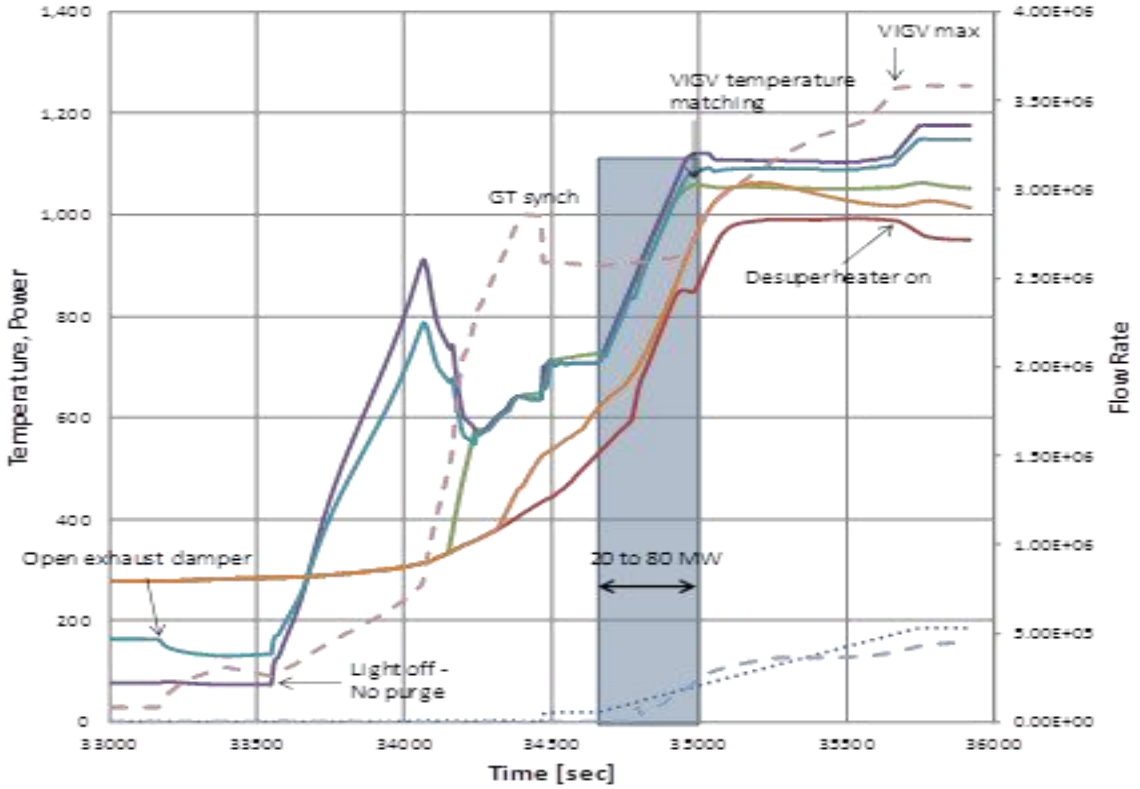
Biomimetic control of IGCC CO_2 capture process

* Zitney, S.E., D. Bhattacharyya and R. Turton, "17 - Dynamic IGCC system simulator," In T. Wang and G.J. Stiegel (Eds.), *Integrated Gasification Combined Cycle (IGCC) Technologies*, Woodhead Publishing, pp. 665-697, http://dx.doi.org/10.1016/B978-0-08-100167-7.00015-9, (2017).
** T. Bankole, D. Bhattacharyya, B. Gebreslassie, U. Diwekar, A biomimetic approach to fast selection of optimal controlled variables using multiagent algorithms and a decomposition approach, Chemical Engineering Science, Vol. 203, 2019, Pp. 475-488.
*** G. Mirlekar, B. Gebreslassie, U. Diwekar, F.V. Lima, Biomimetic model-based advanced control strategy integrated with multi-agent optimization for nonlinear chemical processes, Chem. Eng. Res. and Des., Vol. 140, 2018, Pp. 229-240, 62.

Power Plant Digital Twin
Enhanced Strategies for Flexible Operations

- Collaborated with Associated Electric **580 MWe** NGCC power plant
- Leveraged Combined Cycle portion of NETL IGCC dynamic simulator
- Used operating data and procedures to establish dynamic baseline

- Improved operation and control procedures to reduce temperature gradients during cycling operations



Liese, E.A. and S.E. Zitney, "Using Dynamic Simulation to Evaluate Attemperator Operation in a Natural Gas Combined Cycle with Duct Burners in the Heat Recovery Steam Generator," 140(1):011801-011801-6. doi:10.1115/1.4037709, ASME, *J. Eng. Gas Turbines Power*, (2017).

Conclusions and Future Work

- **Era of digital transformation is accelerating**
- **Energy industries are pursuing opportunities for improving flexible power plant operations**
  - Reduce downtime and O&M costs
  - Increase efficiency, productivity, and profitability
- **Digital Twins are key enabling technologies for R&D and industrial application**
  - Advanced process control and optimization
  - Sensor network design, monitoring, and fault diagnosis
- **Future applications of Digital Twins**
  - Cyber-physical systems for operations and control testing
  - Cybersecurity system testing and validation


(Source: Schneider Electric)

Websites and Contact Information

Office of Fossil Energy: www.energy.gov/fe/office-fossil-energy

NETL: www.netl.doe.gov/

Stephen E. Zitney, Ph.D.

U.S. Department of Energy
National Energy Technology Laboratory
3610 Collins Ferry Road
P.O. Box 880
Morgantown, WV 26507-0880
(304) 285-1379
Stephen.Zitney@netl.doe.gov