MODELING, SIMULATION AND ADVANCED CONTROLS FOR PROTOTYPE CHEMICAL LOOPING

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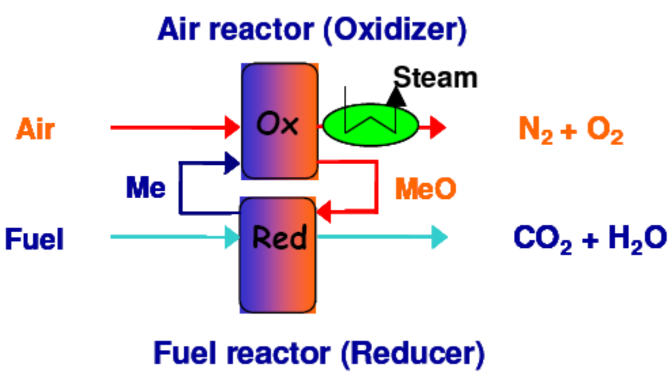
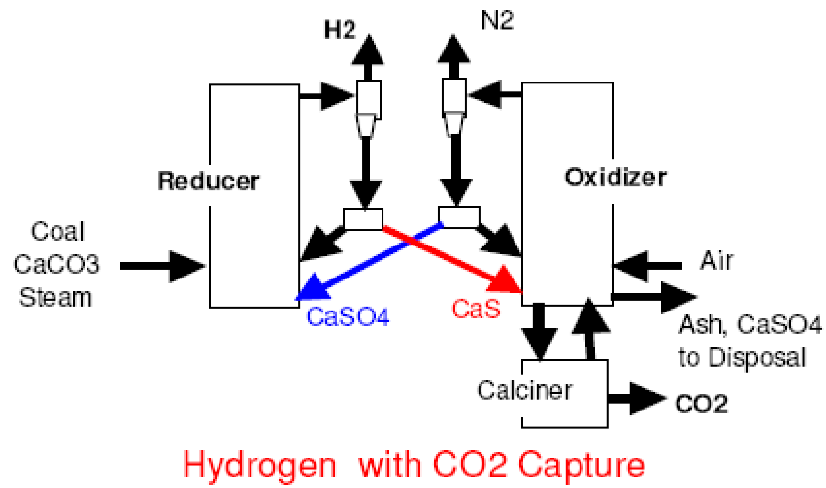
Agenda

What is Chemical Looping (CL)?

- Chemical Looping (CL)
  - A multi-loop coal combustion/gasification process
  - Using a solids oxygen carrier for separating N_2 and O_2 in air
  - Easy CO_2 capture for use or sequestration



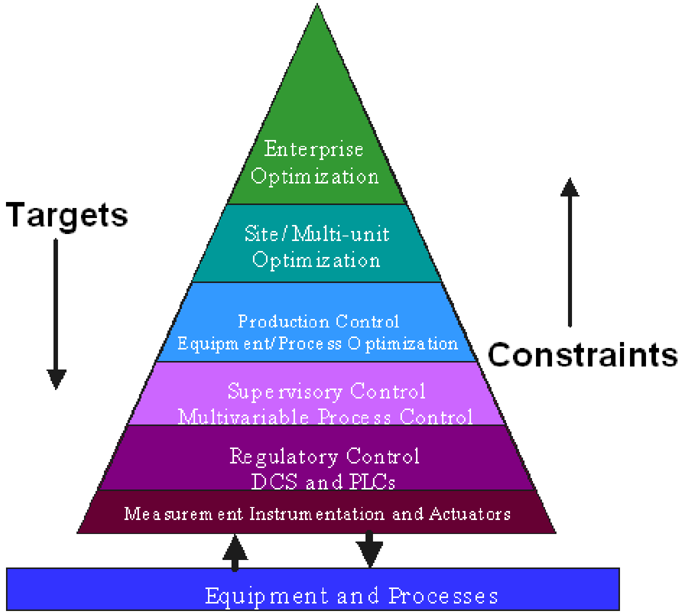
Alstom's MeOx Based Chemical Looping



Alstom's Calcium Based Chemical Looping

What is Advanced Controls?

- Advanced Controls
  - Computer based algorithm/strategy/system that deviates from PID control
  - Usually an optimization solution involved in controller action
  - **Model-Based Predictive Control** (**MPC**) is a typical advanced controller – fit in modern enterprise optimization hierarchy
- Why Advanced Controls
  - Improve capacity and product yield
  - Reduce energy consumption
  - Improve process safety and reduce environmental emissions
  - Increase responsiveness



Why Advanced Controls for CL?

- Multivariable control for better coordination of multi-loop interactions in CL
- Robust control to reject disturbances such as fuel and solids flow variations
- Enable fast load change in wide range operation to better support smart grid
- Enable economic optimization for production cost, energy cost saving and emission (CO_2) cost reduction

What is this Project about?

- Project Title

  Development of Computational Approaches for Simulation & Controls for Hybrid Combustion-Gasification Chemical Looping (CL) Plant

- Project Goal

  To characterize the Chemical Looping process dynamics, and apply advanced multivariable controls to enable optimization of future CL plant operating performance and overall economics.

- Project Sponsorship

  - DOE/NETL (Virtual Engineering of Advanced Power Generation Systems Area1: Sensors & Controls Systems)
  - Alstom – Thermal Power

CL Controls Project Milestones

- DOE/Alstom Project Tasks

Phase I: Jul 2007 - Sep 2009 (Completed)

Milestone 1. Process and Control Performance Benchmark (Taft Engineering)
Milestone 2. Process Characterization/Specification
Milestone 3. Develop PDU Model and Simulation
Milestone 4. Validate Process Model
Milestone 5. Advanced Modeling and Controls work @ UIUC
Milestone 6. Design and Build APC Control Modules and Link to Simulator
Milestone 7. Project Management,Reporting and Presentations
Milestone 8. Investigation and development of sensors for controls

CL Controls Project Milestones

- DOE/Alstom Project Tasks

Phase I Extension: Oct 2009 ~ July 2012

Milestone 1. Prototype Process Characterization/Specification

Milestone 2. Extend Modeling & Simulation to Prototype Process

Milestone 3. Control Analysis for Prototype Scale

Milestone 4. Advanced Sensor Development and Testing

Milestone 5. Project Management, Reporting and Presentations

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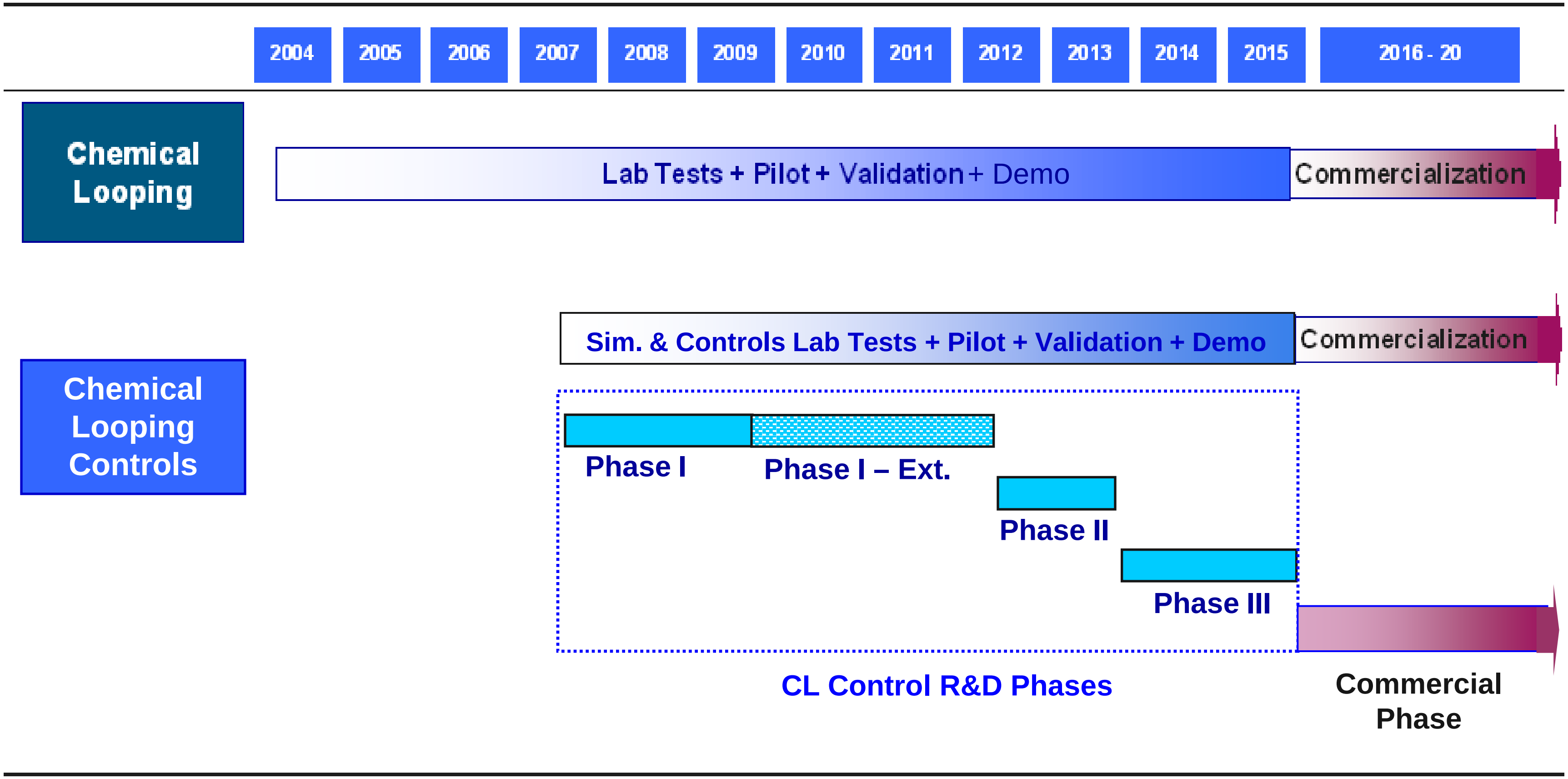
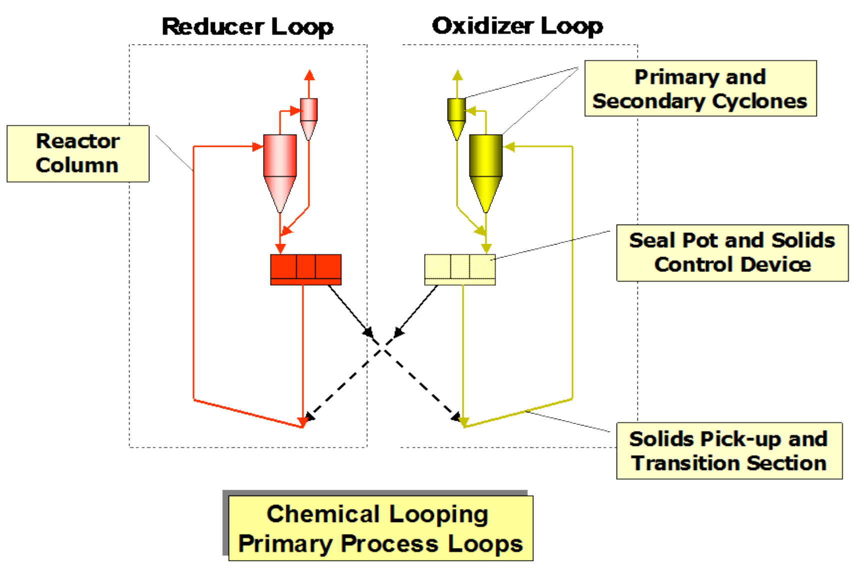
CL Advanced Controls Development Plan
Alstom CL Technology Development Roadmap



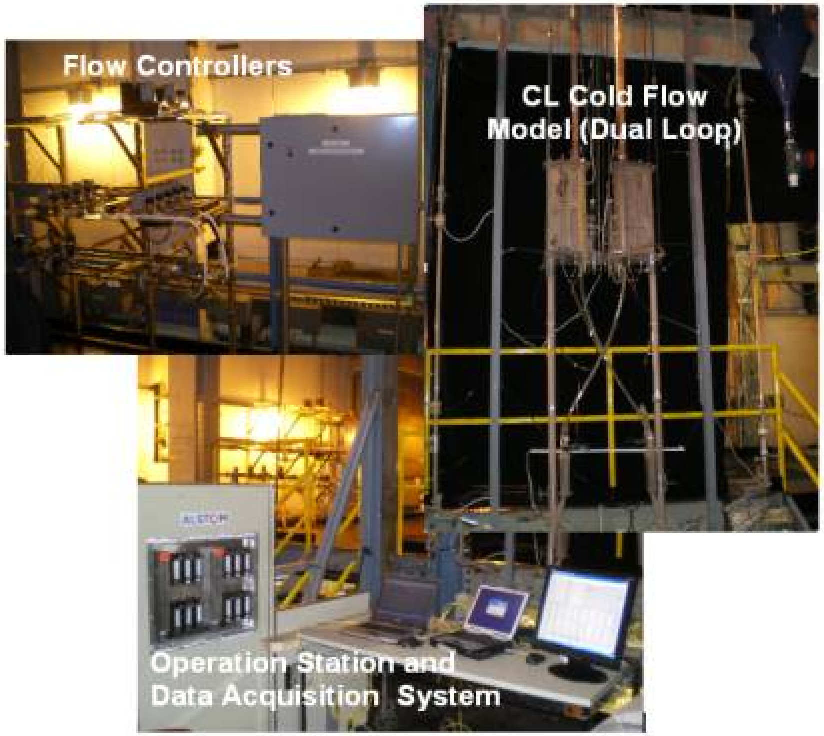
Chemical Looping (CL) Simulation and Advanced Controls is aligned with CL Process Development in Alstom's Chemical Looping Program

CL Advanced Controls Development Plan
Phase I: Modeling & Control of CL Solids Transport

- Step 1: Solids Transport Controls



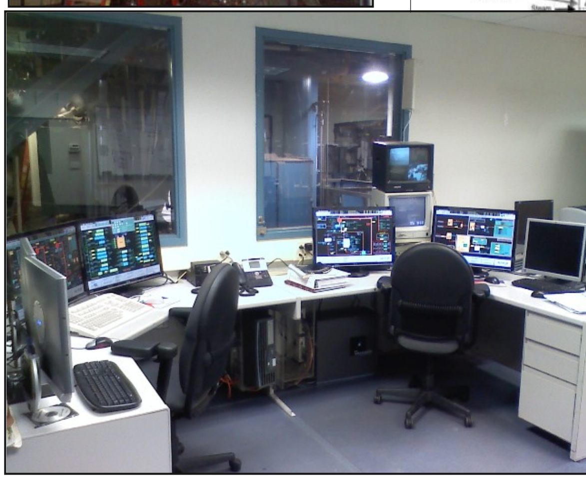
CL Solids Transport Process Diagram

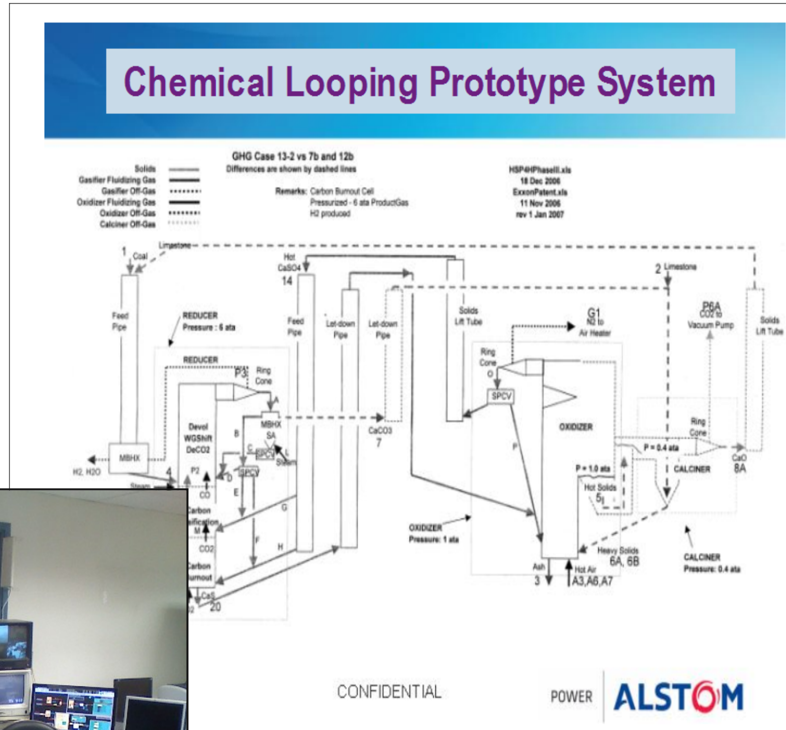


CL Cold Flow Test Facility for Solids Transport Control Investigations

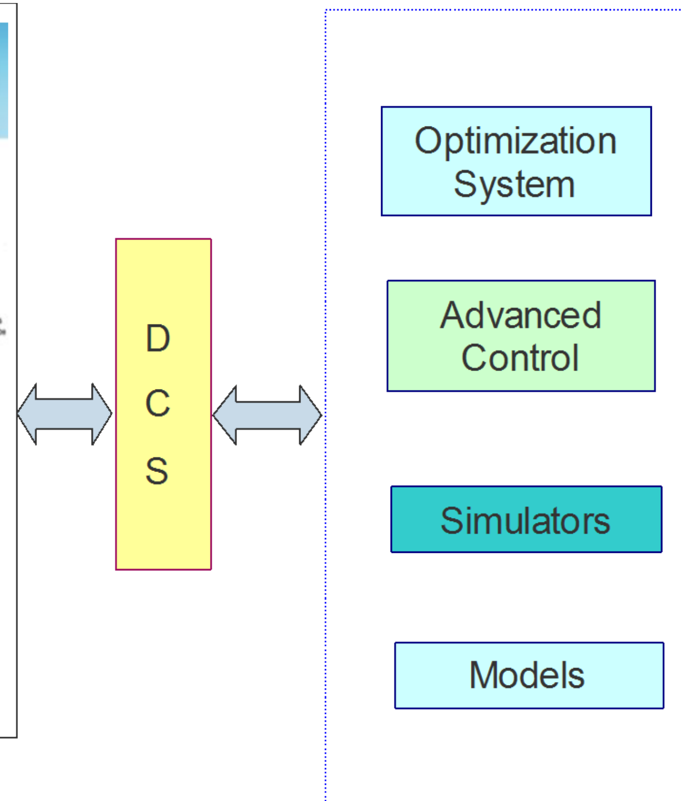
- Step 2: Hot Loops with CL PDU

CL Advanced Controls Development Plan
Phase II: Modeling and Control of CL Prototype Plant





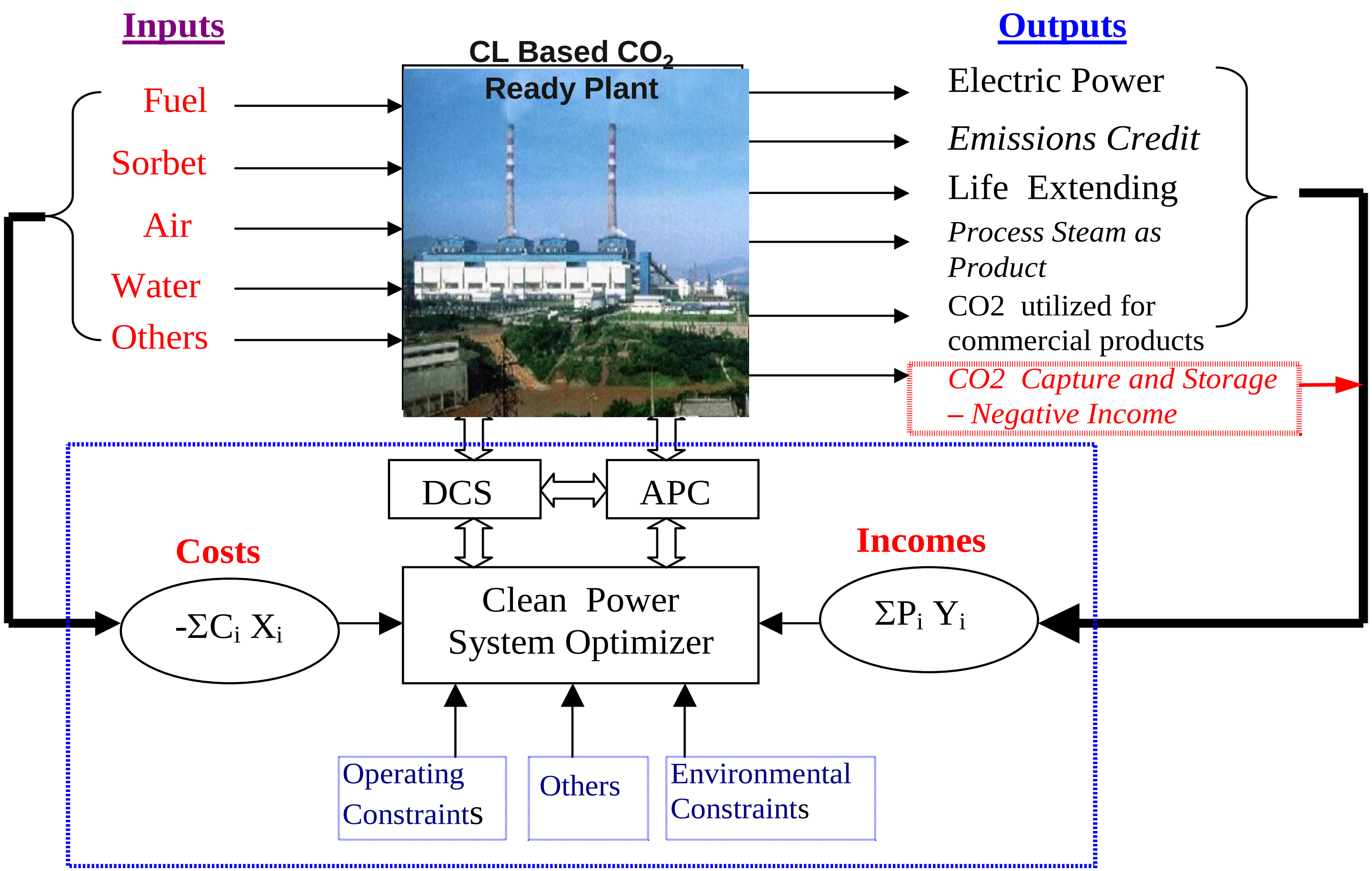
CL Prototype (3MW) Process Design by Alstom's CL Process Team



Simulation and Control of CL Prototype Facility

CL Advanced Controls Development Plan
Phase III, IV: Utility Scale Demo and Commercialization

Integrated Controls Optimization of Utility Scale Plants



New Control System Platform with Optimization Functionalities

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CL Prototype Dynamic Model Equations

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The Governing Equations for Gas Phase:

$$\frac{\partial}{\partial t}(\varepsilon\rho_g)+\frac{\partial}{\partial z}(\varepsilon\rho_g v_g)=0$$

$$\frac{\partial}{\partial t}(\varepsilon\rho_g v_g)+\frac{\partial}{\partial z}(\varepsilon\rho_g v_g^2)+\varepsilon\frac{\partial P}{\partial z}+\varepsilon\rho_g g+\frac{\varepsilon\rho_g v_g^2 f_{gF}}{r}+(1-\varepsilon)\rho_s F_D\left(v_g-v_s\right)=0$$

$$\frac{\partial}{\partial t}\left[\varepsilon\rho_g\left(h-\frac{P}{\rho_g}+\frac{v_g^2}{2g}\right)\right]+\frac{\partial}{\partial z}(\varepsilon\rho_g \mathbf{v}_g\left(h+\frac{v_g^2}{2g}\right))+\frac{\partial}{\partial z}\left(k_g\frac{\partial T_g}{\partial z}\right)$$

$$-\frac{6}{d_p}(1-\varepsilon)h_{sg}\left(T_s-T_g\right)+\frac{2h_{wall}\left(T_g-T_{amb}\right)}{r}+S_{rg}=0$$

The Governing Equations for Solids Phase:

$$\frac{\partial}{\partial t}((1-\varepsilon)\rho_s)+\frac{\partial}{\partial z}((1-\varepsilon)\rho_s v_s)=0$$

$$\frac{\partial}{\partial t}((1-\varepsilon)\rho_s v_s)+\frac{\partial}{\partial z}((1-\varepsilon)\rho_s v_s^2)+(1-\varepsilon)\rho_s g-(1-\varepsilon)\rho_s F_D(v_g-v_s)=0$$

$$(1-\varepsilon)\rho_s c_{ps}\frac{\partial T_s}{\partial t}+(1-\varepsilon)\rho_s c_{ps} v_s\frac{\partial T_s}{\partial z}+\frac{6}{d_p}(1-\varepsilon)h_{sg}\left(T_s-T_g\right)+S_{rs}=0$$

CL Prototype Dynamic Model Equations

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The Governing Equations for Species Balance:

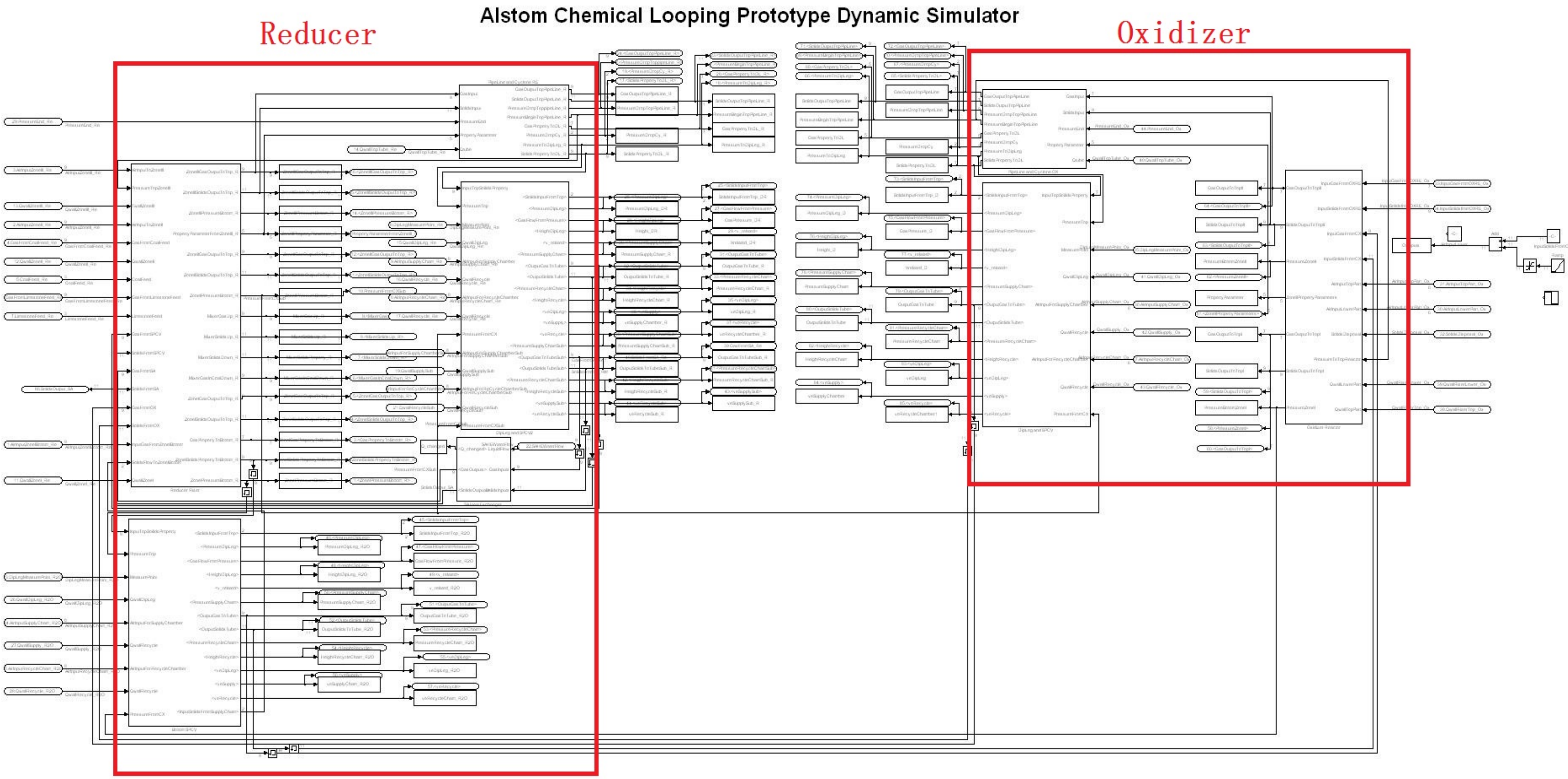
$$V\frac{d}{dt}\left(x_i^s(1-\varepsilon)\rho_s\right)=\dot{m}_{in\_i}^s-\dot{m}_{in\_i}^s+VM_{sw}^iR_i^s$$

$$V\frac{d}{dt}\left(x_i^g\varepsilon\rho_g\right)=\dot{m}_{in\_i}^g-\dot{m}_{out\_i}^g+VM_{gw}^iR_i^g$$

with

$\sum_i x_i^s = 1$ and $\sum_i x_i^g = 1$

CL 3MWth Prototype Process Dynamic Simulator



The dynamic simulation model has been validated by using design data and preliminary test data from the prototype facility.

Agenda

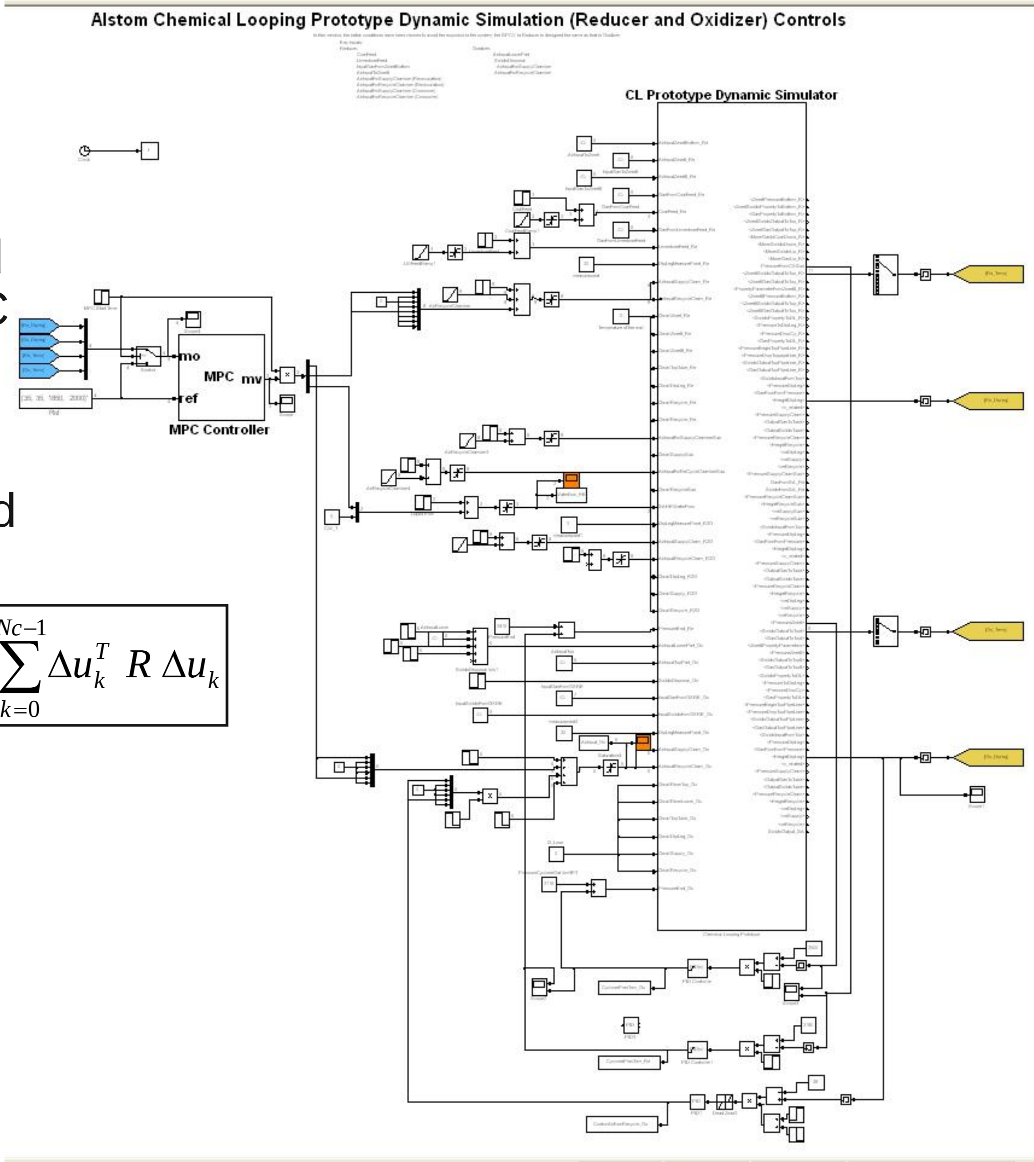
1	Introduction
2	CL Advanced Control Development Plan
3	CL Prototype Dynamic Model
4	MPC Design and Simulation Results
5	Conclusions and Future Work

CL Prototype Process MPC Design

- MPC designed to control
  - Reactor temperatures
  - Reactor Inventories

- Test data from the simulator used to build a dynamic model for MPC

- Different cases of control simulations carried out for MPC and PID controllers and compared



$$\min_{\Delta u} J, \quad with\ J = \sum_{k=1}^{Np} (\hat{y}_k - y_{s,k})^T\ Q\ (\hat{y}_k - y_{s,k}) + \sum_{k=0}^{Nc-1} \Delta u_k^T\ R\ \Delta u_k$$

Subject to

$$\hat{y}_{k+1} = f(y_{past}, u_{past}, u_k, \theta)$$

$$u_{\min} \le u_k \le u_{\max}$$

$$y_{\min} \le y_k \le y_{\max}$$

$$\Delta u_{\min} \le \Delta u_k \equiv u_k - u_{k-1} \le \Delta u_{\max}$$

Control Simulation Results – Case 1

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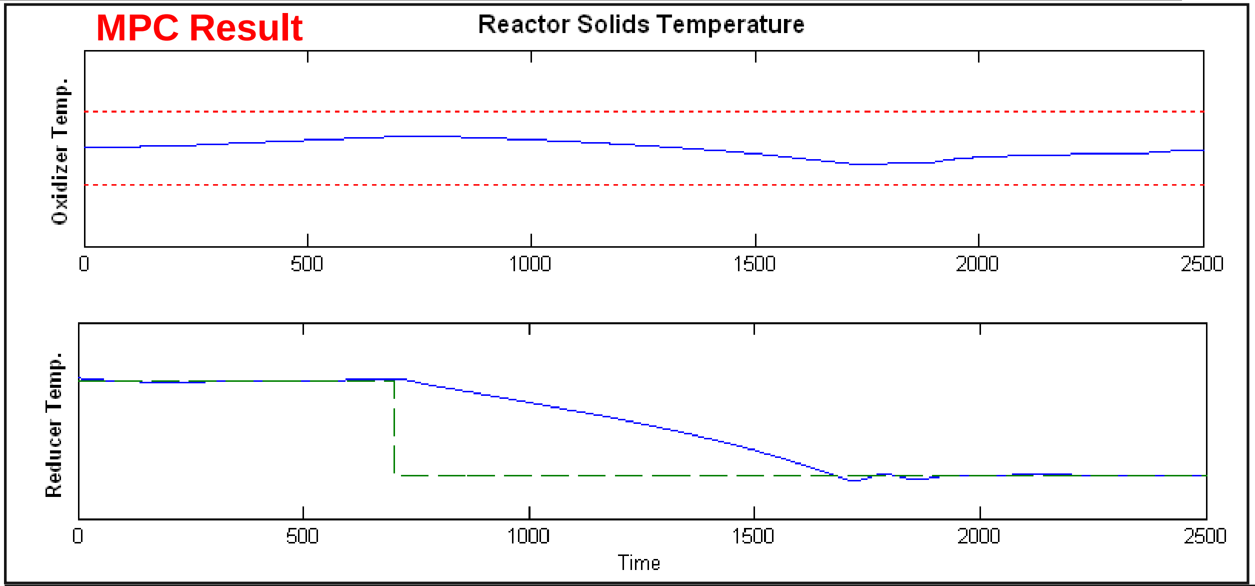
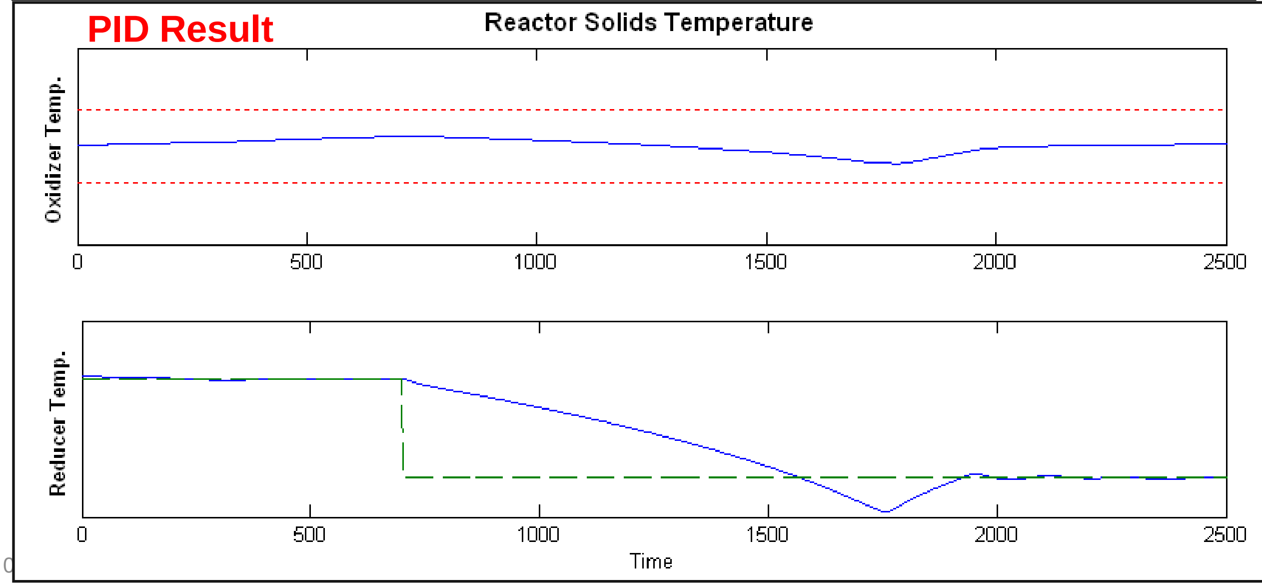
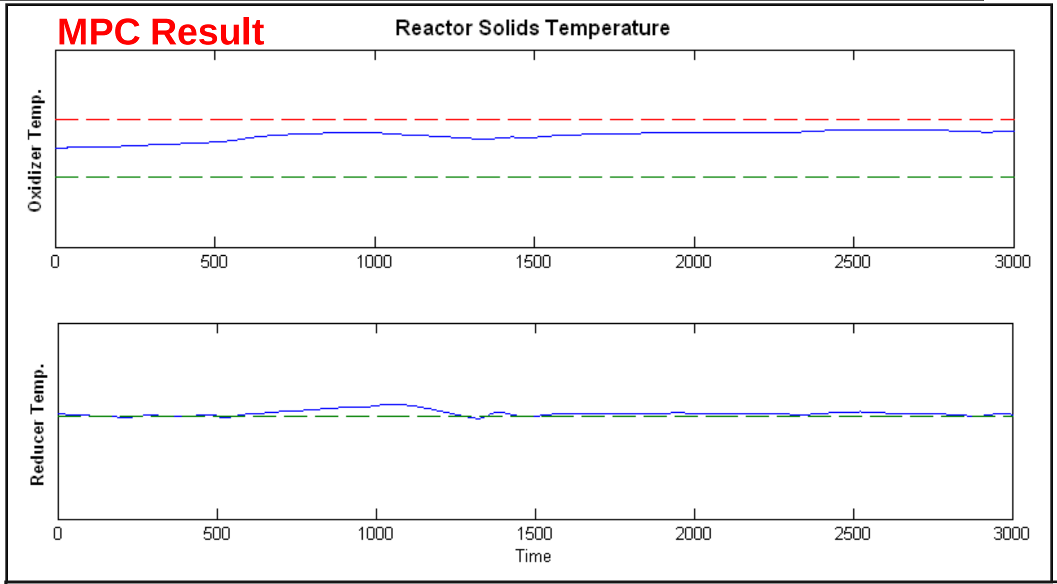
- Case 1: Reactor temperature setpoint changed @ t = 700
- MPC controlled the reactor temperature with less overshoot
- Dynamic model in MPC able to predict the process response and pre-act accordingly

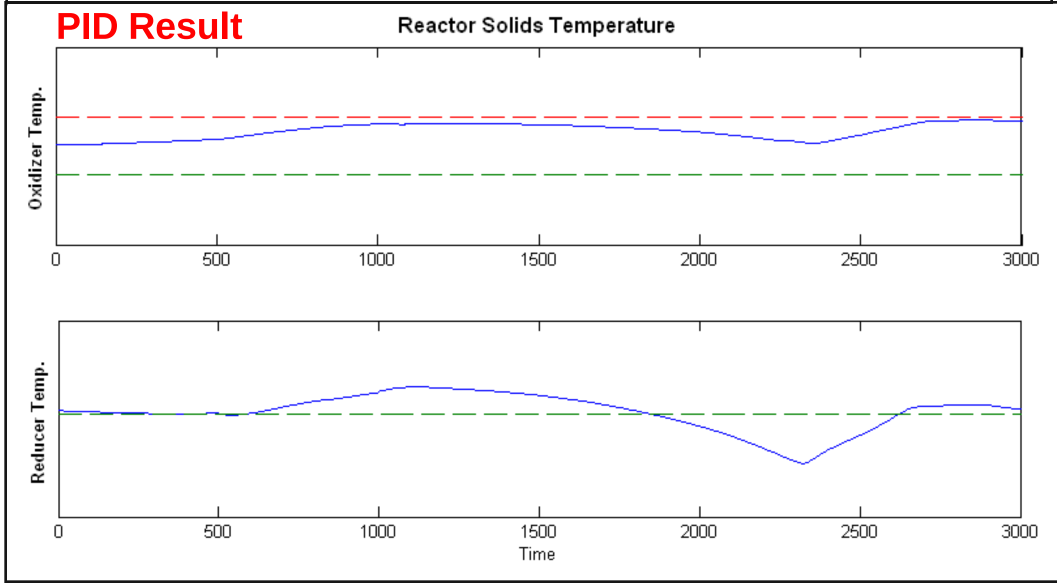




Control Simulation Results – Case 2

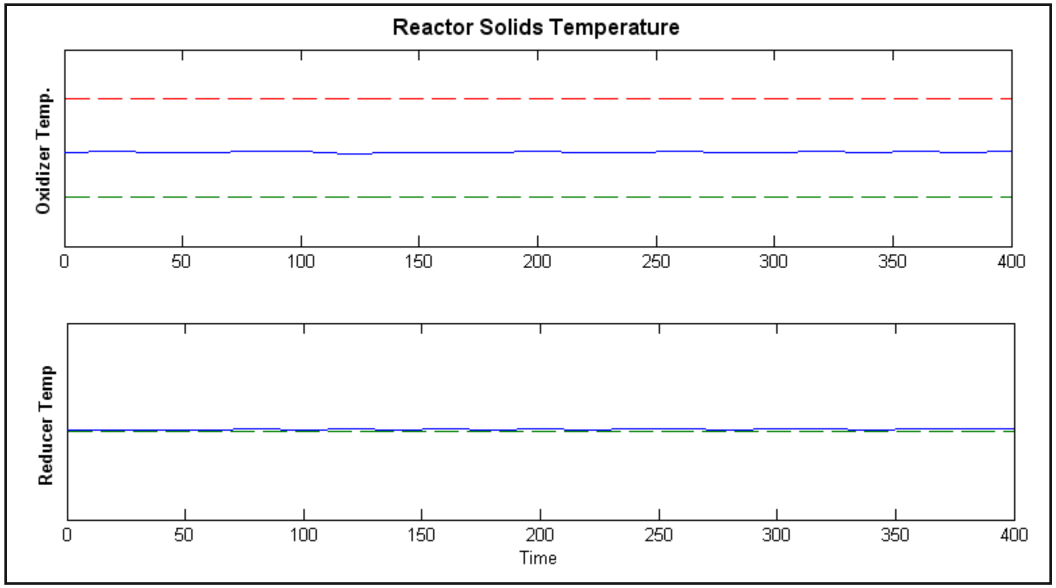
- Case 1: Unmeasured step disturbance in a heat exchanger introduced between @ t = 700 and t = 1200
- MPC controlled the temp. with less fluctuation
- MPC able to predict responses to current control actions, utilize multiple variables and monitor MV saturation to better handle the disturbance in the process





CL Prototype Process NMPC Design

- A nonlinear MPC (NMPC) based on reduced order first principles model designed and developed
- NMPC controller being tested and tuned on the CL Prototype dynamic simulator
- Simulation results show good control performance
- Work underway to prepare for real-time application in the 3MWth CL Prototype facility



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Summary and Conclusions

- Technical approach to modeling and controls of CL pilot scale and 3MWth Prototype proved feasible
- CL 3MWth Prototype dynamic simulator developed and validated with design data
- CL 3MWth Prototype control schemes (PID and MPC) tested on the dynamic simulator
- Advanced sensors are also prepared to be installed and tested in the 3MWth CL Prototype facility

Future Work

- The CL Prototype dynamic simulator will be further refined by using operation and test data from the 3MWth CL Prototype facility
- The MPC design is planned to be installed and tested in the 3MWth CL Prototype facility
- Work on nonlinear MPC based on reduced order first principle model and empirical models will be continued
- Integrated advanced controls designs for commercial demonstration CL project

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