ALSTOM's Chemical Looping Combustion Prototype for CO_2 Capture from Existing Pulverized Coal Fired Power Plants

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2012 CO_2 Capture Technology Meeting , July 9 – 12, 2012

NETL

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Agenda

1st topic	General Project & Technology Background	
2nd topic	Phase 0 to III Activities	
3rd topic	Phase IV Activities and Status	
4th topic	Next Steps	

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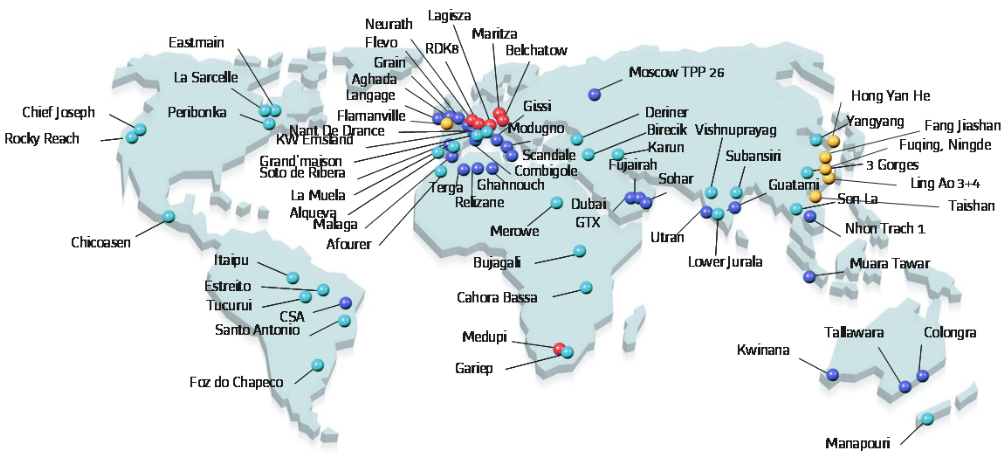
The Alstom Group:
a Worldwide Leader in Power Generation



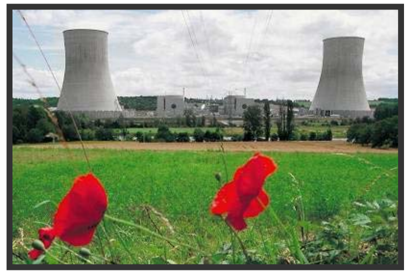
Over 41 GW under execution

- Nuclear
- Hydro
- Steam → **Chemical Looping Technology Development**
- Gas

Full Power Systems Portfolio


N 1 in hydro power


N 1 in integrated power plants


N 1 in conventional nuclear power island


Recent acquisitions of solar & wind power


N 1 in air quality control systems


N 1 in services for electric utilities

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Project Overview
Project Goals and Objectives

- Chemical Looping Program:
  - Develop and commercialize chemical looping process to meet the goals for new or existing coal-fired power plants.
- Prototype Project:
  - Design (BP1), build, and test (BP2) a 3 MWth Prototype to demonstrate Chemical Looping
    - Systematic Testing
    - Extended auto-thermal operation
  - Obtain engineering and operating information necessary to design and build a reliable follow-on demonstration plant.

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Alstom's Chemical Looping Development Targets:

- Over 90% CO_2 capture from coal
- Less than $20/ton avoided cost of CO_2 capture
- Capital cost 20% < conventional steam plant (w/o CO_2 capture)
- Applicable to retrofit and new coal-fired power plants
- Retrofit < 20% increase in COE
- Beat steam power and IGCC performance and economics, world-wide
- Medium-Btu syngas or hydrogen without oxygen plant
- Economical H_2 production at low cost

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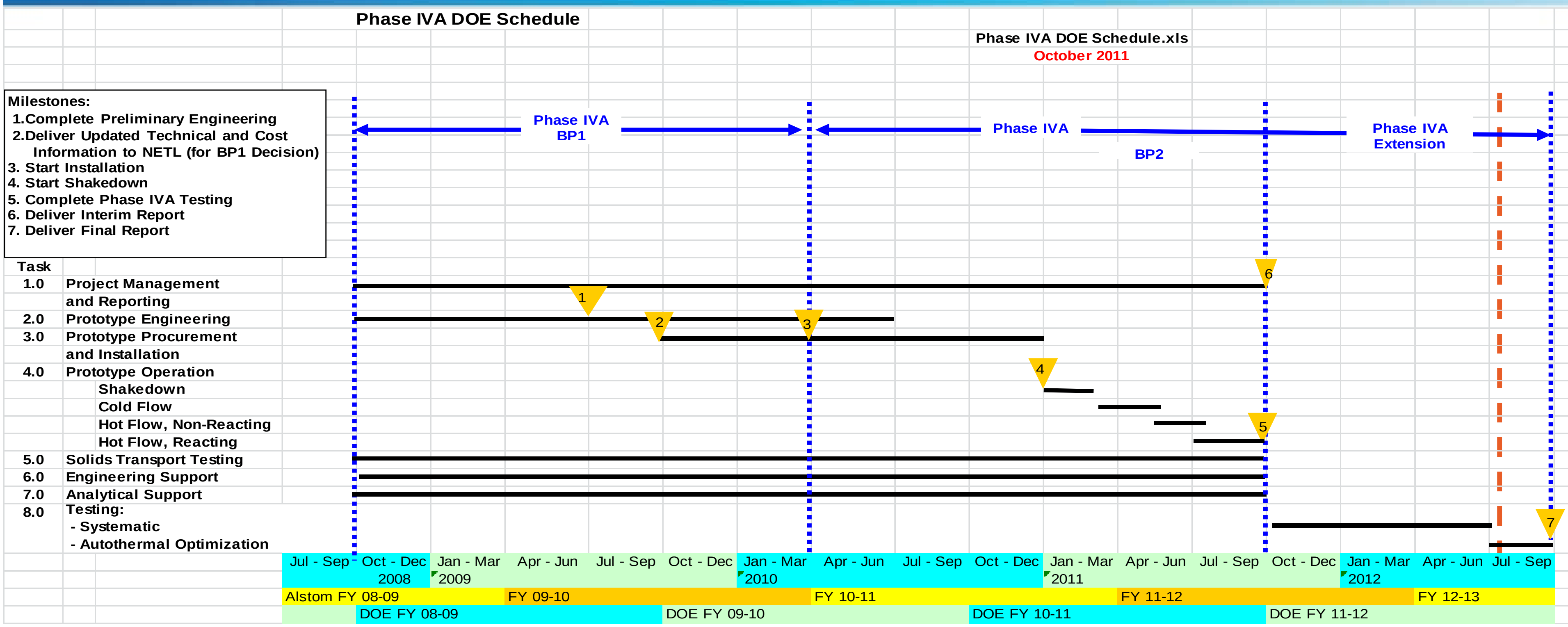
Chemical Looping Prototype Schedule As Planned



Major Milestones:

1. Complete Preliminary Engineering
2. Deliver Updated Technical and Cost Information to NETL (for BP1 Decision)
3. Start Installation
4. Start Shakedown
5. Complete Phase IVA Testing
6. Deliver Interim Report
7. End of Phase IVA Program

Phase IVA is on Schedule

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Project Overview – Phase IV Funding

Total Budget Period 1 & 2
October 2008 to September 2011

DOE Funding	$7,395,624
Alstom Funding	$1,848,906
Total Budget	$9,244,530

Total Budget Period 2 Extension
October 2011 to Present

Alstom Funding	$1,500,000

Total Budget 2008 to Present	$10,744,530

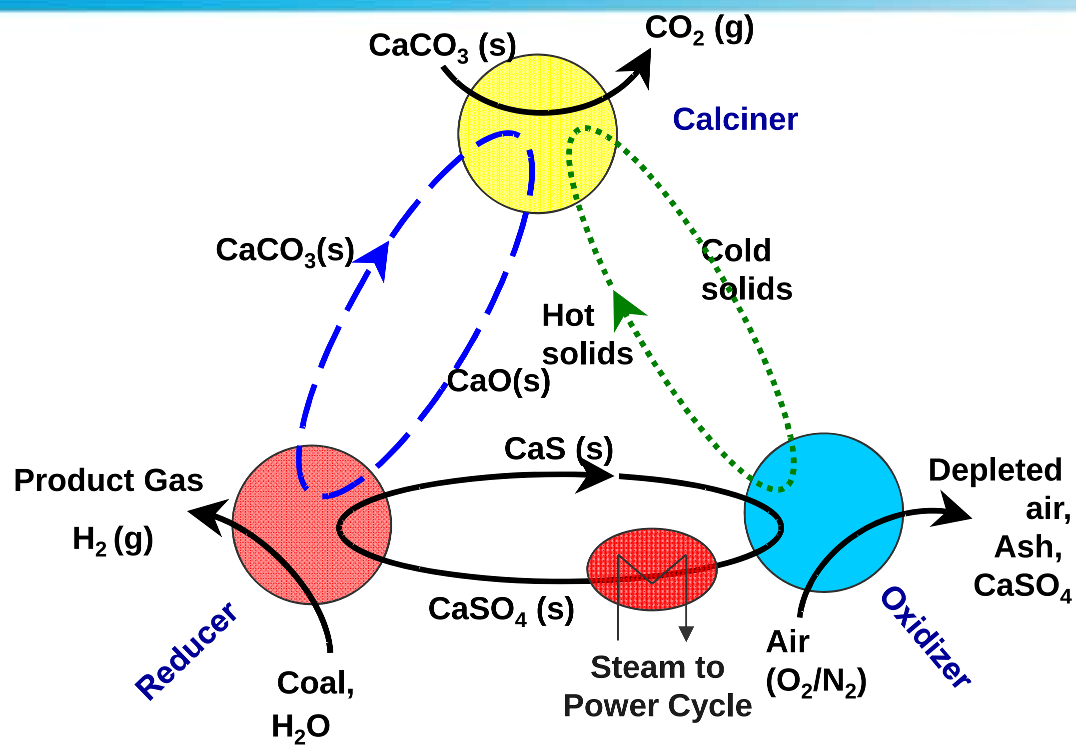
Participants:

Alstom's Limestone Based Chemical Looping (LCL™) Concept & Process Options

Option 1 – **Chemical looping combustion**
- Excess air ($CaSO_4$) to fuel
- Product gas is CO_2
- Heat produces steam for power

Option 2 – **Chemical looping gasification**
- Excess fuel to air ($CaSO_4$)
- Product gas is Syngas
- No inherent CO_2 capture

Option 3 – **Hydrogen production**
- Add CaO-$CaCO_3$ to Option 2
- Add calciner
- Product gas is H_2
- Calciner off-gas is CO_2



Main Reactions:

<u>Air Reactor (Oxidizer)</u>

CaS + 2O_2 -> CaSO4 + Heat

<u>Fuel Reactor (Reducer)</u>

2 C_{fuel} + $CaSO_4$ + Heat -> CaS + 2 CO_2

8 H_{fuel} + $CaSO_4$ + Heat -> CaS + 4H2O

Alstom's LCL™ process is suited to coal

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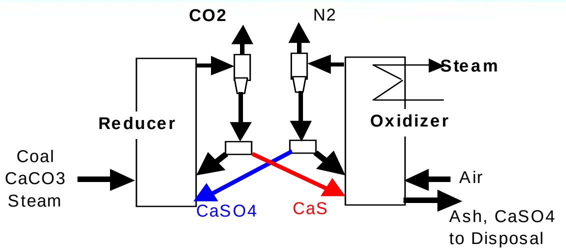
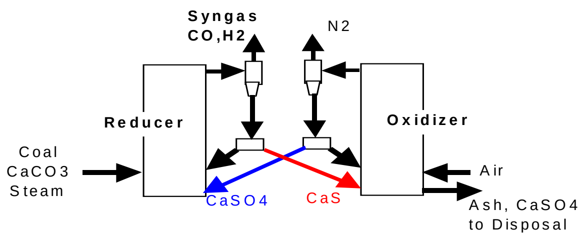
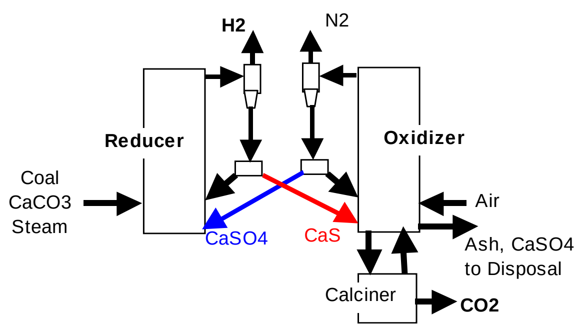
Chemical Looping Process: Options and Applications



Option 1 – Combustion with CO2 Capture



Option 2 – Syngas with no CO2 Capture



Option 3 – Hydrogen with CO2 Capture

Applications – LCL™

- CO_2 Capture – PC Retrofit
- CO_2 Capture – CFB Retrofit
- CO_2 Capture-Ready Power Plant
- Advanced Steam Cycles with CO_2 capture

- IGCC with Down-Stream CO_2 Capture
- Industrial Syngas production
- Coal-to-Liquid Fuels

- CO_2 Capture – PC Retrofit
- CO_2 Capture – CFB Retrofit
- CO_2 Capture-Ready PC/CFB Power Plant
- Advanced Steam Cycles with CO_2 capture
- IGCC with CO_2 Capture
- Fuel Cell Cycles with CO_2 Capture
- Industrial Hydrogen with CO_2 Capture

Flexible technology with low cost

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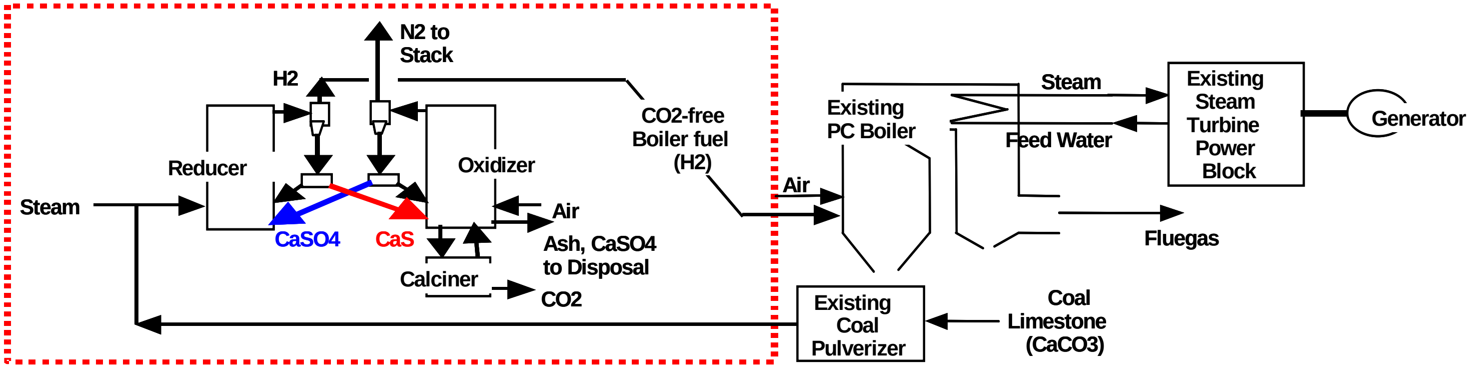
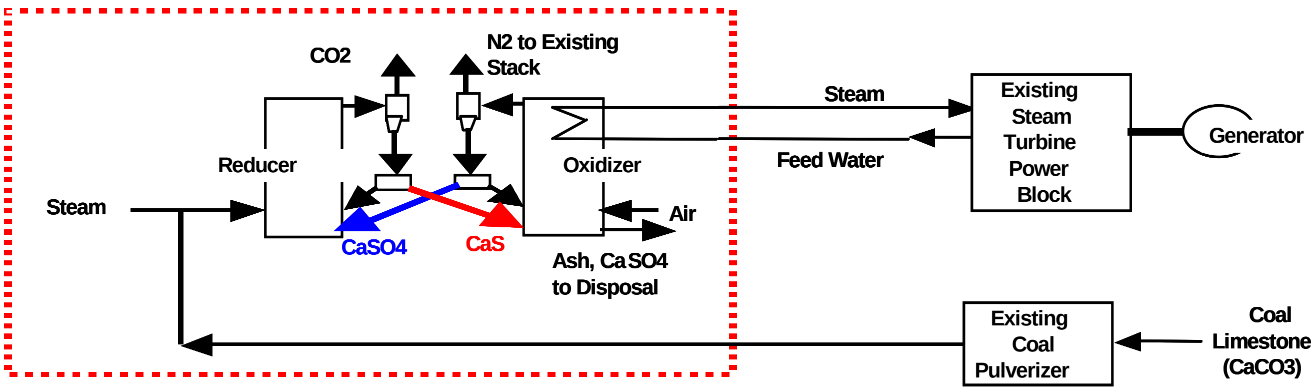
Chemical Looping Overview
Retrofit Options



Concept 1 –Chemical Looping CO_2 Free Fuel; Minimum Boiler Modifications (Option 3)



Concept 2 –Chemical Looping Oxidize Replaces/Modifies Boiler (Option 1)

Retrofit Options at < 20% Increase in COE with CO_2 Capture

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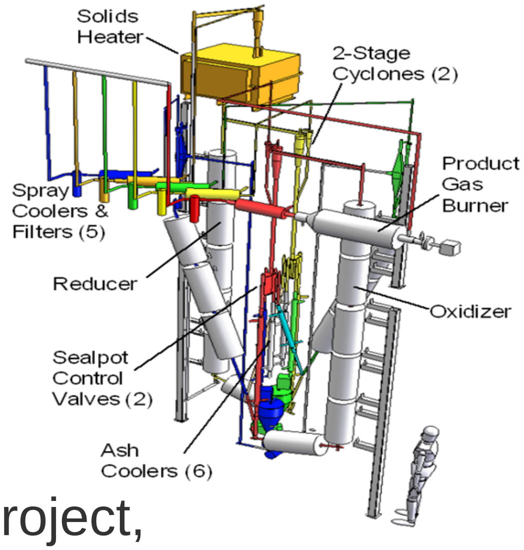
Limestone CLC Development Timeline

- Earlier Program:
  Hot Solids Gasification: 1996-2001
  - ✓ Process and Sorbent Investigation
  - ✓ Economic Evaluation
  - ✓ Lead to Chemical Looping Program



- Chemical Looping Development
  - ✓ Phase 0 (2001) - Alstom's Internal Development Project, Construction of the Process Development Unit (PDU)
  - ✓ Phase I (2003) - DOE Program Started, Verified Sorbent Chemistry and Solids Transport
  - ✓ Phase II (2005) -Verified Gasification Chemistry and Process Control Strategy
  - ✓ Phase III (2006) - Developed Automatic Control System
  - ✓ Phase IVA (2008) - Built 3 MW Prototype, Shakedown and Initial testing

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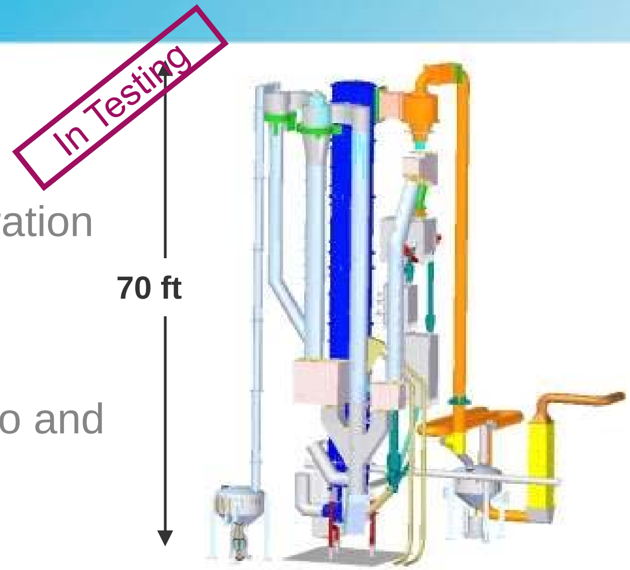
Prototype Construction and Operation
Chemical looping – 3 MWth Limestone based Prototype Coal

- Main objectives:
  - Design, engineering, construction, commissioning and operation of a 3 MWth CaS prototype,
  - Autothermal operation of Limestone-based prototype,
  - Proof of concept – deliver data required to scale up to Demo and commercial size
- 50 month program
  - Shakedown completed
  - First coal fire completed June 2011
  - Autothermal operation Scheduled for August/Sept. 2012
- Total approved budget: 9.25 M$, cost share by US-DOE and Alstom
- Partners: US-DOE/NETL & Alstom



3 MWth Prototype Model

Rear View of Prototype Building

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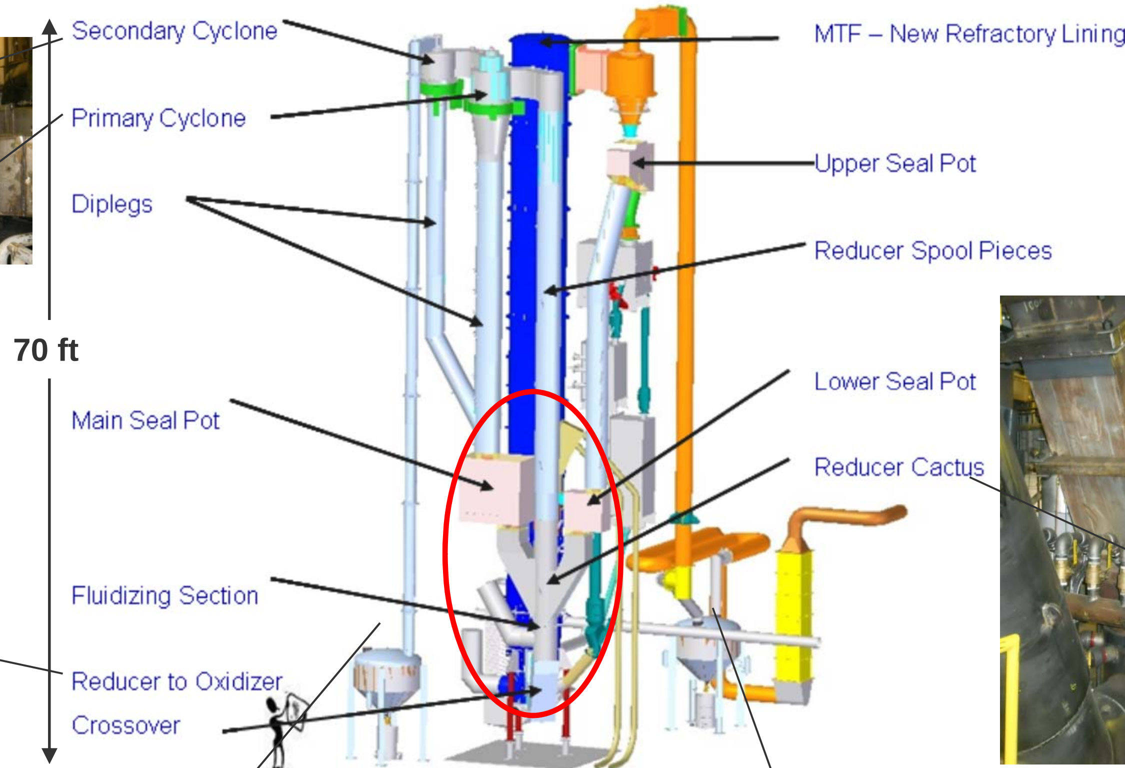
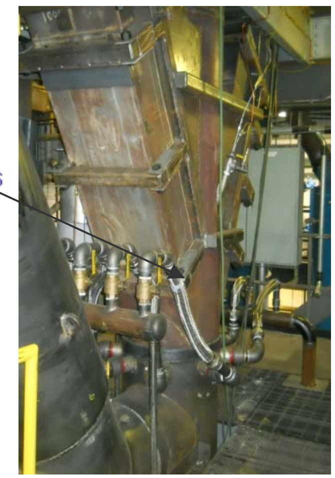
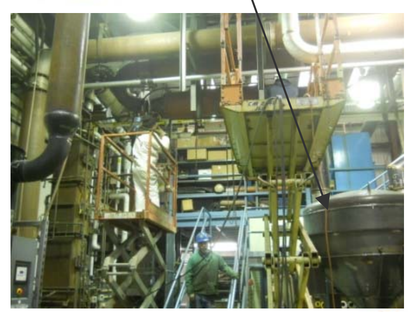
Chemical Looping Prototype Component Construction







The Prototype was integrated into the existing Multi-use Test Facility (MTF)

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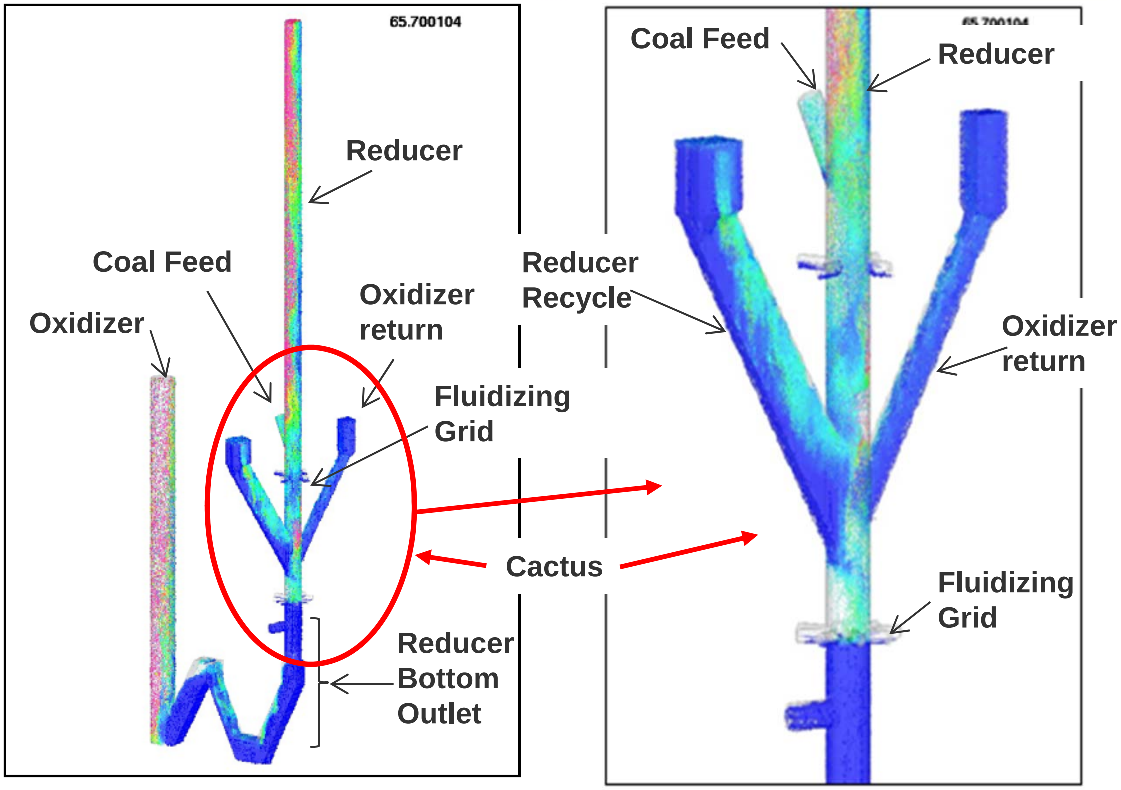
Prototype Validation: Computational Fluid Dynamics



Barracuda Simulation of the Chemical Loop reducer column(color range 0 – 25m/s)

Mixing of solids streams in Cactus above the fluidizing gas grid 0-25 m/s

Study and improve:

- Fluidization
- Solids transport
- Mixing in "Cactus"
- Residence times
- Fixed carbon retention in reducer

Improving LCL™ Process

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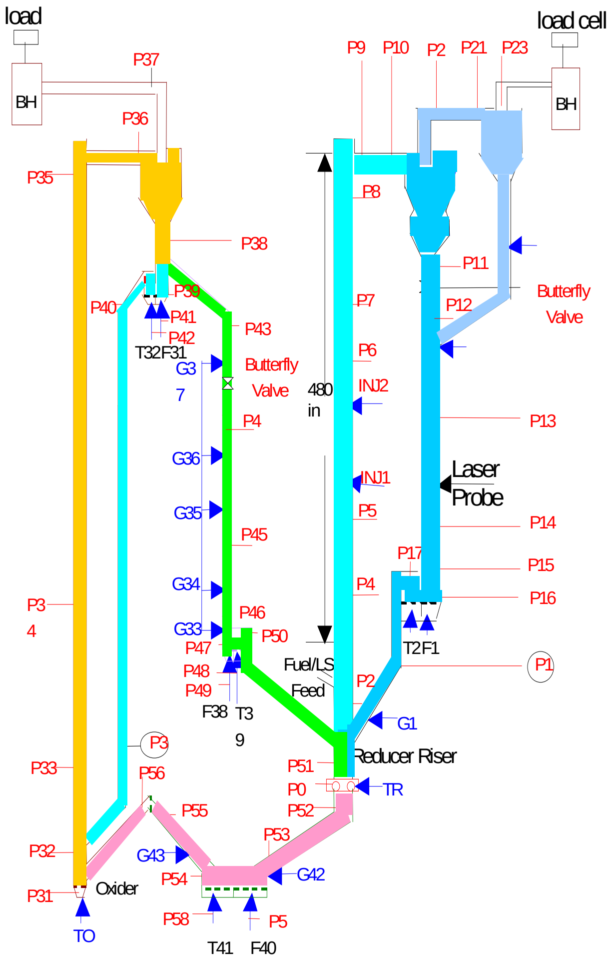
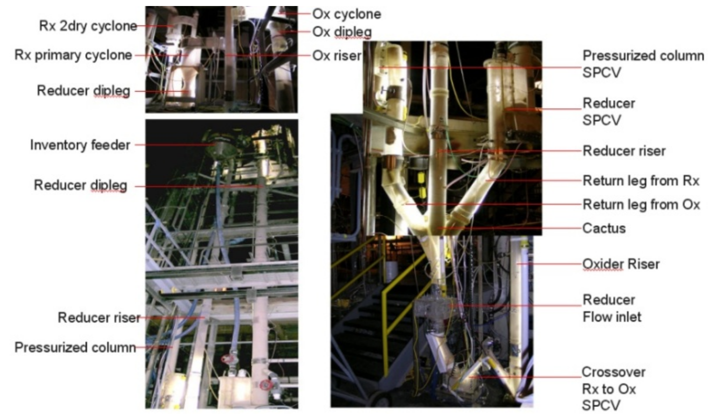
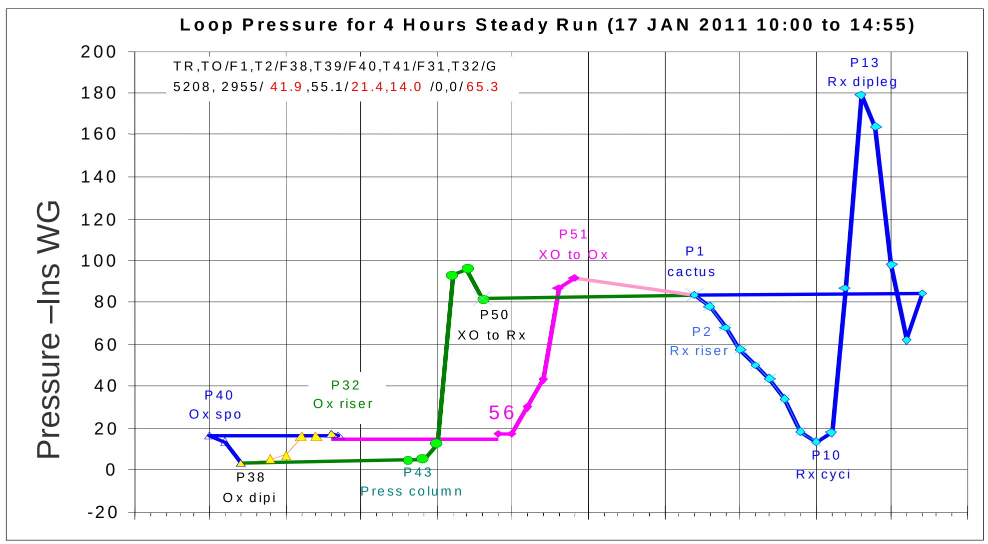
Prototype Validation: Cold Flow Model Testing







Stable coupled operation with smooth solids transport

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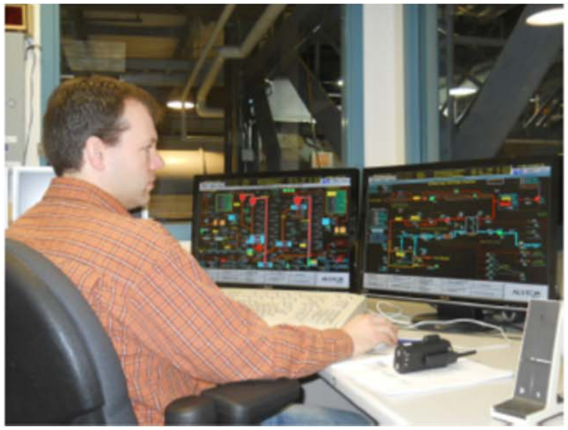
Prototype Testing Status

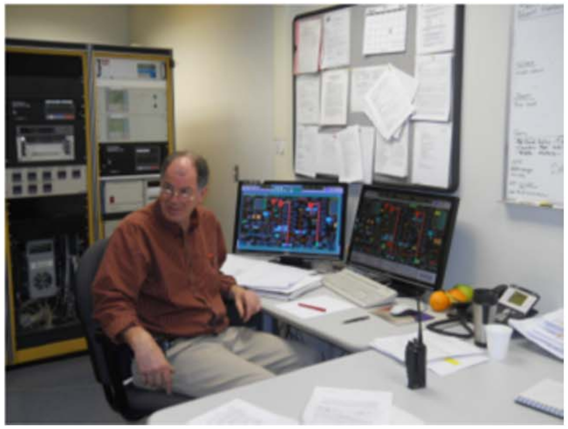
Main Milestones:

- June 2011 - First coupled run with Pitts #8 Coal
- Sept. – Oct. 2011 - Series of short runs with Pitt.#8 coal
- May 2012 - Reducer tests decoupled, nitrogen blown runs with Adaro coal and charcoal – All reducer reactions observed
- June 2012 – Extended reducer tests with Adaro Coal – All reducer reactions observed

Major Achievements:

- Controlled solids recirculation in CFM & prototype.
- Coal firing at low reactor temps with low tar formation.
- Coal firing at design temperature with no evidence of tar formation.
- SAHE operation.
- Hot restart after main fuel trip.
- Production of CO_2 (Option 1) and Syngas (Option 2).
- Combustion reactions with chemical looping reactions.





Research Operators in Control Room During Hot Coupled Testing

Hot Coupled Loop Operation Achieved with Coal & Charcoal

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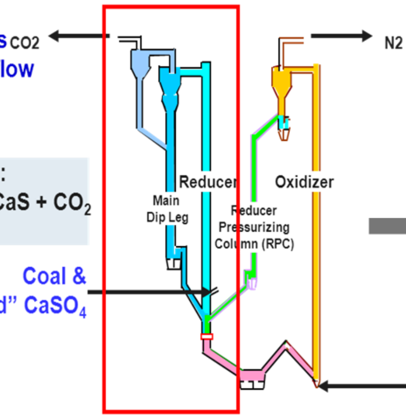
Prototype Validation: “Decoupled” Tests Towards Autothermal

Decoupled Reducer Test

Reducer data produced:
- Coal and CaSO4 conversions
- Solids recycle rate per coal flow
- Reducer solids loading



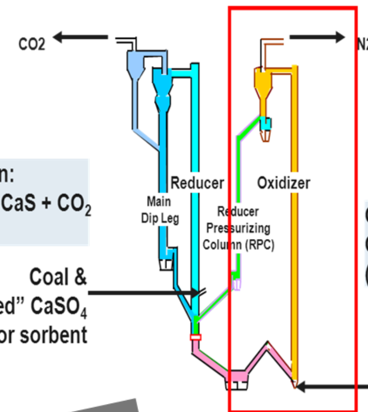
Reducer Reaction:
$CaSO_4$ + Coal ⇔ CaS + CO_2
(endothermic)

Coal & “Purchased” $CaSO_4$

Air & Natural Gas for heat to drive Reducer reactions

Decoupled Oxidizer Test

Oxidizer data produced:
- CaS -> CaSO4 conversions
- Solids recycle rate per CaS conversion
- Sulfur retention data
- Oxidizer solids loading



Reducer Reaction:
$CaSO_4$ + Coal ⇔ CaS + CO_2
(endothermic)

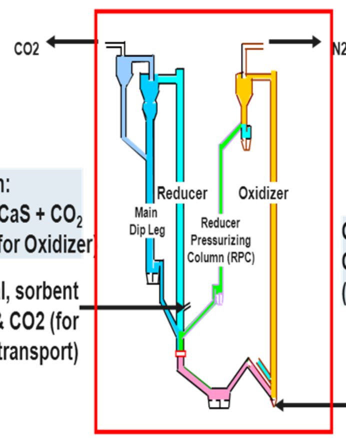
Coal & “Purchased” $CaSO_4$ or sorbent

Oxidizer Reaction:
CaS + Air ⇔ $CaSO_4$ + heat
(exothermic)

Air burns CaS from reducer for heat to drive Reducer reactions. Natural Gas, if required

Integrated Autothermal Test

Autothermal test data produced:
- Sustained operation without nat gas
- Coal conversion rate
- CaS -> CaSO4 conversions
- Carbon carry-over to Oxidizer
- Sulfur release data
- Solids recycle rate per CaS conversion
- Reducer and Oxidizer solids loading



Reducer Reaction:
$CaSO_4$ + Coal ⇔ CaS + CO_2
(to produce CaS for Oxidizer)

Coal, sorbent & CO2 (for Solids transport)

Oxidizer Reaction:
CaS + Air ⇔ $CaSO_4$ + heat
(to produce heat & CaSO4 for Reducer)

Air burns CaS from reducer for heat to drive Reducer reactions.

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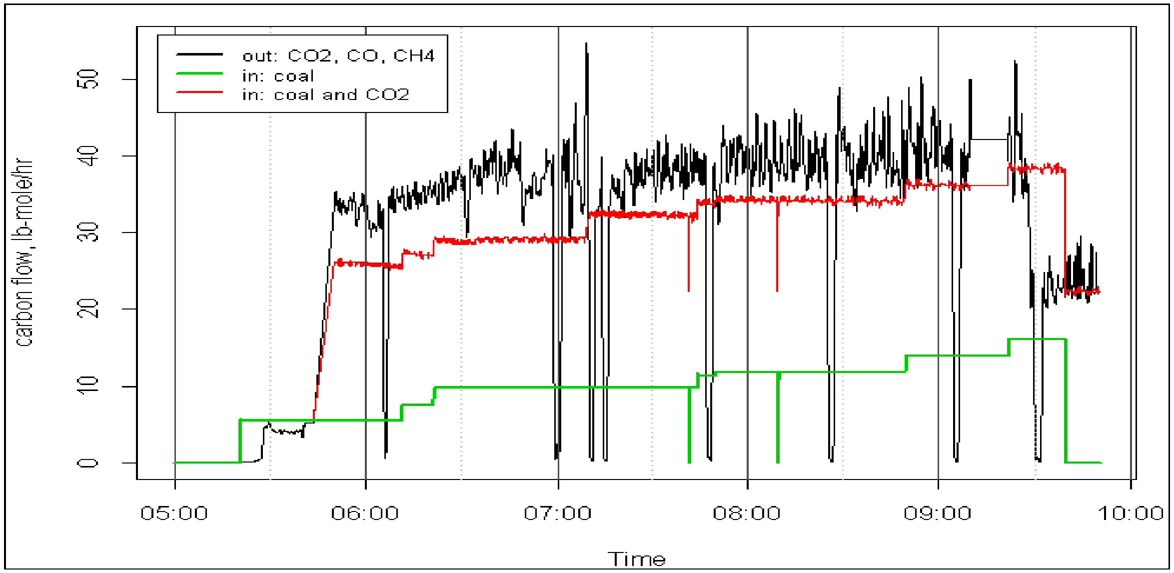
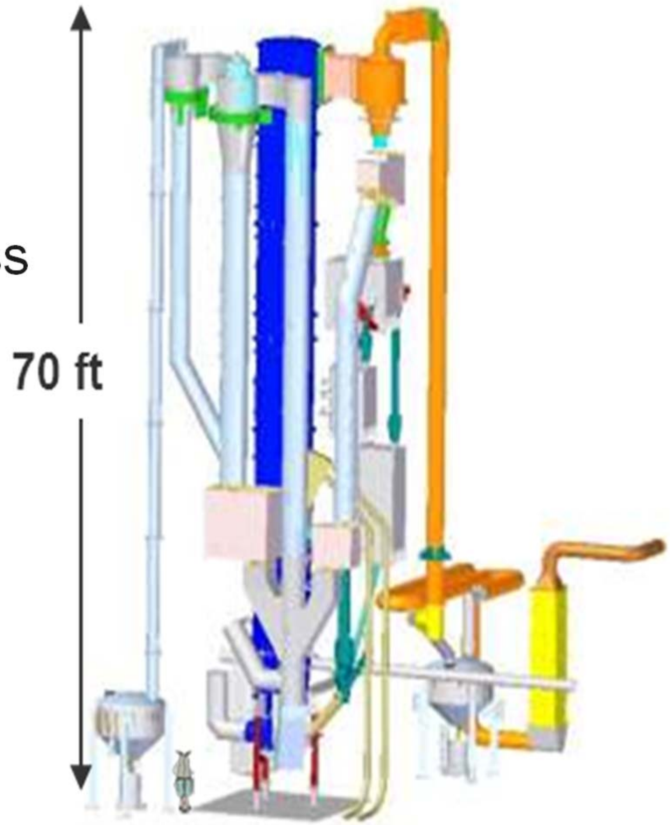
Prototype Reducer tests: Preliminary Testing Results

Significant Observations:

- All LCL™ reactions realized
- High carbon burnup efficiency > 98%
- Negligible carbon carryover to oxidizer
- Oxygen demand - 15 to 20%
- SO_2 release can be minimized by varying excess air ($CaSO_4$) to fuel ratio





3 MWth Prototype Model

Hot Coupled Loop Operation Achieved with Coal & Charcoal

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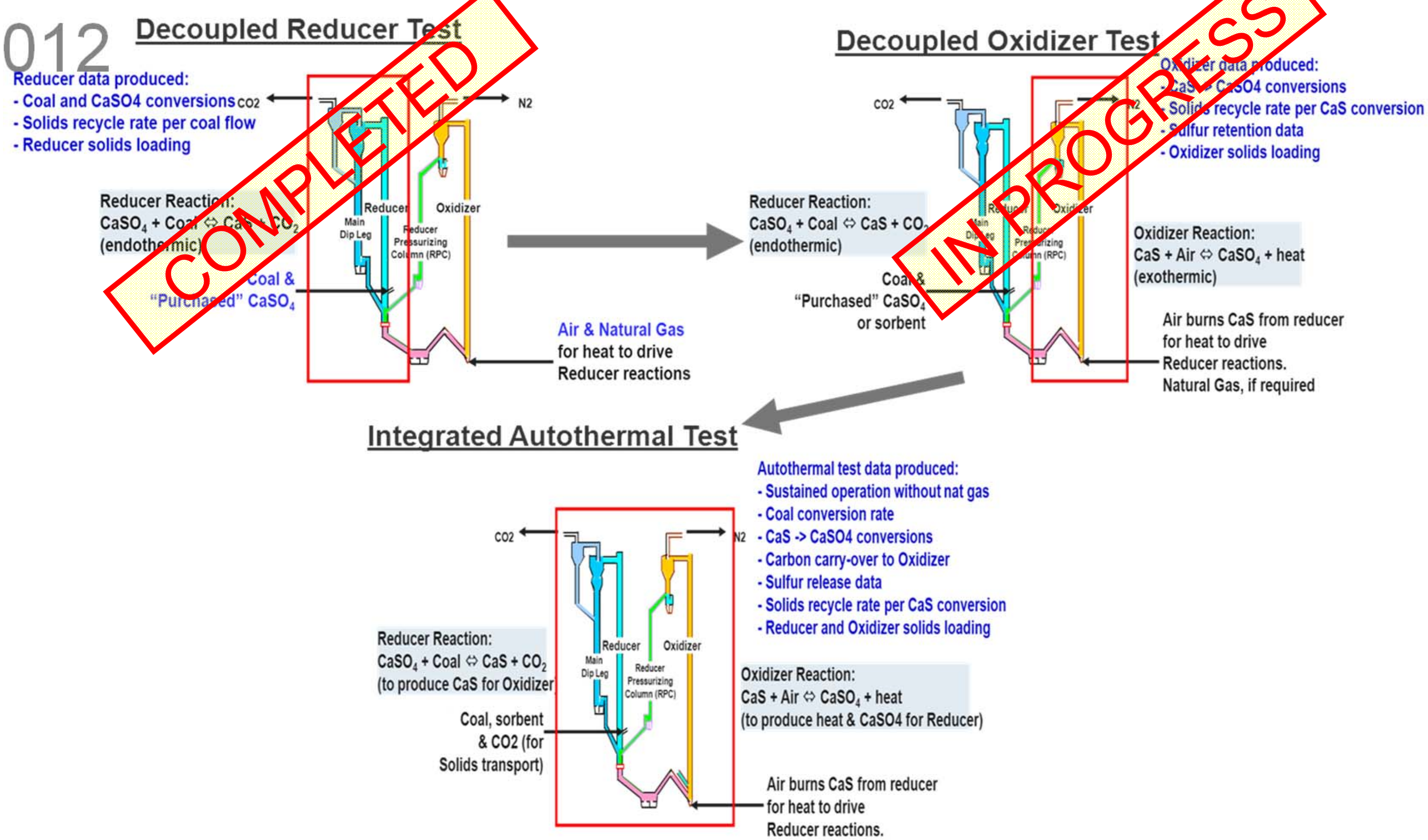
Limestone Based Chemical Looping Path Forward

- Oxidizer Testing: July – August 2012
- Coupled Autothermal Operation: August -September 2012



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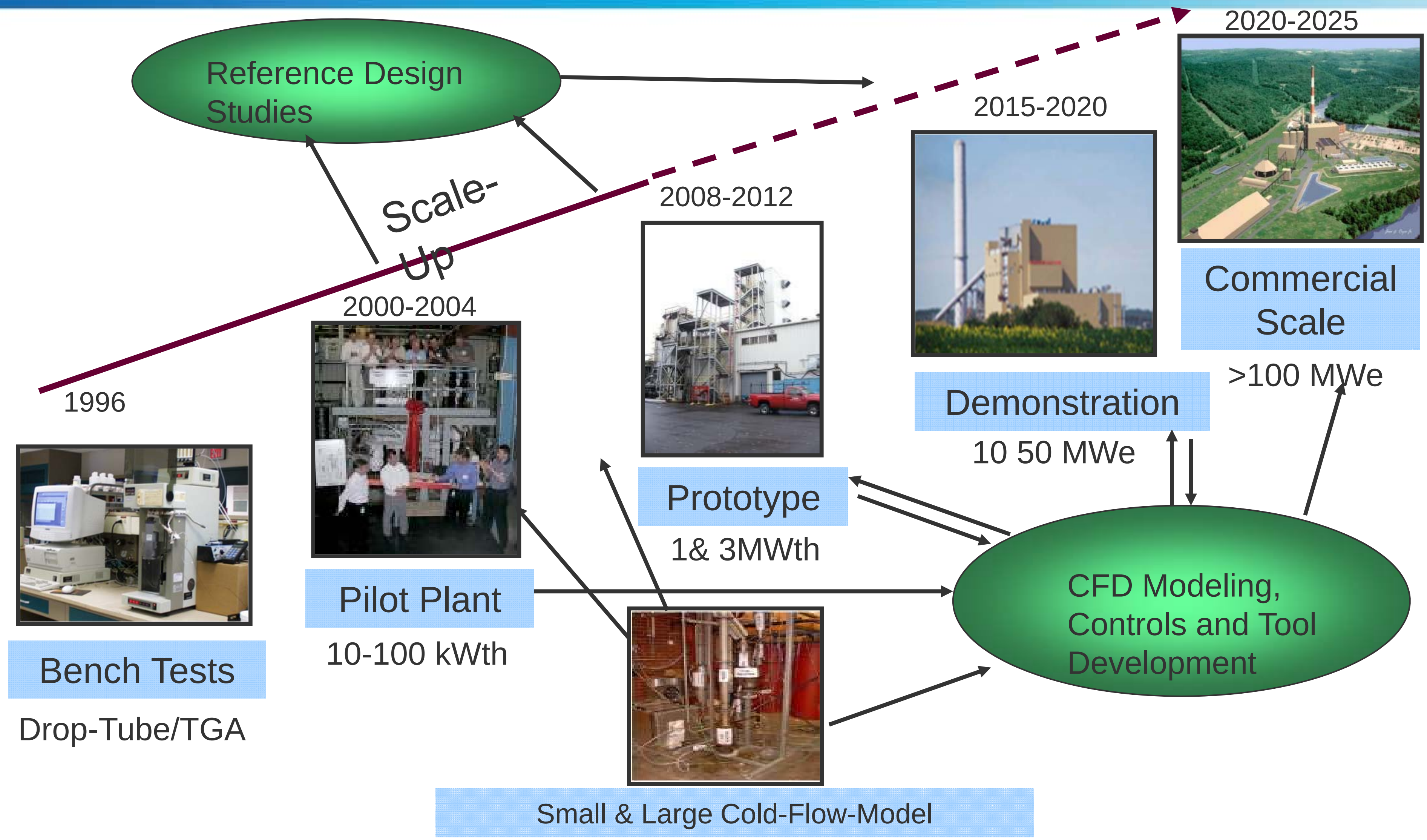
LCL™ Process Development Steps
Managed Development and Scale-up



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  - US-DOE/NETL, Alstom
- Key Team Members:
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Significant Progress Thanks to These Contributions

Thank You!

Any Questions?

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