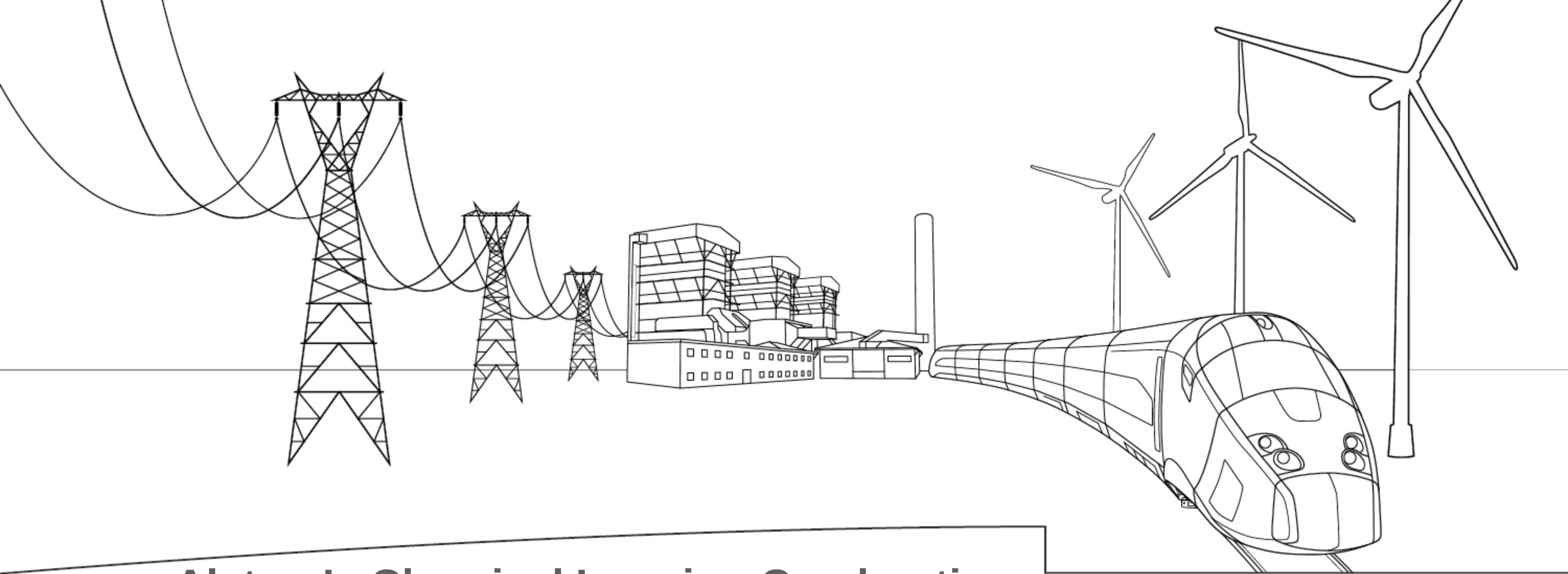

Alstom's Chemical Looping Combustion Technology with CO_2 Capture for New and Existing Coal-Fired Power Plants

Ray Chamberland

Herbert Andrus, Jr.(PI), Carl Edberg (Co-PI)

ALSTOM Power Inc.

U.S. DOE/NETL CO_2 Capture Technology Meeting

Pittsburgh, PA

June 26, 2015

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Shaping the future

Overview

Project Overview

Limestone CLC Development

Limestone CLC Project Scope

Conclusions and Future Plans

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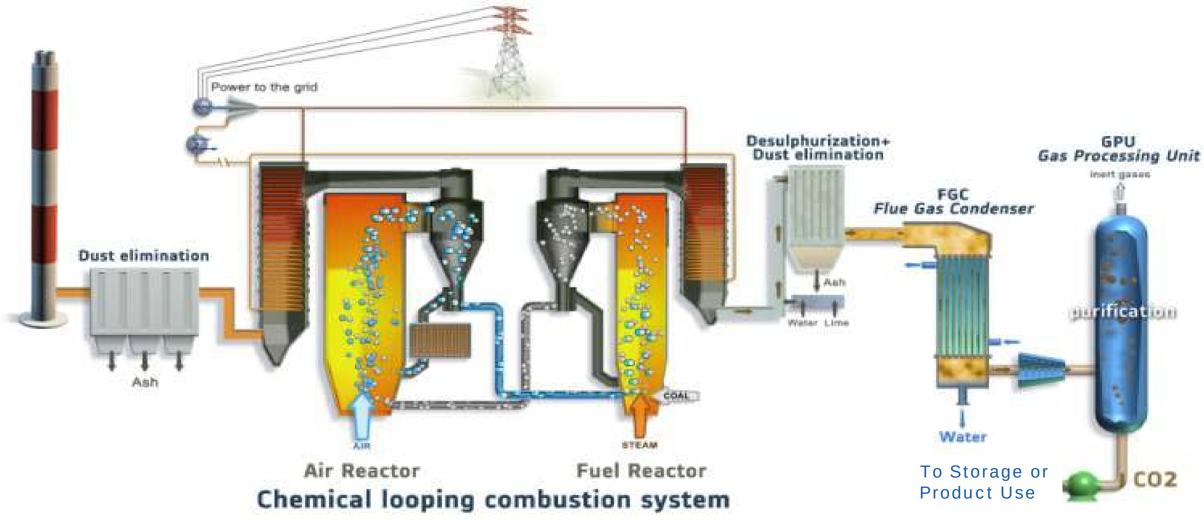
Alstom Limestone Chemical Looping Process
Key Attributes



- Avoids large investment costs and parasitic power associated with cryogenic air separation units (ASUs),
- Flexibility for coal-based power generation with CO_2 capture from coal via combustion/steam generation or hydrogen production/ GTCC as well as syngas for chemical feedstock,
- Uses abundant, low cost limestone to provide oxygen carrier,
- Builds upon Alstom's proven CFB technology and uses conventional materials and fabrication techniques,
- Techno-economic assessments consistently show Chemical Looping-based power generation systems have the potential for the lowest cost of electricity with CO_2 capture.

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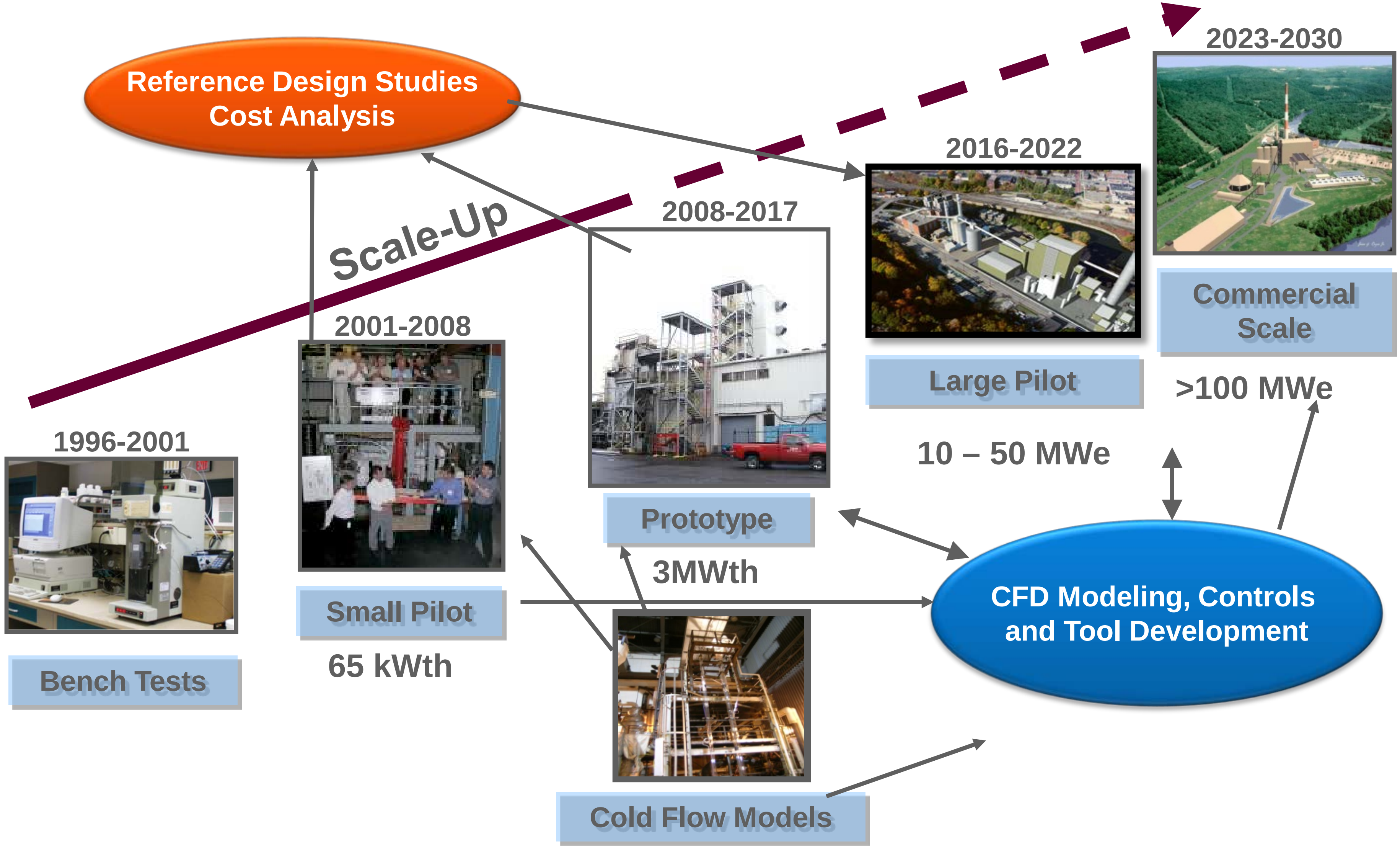
Limestone Chemical Looping Combustion (LCL-C™) Commercialization Plan



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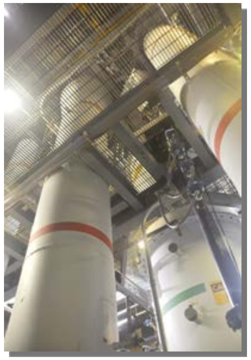
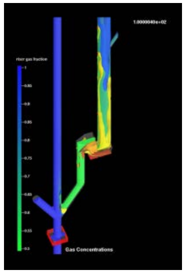
Alstom Limestone Chemical Looping Development
Project Objectives



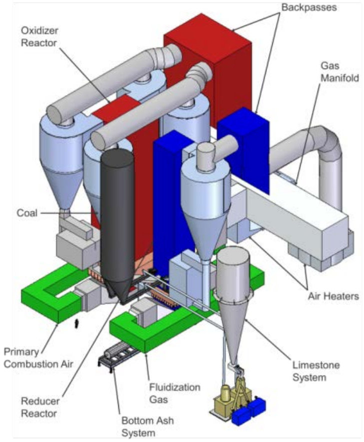

- Achieve good LCL-C™ performance by addressing technology gaps:
  - Solids Management
  - Carbon Capture
  - Sulfur Retention

with

  - CFD / Cold Flow Modeling
  - Benchscale testing
  - Engineered modifications / testing of 3 MWth LCL-C™ Prototype

- Re-examine techno-economic analysis based on updated test results



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Alstom Limestone Chemical Looping Development
Project Summary

- Team
  - Herb Andrus, Jr – Principle Investigator
  - Carl Edberg – Co-Principle Investigator
- Total: $11.1M ($8.9M DOE / $2.2M Alstom)
  - Phase 1: $1.25M ($1M DOE / $0.2M Alstom); Oct 2012 to Sept 2013
  - Phase 2: $9.9M ($7.9M DOE / $2M Alstom); Oct 2014 to Sept 2016
- Funding Sources
  - DOE/NETL
  - Alstom
  - ICCI
  - NDIC

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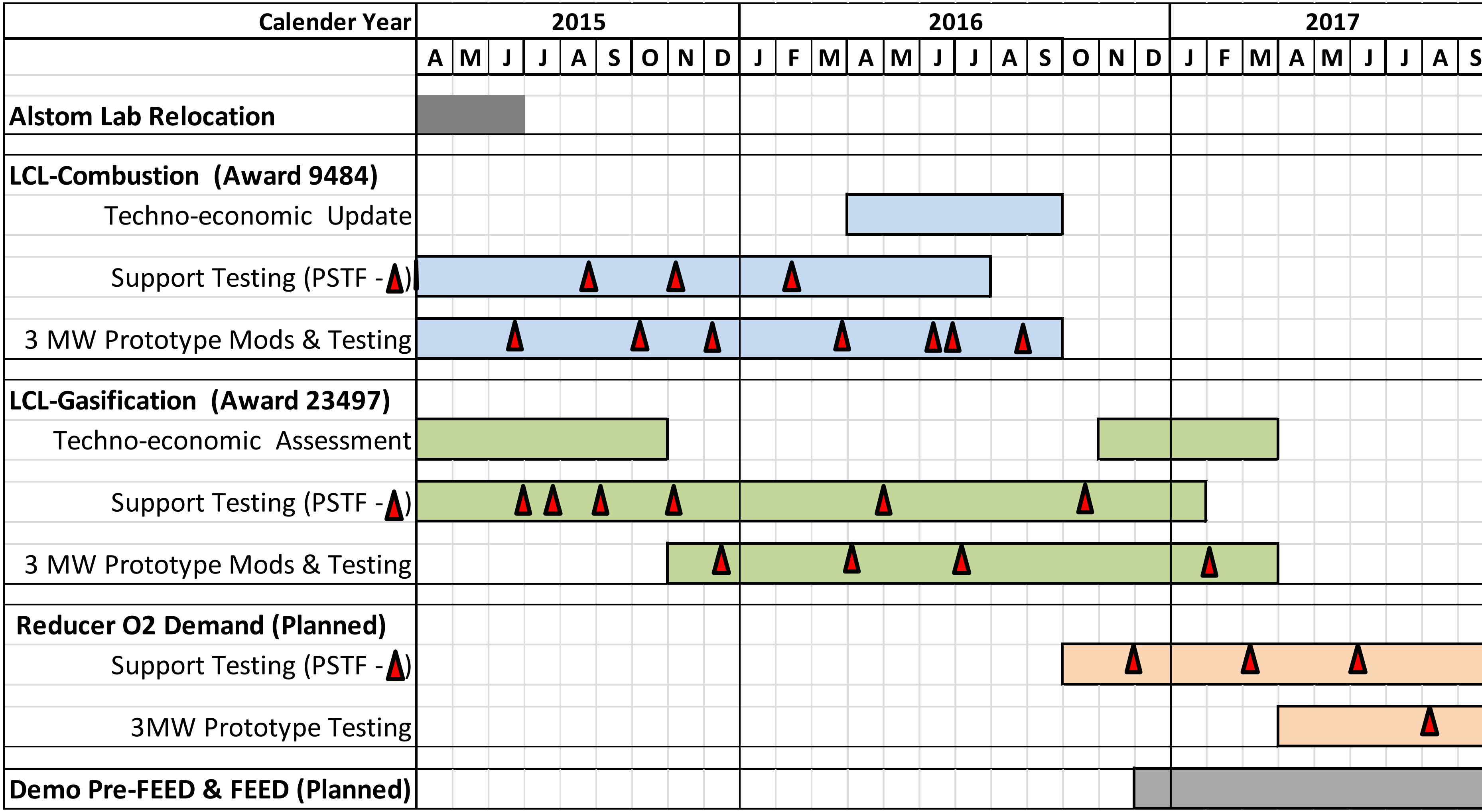
Alstom Limestone Chemical Looping Development Schedule



Phase II Deliverables.xls 1 Nov 2013

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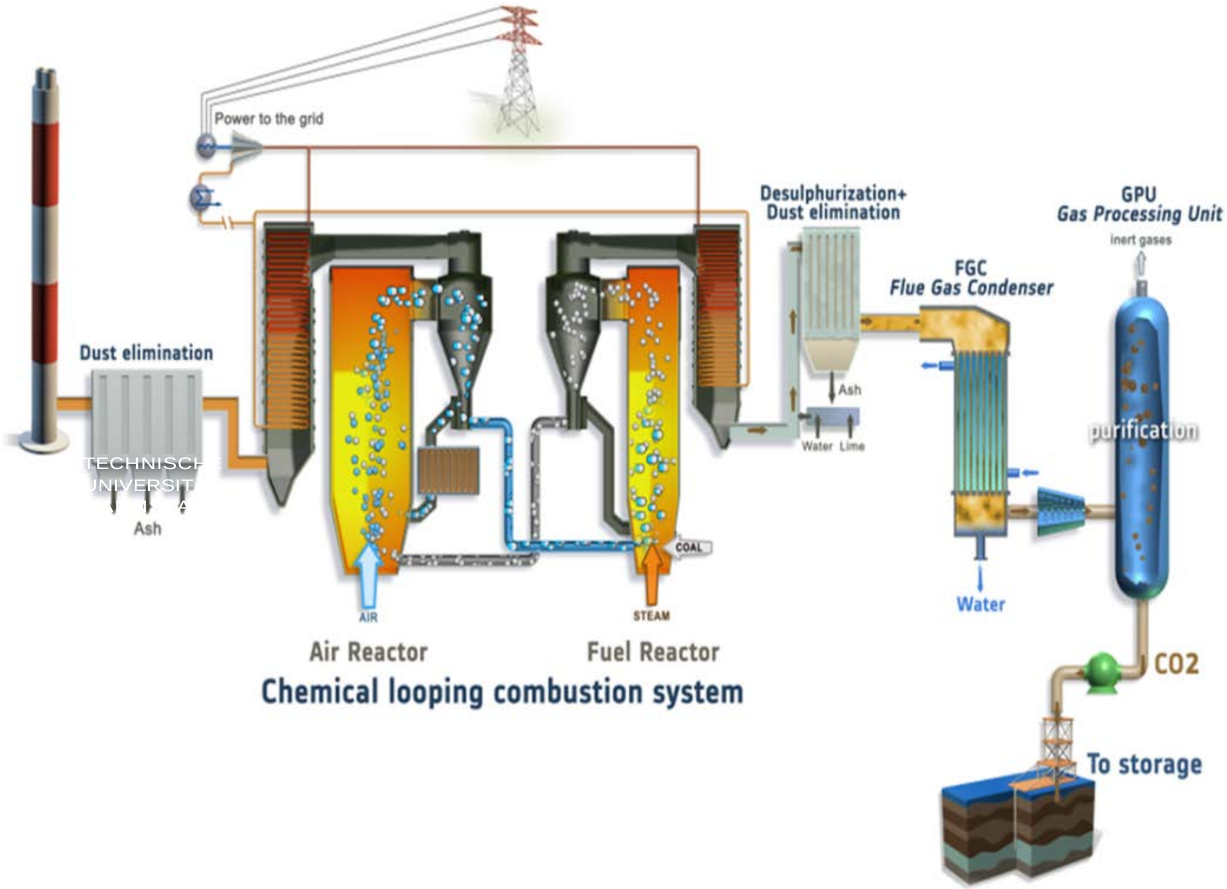
Chemical Looping
Fossil fuel Power with CCS at lowest cost

“Breakthrough CCS Technology” **“Transformational Coal Power Technology”**



CO_2 capture process in oxy-combustion using solid oxygen carriers rather than an ASU (cryogenic O_2 production), avoiding related cost & energy

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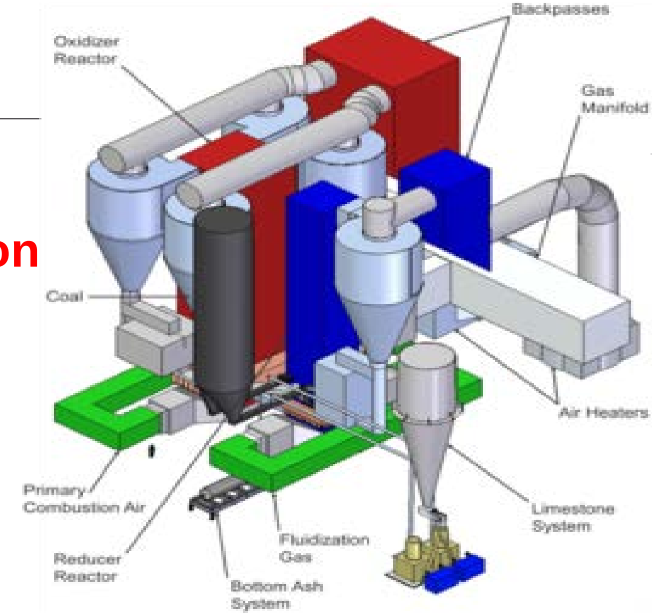
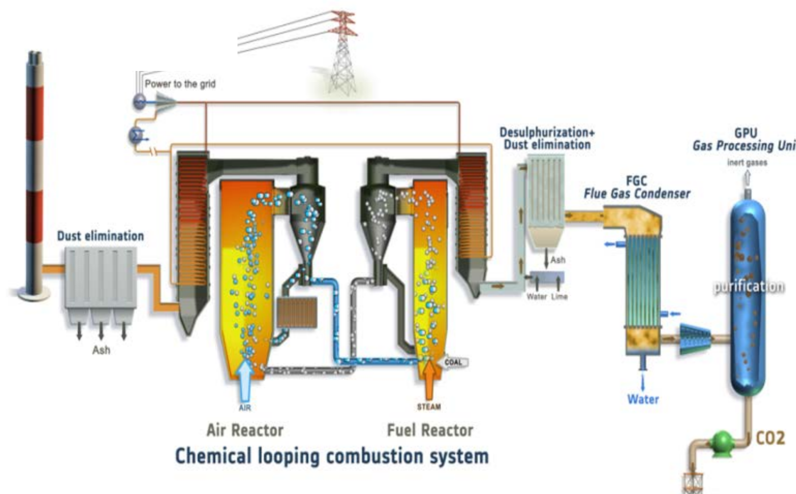
Chemical Looping Power Plant

- **Product Attributes:**
  - **Lowest Cost option for Coal Power Generation with CCS**
  - Lowest energy penalty
  - Fuel flexible
  - Near zero emissions
  - Useful solid ash by-product
  - Application flexible
    - Coal Power, Syngas, Hydrogen
  - Feasible with CFB basis

- **Targets:**
  - **Efficiency <10% CCS penalty vs Plant without CCS**
  - **LCoE <30% increase vs. Plant without CCS (stretch target < 20%)**
  - **CO2 Capture Cost < 25 $ /ton (stretch target < 15 $ /ton)**



Chemical Looping Combustion Steam Generator (550 MWe)



CLC Power Power Plant

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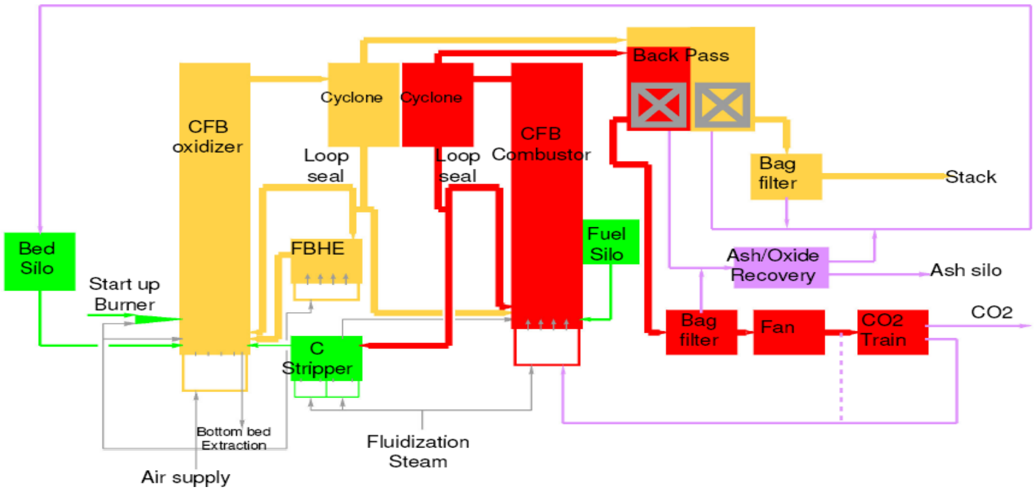
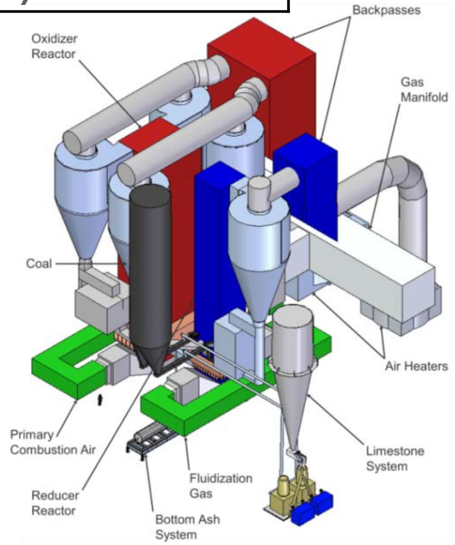
Alstom Chemical Looping Reference Studies

Reference Plant Studies		
Date	**Plant Size**	**Study**
2013	550 MWe	Award 9484 Phase 1 (4 Cases Completed) (DOE)
2012	550 MWe	Update of 2003 Study (DOE)
2006	400 MWe	CO_2 Product Gas (Alstom)
2005	455 MWe	ENCAPco$_2$ (EU-FP6)
2003	220 MWe	Green House Gas Control (DOE)





Chemical Looping Based Steam Power Plant with CCS

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Chemical Looping Development
Phase 1 - LCL-C™ Techno-economic Analysis

	Baseline: US DOE SCPC plant, no capture	US DOE Oxy-SCPC plant	Alstom SC Chem Loop Plant, Case 1
Nominal output (net, MW)	550	550	550
Capacity factor (%)	85	85	85
HHV efficiency (% HHV)	39.3	29.3	35.8
CO_2 capture (%)	**0**	**93**	**97**
CO_2 emitted rate (lb/MWh)	1210	113	40
EPC overnight cost ($/kW)	2452	3977	2795
Cost of Electricity Breakdown			
Fuel ($/MWh)	25.53	34.25	28.04
Capital ($/MWh)	38.19	66.23	46.55
O&M fixed ($/MWh)	9.48	14.24	10.58
O&M variable ($/MWh)	7.74	9.54	11.53
T&S adder to COE ($/MWh)	0	8.29	7.08
1st yr COE (w/o T&S, $/MWh)	80.95	124.25	96.7
LCOE (w/o T&S, $/MWh)	**102.64**	**157.55**	**122.62**
Fuel cost ($/MMBtu)	2.94	2.94	2.94
Construction period (yrs)	5	5	5
Operational period (yrs)	30	30	30
% Increase – Levelized COE		**53.5**	**19.5**

DOE goal: >90%

DOE goal: <35%

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Alstom - Chemical Looping Process
Managed Development and Scale-up Steps

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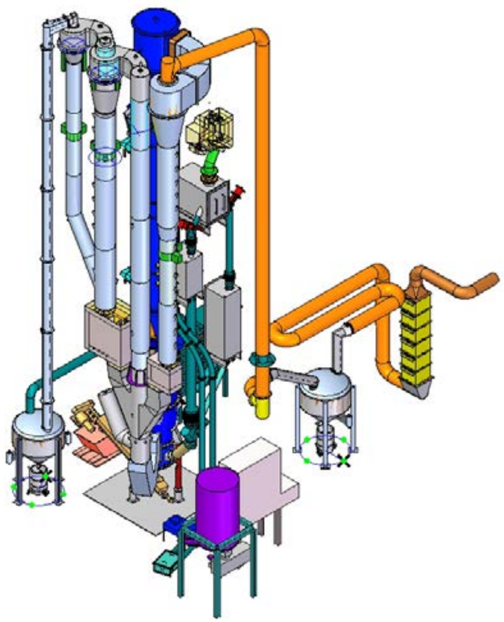
Alstom LCL™ Testing Program
Limestone-based Process



- Main objectives:
  - Autothermal operation of 3-MWth prototype in combustion mode – CT, USA
  - Address technical gaps through prototype testing
  - Obtain info to design, build and operate a demo plant
- Achievement:
  - First autothermal operation achieved in July 2012; 40 hrs in May 2013
  - As of Nov 2013, 350+ hrs of operation and 75+ hrs in autothermal mode
  - Relocated 3-MWth pilot
- Next steps:
  - Further develop LCL™ process in 2015

Largest chemical looping facility in the world, and only one operated in autothermal mode so far

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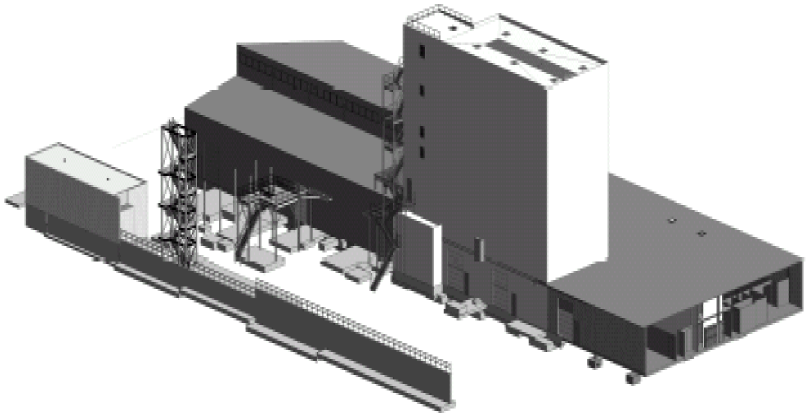
Alstom Test Facility Relocation

Day Hill Road Campus – Windsor, CT
Engineering and R&D

June 2010

Windsor Test Facilities Fully Operational

Oct 2013



Move to Tobey Road – Bloomfield, CT R&D Test Facilities – Feb 2014

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Chemical Looping Facility – Construction/Relocation
Now Ready to Continue Testing

Cut Opening - April 2014

Tower Steel - June 2014

Tower Complete - March 2015

Outside Equipment Complete March 2015

Aerial View of Alstom R&D Test Facilities June 2015

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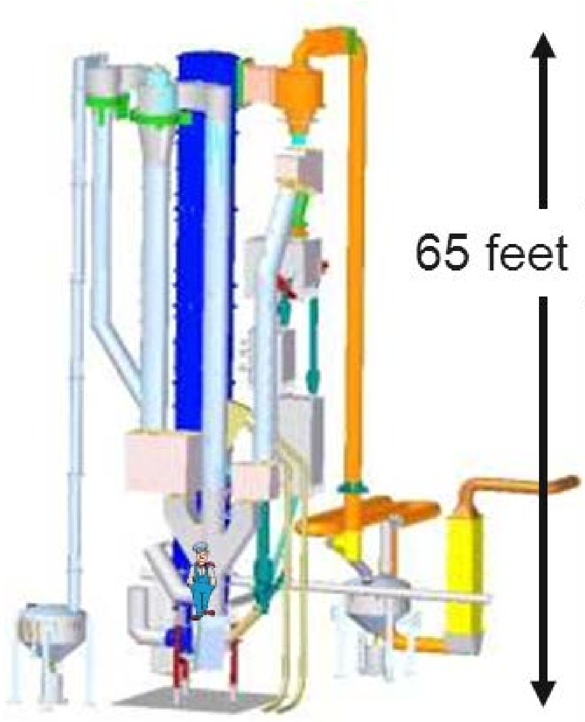
Limestone Chemical Looping (LCL™) Development
Phase 2 – Prototype Testing - Addressing Gaps

Three Main Areas to Address:
Solids Management, Carbon Capture and Sulfur Retention



Prototype (3 MWt)

ID	TECHNICAL GAP	AFFECTS
1	High Solids Loss Rate	operability
2	Main DipLeg Flushing	operability
3	Solids stability	operability
4	Sorbent Activation	operability
5	Sulfur Capture / Loss	operability
6	Low temperatures during some tests	operability
7	Carbon Carryover to Oxidizer	performance

(Additional Gap: Reducer Gas Oxygen Demand – To Be Addressed in Future)

Define Gap / check solution:

Prototype Performance Shortfall
Analyze Prototype Data
Define Bench Test

find solution:

40-Ft CFM for Solids Transport

50-Ft & Bench Test Rig(s) for Chemistry, Conversions, Transport

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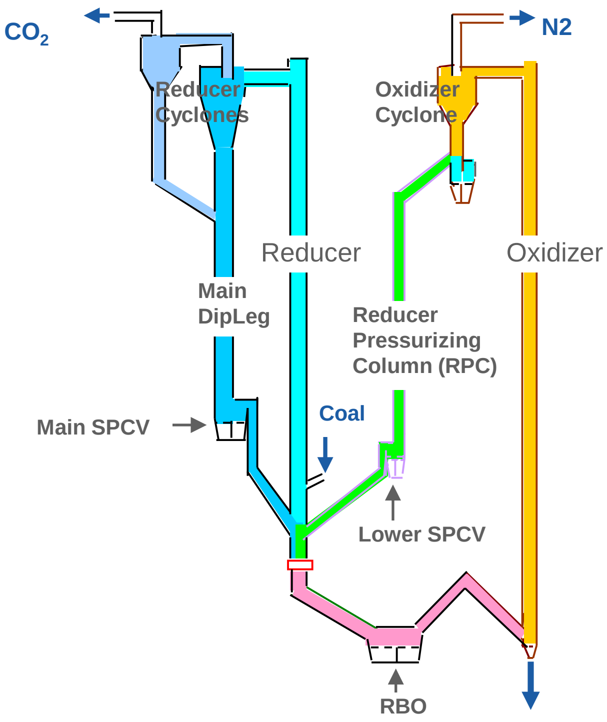
LCL-C™ Prototype Testing
Solids Transport Management

Key Issues:

DipLeg Inventory Control - Affects:
- Solids loss thru cyclone
- Carbon conversion

DipLeg Gas Generation - Affects:
- DipLeg solids inventory control
- Solids recycle rate control and stability.
  - Sulfur retention via solid/gas stoichiometry
  - Recycle rate controls Reducer temperature



Solids Management Critical to Operability and Performance

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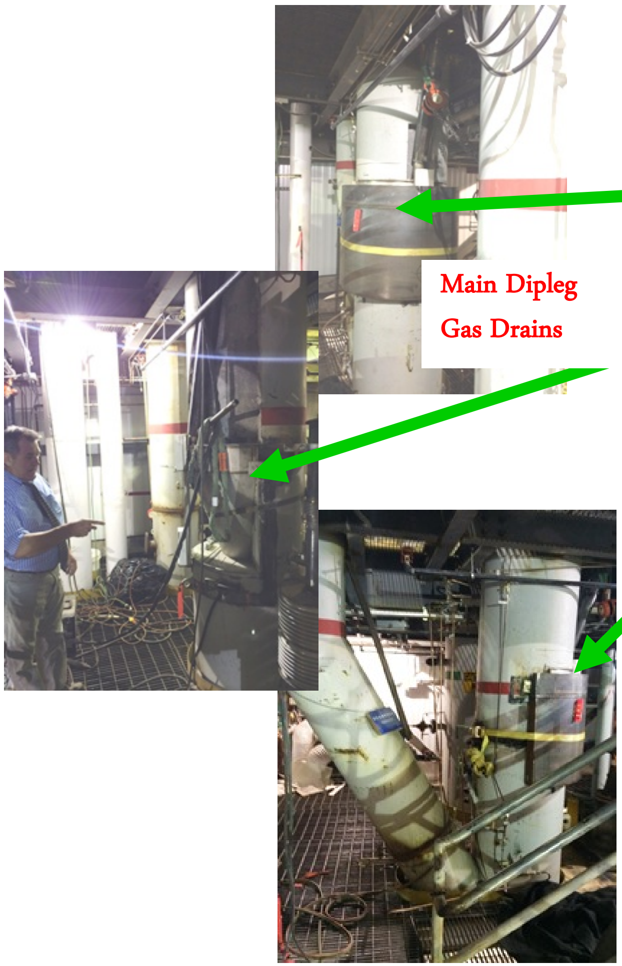
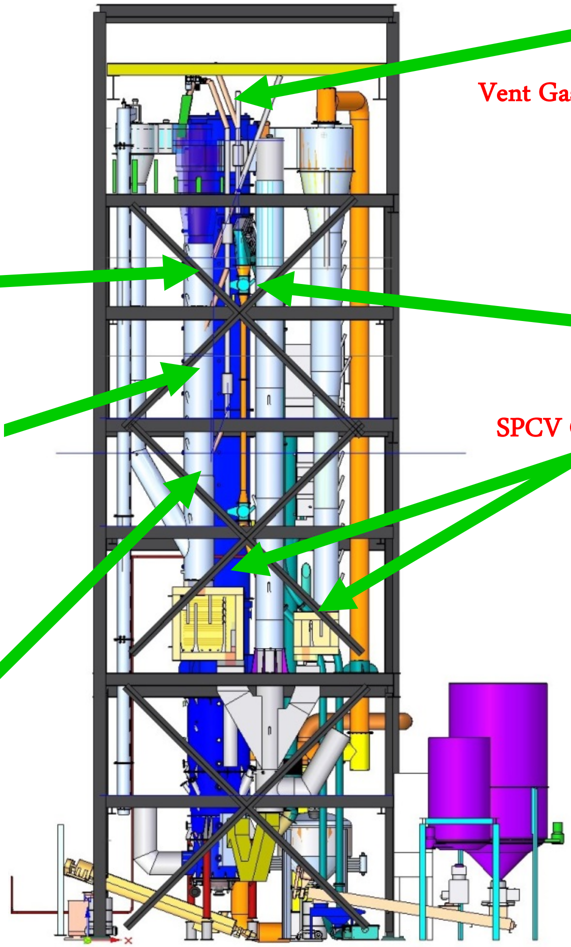
LCL-C™ Prototype Testing
Test 2 Modifications – Gas Drain System

Purpose: Solids Control with coal-firing





Phase II Deliverables.xls 1 Nov 2013

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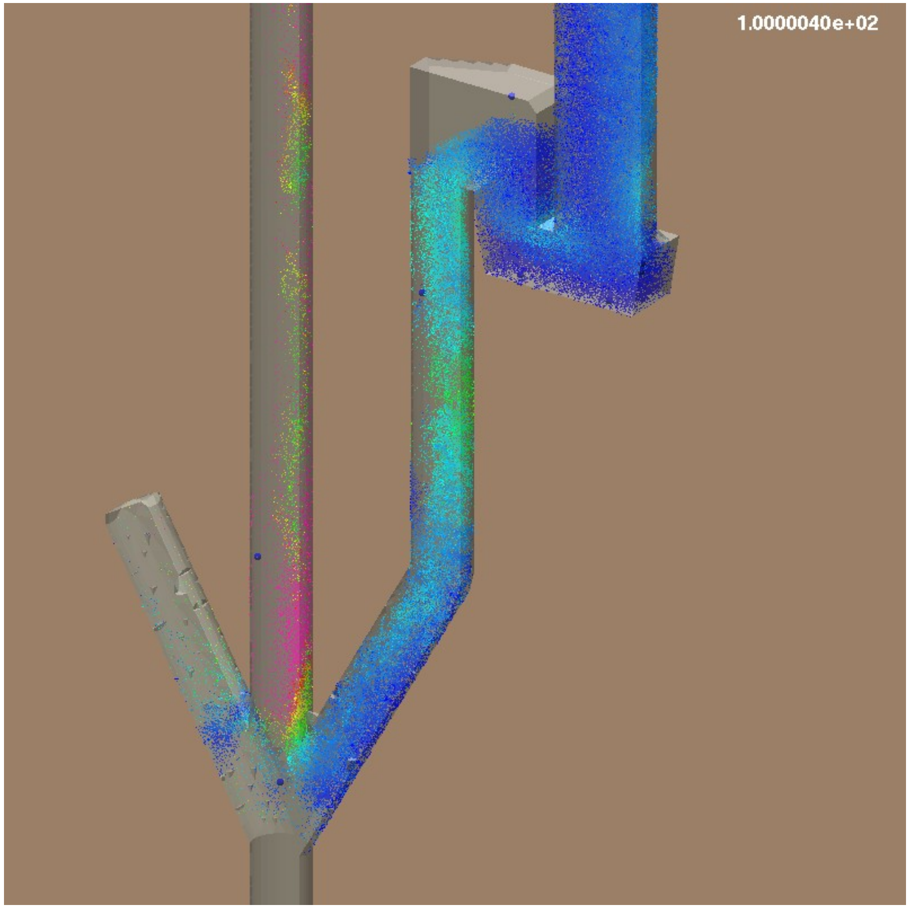
Support Testing - Physical Flow Model and CFD Modeling

- 40ft Cold Flow Model



- ~ 1 million computational particles
- 78,000 cells (discounting null cells)
- 40 sec real time/day

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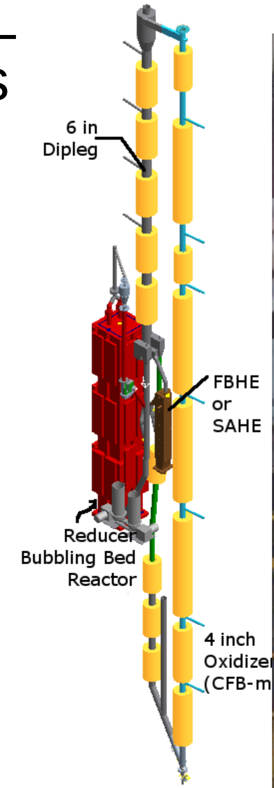
Small-Scale Testing and Process Development

100mm Pilot-Scale Test Facility (PSTF)

Map conditions to better understand behavior – single and double loop tests, vary reactor sizes

- Assess effects and optimize key parameters such as reducer and oxidizer stoichiometry and temperatures, reducer steam flow
- Reducer carbon conversion and residence time requirements
- Coal volatile cracking and conversion
- Oxidizer CaS oxidization behavior
- Oxidizer/Reducer sulfur capture and release mechanisms
- Solids flow and circulation behavior
- Behavior of different fuel types
- Evaluate carrier behavior and performance, different limestone types, carrier mixtures and additives



100 mm Dia. 50ft. Riser (Oxidizer or Reducer)

Scheduled to be completed July 2015

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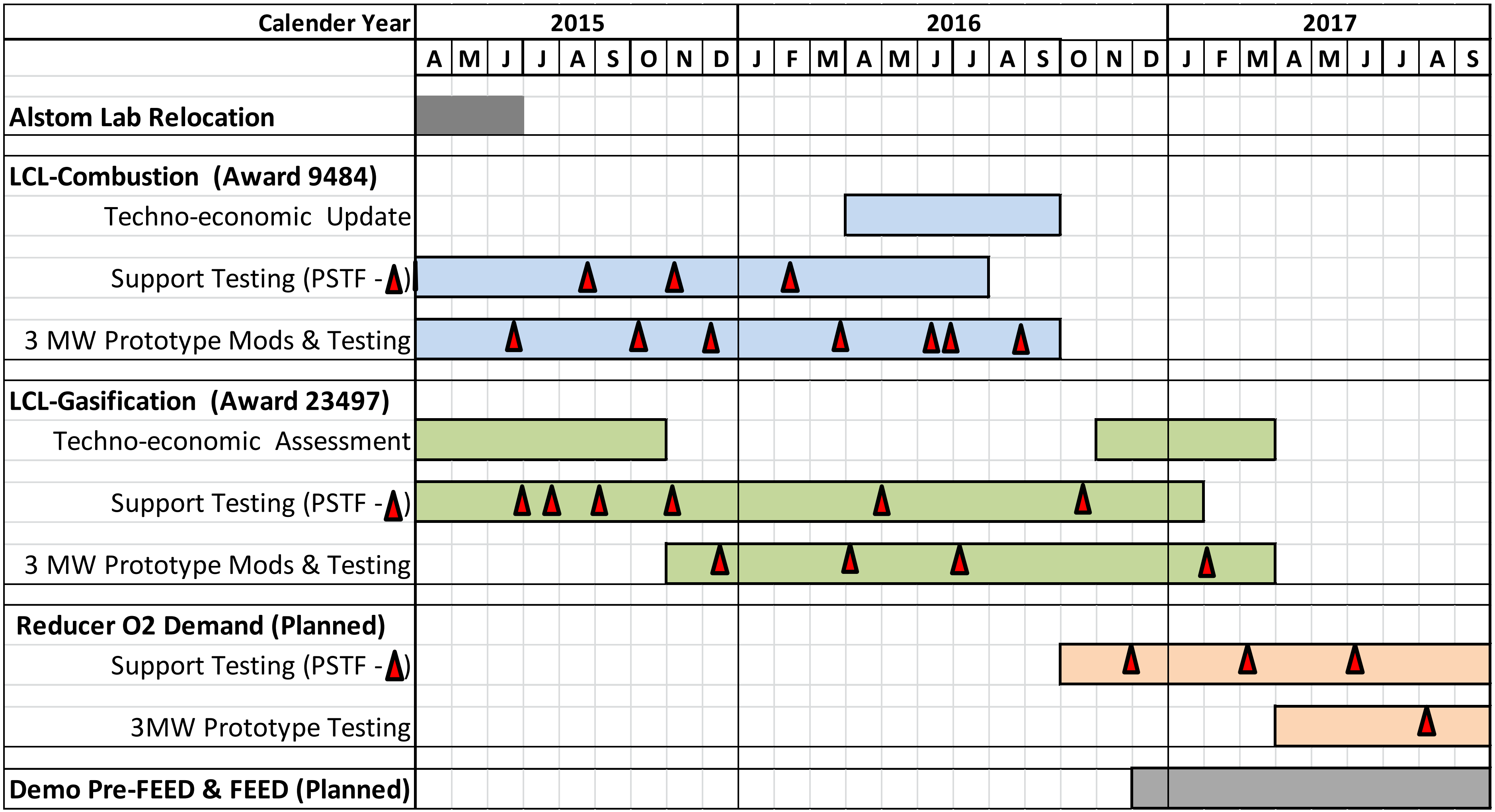
Limestone Chemical Looping Development
Current Workscope & Schedule



Phase II Deliverables.xls 1 Nov 2013

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Alstom Limestone Chemical Looping Summary

- Techno-economic studies continue to indicate that Limestone Chemical Looping technology has the potential for lowest cost coal-based power generation with CO_2 capture.
- Alstom been developing chemical looping technologies for more than a decade:

  Significant knowledge and understanding has been developed through comprehensive testing, modeling and engineering studies.
- Autothermal operation has been achieved at the 3 MW_{th} scale confirming chemical looping reactions and performance potential.
- Development gaps have been identified and comprehensive programs established to address them.
- **Alstom is on track with its commercialization roadmap and is pursuing development of large pilot project.**

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Acknowledgements and Disclaimer

Acknowledgement

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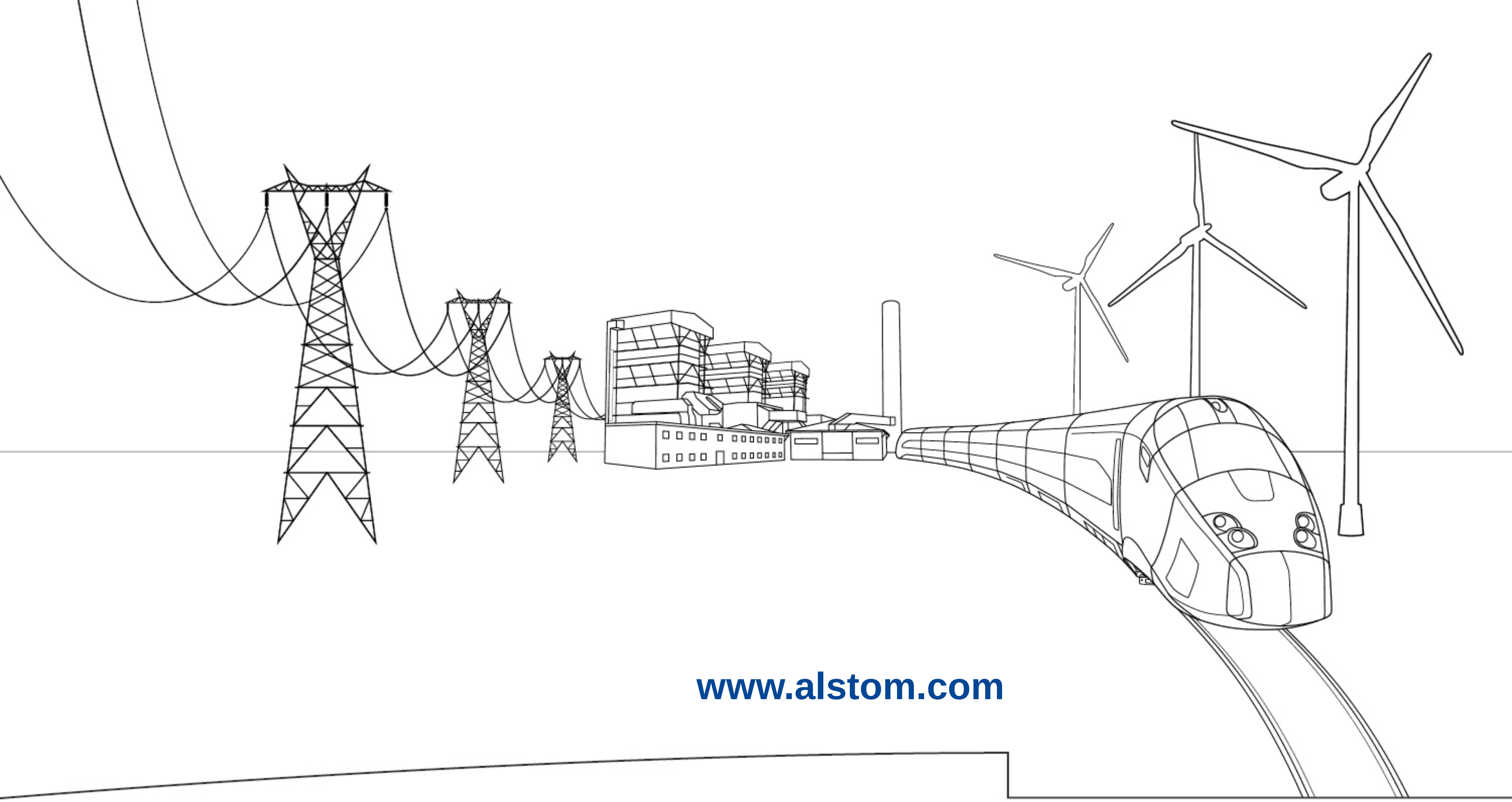

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