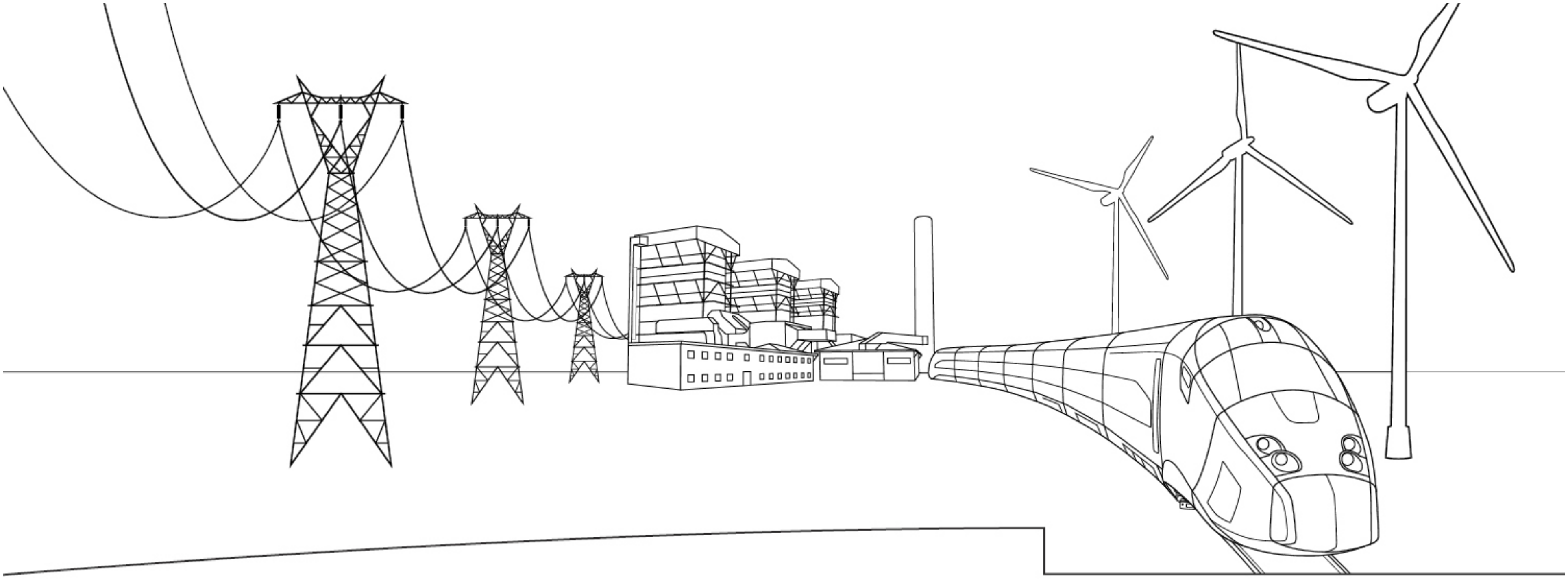

Alstom's Limestone-based Chemical Looping Development For Advanced Gasification

DOE/NETL Agreement DE-FE0023497

Armand Levasseur

ALSTOM Power Inc.

DOE Workshop: Gasification Systems and Coal & Biomass to Liquids

Morgantown, WV

August 10, 2015

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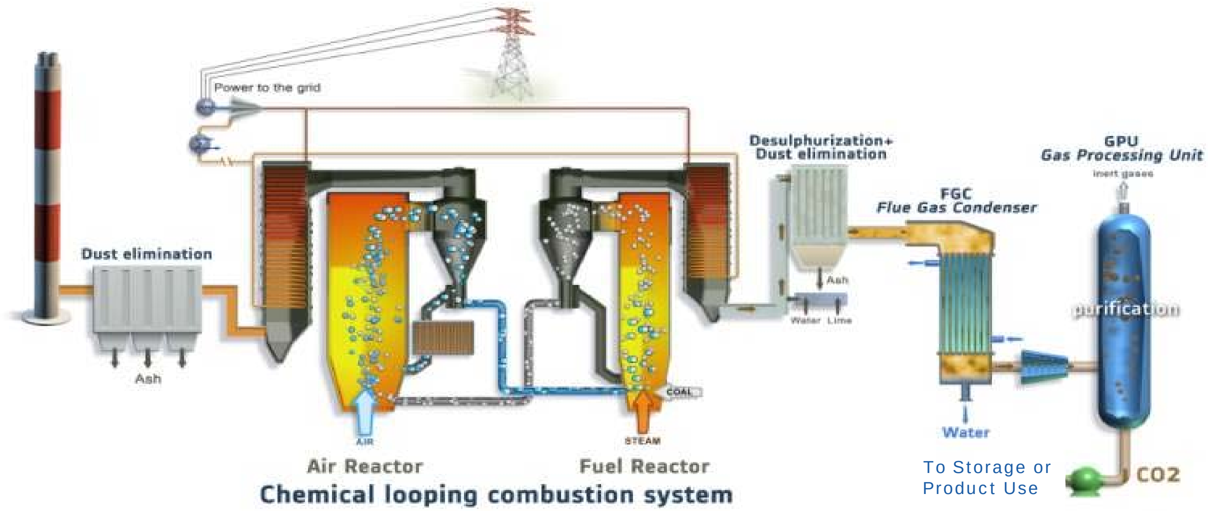
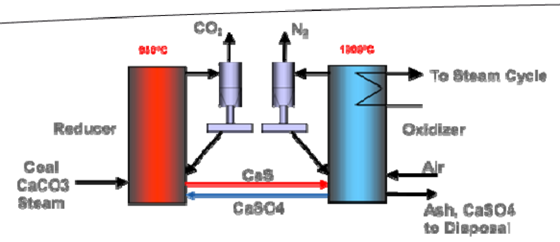
Shaping the future

Alstom Limestone Chemical Looping Process
Key Attributes



- Avoids large investment costs and parasitic power associated with cryogenic air separation units (ASU's),
- 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 costs of electricity with CO_2 capture.

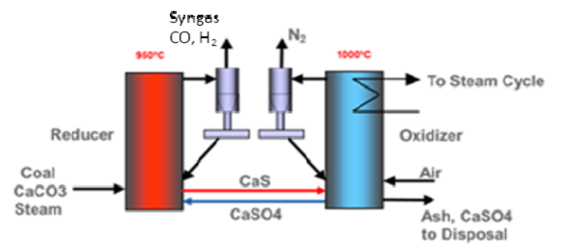
Limestone Chemical Looping Process:
Options and Applications



Option 1 – Combustion with CO2 Capture – LCL-C™

Combustion

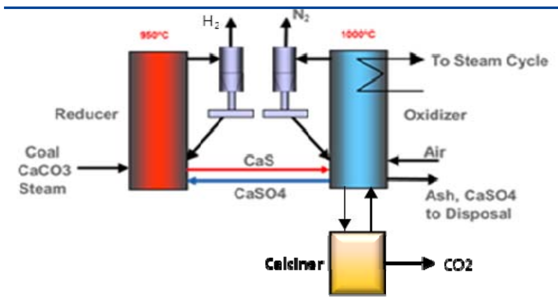
- CO_2 Capture – PC/CFB Retrofit
- CO_2 Capture-Ready Power Plant
- Advanced Steam Cycles with CO_2 Capture



Option 2 – Syngas with no CO2 Capture – LCL-Gas™

Syngas

- IGCC with or without Down-Stream CO_2 Capture
- IGCC with Water-Gas Shift for H2 (CO_2 Capture)
- Industrial Syngas production
- Coal-to-Liquid Fuels



Option 3 – Hydrogen with CO2 Capture – LCL-H2™

Hydrogen

- Fuel Cell Cycles with CO_2 Capture
- Hydrogen for IGCC with CO_2
- Industrial Hydrogen with CO_2

Main Reactions:

Oxidizer (Air Reactor)

$CaS + 2O_2 \rightarrow CaSO_4 + Heat$

Reducer (Fuel Reactor)

$C_{fuel} + CO_2 + Heat \rightarrow 2CO$

$2CO + CaSO_4 \rightarrow CaS + 2CO_2$

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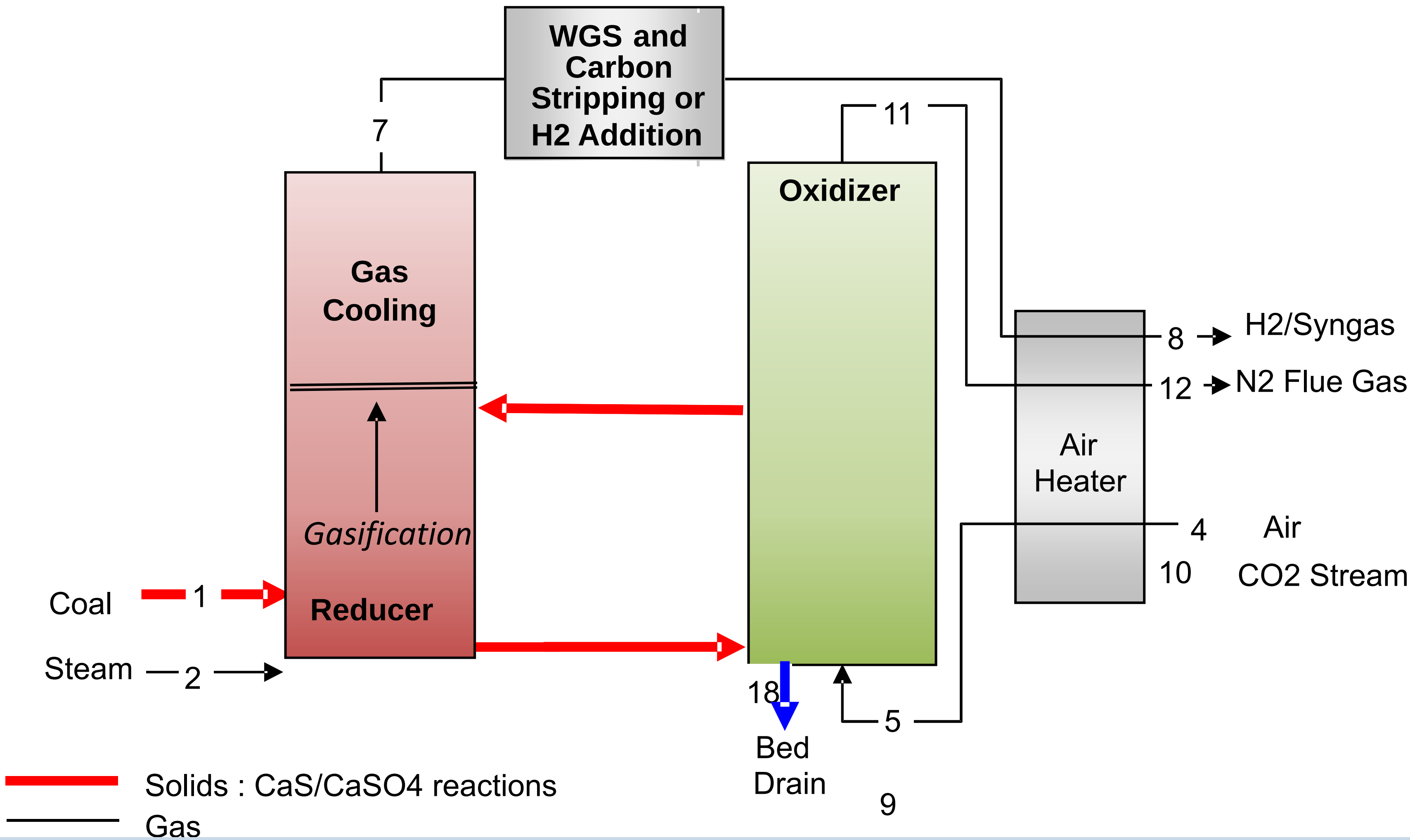
Alstom LCL-G™ System Concept Near-Term Syngas



Primary focus for this project is Near Term Concept

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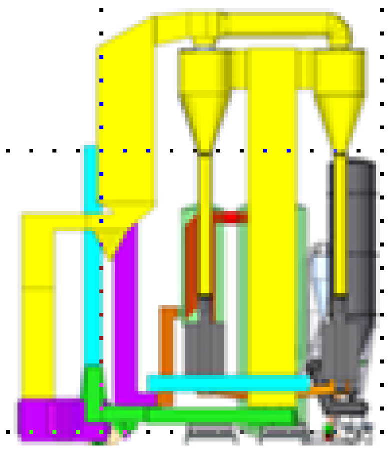
Techno-Economic Study: LCL-Gasification

Study Cases:

Two cases compared against DOE's Baseline Cases:

- **LCL-G™ based power plant** with >90% carbon capture (IGCC using H_2 product gas)
- **LCL-G™ based coal-to-liquid plant** (syngas product H_2/CO >2.0) with Fischer-Tropsch / refinery for making diesel fuel

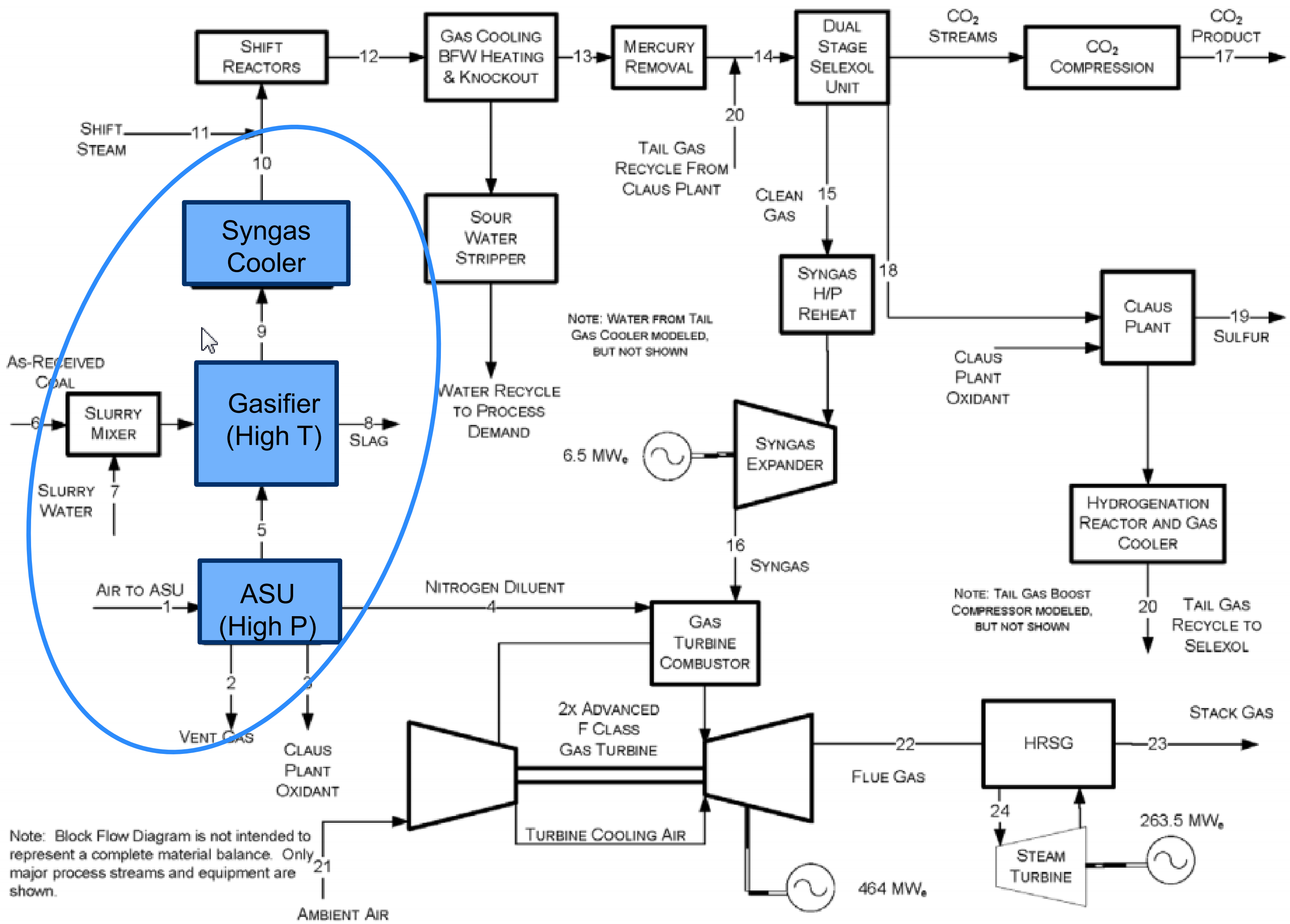


DOE Baseline Cases:

- GE IGCC with CO_2 capture (Case 2 – Vol 1)
- Shell CTL plant for making diesel fuel (Case 4 – Vol 4)

IGCC Base Case (IGCC w CO_2 Capture)

DOE Baseline Report Case 2 – Volume 1



Limestone Chemical Looping
Preliminary Economics for Power Generation

		POWER CASES				
		IGCC Base	PC Base	LCL-C™	H2 for Power	
	Time Frame	Today	Today	After DOE 9498	After DOE 23497	After 2020
	Gasifier/Combustor	GE IGCC	SCPC	LCL-C™	LCL-G™	LCL-G™
		DOE	DOE	Alstom	Alstom	Alstom
	CO2 Capture Method	WGS/Selexol	None	LCL-C™	WGS/Selexol	LCL-G™
	Purpose	Power	Power	Power	Power	Power
	Steam Cycle	Subcritical	SC	SC	Sub Critical	SC
	Combustion Turbine	7 FA	-	-	7FA	7HA
	Reducer/Boiler/Gasifier Press (ata)	55	1	1	1	7
	Carbon Capture (% of Coal)	**90**	**0**	**97**	**90**	**98**
Performance Fuel Fired	(lb/hr)	487,011	409,528	449,595	450,000	450,000
Fuel Fired, HHV	(MMBtu/hr)	5,681	4,778	5,245	5,250	5,250
Reducer,Gasifier,Boiler	Stoichiometry	39	120	120	43	58
SynGas Energy, HHV	(% of Input)	68	-	-	75	50
Power Steam Energy, HHV	(% of Input)	15	-	-	20	45
Gross Power	"	734,000	580,400	649,700	765,298	825,040
Net Power	"	543,250	549,990	550,003	650,420	713,553
Net Plant eff., HHV	**(%)**	**32.6**	**39.3**	**35.8**	**42.3**	**46.4**
Total Plant Cost		1,783,649	1,097,067	1,246,480	1,283,798	1,277,370
	Capacity Factor	80	85	85	80	85
	Relative Capital Cost / Coal Flow	1.00	0.57	0.65	0.60	0.51
		1.76	1.00	1.15	1.05	0.90
	Relative Gasification Cost / Coal Flow	1.00	0.87	0.79	0.61	0.55
		1.15	1.00	0.91	0.70	0.63
	Relative Cost of Elect w/ CO2 T&S	**1.00**	**0.58**	**0.75**	**0.68**	**0.59**
		1.71	**1.00**	**1.29**	**1.17**	**1.00**

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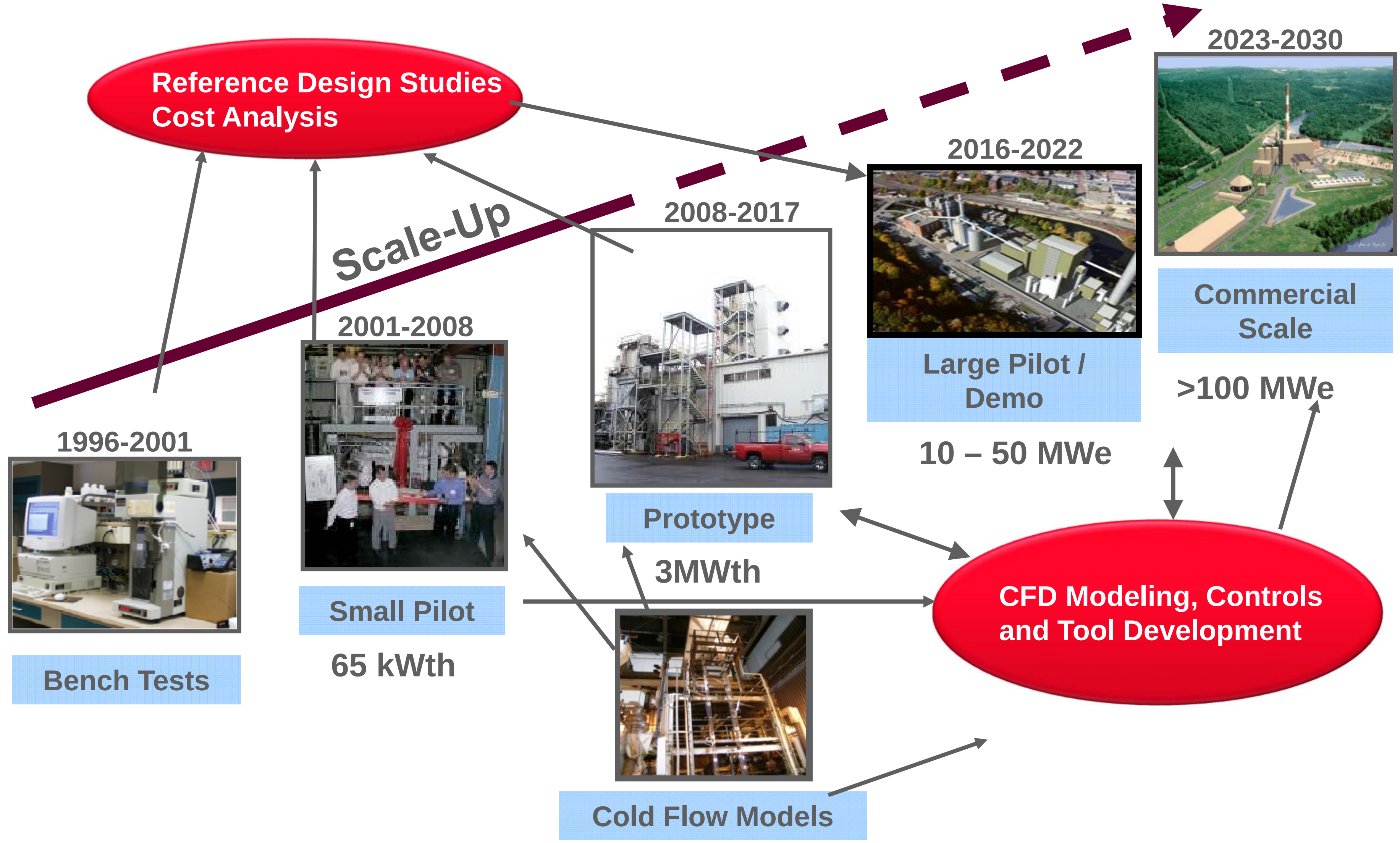
Limestone Chemical Looping
Preliminary Economics for Coal-to-Liquids

		DIESEL CASES				
		Petro Diesel	DOE-base	SynGas for CTL (Diesel)		
	Time Frame	Today	Today	After DOE 23497	After DOE 23497	After 2020
Gasifier/Combustor		-	Shell Gasifier	LCL-G™	LCL-G™	LCL-G™
		DOE	DOE	Alstom	Alstom	Alstom
CO2 Capture Method		-	WGS/Selexol	WGS/Selexol	WGS/Selexol	LCL-G™
Purpose		Petroleum	SynGas	SynGas	SynGas	SynGas
Steam Cycle		-	Sub Critical	Sub Critical	Sub Critical	SC
Combustion Turbine		-	7FA	7FA	7FA	7HA
Reducer/Boiler/Gasifier Press (ata)		-	1	1	1	7
Carbon Capture (% of Coal)		**0**	**90**	**60**	**90**	**90**
Carbon Capture (% of Total Carbon)		**-**	**60**	**60**	**60**	**60**
H2/CO to Fischer-Tropsch (molar)		**-**	**2**	**2**	**2**	**3**
Biomass (% of Fuel HHV)		**-**	**30**	**0**	**30**	**30**
Performance Fuel Fired	(lb/hr)	59928 (bpd)	487,011	450,000	450,000	450,000
Fuel Fired, HHV	(MMBtu/hr)	13,379	5,681	5,250	5,250	5,250
Reducer,Gasifier,Boiler Air/Coal	(molar)	-	39	43	43	40
SynGas Energy, HHV	(% of Input)	-	68	75	75	70
Power Steam Energy, HHV	(% of Input)	-	15	20	20	25
Gross Power	"	34,000	180,363	105,174	105,174	185,438
Net Power	"	-	-	-	-	124,271
Net Plant eff., HHV	**(%)**	**85.5**	**51.6**	**57.3**	**57.3**	**53.5**
CBTL Production	(MMBtu/hr)		2,932	3,008	3,008	2,810
CBTL Production	(bbl/day)	53,753	14,211	14,584	14,584	13,624
Total Plant Cost		1,917,000	1,576,566	1,016,880	1,016,880	928,688
	Capacity Factor	90	80	80	80	85
	Diesel production (gal/yr)	706,314,420	165,989,604	170,344,435	170,344,435	169,073,648
	Diesel production (Bbl/day)	46,074	10,828	11,112	11,112	11,029
Relative Capital Cost / Coal Flow		-	1.00	0.63	0.63	0.58
		-				
Relative Gasification Cost / Coal Flow		-	1.00	0.64	0.64	0.59
		-				
Relative Cost of Diesel		**0.58**	**1.00**	**0.56**	**0.73**	**0.66**
		1.00	**1.74**	**0.97**	**1.26**	**1.15**

Limestone Chemical Looping Technology Commercialization Plan



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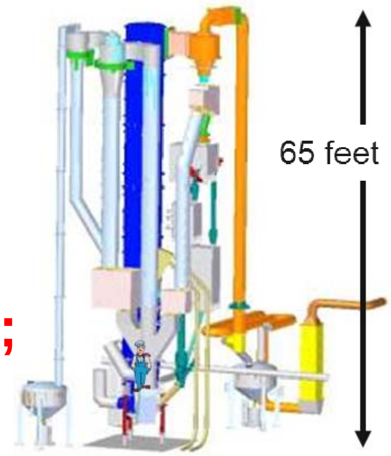
Limestone Chemical Looping Scale-up to 3-MW_{th}

Alstom 3 MW_{th} LCL Prototype – Major Milestones Completed (LCL-Combustion):

- Engineering (Oct 2008 – Apr 2010)
- EPC and Shakedown (Apr 2010 – Dec 2010)
- **First auto thermal operation achieved in July 2012; May 2013**
- Identification of 7 Main Technical Gaps
- Oct 2013 - Autothermal operation and testing to address gaps
- June 2015 - Relocated to New Alstom Lab in Bloomfield, CT
- July 2015 – Prototype re-commissioned and resumed testing (Test 2 completed)



Prototype (3 MWt)

Largest chemical looping facility in the world

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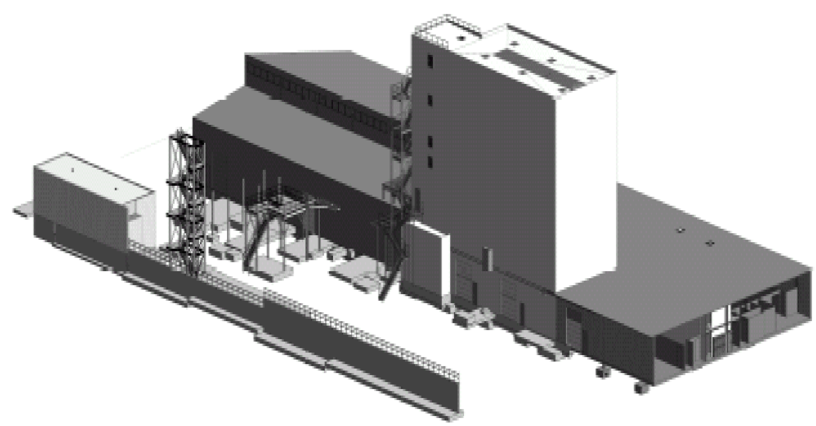
Alstom Test Facility Relocation

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 May 2015

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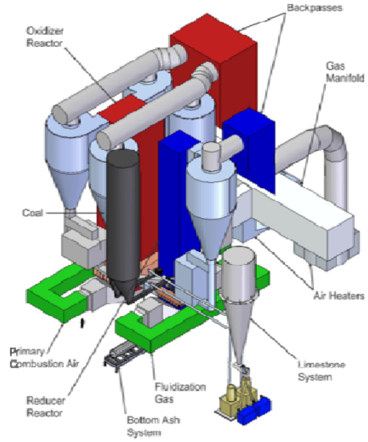
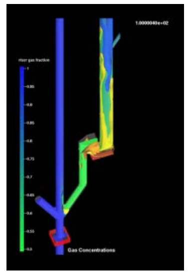
Limestone Chemical Looping (LCL™) Development
Advanced Oxy Combustion – Project Objectives and Status

DOE/NETL Cooperative Agreement No. DE-FE0009484 Phase 1 and 2 - October 2012 to Sept. 2016

- Techno-economic studies on 4 LCL-C™ cases
  Completed June 2013
- Address 7 main technology gaps
  - Seven 3 MW_{th} prototype tests incorporating system modifications
    Test 1 Completed Oct 2013
    Test 2 Completed July 2015
  - Various supporting bench, small pilot, physical flow and CFD modeling studies
    On-going
- Update techno-economic study





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Limestone Chemical Looping (LCL™) Development
Advanced Gasification – Project Objectives and Scope

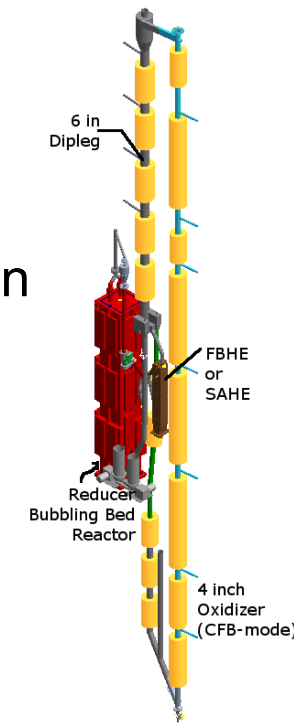
DOE/NETL Cooperative Agreement No. DE-FE0023497 – October 2014 to March 2017

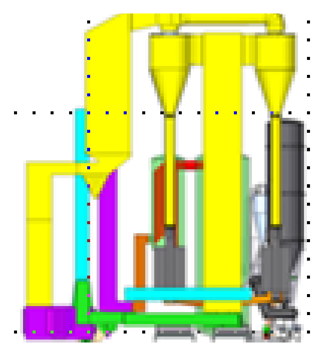
Objective:

To further develop LCL-G™ technology for generation of high-H_2 syngas from coal for liquid fuel production and/or power generation with CO_2 capture.

Scope:

- Small-scale developmental testing (including 100mm diameter 50ft LCL-G pilot tests)
- Cold flow model testing
- Computational modeling simulations
- 3.0 MWth prototype testing
- Techno-economic assessments



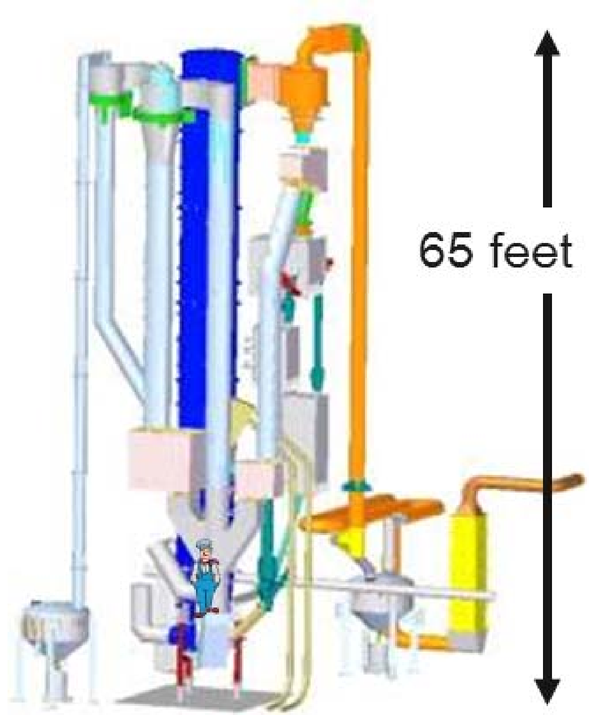


Technology Development Areas

LCL-G™ Technology Development			
	Development Item/Gap	Success Criteria	Testing
1	solids/gas transport	stable & controllable	CFM, PSTF, Prototype (w/ Contract 9484)
2	carbon conversion	> 90% of carbon in coal	Bench, PSTF, Prototype (w/ Contract 9484)
3	sulfur capture/retention	90% of sulfur retained	Bench, PSTF, Prototype (w/ Contract 9484)
4	sorbent activation	Minimal/acceptable degradation	Bench, PSTF, Prototype (w/ Contract 9484)
5	simultaneous WG shift & carbon capture	>90% within 1 second	Bench testing, TEA
6	calcination	calcine < 1 second	Bench testing, TEA
7	product gas stability during load change	10% per minute	PSTF, Prototype testing
8	Biomass co-firing	10 to 50%, HHV	Bench, PSTF
9	Integration w/ F-T Liquefaction	acceptable TEA/TGA	Future Development

Limestone Chemical Looping (LCL™) Development
DOE Award 9484– Prototype Testing - Addressing Gaps

Modifications & Planned Work



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

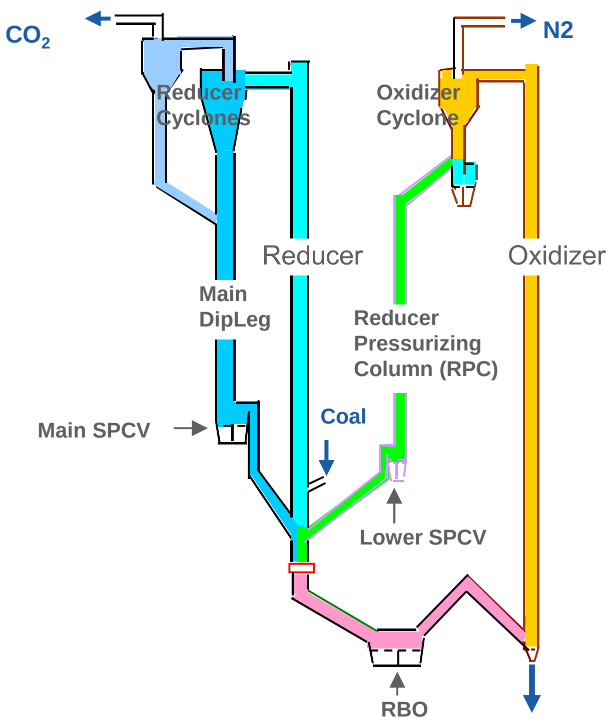
Three Main Areas To Further Address:
Solids Management, Carbon Capture and Sulfur Retention

Award 9494 - LCL-C™ Prototype Testing
Solids Transport Management

Key Issues:

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

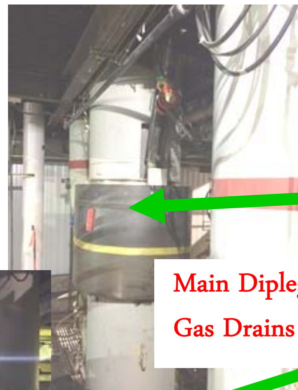
DipLeg Gas Generation - Affects:
- DipLeg solids inventory control
- Solids recycle rate control and stability.
  - Sulfur retention via solid/gas stoichiometry
  - Recycle rate controls Reducer temperature

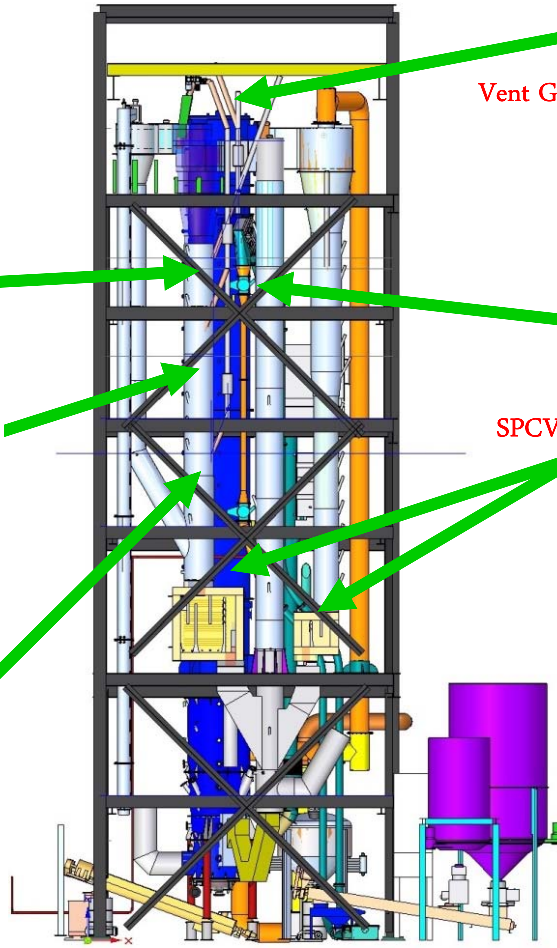


Solids Management Critical to Operability and Performance

Limestone Chemical Looping
Test 2 Modifications – Gas Drain System

Purpose: Solids Control with coal-firing





Phase II Deliverables.xls 1 Nov 2013

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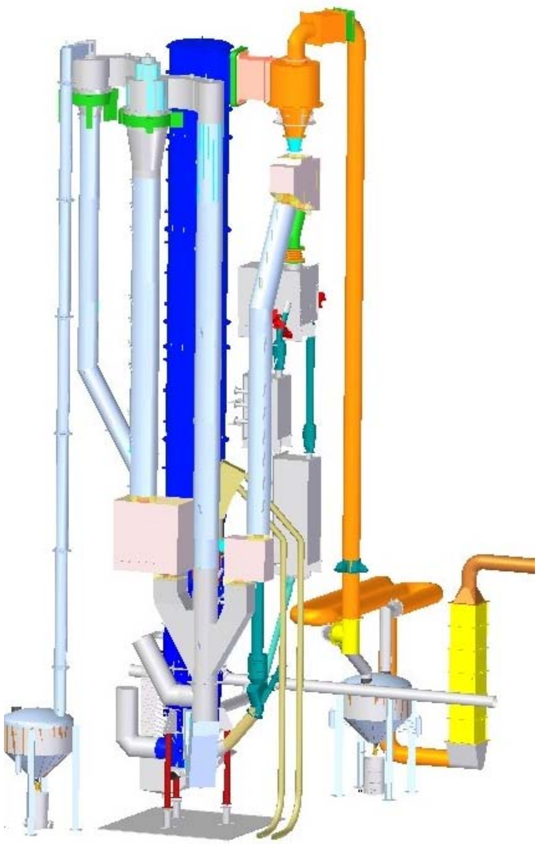
Award 23497 Gasification
3 MWth Prototype Testing

Prototype LCL-G™ test program to maximize syngas H_2, minimize CH_4 and minimize N_2

- Three (3) piggyback LCL-G test campaigns combined with Project 9484 LCL-C test campaigns;
- Final dedicated test after LCL-G modifications



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

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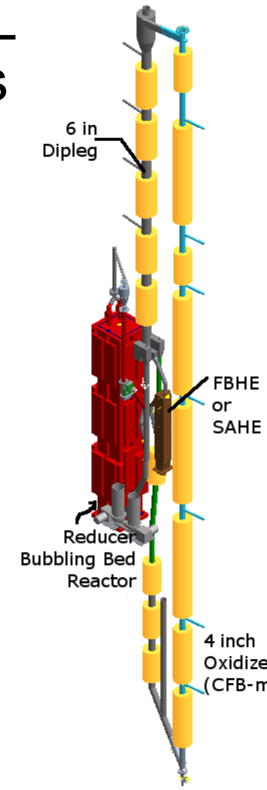
Small-Scale Testing and Process Development

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)

Under Construction – To Be Completed September 2015

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100 mm Pilot Scale Test Facility – Under Construction

Oxidizer

Reducer

Electric and I&C Supply

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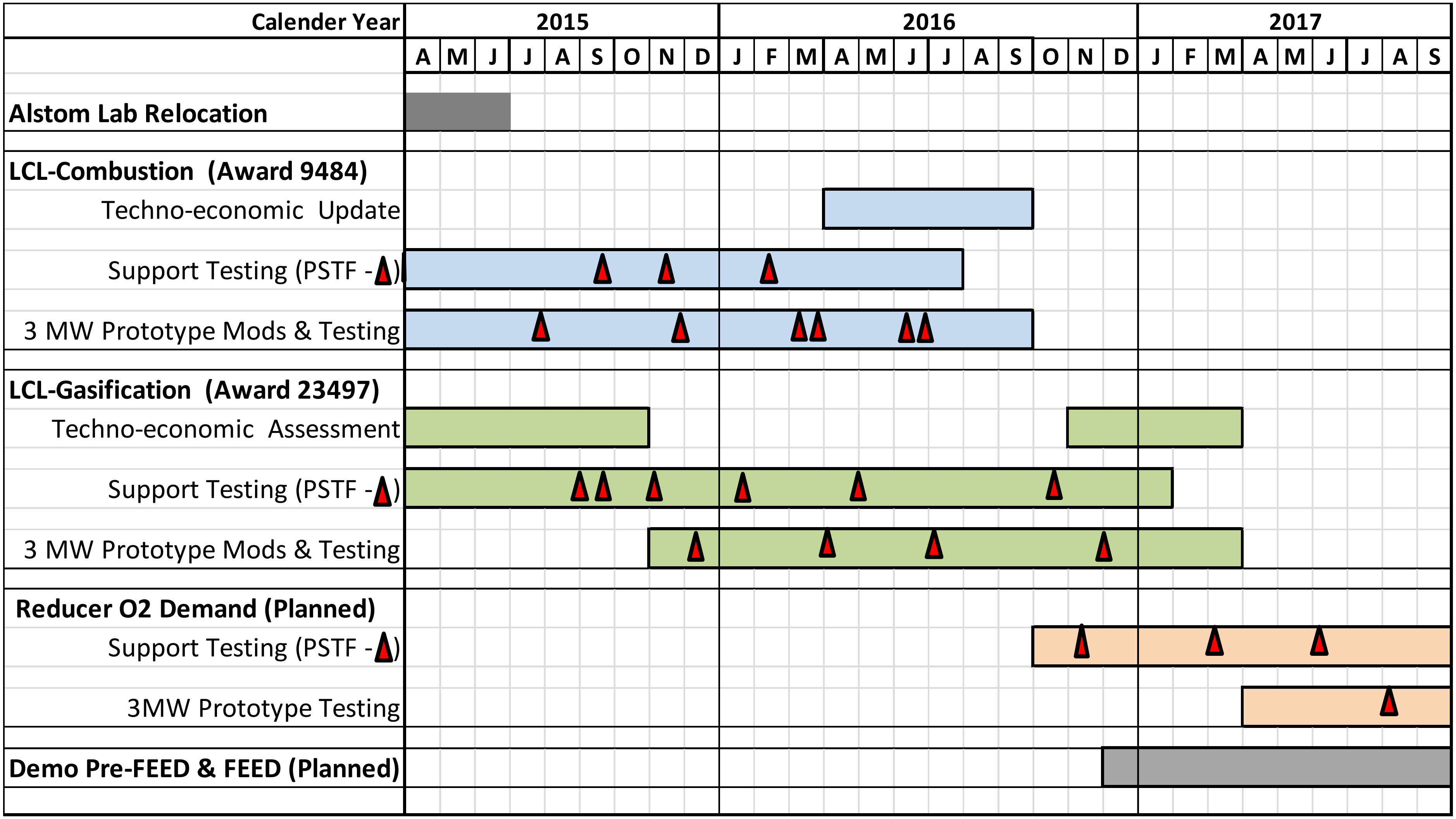
Limestone Chemical Looping Development
Planned Workscope & Schedule



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 are in-progress to address them.
- **Alstom is continuing development efforts and on track with its commercialization roadmap**

Phase II Deliverables.xls 1 Nov 2013

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Acknowledgements and Disclaimer

Acknowledgement

Some of work presented was supported by the U S Department of Energy through the National Energy Technology Laboratories under Agreements DE FE-0009484 and DE FE -0023497. The guidance and direction of NETL Project Manager Briggs White is acknowledged and appreciated.

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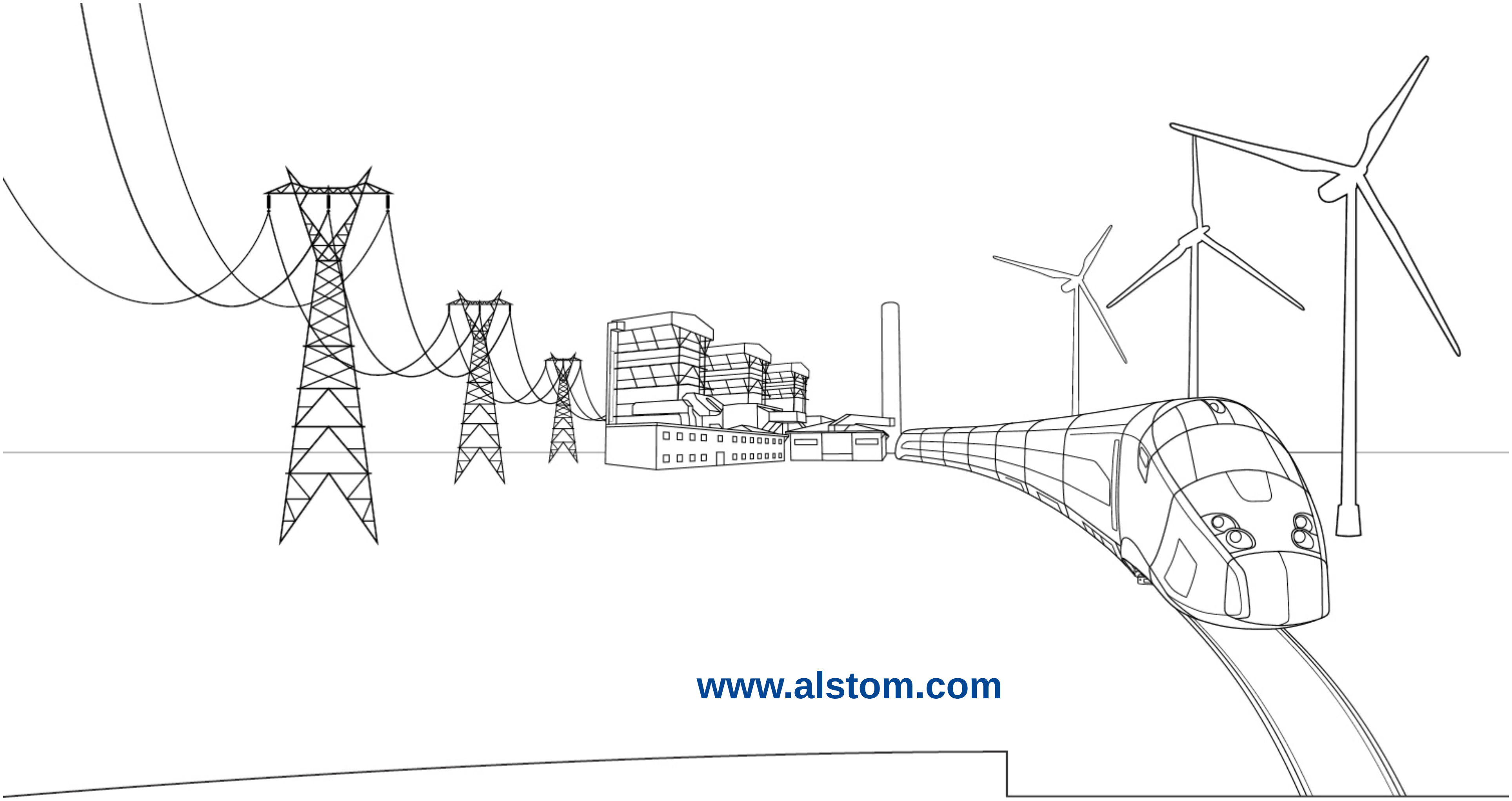

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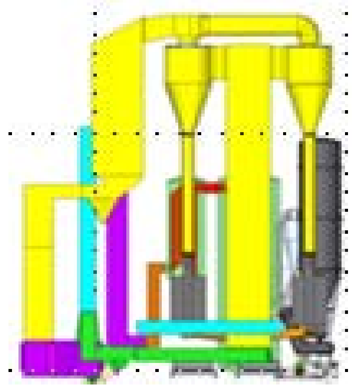
Shaping the future

Techno-Economic Study: LCL-Combustion

Study Cases: 550 MW_e Power Plant with CO_2 Capture

(Applying DOE Economic Methodologies and Guidelines)



- Case 1 – LCL-C™ system using transport reactors
- Case 2 – LCL-C™ system with the Reducer reactor in the CFB mode
- Case 3 – LCL-C™ system of Case 1 with an advanced ultra-supercritical (AUSC, 350bar/730^{o}C/760^{o}C) steam cycle
- Case 4 – LCL-C™ system with pressurized Reducer reactor with an AUSC steam cycle

Comparison Basis:

- State-of-the-art SCPC case – Case 11 from Cost and Performance Baseline for Fossil Energy Plants Volume 1, DOE/NETL-2010/1397
- 1st generation Oxy-combustion PC case – Case 5 from Pulverized Coal Oxy-combustion Power Plants, DOE/NETL-2007/1291 (COE increased 53.5% from Case 11)

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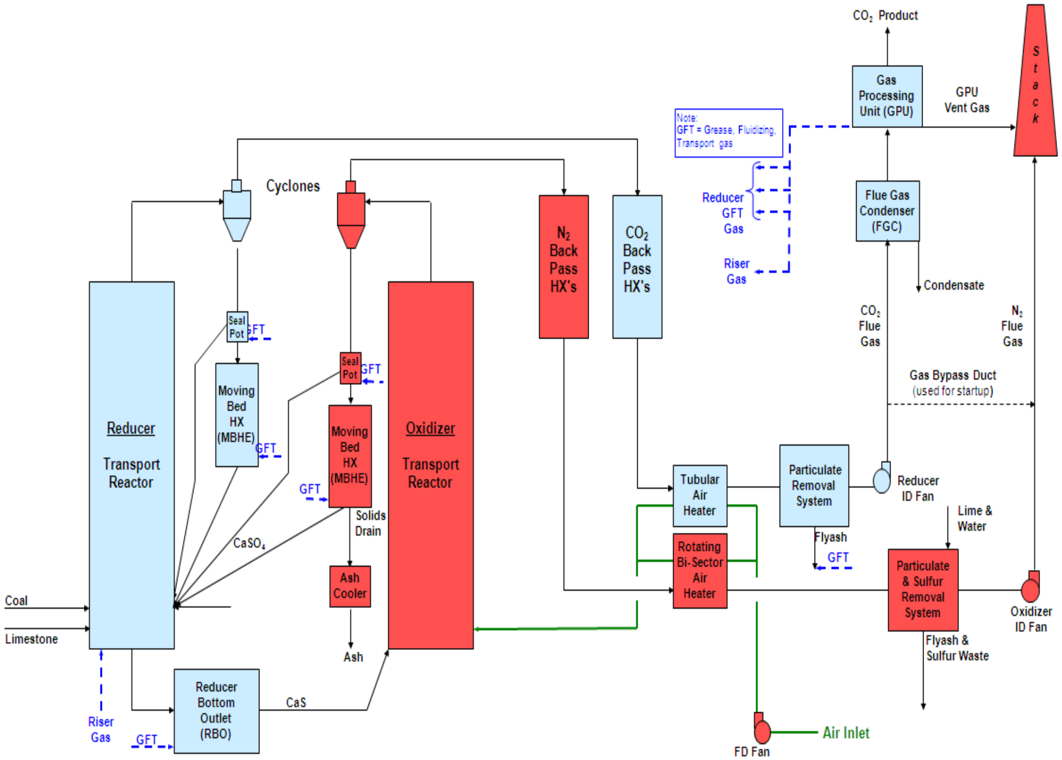
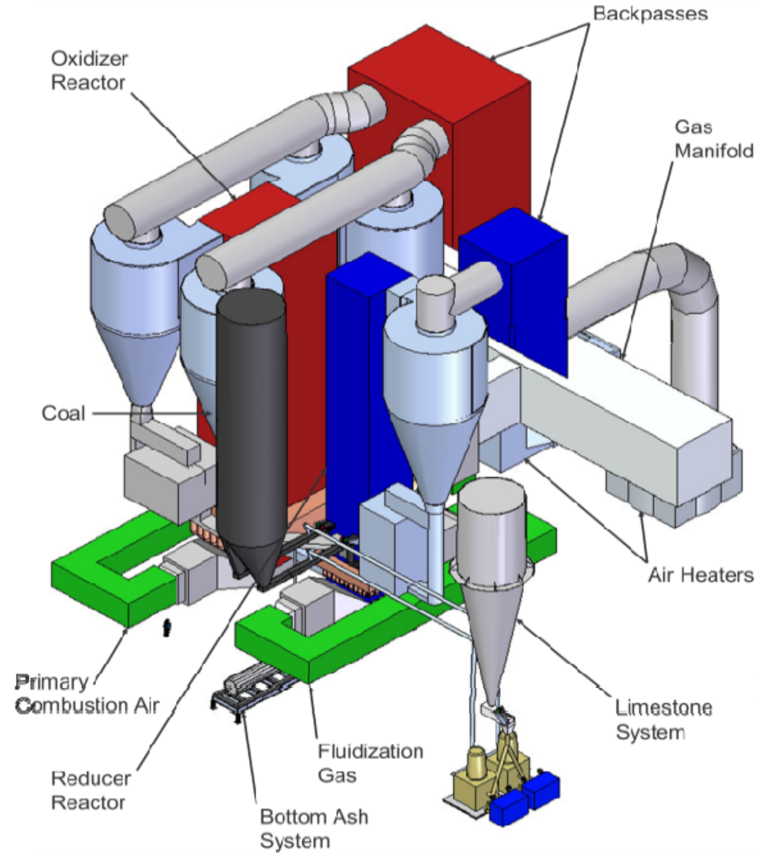
LCL-C™ Power Island Process





Fully integrated with AQCS and CO_2 capture system

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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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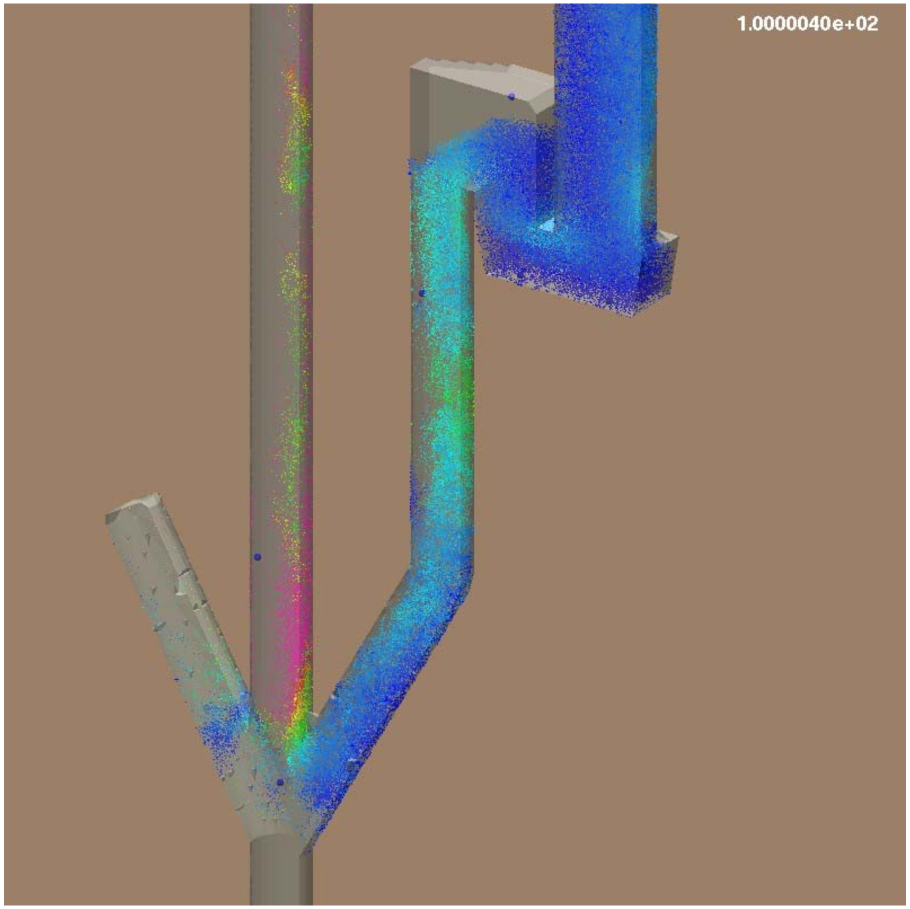
Support Testing - Physical Flow Model and CFD Modeling

- 40ft Cold Flow Model



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