Alstom's [GE] Chemical Looping Combustion Technology with CO_2 Capture for New and Existing Coal-fired Power Plants (FE0009484)

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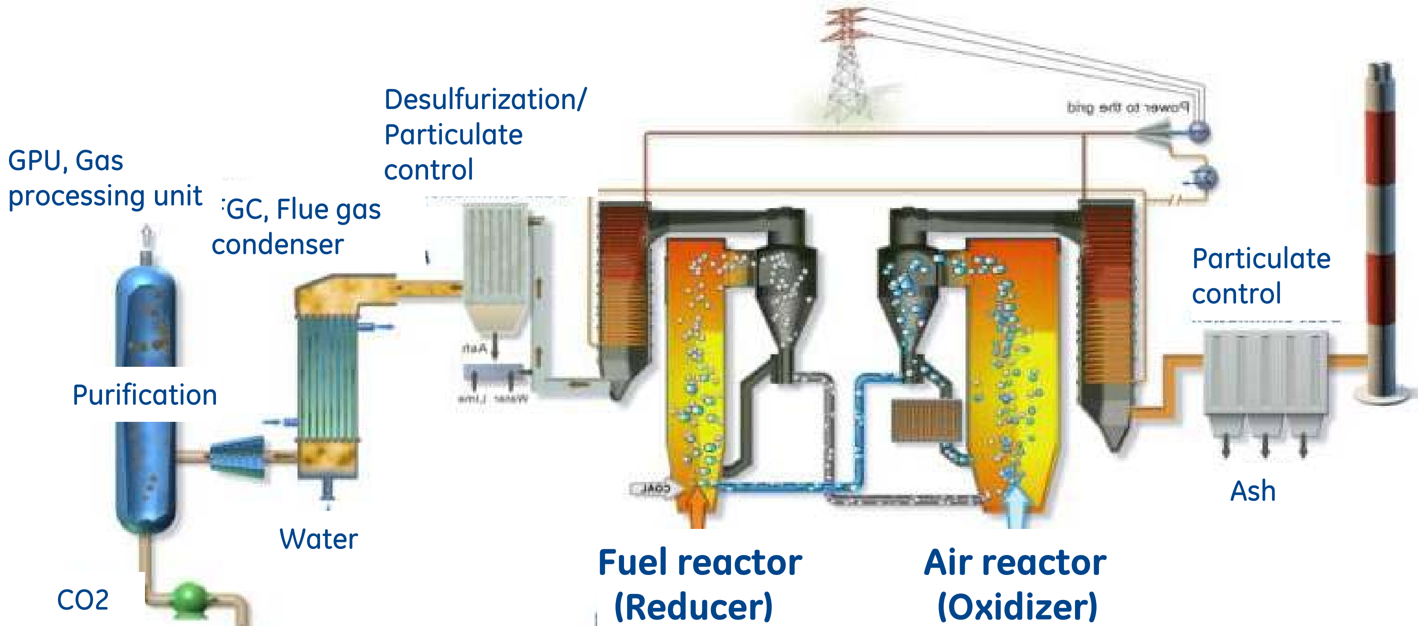
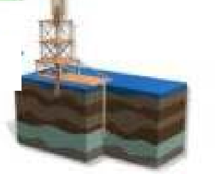
Imagination at work

Chemical Looping Combustion
Advanced oxy-combustion without air separation losses





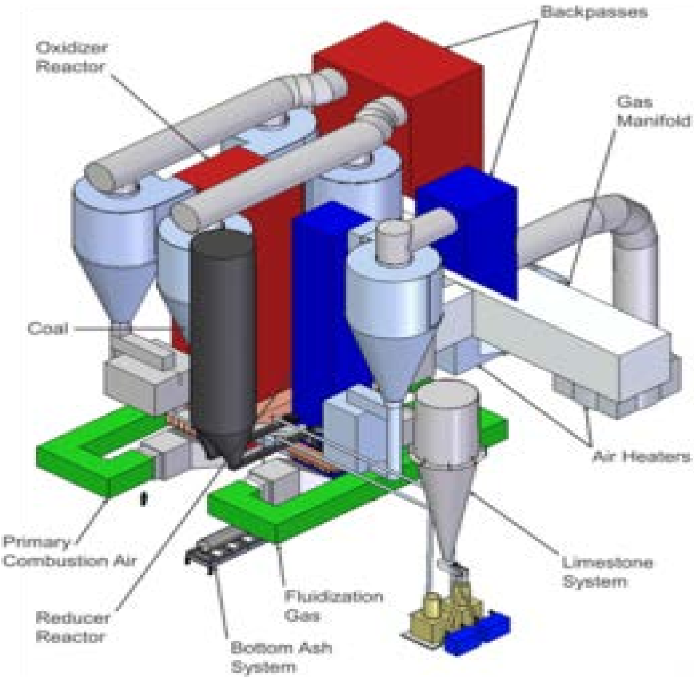
- Avoids CAPEX and high energy consumption of cryogenic air separation unit (ASU)
- No large gas recirculation
- Two interconnected boilers
- Low cost coal-based power generation with CO_2 Capture

GE Limestone Chemical Looping Combustion

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-based power, syngas, hydrogen
- Builds on CFB experience
- Uses conventional construction and materials

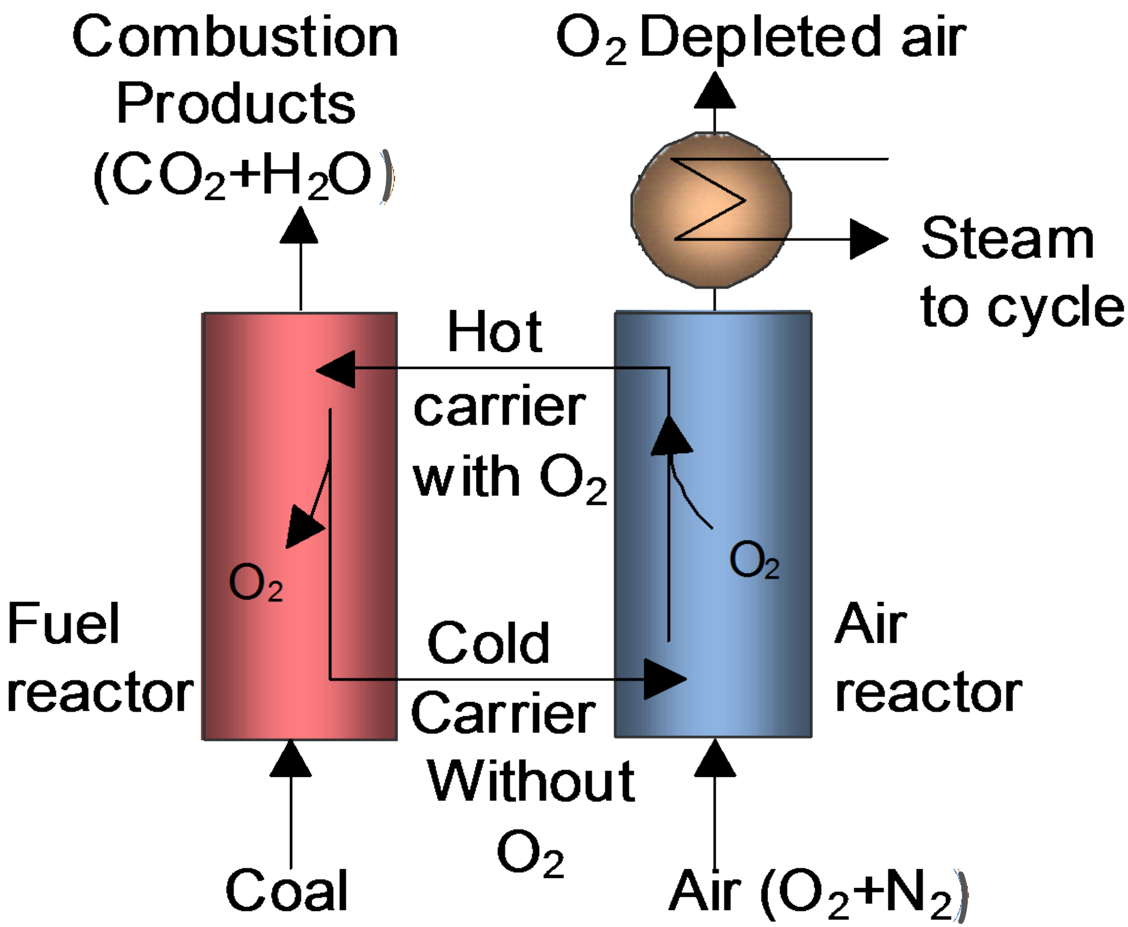
550 MWe Chemical Looping Combustion Steam Generator



Targets:

- LCoE <20% increase vs. Plant without CCS
- CO_2 Capture Cost < $25/ton
- Efficiency <10% CCS penalty vs Plant w/o CCS

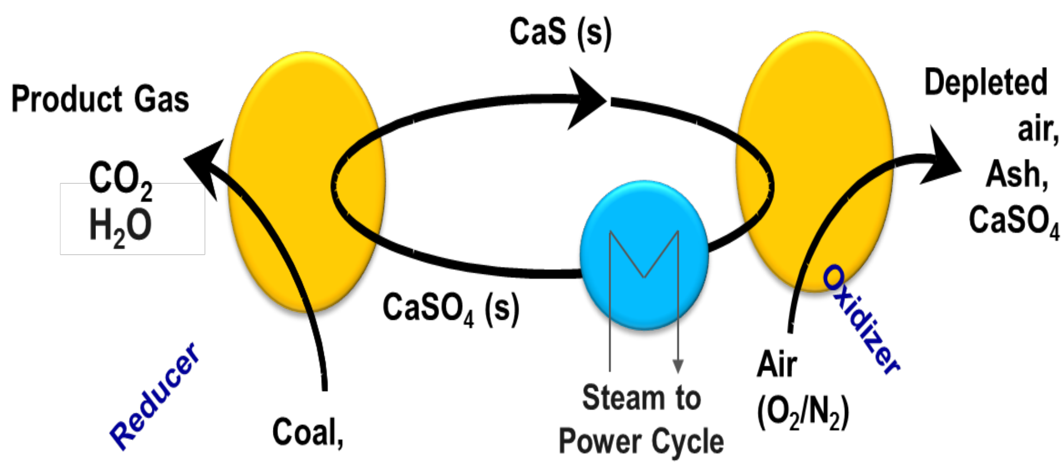
Chemical Looping Combustion Process



Limestone Chemical Looping–Combustion Process

Oxygen carrier:

- CaS-$CaSO_4$ from limestone
- Low cost; availability
- No ash/carrier separation (solids soup like CFB)



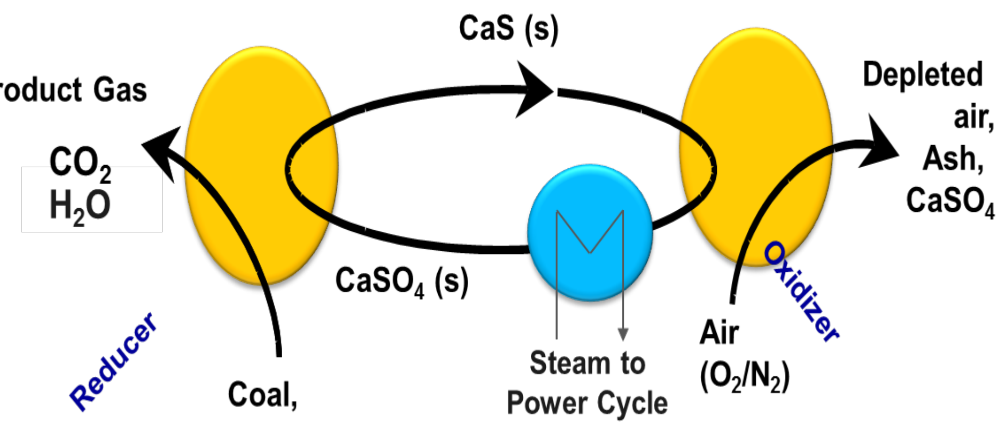
Chemistry:

Reducer:	**Purpose**
$CaO + H_2S => CaS + H_2O$	– Sulfur capture
$C + CO_2 => 2\ CO$	- Carbon gasification
$CaSO_4 + 4\ CO => CaS + 4\ CO_2$	– CO_2/CaS formation
$H_2O + CO <==> H_2 + CO_2$	– Water Gas shift for H_2
$CaO + CO_2 <==> CaCO_3$	– CO_2 capture for H_2
Carbon/carrier separation	– Cold flow tests

Oxidizer:

$CaS + 2\ O_2 => CaSO_4$	– CaS combustion

Possible Unfavorable Side Reactions



Oxidizer

Sulfur Loss side-reaction:

- $CaS + 1.5\ O_2 \Rightarrow CaO + SO_2$

Carbon Carryover side-reaction:

- $C + O_2 \Rightarrow CO_2$

Reducer

Sub-Stoichiometric Reactions:

Low CO concentration

- $CaSO_4 + CO \Rightarrow CaO + CO_2 + SO_2$

Low H_2 concentration

- $CaSO_4 + H_2 \Rightarrow CaO + H_2O + SO_2$

Universal

Sulfur Loss by CaS-$CaSO_4$ direct reaction:

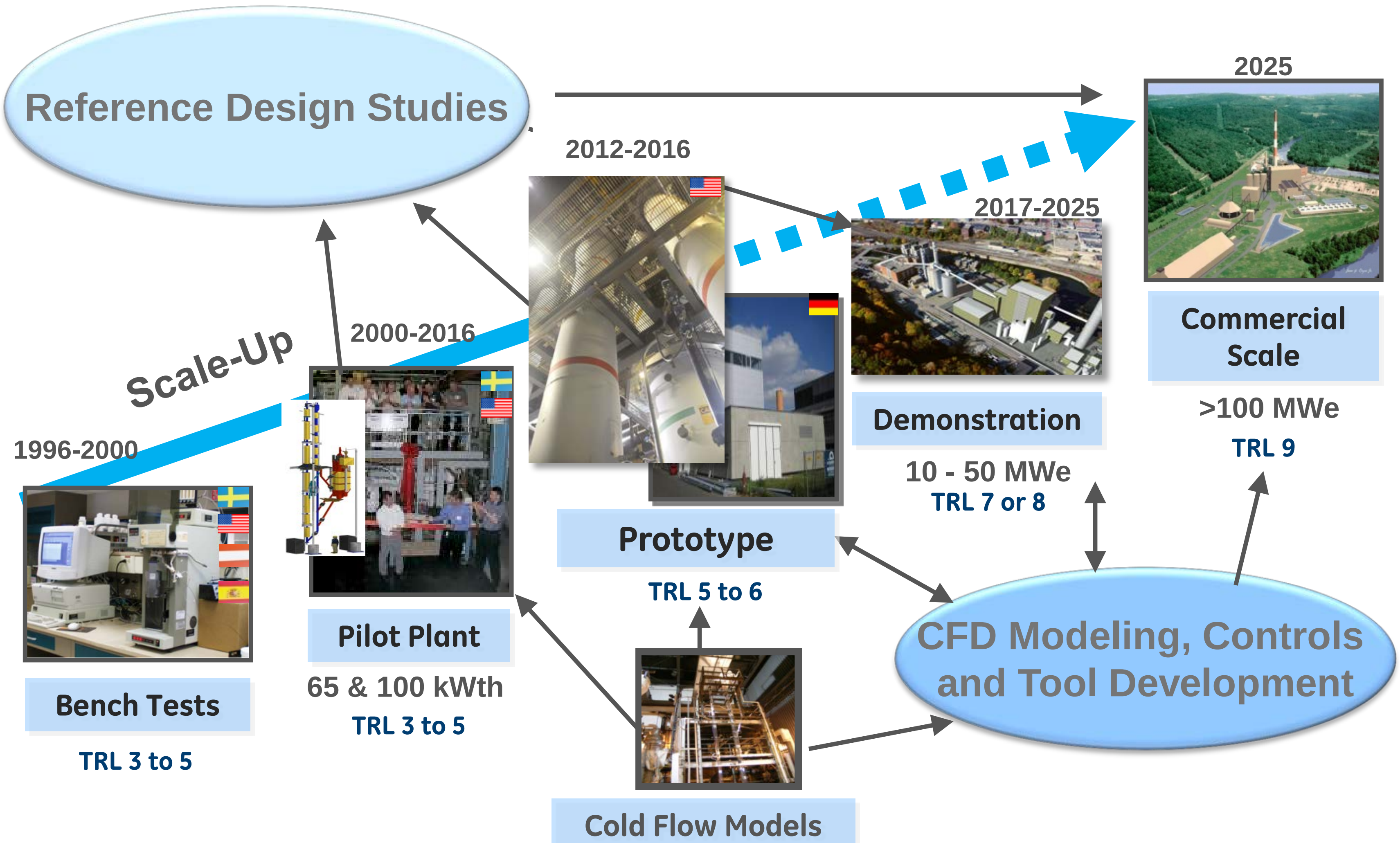
- $3CaSO_4 + CaS \Rightarrow 4CaO + 4SO_2$

$CaSO_4$ thermal decomposition:

- $CaSO_4 \Rightarrow CaO + SO_2 + ½\ O_2$

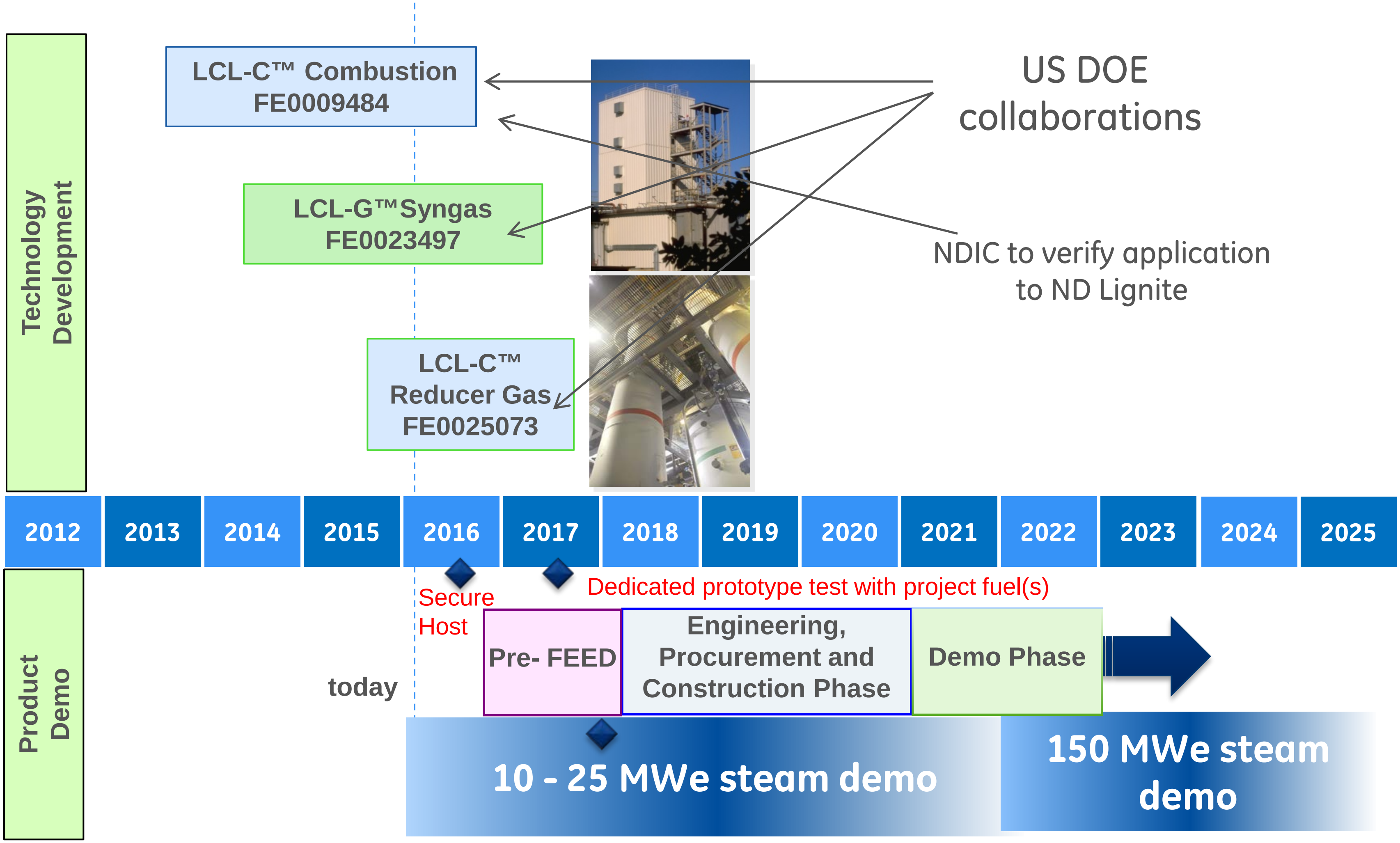
Control process conditions to minimize side reactions and optimize performance

GE - Chemical Looping Development
Managed Scale-up Steps



Progressive development – US & EU – MeOx & CaOx Carriers

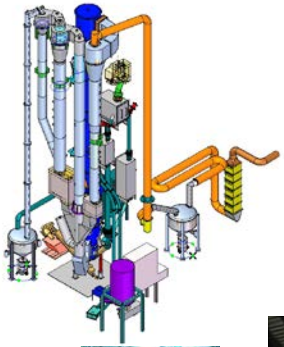
GE – Limestone Chemical Looping Development



Limestone-based Chemical Looping Combustion Project FE0009484

Goal

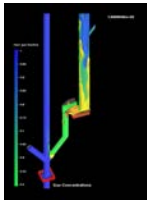
To develop a chemical looping combustion process with 90% CO_2 capture at 20% or less increase in cost of electricity compared to new coal power plants without capture.



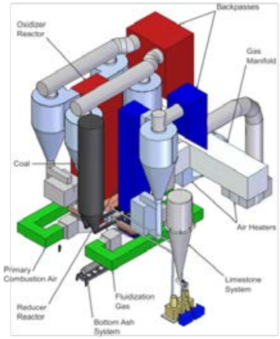
Specific Project Objectives

- Address technology development gaps
  - Solids Transport
  - Carbon Loss / CO_2 Capture
  - Sulfur Retention

  using
  - CFD and Cold Flow modeling
  - Bench-scale testing
  - 100 kWt Pilot-scale Test Facility (PSTF) testing
  - 3 MWt Prototype testing



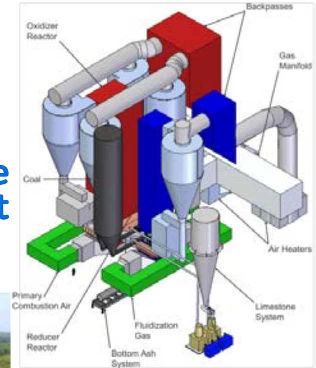
- Generate information needed for 10-25 MWe Demonstration
- Update techno-economic analysis based on test results



Limestone-based Chemical Looping Combustion FE0009484

Project Start: Oct 2013 End: June 2017

550 MWe Plant



Major Milestones Achieved

- Techno-economic studies on four LCL-Combustion cases **Completed June 2013**
- Two 3 MWt test programs with auto-thermal operation assessing technical gaps **Completed Oct 2014 and July 2015**
- Relocated 3 MWt Prototype to new GE Clean Energy Laboratory location (Bloomfield, CT) **Completed Aug 2015**
- Installed new 100 kWt Chemical Looping Facility **Completed Oct 2015**
- Six 100 kWt test programs addressing technical gaps **Completed Nov 2015 – June 2016**

GE Clean Energy Lab Facility in Bloomfield CT

3 MWt Prototype Facility

100 kWt Facility

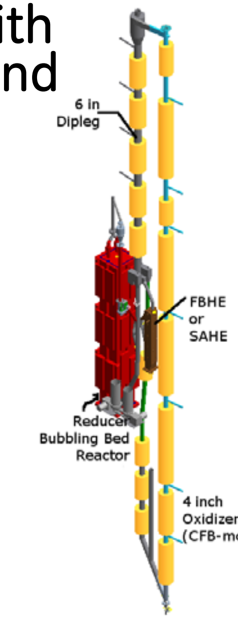
100 kWt PSTF Testing

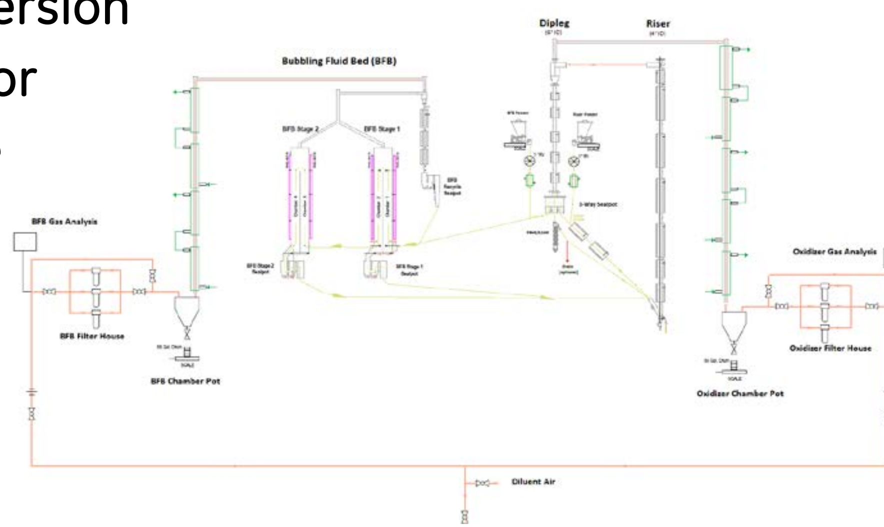
Allows testing under highly controlled conditions with detailed solids and gas mapping to better understand behavior

Configuration flexible to run single and double loop tests, vary Reactor volumes/residences time, etc.

Testing conducted to assess technical gaps and impacts key parameters on performance

- Solids flow and circulation behavior
- Carbon conversion and residence time requirements
- Coal volatile cracking and conversion
- Oxidizer CaS oxidization behavior
- Oxidizer/Reducer sulfur capture and release mechanisms
- Behavior of different fuel types





PSTF Results* - June 2016 Campaign

	1	2	3	4	5	6	7	8
Coal pph	25	25	25	25	25	25	25	25
Steam location	-	-	-	1	2	1,2	1	1
Limestone pph	17.3	17.7	17.8	18.0	17.0	17.5	17.4	17.5
BFB % CO	2.0	3.0	4.5	4.4	5.6	5.3	6.3	8.0
Ox SO2, ppm	371	99	34	0	4	0	26	0
BFB SO2, ppm	3100	2300	2200	1500	1100	1500	1600	200
BFB Total Red S, ppm	-	-	-	-	520	600	-	280
Sulfur Retained, %	**2.9**	**37.4**	**24.1**	**62.5**	**62.4**	**52.5**	**61.5**	**94.0**
% C gasified	**83**	**84**	**80**	**86**	**82**	**79**	**81**	**70**
% C carryover	**15.5**	**14.4**	**15.4**	**12.5**	**15.2**	**14.5**	**13.6**	**20.7**
% Ox demand	**7.9**	**10.3**	**13.3**	**14.3**	**17.3**	**15.9**	**18.3**	**18.7**

* Preliminary results analysis

Performance Summary

	Commercial Goal	3 MW Prototype - Current Level	Project Success Criteria (3 MW Prototype)	100 kW PSTF – Current Level
Carbon Conversion Performance				
Carbon Gasified in Reducer (%)	>95	40 - 50	>80	70 - 85
Unburned Carbon Loss in Ash (%)	<0.5	Up to 20	<5	3 -5
Carbon Carryover to Oxidizer (%)	1	20 - 40	<20	13 -21
Reducer Gas Oxygen Demand (% of Stoichiometry O_2)	<5	25 - 15	<10	8 -19
Sulfur Retention by Reactors				
Sulfur Capture (% of S input)	>85	Net Sulfur Loss	>70	0 - 94
Solids Transport				
Solids Circulation Rate	Design Range	Lower	Design Range	Design Range
Dipleg Flushing (Frequency)	None	Frequent	Rare	None
Solids Loss Rate Thru Cyclones (lb/MBtu- Fired)	As Req'd Stable Inventory	Up to 200	50	70 – 120

Significant Progress Achieved to Targets

GE Limestone Chemical Looping

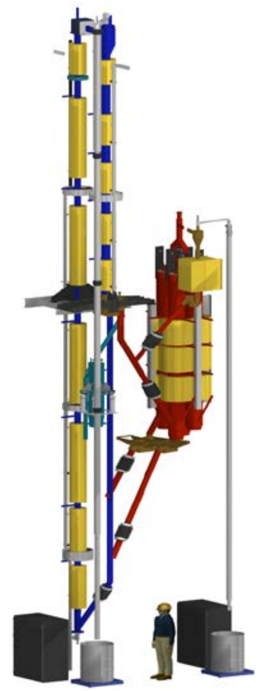
Current status of development

1) **Solids Transport**
   - Need stable solids flow and low solids loss thru cyclone. Experienced solids flow instability during coal firing in 3 MWt tests
   - **Mitigation with mechanical valves; reduced carbon in circulating solids. Have achieved good solids flow control and stable operation at 100 kWt.**

2) **Carbon Loss / Carbon Carryover**
   - Need low loss thru cyclones and low carbon carryover to Oxidizer to achieve % carbon capture target. Carbon loss levels of 1-20% loss thru cyclones and 20-40% carbon carryover to oxidizer during 3 MWt tests
   - **Mitigation with larger fuel reactor and improve solids management at 100 kWt.**

3) **Carrier stability and Sulfur Loss**
   - For limestone carrier, need to control of sulfur
     Still challenge; have achieved acceptable sulfur retention at 100 kWt, further optimize with carbon conversion.
   - For all carriers, need acceptable attrition, agglomeration and reactivity life; achievement currently acceptable

4) **Product Gas Quality (FE 0025073)**
   - Need complete fuel conversion – unburned combustibles in gas from Fuel Reactor
   - **Assessing mitigation by reaction enhancement (mixed carriers, increased temperatures, steam vs CO_2 gasification); on-going**
   - **Assessing mitigation by post processing (O_2, second stage CLC, special GPU with recycle of CO and CH4)**



GE 100 KWt PSTF

Next Steps: Testing Plan

100 kWt PSTF Test 7: Continued Performance Improvements (Sept 2016)

- Continued Parametric Testing (Temperatures, Circulation Rate, Fluidization Flows, CO_2 and Steam Reaction Gas, etc.)
- Addition of Ilmenite (10% and 20% Ilmenite blends)

100 kWt PSTF Test 8/9: LCL-C Optimization (Oct/Nov 2016)

- Reconfigured System As Needed Based On Test 7 Results
- Modify Reducer & Oxidizer Cyclone Systems to Improve Flyash Capture (Sulfur Retention and Carbon Loss Improvement)
- Parametric Testing Over Selected Conditions

3 MWt Prototype Conformation Testing (Feb 2017)

- Validation 100kWt PSTF results and solutions for technical gaps
- Define Performance and key design information

GE Limestone Chemical Looping Combustion

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
- 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 are being addressed
- The 100 kWt PSTF has been an excellent tool to develop chemical looping and address technical gaps
- **Substantial progress has been achieved in addressing Limestone Chemical Looping technical gaps and GE is on track to validate the process for the next step of large pilot demonstration**

Acknowledgements and Disclaimer

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