10 MWe CDCL LARGE PILOT PLANT DEMONSTRATION - Phase I Feasibility DE-FE0031582

DOE Kickoff Meeting

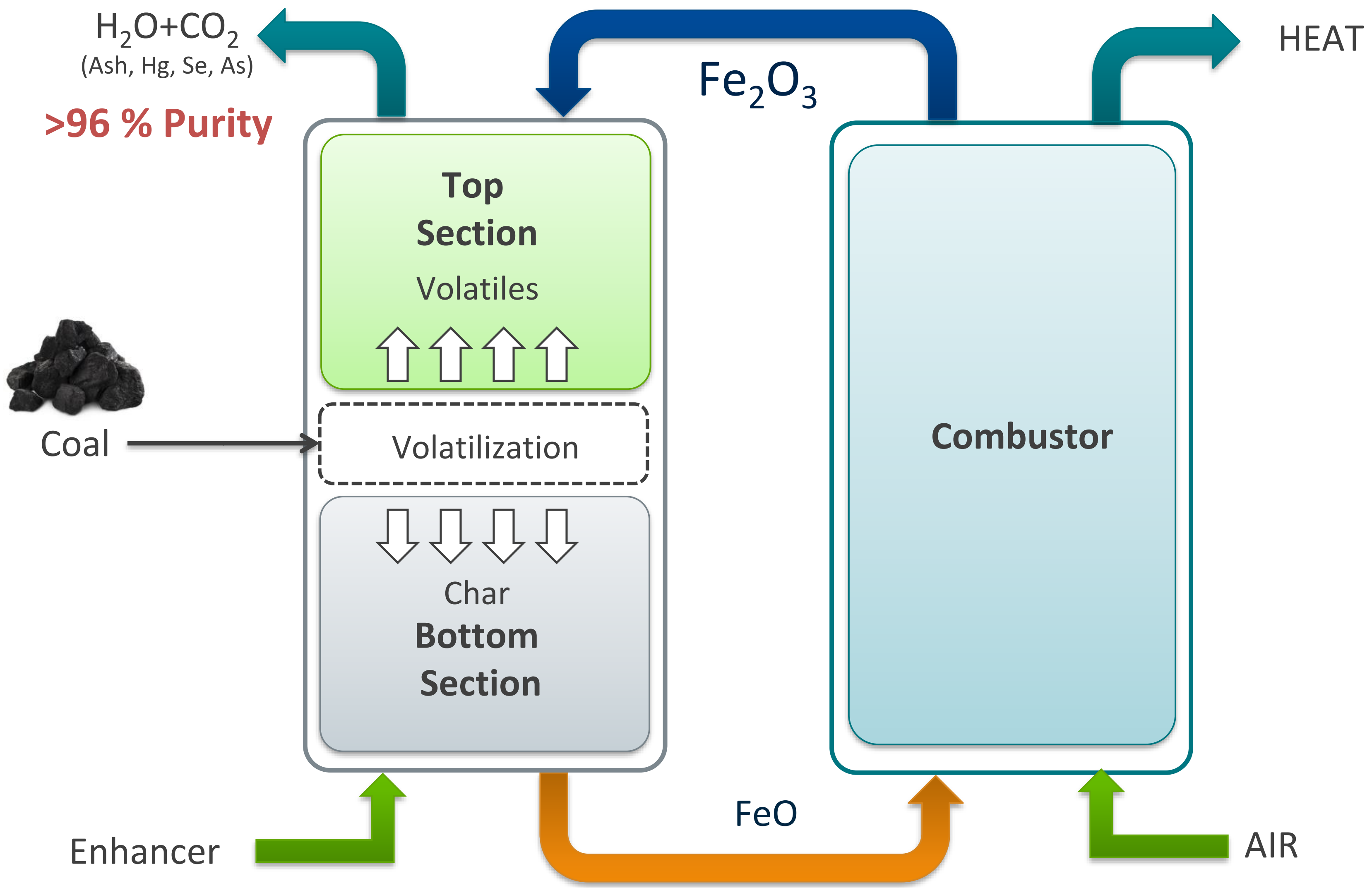
TRANSFORMING OUR WORLD | 150 YEARS

May 22, 2018

Outline

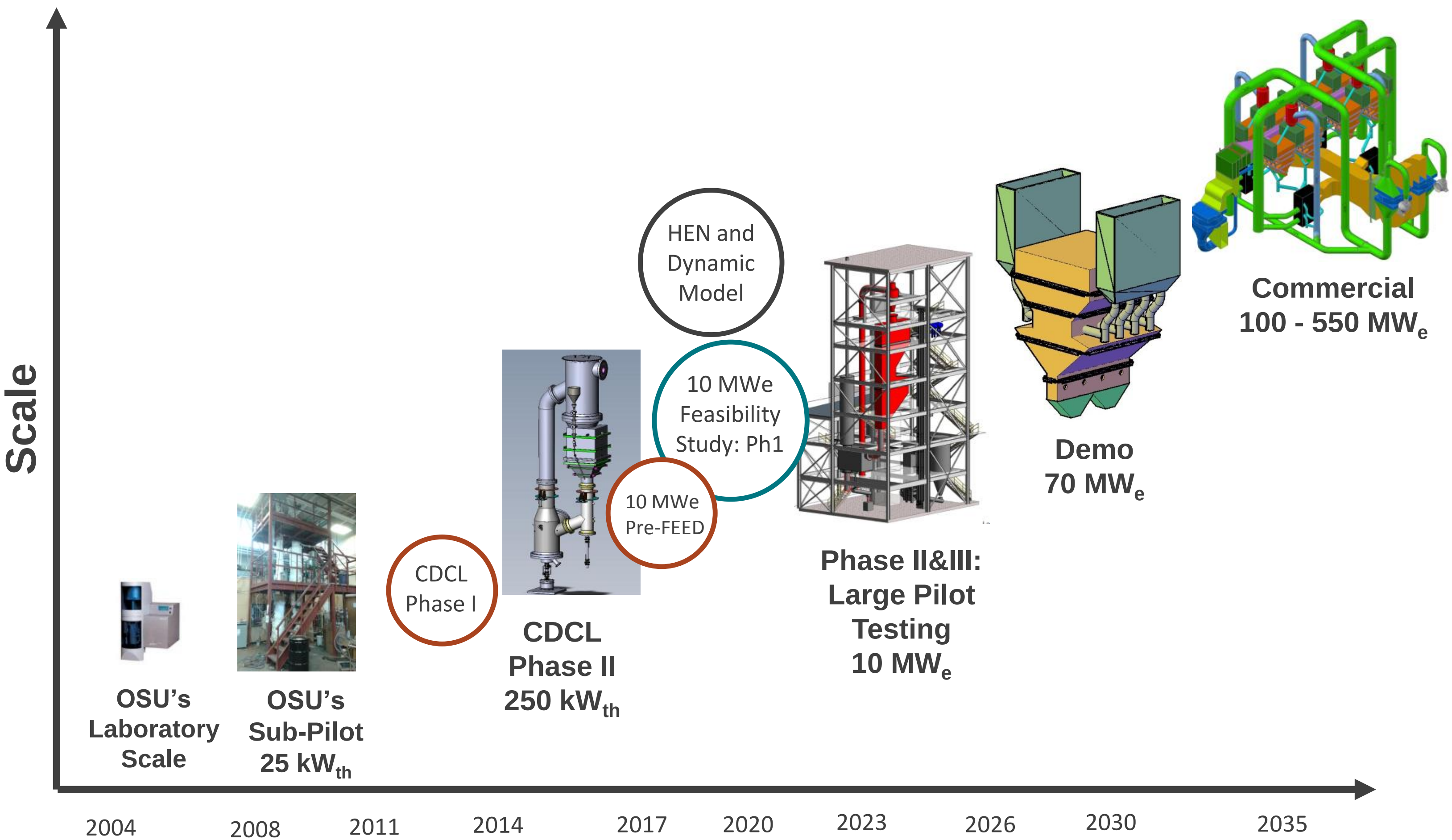
- ❑ **Background**
- ❑ **Technical Approach for 10 MWe Large Pilot**
- ❑ **Project Details**
  - **Objectives**
  - **Project Structure**
  - **Project Schedule**
  - **Project Budget**
- ❑ **Risk Management**

CDCL Process



Two-stage Counter-current Moving Bed

CDCL Commercialization Path



B&W & OSU CDCL Collaboration

DOE Syngas CL Demo at NCCC

Year: 2010-2017

- Design and demonstration of 250 kWth syngas chemical looping facility

DOE Commercialization Phase I

Year: 2012-2013

- Conceptual design of 550 MWe commercial plant
- Techno-economic analysis (>90 % CO_2, <35 % increase in COE)
- Technology gap analysis

DOE Phase II A

Year: 2013-2015

- Laboratory cold model test
- Design of 250 kWth pilot plant
- Cost estimate for construction and test

DOE-ODSA Phase II B

Year: 2015-2017

- Construction and test of 250 kWth CDCL facility

DOE-ODSA Heat Integration

Year: 2016-2018

- Combustor simulation
- Heat exchanger network integration and optimization
- Dynamic model of integrated CDCL-steam cycle

DOE-ODSA Adv. Control

Year: 2015-2017

- Develop HLC-SMC process automation control architecture
- Establish algorithm for high temperature ECVT sensor
- Test process control and optimization concepts at 25 kWth scale

DOE– ODSA 10 MWe pre-FEED

Year: 2017-2019

- Develop a pre-FEED of a 10MWe CDCL pilot plant

Development of Chemical Looping Platform Technology

DE-FE-0009761

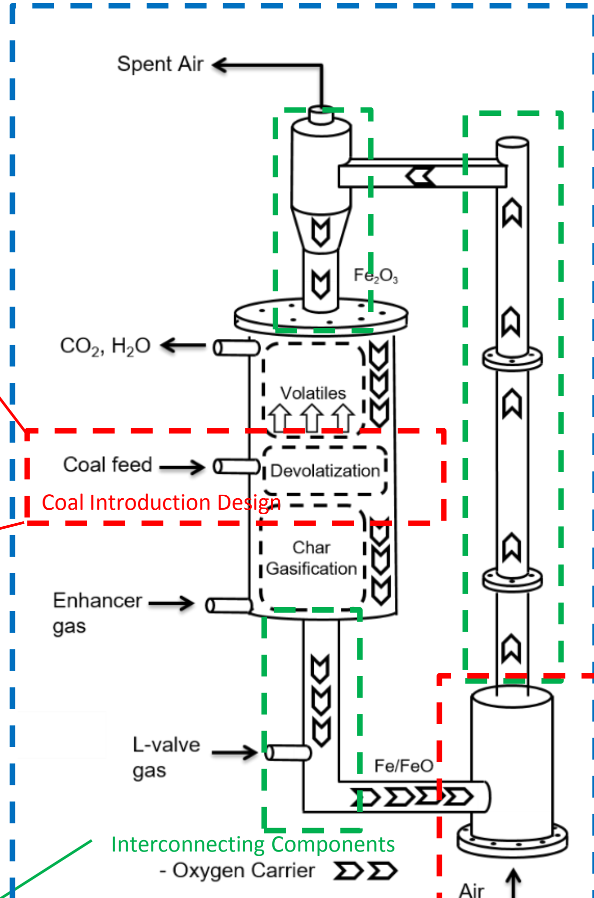
250 kWth pilot unit

DE-NT0005289

25 kWth Sub-pilot unit

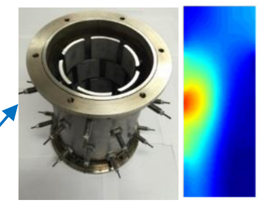
DE-FE-0023915

250 kWth SCL pilot unit



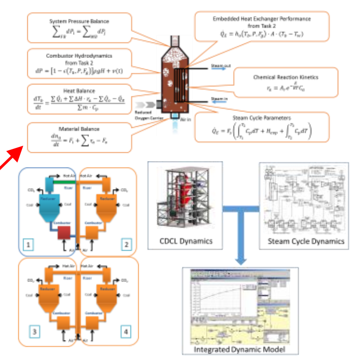
System control

DE-FE-0026334



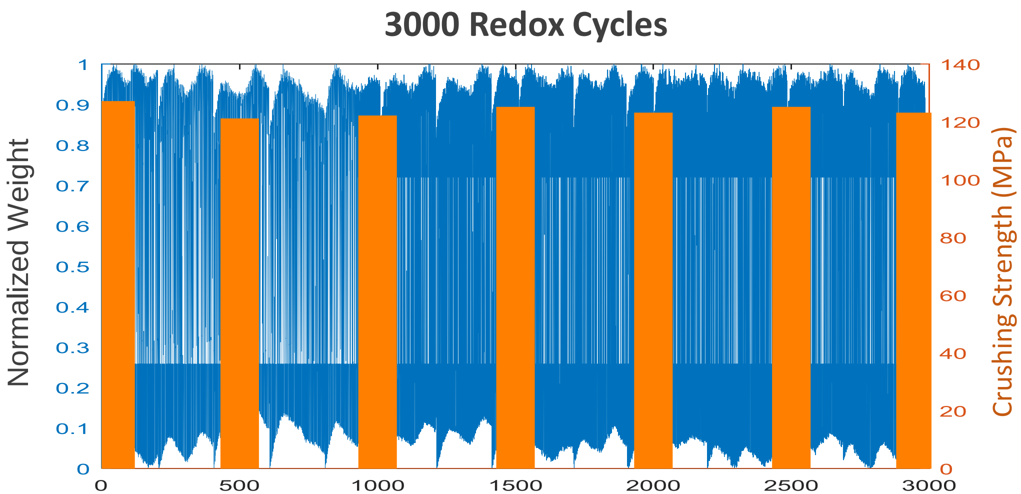
Control and Sensor Development

DE-FE-0029093



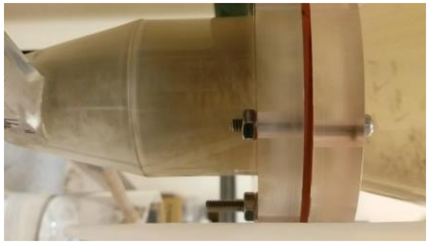
Combustor Development

Particle Development

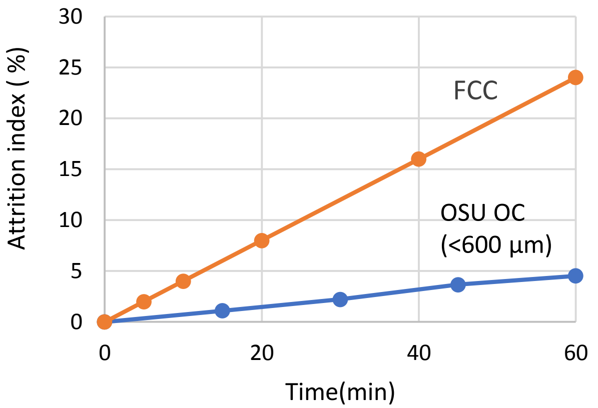


Particle Strength Comparison

Oxygen Carrier/Catalyst Particle	Strength (MPa)
OSU OC	120
Other Chemical Looping Combustion	72
Chemical looping Steam Reforming	26
Commercial WGS Catalyst Pellet	6.8
Traditional ATR Catalyst	6.5



Jet Cup

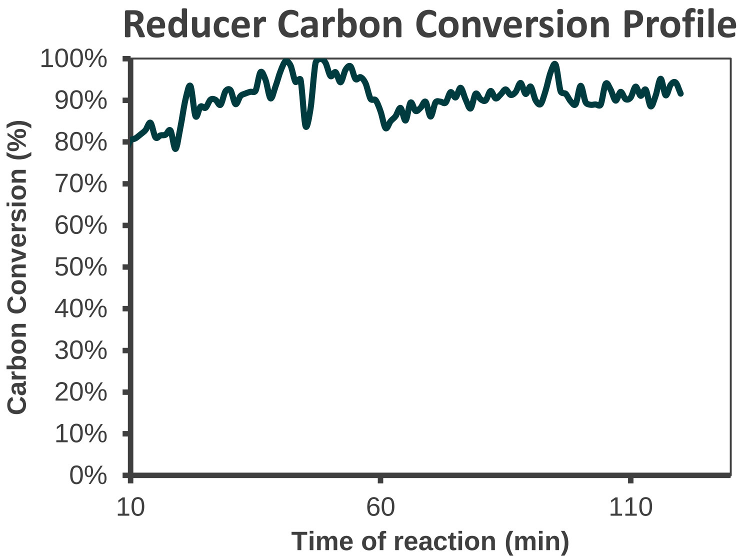


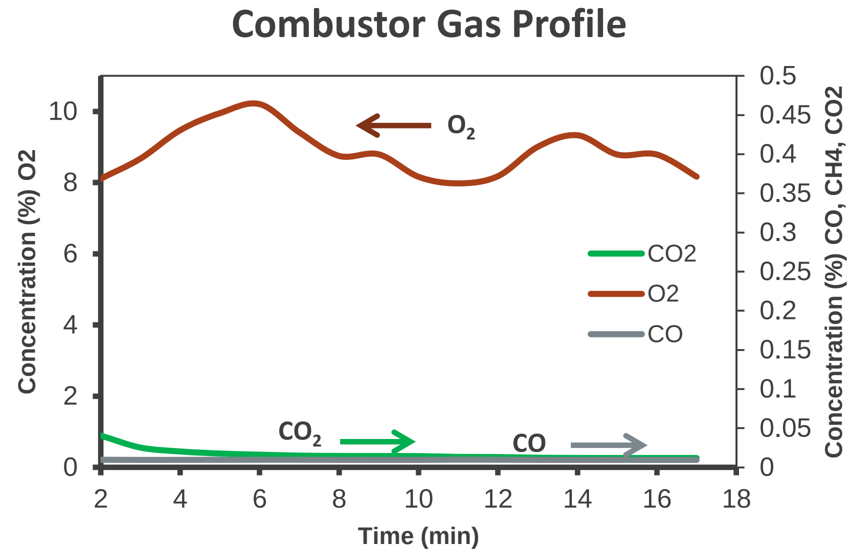
- **Stability over 3000 redox cycles at 1000 °C; equivalent to 8 months of commercial operation**
- **High attrition resistance compared with commercial FCC particles in jet-cup experiment**

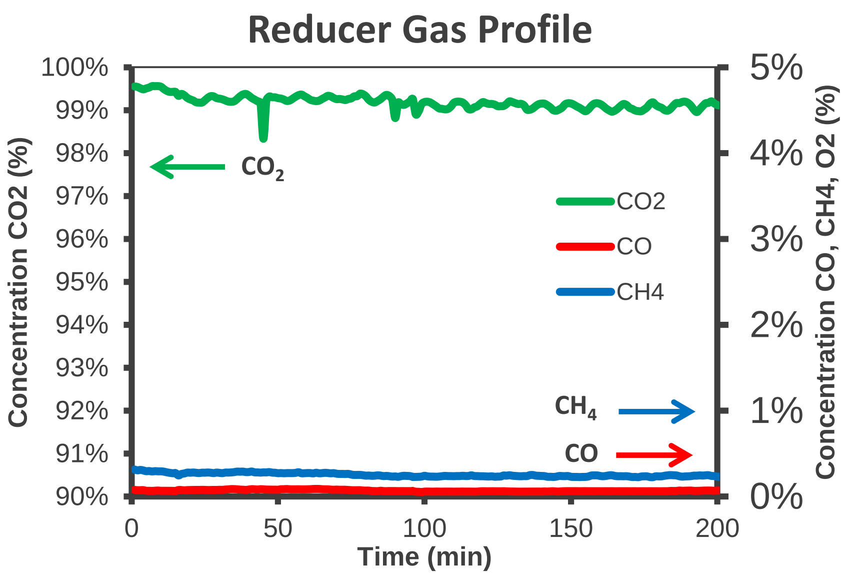
25 kW_{th} Sub-Pilot Demonstration

- > 800 hours of operational experience
- > 200 hours continuous successful operation
- Smooth solids circulation
- Complete ash separation in reducer.
- Achieve nearly pure CO_2 from reducer outlet
- 17 test campaigns completed

200-hour Continuous Sub-Pilot Test







Sample Data: PRB Process Performance

- Continuous steady carbon conversion from reducer throughout all solid fuel loading (5- 25kWth)
- <0.25% CO and CH_4 in reducer outlet = full fuel conversion to CO_2/H_2O
- <0.1% CO and CO_2 in combustor = negligible carbon carry over, nearly 100% carbon capture

Outline

- Background
- Technical Approach for 10 MWe Large Pilot
- Project Details
  - Objectives
  - Project Structure
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- Risk Management

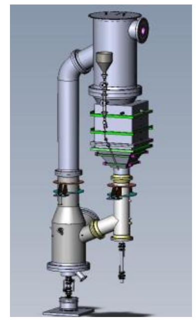
CDCL Technology Development

Laboratory 2.5 kWth

- Particle recyclability and reactivity
- Individual reactions in the reducer and combustor

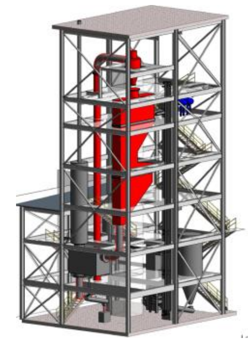
25 kWth

- Integrated operation reducer and combustor for more than 200 hours
- Coal conversions
- CO_2 Purity



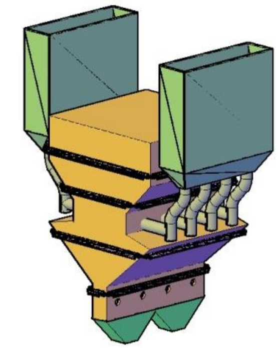
250 kWth

- Adiabatic reducer operation for more than 250 hours
- Process efficiency
- Evaluate emissions
- Large scale particle manufacturing
- Particle attrition



4 x 2.5 MWe

- Long Term operation
- Coal distribution
- Modular integration and operation - Start up, turn down, shutdown cycles
- Steam generation
- Economics



1 x 70 MWe

- Commercial Operation of a single module
- Fabrication

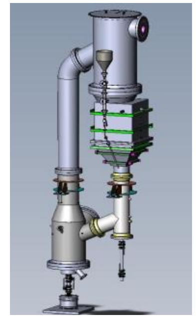
Scale Up Plan

Laboratory
2.5 kWth

x10

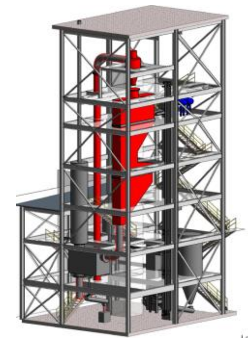
25 kWth

x10



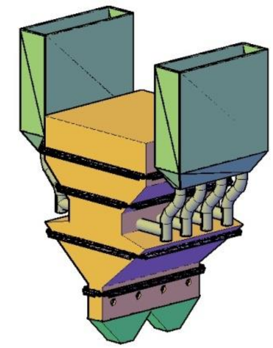
250 kWth

x30



4 x 2.5 MWe

x30



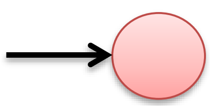
1 x 70 MWe

Critical Dimension Scale up Factor:
x1

Reducer reactor Critical Dimension:
1.5”

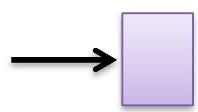
Critical Dimension Scale up Factor:
x4

Reducer reactor Coal distribution Distance:
6”



Critical Dimension Scale up Factor:
x6

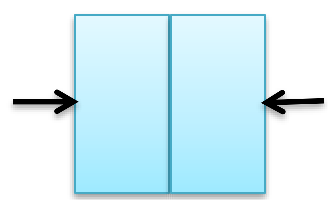
Reducer reactor Coal distribution Distance :
3’



3’

Critical Dimension Scale up Factor:
x2.3

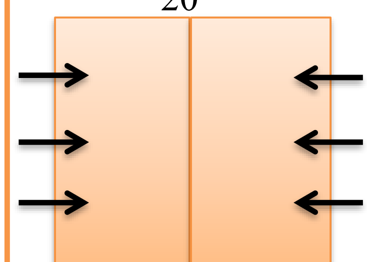
Reducer reactor Coal distribution Distance :
7’



7’ 7’

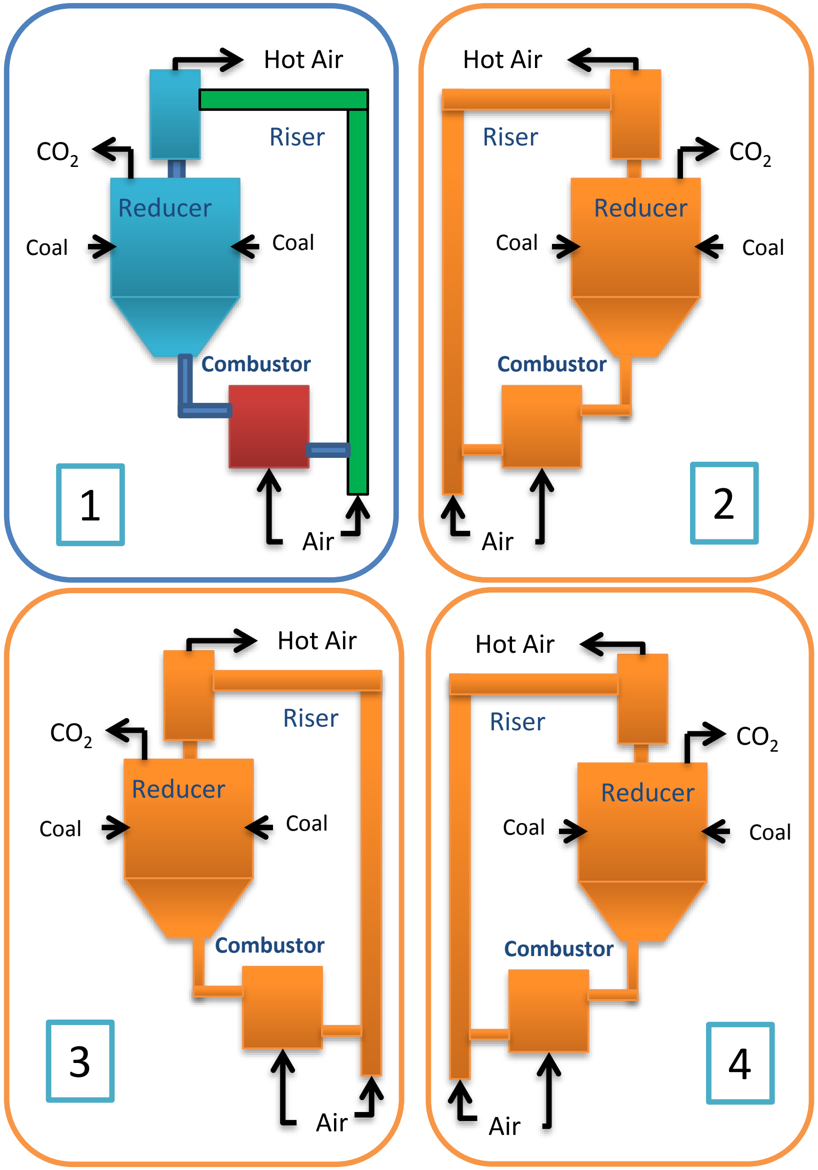
Critical Dimension Scale up Factor:
x2.8

Reducer reactor Coal distribution Distance:
20’



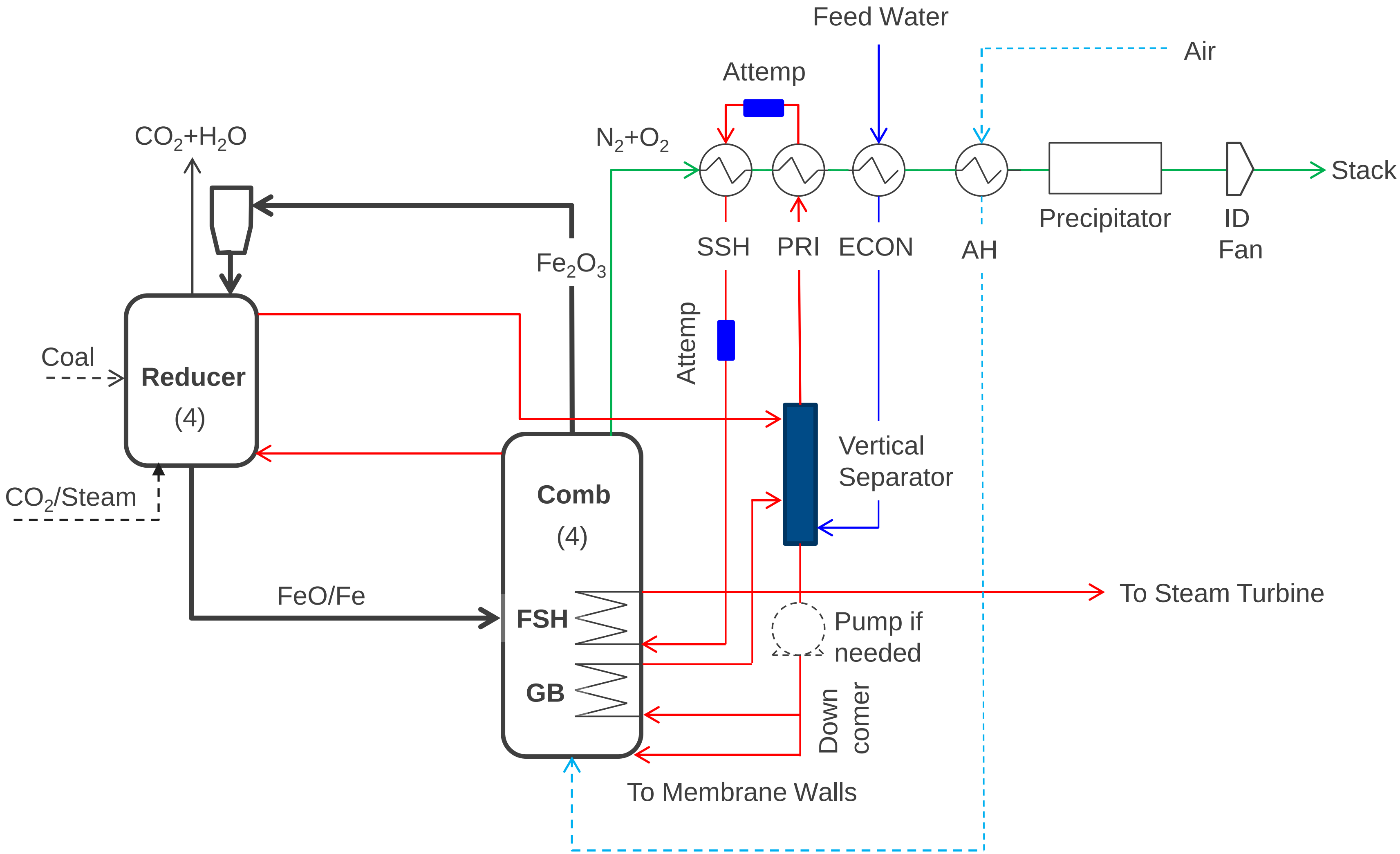
20’ 20’

10 MWe Modular Pilot Design



- 4 Modules of 2.5 MWe
- 1st module will be built and operated to validate the design.
- Following modules will be constructed
- Integration of the modules operation and controls

CDCL Steam Generation Scheme



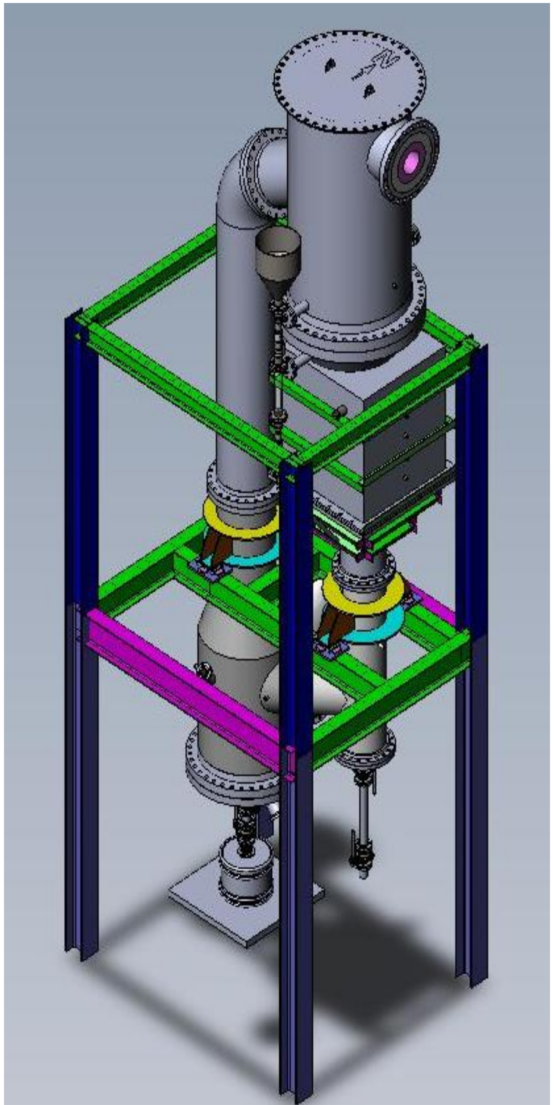
Advantage of Modular Design and Sparing Philosophy

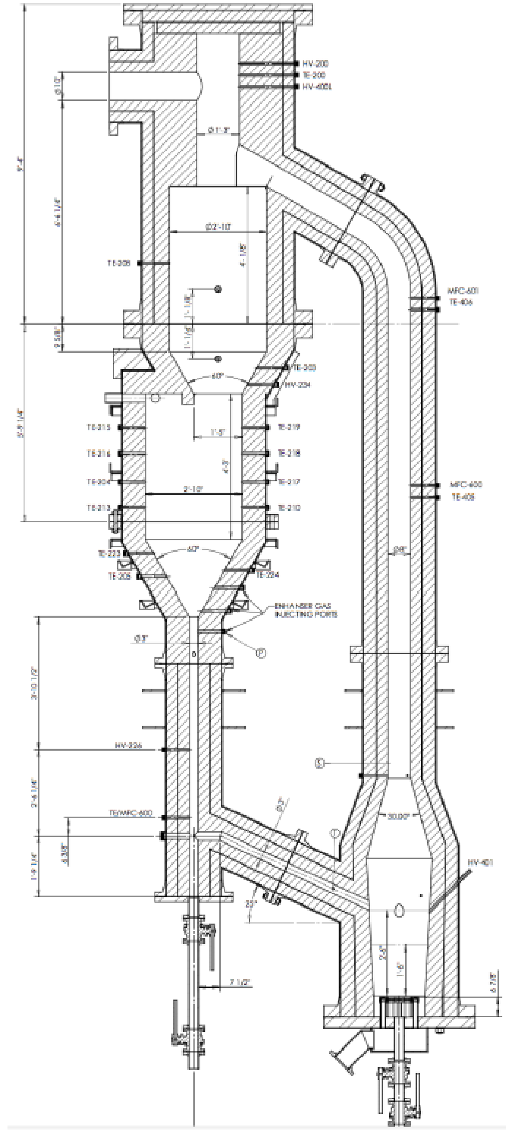
- ❑ **Startup**
  - **Sequential module startup with sharing resources**
- ❑ **High Reliability**
  - **Independent steam generation**
  - **Easier for scheduling maintenance**
  - **4-33% modules provide full load capacity with module-out of service**
- ❑ **Flexible Operation**
  - **Fast response**
  - **Turn down/up**
  - **Particle exchange among modules**

Technology Gap and Mitigation Plan

Design/Technology Issues	Past Mitigation	Ongoing Mitigation	Plan Mitigation
Particles			
Manufacturing Cost	Under OSU's Scope	Particle Manufacturer (JM)	Multiple Manufacturers
Attrition	250 kWth / NCCC	Attrition Tests / 250 kWth	10 MWe Large Pilot
High Temperature Resistance	TGA	TGA / 250 kWth	10 MWe Large Pilot
Reducer			
Coal Injection & Distribution	25 kWth Sub-Pilot	Coal RXN Model / 250 kWth	10 MWe Large Pilot
Char Residence Time	25 kWth Sub-Pilot	Coal RXN Model / 250 kWth	10 MWe Large Pilot
Ash Separation / Enhancer Gas	CFM / 25 kWth Sub-Pilot	CFM / 250 kWth	10 MWe Large Pilot
Char Carryover	CFM / 25 kWth Sub-Pilot	CFM / 250 kWth	10 MWe Large Pilot
Pressure Drop	Phase I /25 kWth Sub-Pilot	250 kWth	10 MWe Large Pilot
CO_2 Purity	25 kWth Sub-Pilot	250 kWth	10 MWe Large Pilot
Sulfur, NOx, Hg Emissions	25 kWth Sub-Pilot	250 kWth	10 MWe Large Pilot
Alkaline Management	2" BFB Studies	2" BFB Studies	10 MWe Large Pilot
Combustor			
Heat Exchanger surface	B&W's CFB Technology	B&W's CFB Technology	10 MWe Large Pilot
Auto-thermal Operation	Phase I (Calculation)	250 kWth	10 MWe Large Pilot
Process			
Operation	25 kWth Sub-Pilot / NCCC	250 kWth	10 MWe (modular)
Start up/Shut down	25 kWth Sub-Pilot / NCCC	250 kWth	10 MWe (modular)
Safety	25 kWth Sub-Pilot / NCCC	250 kWth	10 MWe (modular)

250 kW$_{th}$ Pilot Plant - Design





Pilot Design:

- Reducer Design
- Material and Energy Balances
- Support Structure Design
- Detail Construction Drawings

Specifications

- Materials: Refractory lined Carbon Steel
- Max Operating Temperature: 2012 ^{o}F
- Reducer : Counter-current moving bed
- Combustor : Bubbling bed
- Overall Height: 32 ft
- Footprint = 10’ x 10’
- Thermal Rating: 250 kWth
- Coal Feed Rate: 70 lb/hr
- Coal Size: Pulverized coal
- Particle Transport: Pneumatic
- Oxygen Carrier: Iron based
- Size: 1.5 mm

250 kW_{th} Pilot Plant

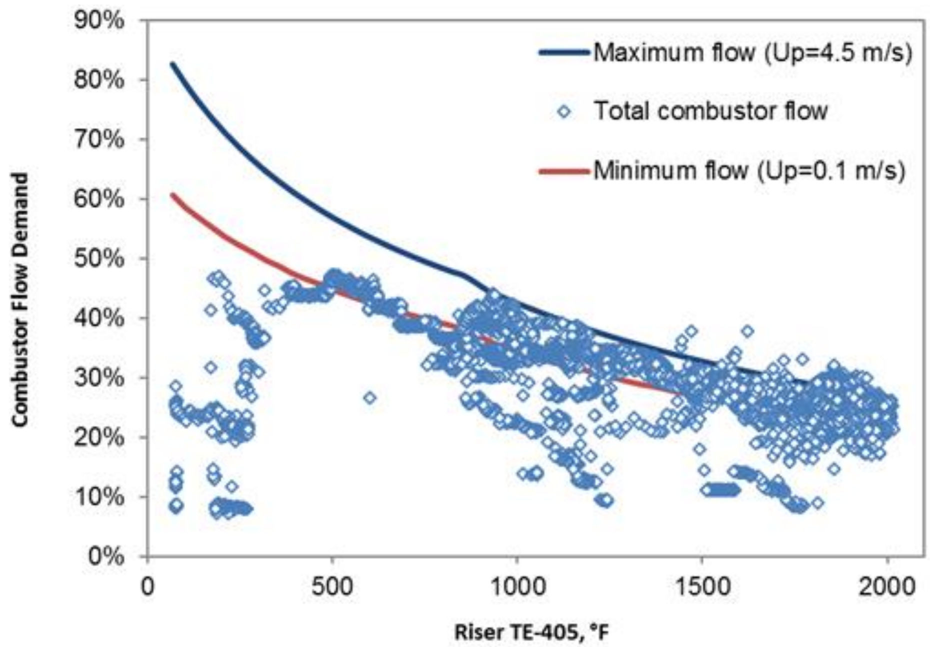
250 kW_{th} Test Campaign Summary

Test Campaigns		Main Achievements	Lessons Learned
#1	Refractory bake out	Heated up to 1600 °F for more than 24 hrs	○ Quench system ○ Need extra NG injection
#2	Unit shake down, start up and operation	• Reached 1800 °F • Achieved expected solid circulation • Characterization of temperature/pressure distributions, gas sampling and analysis	○ Coal injection pressure unbalance ○ Blower capacity low at startup
#3	Coal injection test	• Reached 1950 °F • Injected coal successfully • High volatile conversion • Attrition rate < 0.18%/hr	○ Air infiltration ○ Agglomeration due to over heating

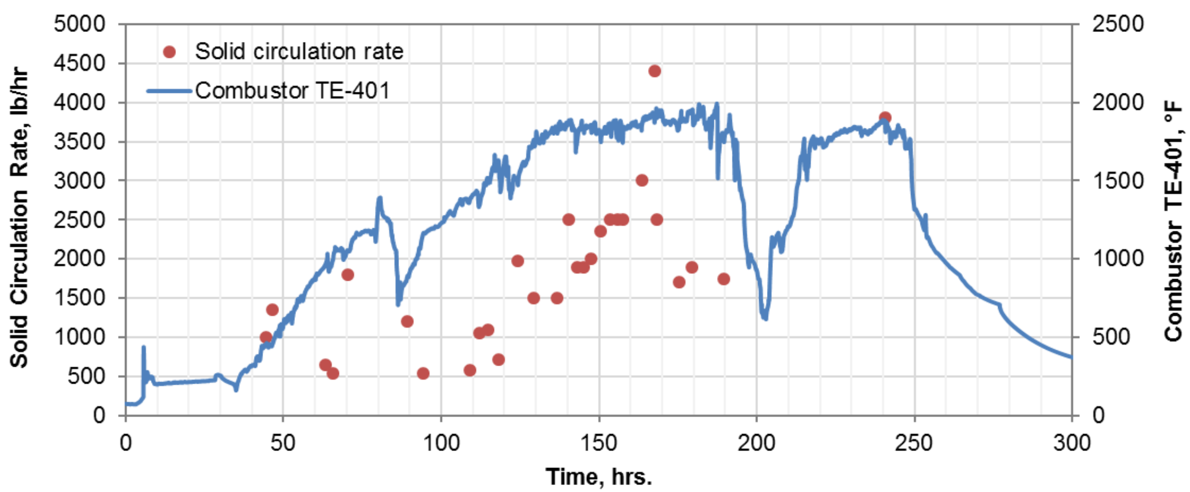
Lessons Learned and Solutions

Lessons Learned	Solutions
High flame temp may cause particle agglomeration	Operate burner under a leaner condition to maintain a lower flame temperature
Air should be preheated to a higher temperature to reduce burner demand	Modify the flange and piping to be stainless steel to allow higher inlet temp of air
Air infiltration exists under vacuum condition	• Seal the reducer better before next test • Operate under positive pressure

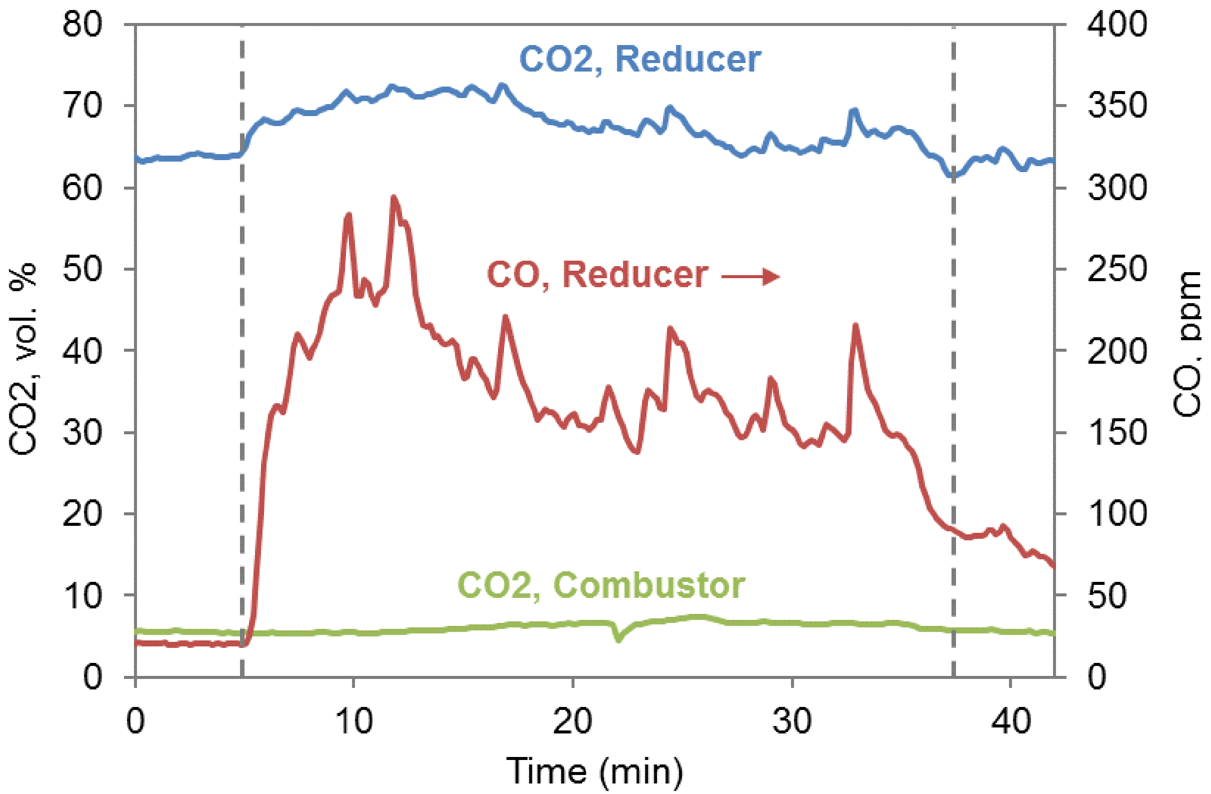
250 kW$_{th}$ Pilot – Test Results



Attrition rate < 0.18%/hr



250 kW_{th} Pilot – Test Results



- high coal volatile conversion
- Carbon slip into the combustor not observed

Goal of Ongoing Work

- Temperature of Bottom Moving Bed reducer above 1650 °F
- Limit the amount of agglomerates and maintain long-term (>300 hours) stable solid circulation
- Demonstrate reduction-oxidation cycling of particles
- Continuous operation with coal injection for minimum 24 hours
- Coal conversion > 90%
- Attrition rate under reaction condition < 0.1%/hr
- Achieve adiabatic reducer operation

Outline

- Background
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Phase I Objectives

- **Form the team**
- **Secure funding and commitments**
- **Host site agreement**
- **Environmental information volume**
- **Cost and schedule estimates for Phase II**

Phase II/III Objectives

NETL — 10 MWe PHASE II

Year: 2019-2020

- 2.5 MWe module design
- CDCL integration with existing plant
- Balance of Plant (BOP) equipment specifications
- Process control specifications
- Proposal and cost estimates for Phase III

NETL — 10 MWe PHASE III-A

Year: 2020-2022

- Construction and operation of first module
- Commissioning first module and BOP

NETL — 10 MWe PHASE III-B

Year: 2022-2025

- Construction of remaining modules
- Commissioning and testing of full plant

Objective: Demonstrate 10 MWe CDCL pilot plant

Project Participants

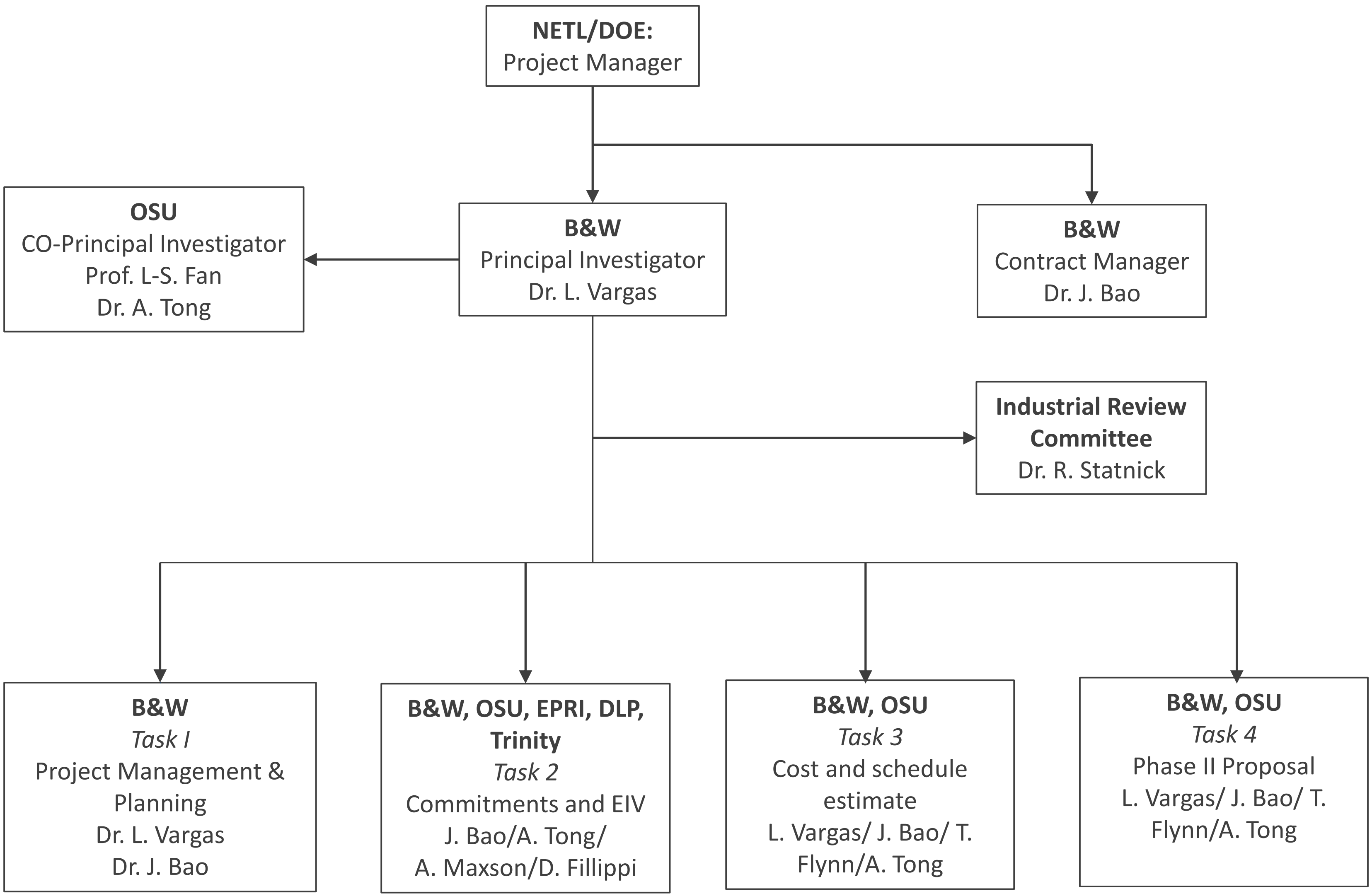
- Federal Agencies
  - DOE/NETL
- State Agency
  - Ohio Development Services Agency
- Project Participants
  - Babcock & Wilcox (B&W)
  - Ohio State University (OSU)
  - Clear Skies Consulting
  - Dover Light & Power (DPL)
    - Trinity Consultants
    - Worley Parsons
  - Electric Power Research Institute (EPRI)
- Industrial Review Committee
  - American Electric Power
  - Duke Energy
  - FirstEnergy
  - CONSOL Energy
  - Johnson Matthey (JM)

Division of Responsibility

Team	Responsibility
Babcock & Wilcox	Project management; technology lead; CDCL engineering design
Ohio State University	Technology support
Clear Skies Consulting	Provide industrial representation and guidance
Dover Light & Power	Provide host site and the related information
Johnson Matthey*	Large-scale oxygen carrier manufacture
EPRI	Techno-economic analysis
Worley Parson	Provide engineering services for the BOP to integrate CDCL equipment
Trinity Consulting	Environmental impact assessment, EIV and NEPA

* Join in Phase II/III

Phase I Team Organization



Tasks and Schedule

10 MWe CDCL Large Pilot Facility	Phase I															
	Budget Period 1															
	FQ3			FQ4			FQ1			FQ2			FQ3			
	2018									2019						
Project Tasks / Description	4	5	6	7	8	9	10	11	12	1	2	3	4	5	6	7
1.0 Project Management, and Reporting (Phases I, II, III)																
1.1 General Project Management	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■
1.2 Project Review Meetings																
1.3 Quarterly Progress Reports			■			■			■			■				
1.4 Project Final Report and Close-out Documents															■	■
Milestone: Final Report																■
PHASE I																
2.0 Project Commitment and Complete Environmental Information Volume (EIV)																
2.1 Host Site Agreement and Team Commitments	■	■	■	■	■	■										
2.2 Draft Environmental Assessment				■	■	■	■	■								
2.3 Develop Environmental Information Volume					■	■	■	■	■							
Milestone: Environmental Information Volume (EIV)										■						
2.4 Draft State of Ohio EPA Permit-To-Install (PTI)											■	■	■	■		
2.5 Draft Mitigation Action Plans (MAP)											■	■	■	■		
3.0 Cost and Schedule Estimates for Phase I																
3.1 Develop Phase II Project Work Breakdown Structure (WBS)						■	■	■	■	■						
3.2 Prepare a Cost Breakdown and Estimate for Phase II Workscope								■	■	■	■					
Milestone: Cost Breakdown Structure for Phase II												■				
Milestone: Cost Estimate for Phases II and III												■				
Milestone: Topical Report												■				

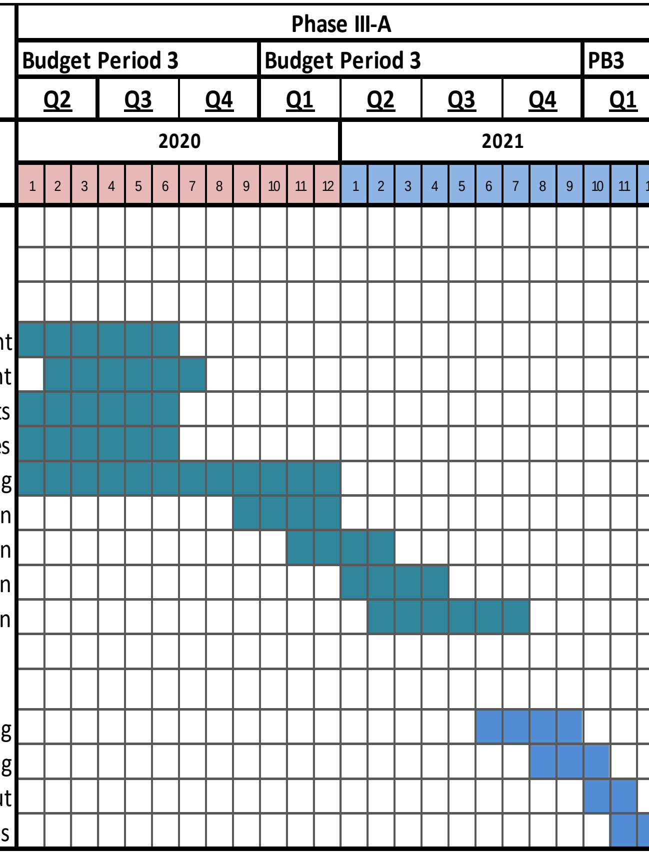
B&W

10 MWe CDCL Large Pilot Facility

Project Tasks	Description	1	2	3	4	5	6	7	8	9	10	11	12
		Phase II											
		Budget Period 2									BP3		
		Q2			Q3			Q4			Q1		
		2019											
	PHASE II												
5.0	**Release of Functional Specifications**												
5.1	Heat and Material Balance	X	X	X									
5.2	Mechanical Design and Drawings		X	X									
5.3	Electrical Designs and Drawings		X	X									
5.4	General Arrangement Drawings			X	X								
5.5	Hazard Design and Operation (HAZOP)				X	X	X						
5.6	NEPA Study	X	X	X	X	X	X						
5.7	Phase III Test Plan					X	X	X					
5.8	Operating Procedures							X					
6.0	**Balance of Plant Equipment Specifications**												
6.1	Balance of Plant Specifications and Modifications	X	X	X									
6.2	Environmental Control Equipment			X	X								
6.3	CO2 Compression Equipment				X	X							
6.4	Waste Treatment and Disposal					X	X						
7.0	**CDCL Integration with Existing Steam Turbine Equipment Specifications**												
7.1	Steam Turbine Components		X	X									
7.2	CDCL Specific Piping and Instrumentation Drawings				X	X	X	X					
8.0	**Process Controls Specifications & Drawings**												
8.1	Plant PLC specifications	X	X	X	X								
8.2	Upgrade Existing Controls to Accommodate CDCL unit			X	X	X	X						
8.3	Focal Point Optimization					X	X						
8.4	ProTRAX Dynamic Model & Simulator					X	X						
8.5	P&IDs and Drawings		X	X	X	X	X	X					
9.0	**General Arrangement Drawings (Process and Equipment)**												
9.1	CDCL Equipment Arrangement Drawings				X	X							
9.2	Balance of Plant General Arrangement Drawings						X	X					
10.0	**Building and Utilities Design and Cost Estimate**												
10.1	General Construction - project manager, construction supervision	X	X	X									
10.2	Site Construction -building excavation, utilities, pavements, site upgrades		X	X									
10.3	Concrete - building and equipment foundations concrete			X	X	X							
10.4	Masonry, Metals, Wood & Plastic, Building Envelope, Doors & Windows, Finishes				X	X							
10.5	Special Construction, Fire Protection, Restrooms, Lighting, General Utilities					X	X						
11.0	**Prepare Phase III Proposal & Firm Cost Estimate**												
11.1	Prepare Firm Cost Estimate and Schedule							X	X				
11.2	Prepare Phase III Proposal									X			
12.0	**Purchase Requisitions for Mechanical Components**												
12.1	CDCL-Specific Components - fabricated and purchased										X	X	
12.2	CDCL Piping and Instrumentation Drawings											X	X
13.0	**Purchase Requisitions for Instrumentation and Controls**												
13.1	PLC Components and Upgrade to Existing controls Requisitions										X	X	
13.2	Balance of Plant Instrumentation and Controls Requisitions										X	X	
13.3	CDCL Integration with Existing Steam Turbine Equipment Requisitions											X	X
14.0	**Order long-lead items (optional)**												
	Order Steel and Materials of Construction												X

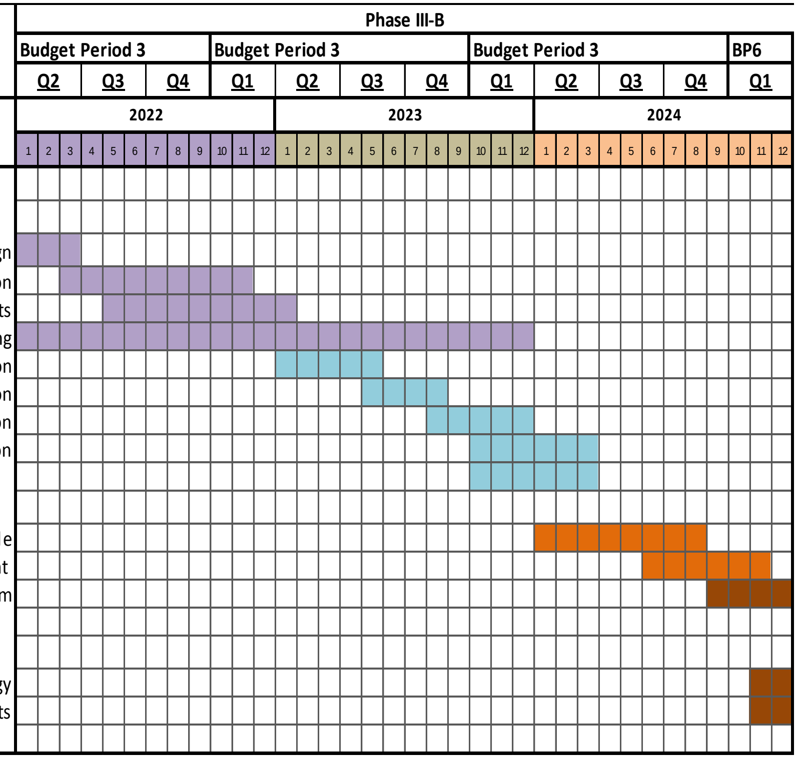
10 MWe CDCL Large Pilot Facility

Project Tasks	Description
	PHASE III -A
15.0	**Construction and Operation - First Module**
15.1	Equipment Procurement
15.2	Procurement of Electrical and Instrumentation Equipment
15.3	Fabricated Components
15.4	Supplies and Consumables
15.5	Oxygen Carrier Manufacturing
15.6	Building Erection
15.7	Equipment Installation
15.8	Fabricated Components Installation
15.9	Instrumentation and Controls Installation
16.0	**Commissioning of First Module and BOP Equipment**
16.1	Individual Equipment Commissioning
16.2	Cold-Flow Tests Commissioning
16.3	Hot-flow Test Commissioning and Refractory Dry out
16.4	Upgrades to First Module Design Specifications



10 MWe CDCL Large Pilot Facility

Project Tasks	Description
	PHASE III-B
17.0	**Construction of remaining modules**
17.1	Upgrades to remaining module design
17.2	Equipment and Instrumentation
17.3	Fabricated Components
17.4	Supplies and Oxygen Carrier Manufacturing
17.5	Construction
17.6	Equipment Installation
17.7	Fabricated Components Installation
17.8	Instrumentation and Controls Installation
18.0	**Commissioning and testing of full plant**
18.1	Commissioning of second, third and fourth module
18.2	Commissioning of full plant
18.3	Operation and Testing of Complete System
19.0	**Final Report Preparation**
19.1	Update on Thecno-Economic Assessment of the CDCL technology
19.2	Final Report and Close Out Documents



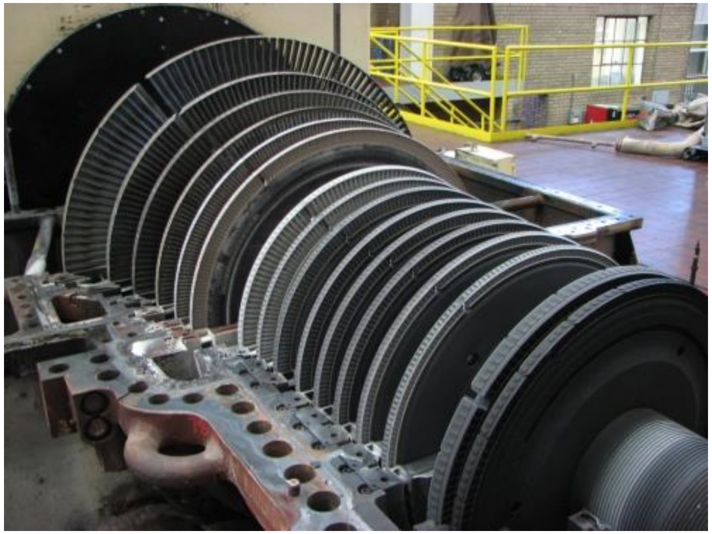
Host Site: Dover Light & Power

Existing

- 20 MWe Stoker coal fired boiler

Planning

- 10 MWe natural gas package boiler
- 10 MWe CDCL unit
- Increase power capacity
- Preserve a balance between coal and natural gas
- Potential CO_2 market from local industries



20 MWe Steam Turbine

Project Budget

Recipients	Federal	Cost-share	Total
PHASE I (4/1/2018 – 7/31/2019)			
B&W	$377,859	$50,000	$427,859
OSU	$240,000	$72,500	$312,500
EPRI	$79,732	$19,932	$99,664
DL&P	$0	$35,000	$35,000
Clear Skies	$43,603	$10,901	$54,504
Total	**$741,194**	**$188,333**	**$929,527**
Percent	79.74%	20.26%	100%
PHASE II (2019-2020) - Estimated			
Total	$3,000,000	$750,000	$3,750,000
PHASE III (2020-2025) - Estimated			
Total	$40,000,000	$10,000,000	$50,000,000

Outline

- Background
- Technical Approach for 10 MWe Large Pilot
- Project Details
  - Objectives
  - Project Structure
  - Project Schedule
  - Project Budget
- **Risk Management**

Risk Management

Description of Risk	Probability	Impact	Risk Mitigation Strategies
Delay in design activities	Moderate	Moderate	Sequence the design activities to ensure that the cost estimates for Phases II can be developed
Unavailable resources	Moderate	Moderate	• Accommodate B&W's personnel to satisfy the project needs as well as B&W commercial needs • Give this project high priority • Look for contractors outside B&W
Poor Project Execution	Low	Moderate	• B&W has extensive experience executing similar or larger DOE projects • Develop project breakdown structure and task activities • Track performance against deliverables and milestones
Delay in contract release	Low	Moderate	B&W has many contracts with DOE-NETL and has compiled terms and conditions so contract negotiation should be quick.
Cost overruns	Low	Moderate	• Track costs associated with major tasks separately • B&W will notify DOE on any possible budget variance and how to remedy the situation
Safety	Low	High	No operation of experimental or commercial facilities is required as part of the Phase I scope
Unable to acquire the design data specific to 10 MWe plant	Moderate	High	• Continue with the design of the plant until we gather the required information • Perform additional 250 kWth pilot tests to gather such information with non-federal funds • Install one module first and test it

Acknowledgements

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