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THE INSTITUTE FOR CLEAN AND SECURE ENERGY

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Integrated Oxygen Production and CO_2 Separation through Chemical Looping Combustion with Oxygen Uncoupling

Project DE-FE0025076

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Project Kickoff Meeting

22 October 2015

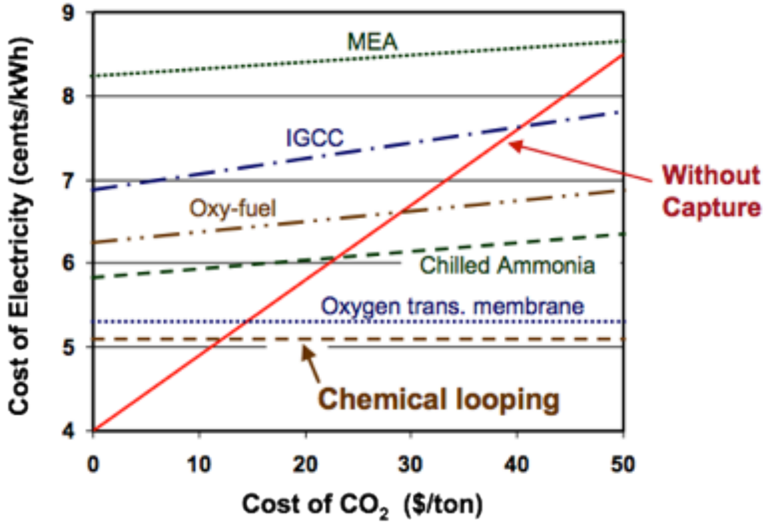
INSTITUTE FOR
Clean and Secure Energy
THE UNIVERSITY OF UTAH

Outline

- Background – Chemical Looping Combustion
- Chemical Looping R&D at the University of Utah
- Project Details
  - Project objectives
  - Technical approach
  - Project structure
  - Project schedule
  - Project budget
  - Project management plan
- Current Status

Project Background: Chemical Looping Combustion

- Chemical Looping Combustion (CLC) identified as lowest energy penalty/ lowest cost CO_2 capture technology
- Technology introduced ca. 2001, great growth in research since then
- Most research focusing on processing gaseous fuels; less focus on coal
- UofU has been researching CLC since 2008
  - Six projects
  - Funding through U.S. DOE, U. Wyoming, ICCI, NSF
  - 12 published papers, 3 under review, many conference presentations



Chemical Looping – General

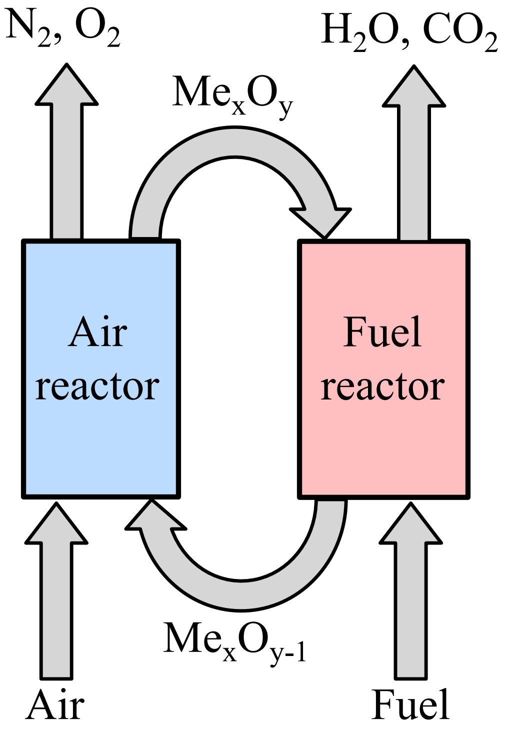
Air Reactor:

$$\tfrac{1}{2}\, O_2 + Me_xO_{y-1} \rightarrow Me_xO_y$$

Fuel Reactor:

$$C_nH_m + \left(2n + \tfrac{m}{2}\right) Me_xO_y$$

$$\rightarrow \left(2n + \tfrac{m}{2}\right) Me_xO_{y-1} + n\, CO_2 + \tfrac{m}{2} H_2O$$



CLC of Solid Fuels (gasifier-based)

Air Reactor:

$\frac{1}{2} O_2 + Me_xO_{y-1} \rightarrow Me_xO_y$

Gasifier:

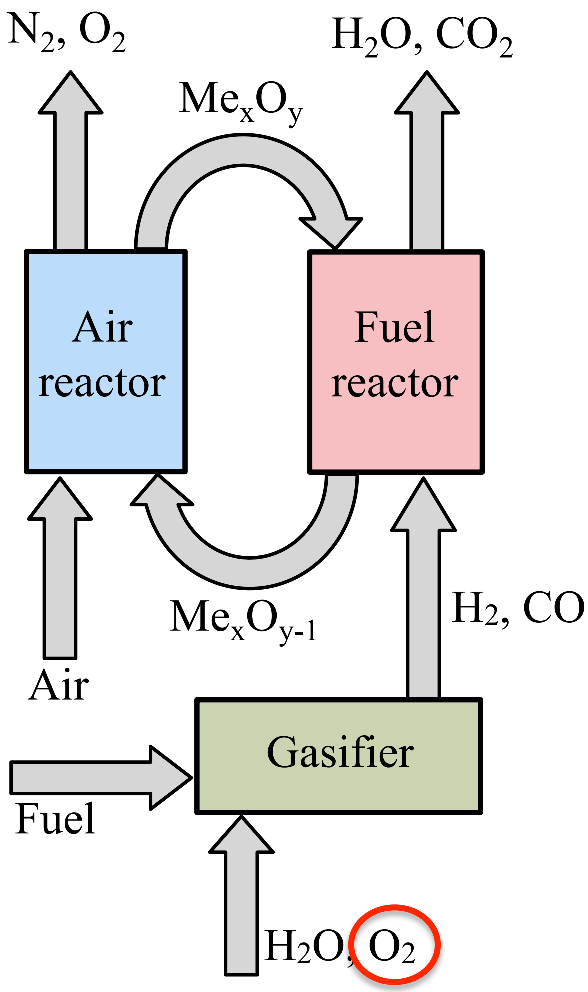
$C + H_2O \rightarrow H_2 + CO$

$C + \frac{1}{2} O_2 \rightarrow CO$

Fuel Reactor:

$CO + Me_xO_y \rightarrow Me_xO_{y-1} + CO_2$

$H_2 + Me_xO_y \rightarrow Me_xO_{y-1} + H_2O$



iG-CLC: in-Situ Gasification-CLC

Air Reactor:

$\frac{1}{2} O_2 + Me_xO_{y-1} \rightarrow Me_xO_y$

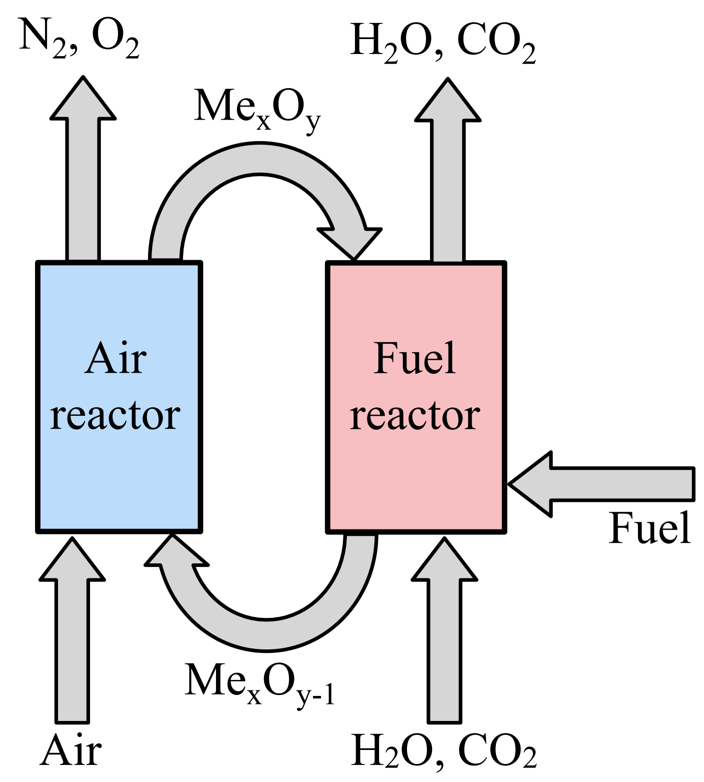
Fuel Reactor:

$C + H_2O \rightarrow H_2 + CO$

$C + CO_2 \rightarrow 2\ CO$

$CO + Me_xO_y \rightarrow Me_xO_{y-1} + CO_2$

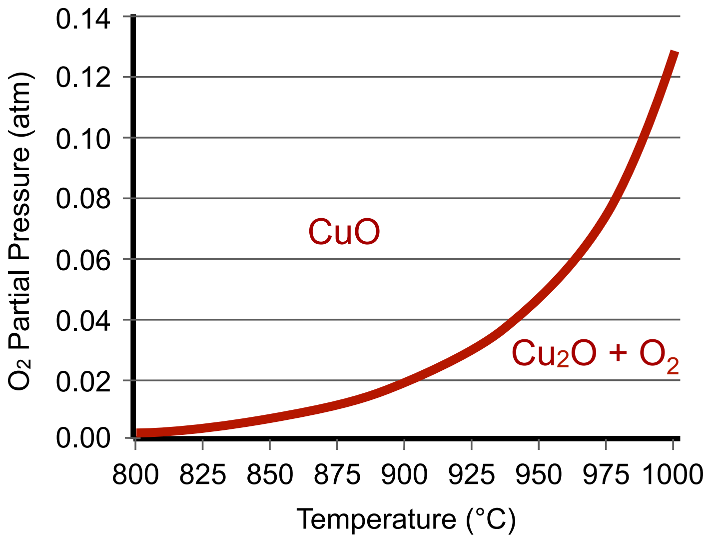
$H_2 + Me_xO_y \rightarrow Me_xO_{y-1} + H_2O$



CLC with Oxygen Uncoupling

$$Cu_2O(s) + \frac{1}{2} O_2(g) \leftrightarrow 2\,CuO(s)$$

- Thermodynamics
  - At high temperature, equilibrium of the metal oxidation reaction favors Cu_2O
  - Equilibrium partial pressure of O_2 is about 0.05 atm at combustion temperatures
- Reactor system configuration
  - Air reactor: high concentration of O_2 forces reaction to the right
  - Fuel reactor: low concentration of O_2 forces reaction to the left
- Very few metal/metal oxide combinations exhibit CLOU behavior



CLOU for Solid Fuels

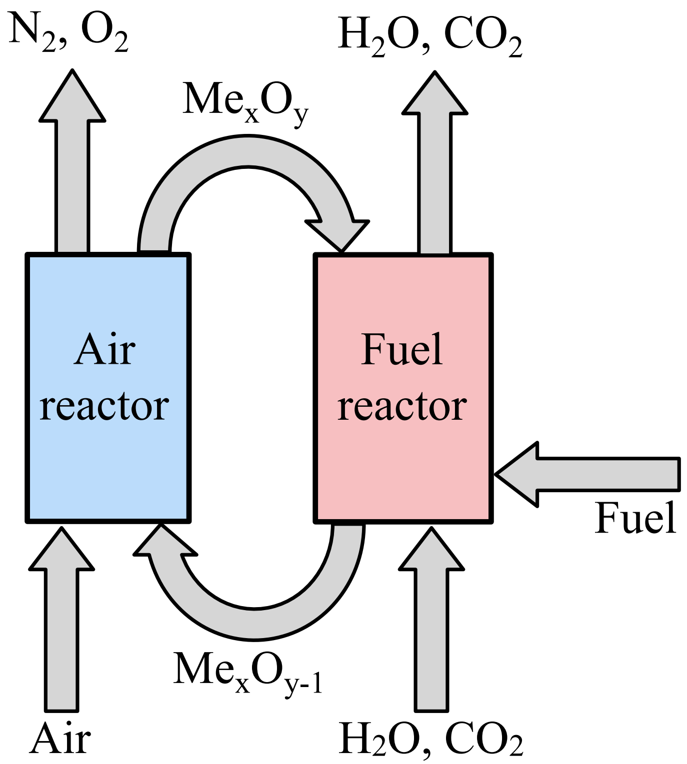
Air Reactor:

$\frac{1}{2} O_2 + Me_xO_{y-1} \leftrightarrow Me_xO_y$

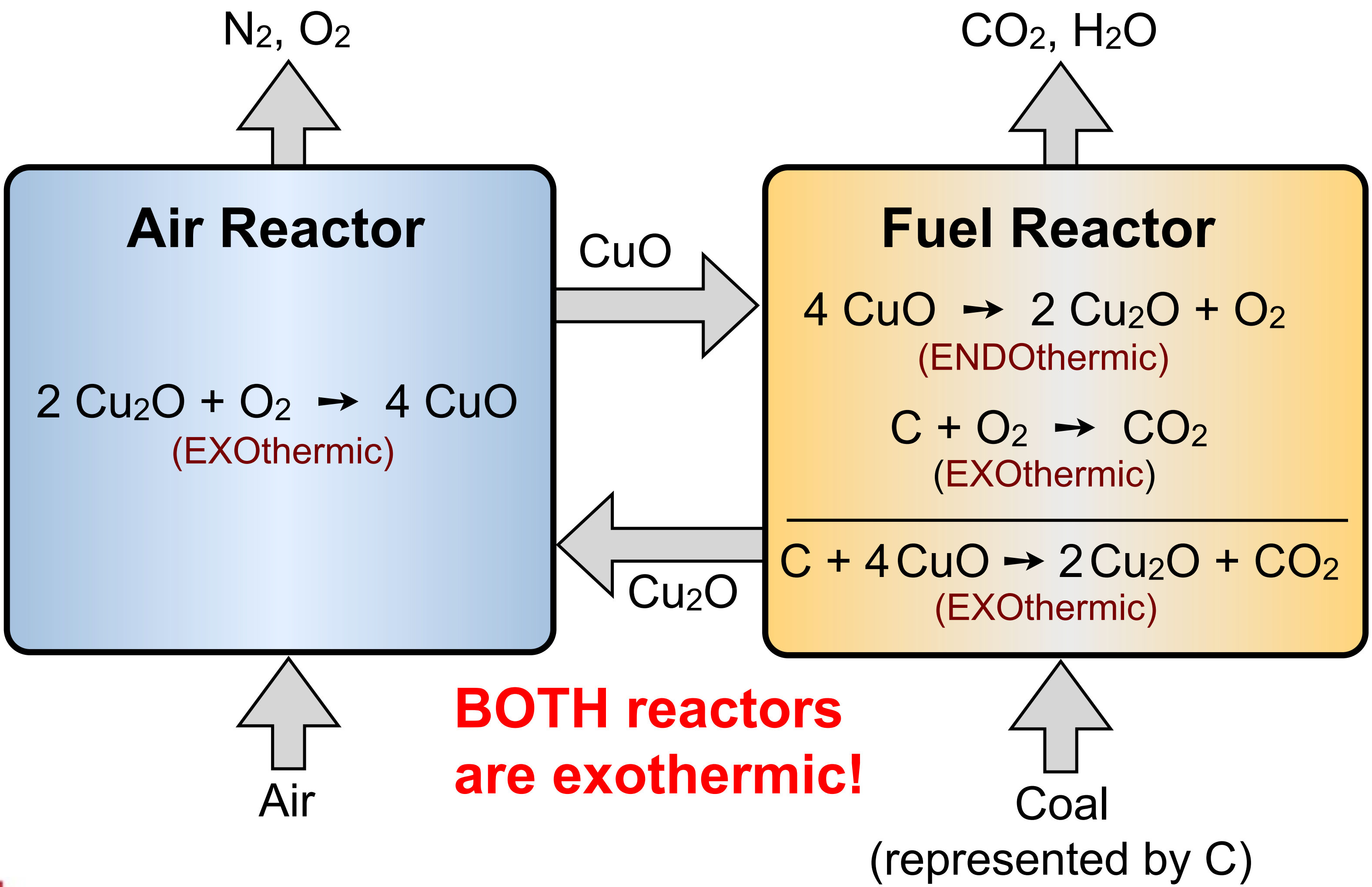
Fuel Reactor:

$Me_xO_y \leftrightarrow Me_xO_{y-1} + \frac{1}{2} O_2$

$C + O_2 \rightarrow CO_2$



CLOU Heat Balance



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Area 1:

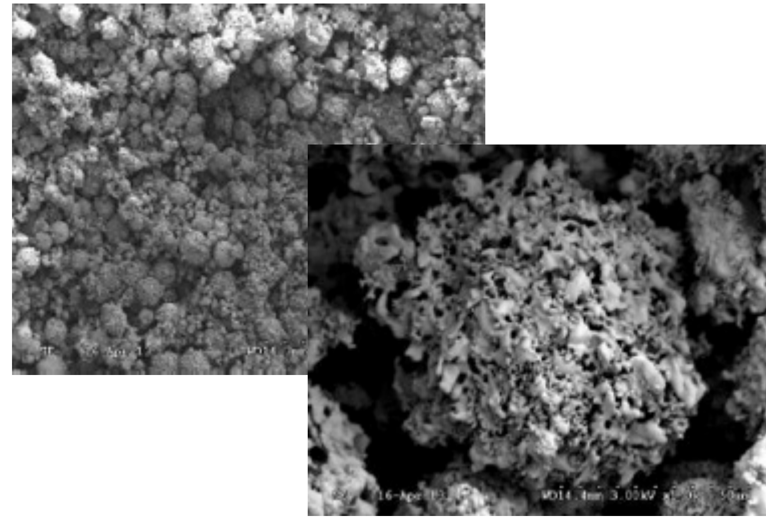
Oxygen carrier development, characterization and production scale-up

Previous Research at University of Utah: Oxygen Carrier Development

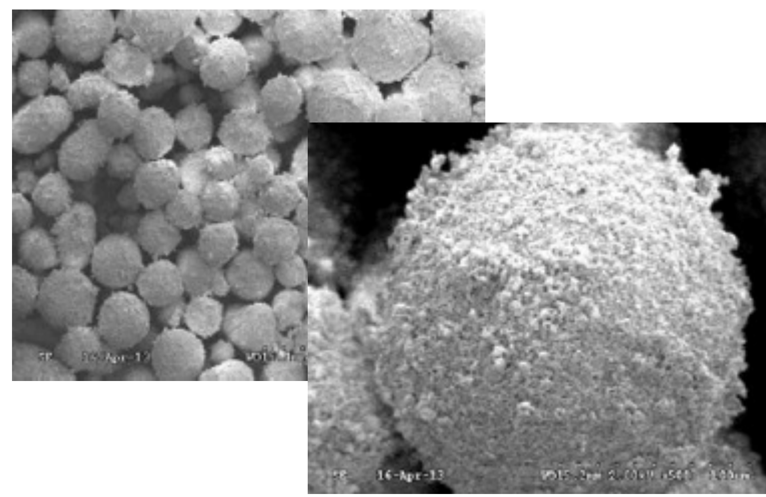
- Oxygen carrier is key to CLC technology
- Desirable properties
  - Inexpensive
  - Readily available
  - Benign
  - Physically robust
  - High oxygen carrying capacity
  - Fast rates of oxidation and reduction
  - Sustained reactivity over thousands of cycles
- University of Utah focusing on CLOU carriers
  - Need production at scales of 1+ tons

Oxygen Carriers: “Off the shelf”

- **50_TiO2_MM**
  - 50% CuO by weight
  - TiO_2 support
  - Mechanically mixed,
    then extruded, calcined, sieved
  - Provided by ICPC, Poland

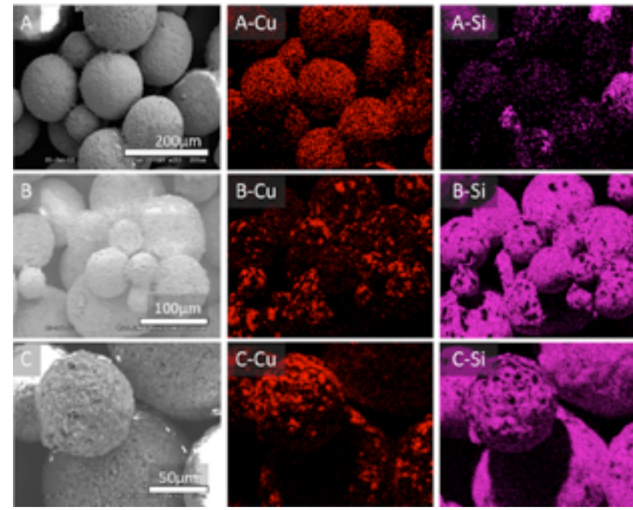


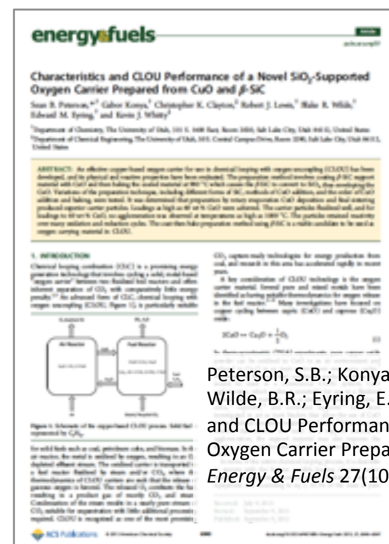
- **45_ZrO2/MgO_FG**
  - 45% CuO by weight
  - MgO-stabilized ZrO_2 support
  - Mechanically mixed,
    then freeze granulated, calcined
  - Provided by Chalmers U, Sweden



Oxygen Carriers: UofU SiO_2-based

- SiO_2 support
  - Formed by starting with SiC, then calcining
  - Two forms of SiC used
    - SiC powder (abrasive grit)
    - SICAT SiC spheres (catalyst support)
- CuO added by wet impregnation
  - Rotary evaporator technique
  - Bake-then-coat vs coat-then-bake
  - 15, 20, 40 and 60% CuO loadings
  - Number of CuO impregnation cycles was varied from 1 to 10




energy&fuels

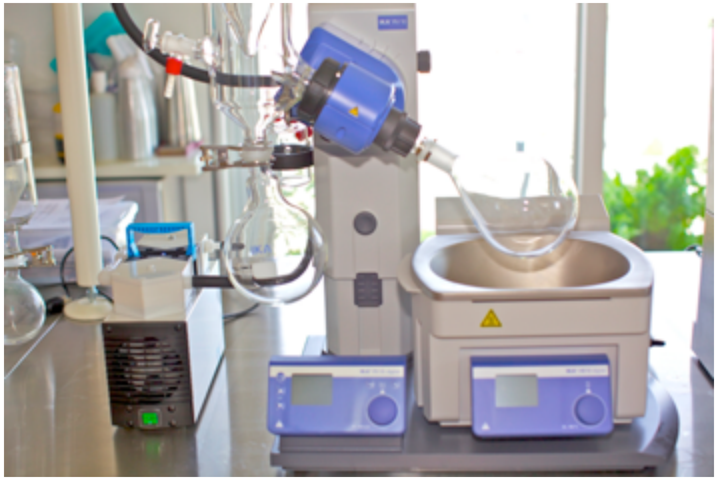
Characteristics and CLOU Performance of a Novel SiO_2-Supported Oxygen Carrier Prepared from CuO and β-SiC

Peterson, S.B.; Konya, G.; Clayton, C.K.; Lewis, R.J.; Wilde, B.R.; Eyring, E.M.; Whitty, K.J. Characteristics and CLOU Performance of a Novel SiO2-Supported Oxygen Carrier Prepared from CuO and β-SiC, *Energy & Fuels* 27(10):6040-6047 (2013).

CuO-on-SiC Oxygen Carrier Production

- Combine water, cupric nitrate hydrate, and silicon carbide
- Rotary evaporate water
- Calcine at ~300°C for 1 hr
- Next addition

% CuO Loading / Additions	10/2	20/1	20/2	20/4	40/1	40/2
Particle Density (g/ml)	3.31	3.22	3.29	3.43	4.15	4.005
Theoretical CuO Loading (wt%)	9.94	19.8	20.0	19.9	39.8	39.7
Theoretical O_2 carrying capacity (wt%)	1.00	1.99	2.01	2.00	4.00	3.99

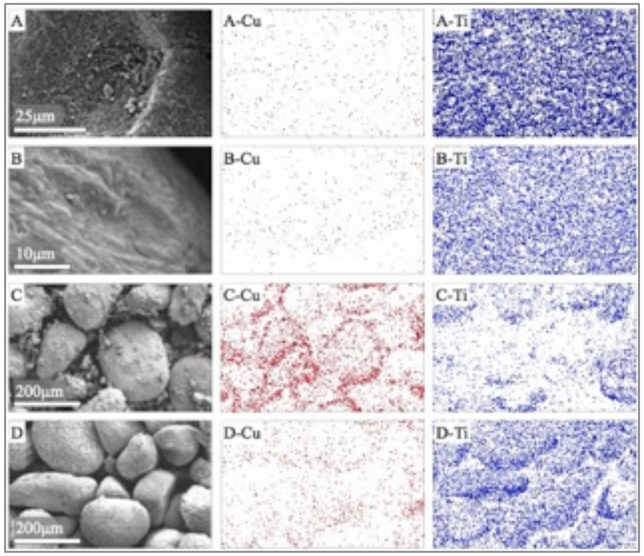


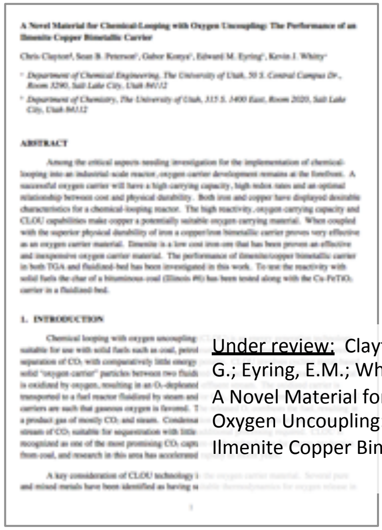
$$2Cu(NO_3)_2 \rightarrow 2CuO + 4NO_2 + O_2$$

$$CuO \rightarrow Cu_2O + \frac{1}{2} O_2$$

Oxygen Carriers: UofU Copper-on-Ilmenite

- Ilmenite ($FeTiO_3$) used as support
  - Conventional CLC carrier (Ti/Fe)
  - Well characterized
  - Inexpensive (< $100/ton)
- Wet impregnation
  - Rotary evaporator technique
  - Tested activated and non-activated ilmenite
  - 20 and 30% CuO loadings
  - CuO added in 6 to 9 cycles




A Novel Material for Chemical-Looping with Oxygen Uncoupling: The Performance of an Ilmenite Copper Bimetallic Carrier

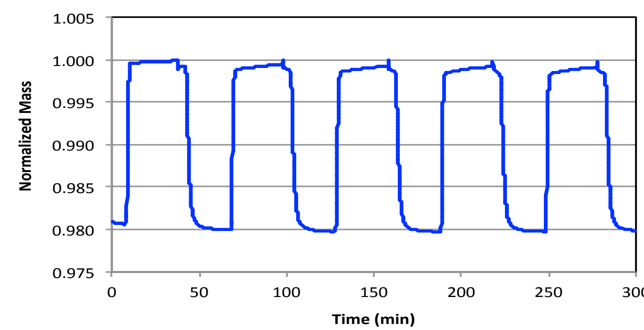
ABSTRACT

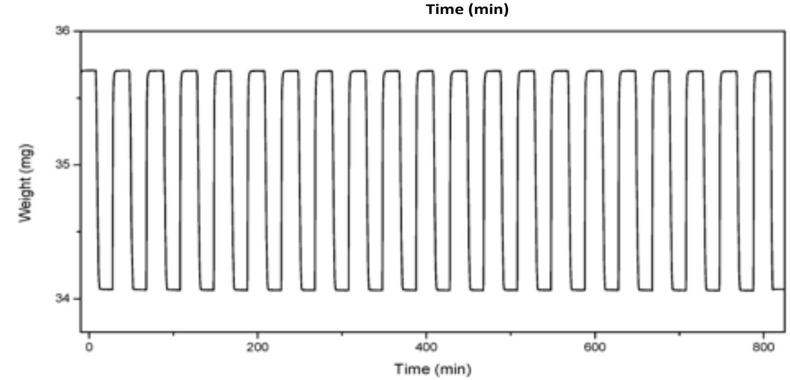
1. INTRODUCTION

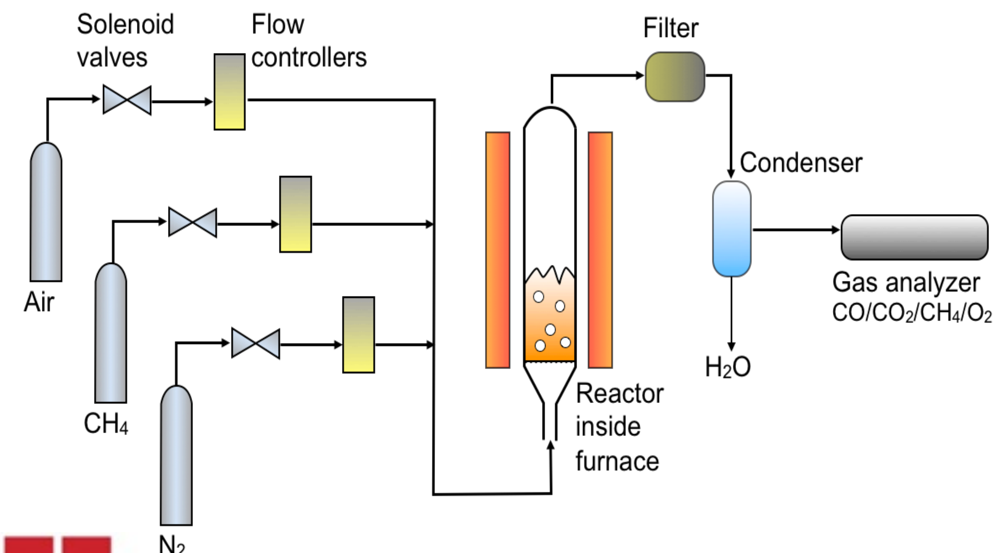
Under review: Clayton, S.K., Peterson, S.B.; Konya, G.; Eyring, E.M.; Whitty, K.J.
A Novel Material for Chemical-Looping with Oxygen Uncoupling: The Performance of an Ilmenite Copper Bimetallic Carrier

Lab-Scale Experimental Systems

- Thermogravimetric apparatus (TGA)
  - Oxygen carrying capacity
  - Confirm active metal loading
  - Reaction kinetics
- Batch fluidized bed reactor (QFB)
  - Fluidized environment
  - Evaluation of agglomeration propensity
  - Fuel conversion studies







Rationale for Oxygen Carrier Development

- Development efforts are driven by the requirements of our PDU, which requires several tons of oxygen carrier over the course of our research program
  - PDU needs 150-200 kg inventory
  - Low cost is important ("copper on dirt")
  - Our current CuO-on-SiC carrier costs $15-25 per kg

- We welcome collaboration with anyone who can provide at least 500 kg of CLOU carrier
  - Can provide evaluation of carrier in "real world" environment

Area 2:

Reactor performance and evaluation of CO_2 capture and carbon conversion efficiencies

Previous Research at University of Utah: Reactor Design and Process Evaluation

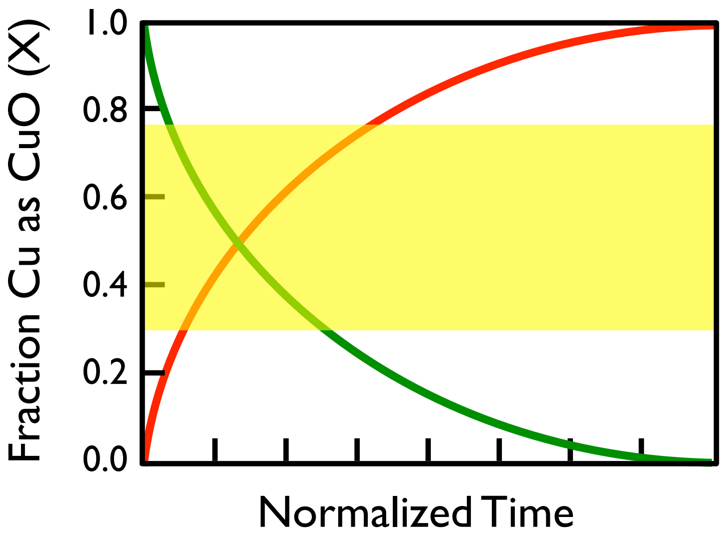
- Focus on
  - Reaction fundamentals
  - Carbon conversion
  - Fluidized bed reactor design
  - CO_2 capture efficiency and purity
- Several scales
  - Fundamental lab-scale
  - Small process bench-scale
  - Pilot scale

Rate Determination: Overall Objectives

- Develop better understanding of oxidation and reduction mechanisms for Cu-based carriers
  - Work recently performed at e.g. Chalmers, CSIC, Columbia U.
- Evaluate dependence of rates on carrier properties
  - e.g., in the absence of mass transfer limitations, will all carriers with 30% CuO behave the same?
- Ultimately, develop universal rate expressions suitable for incorporation into system models, perhaps of the form
  - For oxidation: $rate = A\exp\left(E_a/RT\right)\left[P_{O2} - P_{O2,eq}\right]^{\alpha}\left[Cu_2O\right]^{\beta}$
  - For reduction: $rate = A\exp\left(E_a/RT\right)\left[P_{O2,eq} - P_{O2}\right]^{\alpha}\left[CuO\right]^{\beta}$

Range of Interest for Reaction Rates

- X = fraction of Cu as CuO, with remainder as Cu_2O
- PDU design assumption: Carrier cycling between X = 0.75 exiting air reactor and X = 0.30 exiting fuel reactor

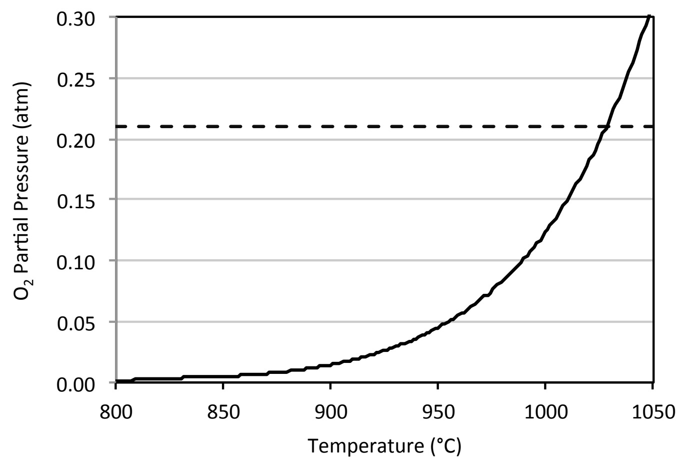


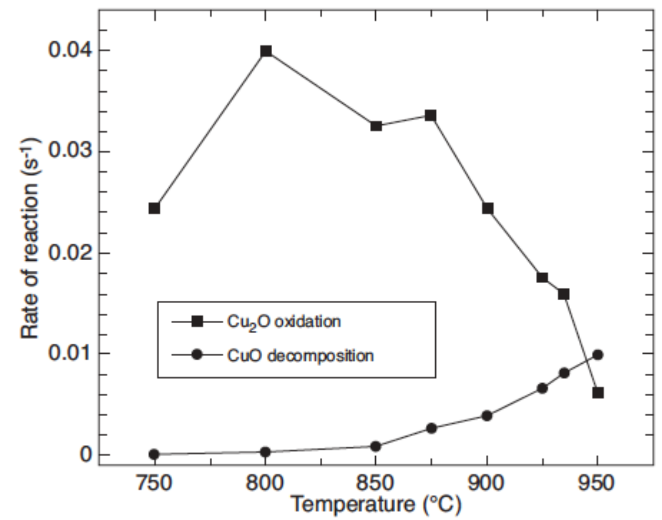
Oxidation:
$2Cu_2O + O_2 \rightarrow 4CuO$

Reduction:
$4CuO \rightarrow 2Cu_2O + O_2$

Oxidation of Cu_2O to CuO

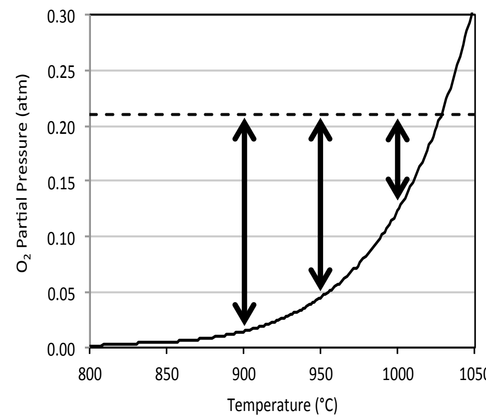
- Oxidation experiments present interesting challenge
  - Driving force for oxidation decreases with temperature
  - Fundamental chemical rate increases with temperature (E_a)
  - Possible grain boundary sintering may also contribute to reduced rate at high temperature
- Resulting "oxidation rate peak" observed by many groups
- Deciphering true kinetics is challenging

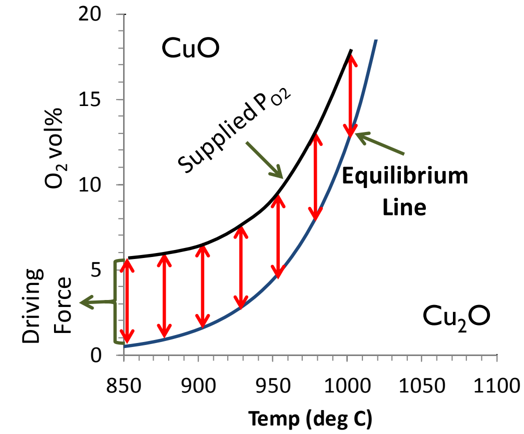




Oxidation: Isolating Influences of O_2 Driving Force and Temperature

- Oxidation rate affected by
  - Temperature (fundamental kinetics)
  - O_2 driving force, which depends on temperature
- Series of experiments to isolate these influences
  - Hold T constant while changing O_2 driving force
  - Hold O_2 driving force constant while changing T
- Rate evaluation allowed distinction between rate influences



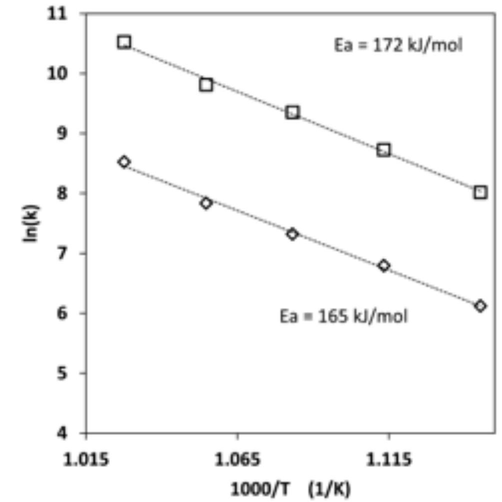


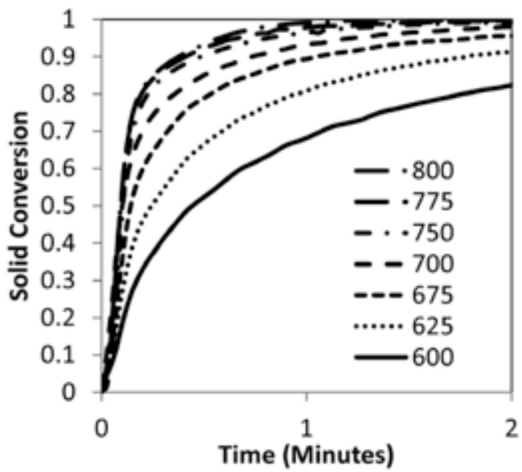
Experiment number	Temperature (°C)	Equilibrium O_2 part. press. (atm)	Supplied O_2 part. press. (atm)	O_2 "driving force" (atm)
1	876	0.010	0.050	0.040
2	962	0.060	0.100	0.040
3	994	0.110	0.150	0.040
4	1017	0.170	0.210	0.040

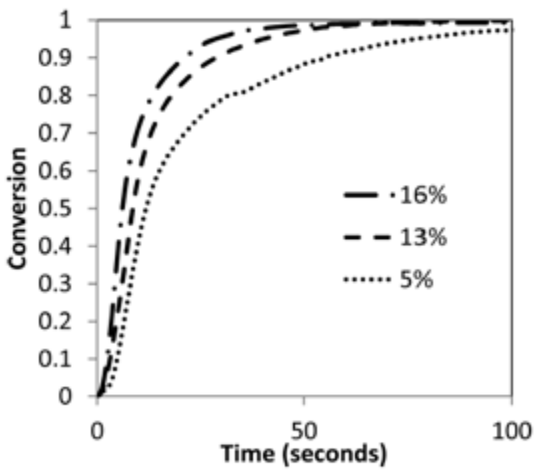
Experiment number	Temperature (°C)	Equilibrium O_2 part. press. (atm)	Supplied O_2 part. press. (atm)	O_2 "driving force" (atm)
1	850	0.005	0.050	0.045
2	850	0.005	0.100	0.095
3	850	0.005	0.150	0.145
4	850	0.005	0.210	0.205

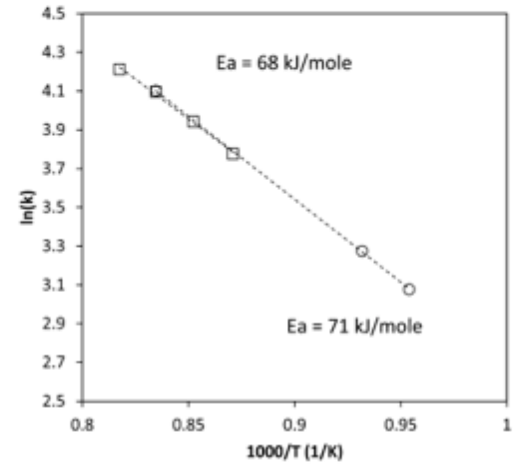
Measured Oxidation Rates

- Range of experimental conditions
  - Temperature
  - Reacting gas composition
- Four types of carrier materials
  - Various production techniques
  - Various CuO loadings









Modeling of Oxidation Rates

- Mechanism determined to be more challenging than simple reversible reaction kinetics
- Two regimes of reaction behavior identified
  - Low temperature, non-CLOU region
    - Best described by pore blocking kinetic mechanism

$$\frac{dX}{dt} = k\frac{1}{\exp\left(\frac{X}{\lambda}\right)}\left[P_{O_2}^{\beta} - P_{O_2,eq}^{\beta}\right]$$

  - High temperature CLOU region
    - Activation energy must be separated into thermodynamic and kinetic barriers
    - Best described by nucleation and growth mechanism

$$[-\ln(1 - X)]^{1/n} = k_{app} \times t$$


I&EC research

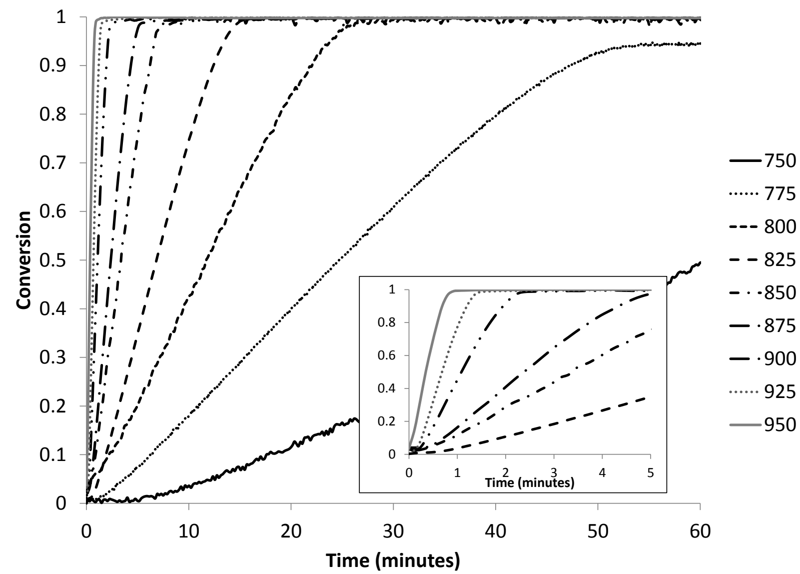
Oxidation Kinetics of Cu_2O in Oxygen Carriers for Chemical Looping with Oxygen Uncoupling

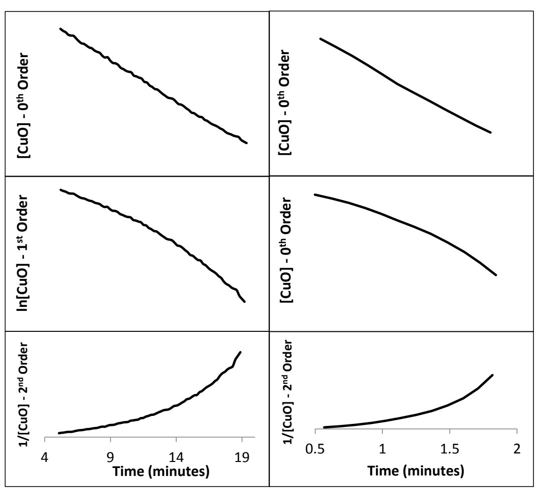
Christopher K. Clayton, H. Y. Sohn, and Kevin J. Whitty

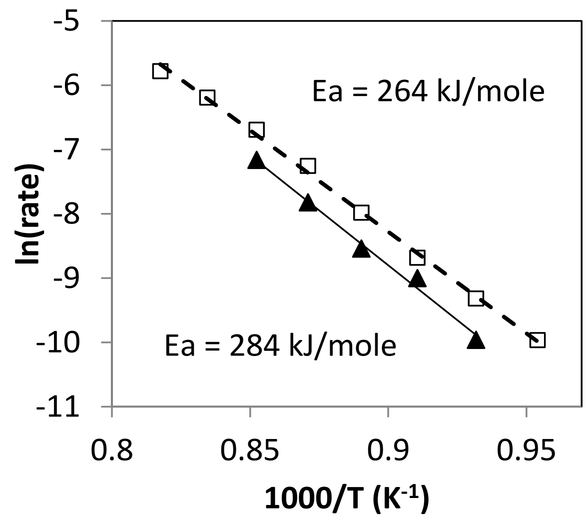
Clayton, C.K., Sohn, H.Y., Whitty, K.J. Oxidation Kinetics of Cu2O in Oxygen Carriers for Chemical Looping with Oxygen Uncoupling *I&ECR* 53:2976-2986 (2013).

Measurement of CuO Reduction Rates

- Similar to oxidation studies
- Range of conditions
  - Temperature
  - Gas composition
- Challenge of having absolutely zero O_2 in gas phase
- Reaction order in CuO = 0
- Apparent activation energy 274 kJ/mol



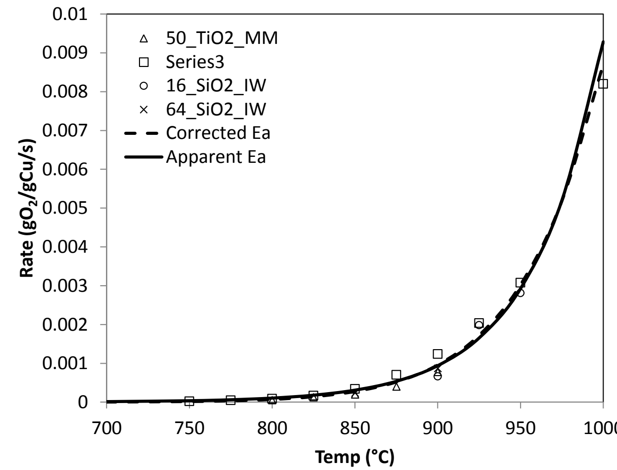




Modeling of Carrier Reduction Rates

- Any oxygen in gas phase reduces driving force for reduction
- Used similar methodology to deciphering specific influences for oxidation
  - Vary ($p_{O2,eq} - p_{O2}$) at constant temperature
  - Hold ($p_{O2,eq} - p_{O2}$) constant at various temperatures
- Could decipher constants in rate expression
- Universal rate expression:

$$\text{rate}\left(\frac{g}{s}\frac{1}{g_{Cu}}\right) = 3.90 \times 10^{-4} \exp\left(-\frac{62,000}{R \times T}\right)[6.057 \times 10^{-11} \exp^{0.02146 \times (T-273)} - P_{O2}]$$




Applied Energy

Measurement and modeling of decomposition kinetics for copper oxide-based chemical looping with oxygen uncoupling

Christopher K. Clayton, Kevin J. Whitty

Clayton, C.K., Whitty, K.J., Measurement and Modeling of Decomposition Kinetics for Copper-Oxide Based Chemical Looping with Oxygen Uncoupling, *Applied Energy* 116:416-423 (2013).

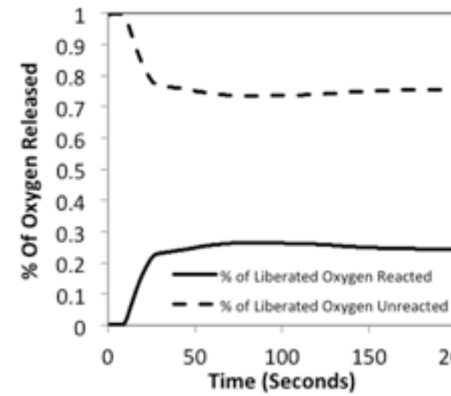
Coal Conversion in Lab-Scale Fluidized Bed

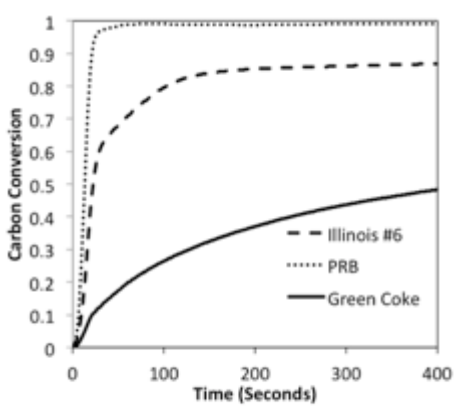
- Three fuels tested
  - Illinois #6
  - Black Thunder PRB
  - Green petcoke
- Two carriers tested
  - 45% CuO on ZrO_2
  - 50% CuO on TiO_2
- Fuel introduced batch-wise
  - Dropped onto top of bed shortly after turning off air
- Conversion performance determined based on concentrations of gases in reactor effluent

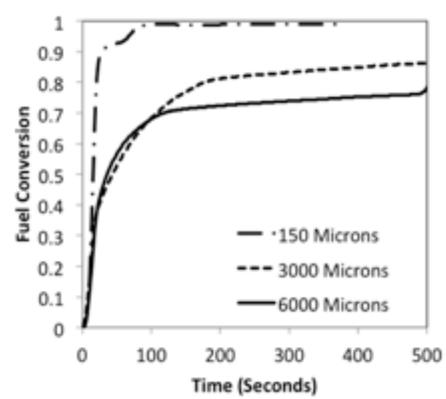
Fuel Type	Illinois #6 Bituminous	Black Thunder PRB Sub-bituminous	Green Coke Petroleum Coke
Proximate Analysis			
Moisture (wt% as received fuel)	2.54	21.30	0.4
Ash (wt% Dry)	12.33	6.46	0.39
Volatile matter (wt% dry)	39.40	54.26	11.03
Fixed carbon (wt% dry)	48.28	39.28	88.01
Ultimate Analysis (wt% dry ash-free)			
Carbon	78.91	74.73	89.21
Hydrogen	5.50	5.40	3.78
Nitrogen	1.38	1.00	1.73
Sulfur	4.00	0.51	5.82
Oxygen	10.09	18.27	4.41
Chlorine	0.11	0.08	-
Heating Value			
HHV, dry (Btu/lb)	12,233	12,815	15,622

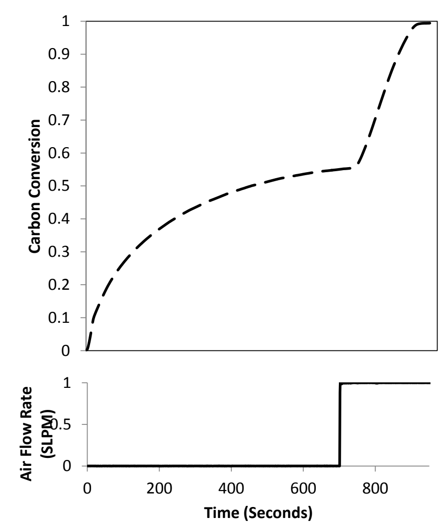
Coal Conversion Performance

- Ranking of fuel conversion
  - PRB > Illinois #6 > petcoke
- Particle size matters
  - Smaller is faster
  - Largest particles not converted in the time needed to release all oxygen from CLOU particles
    - Consequence of batch design



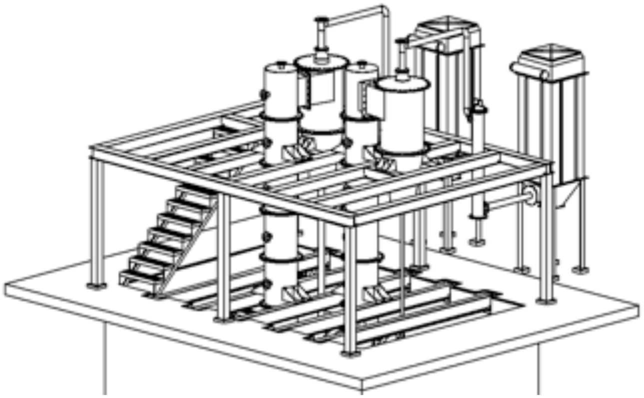


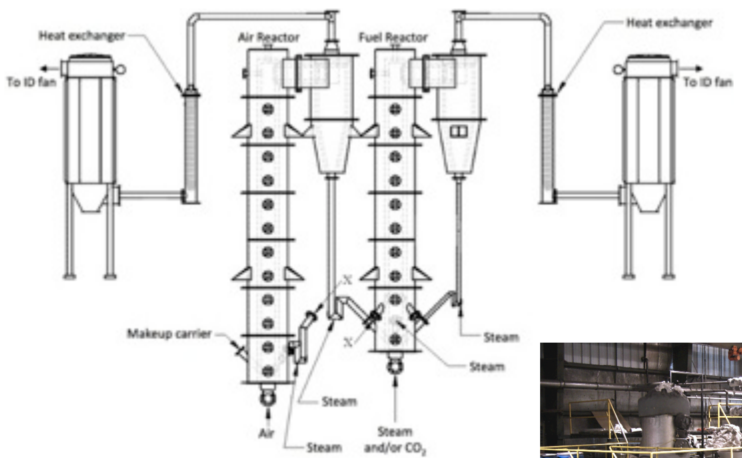




University of Utah CLC System

- Targeting Wyoming PRB Coal
- Under construction at Industrial Combustion and Gasification Research Facility (ICGRF)
- Target 100 kW_{th}. Systems can handle 220 kW_{th}





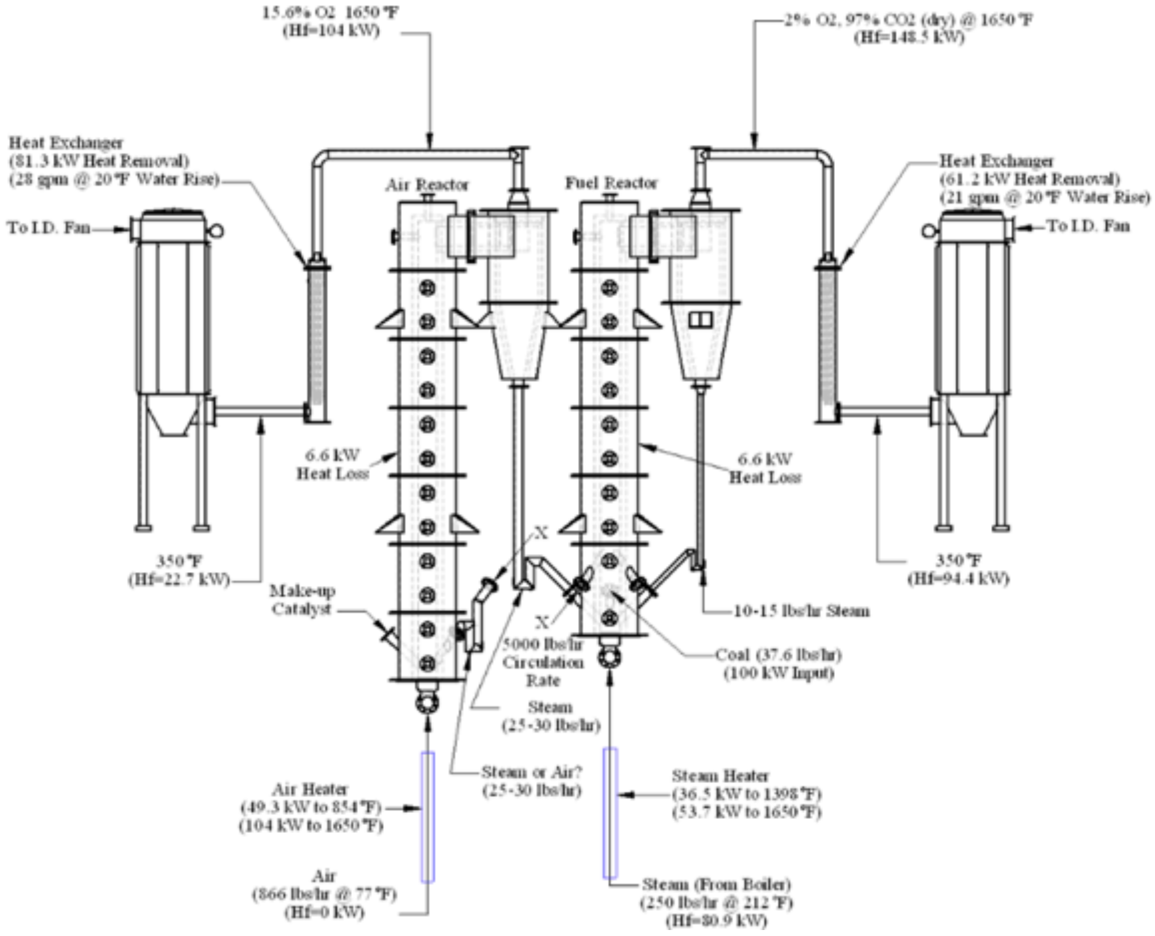

Combustion Lab

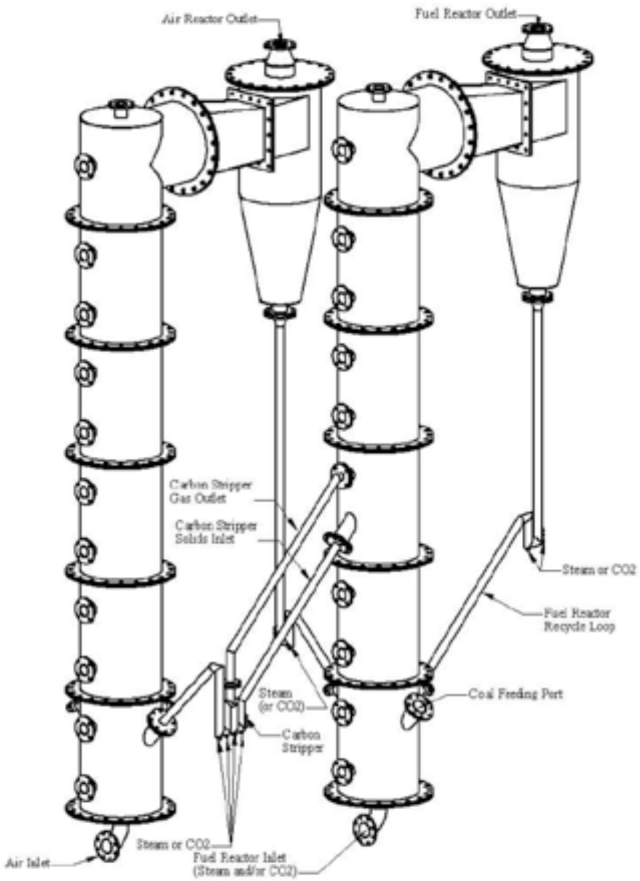

CLC Rig Sept 2012


Gasification Lab

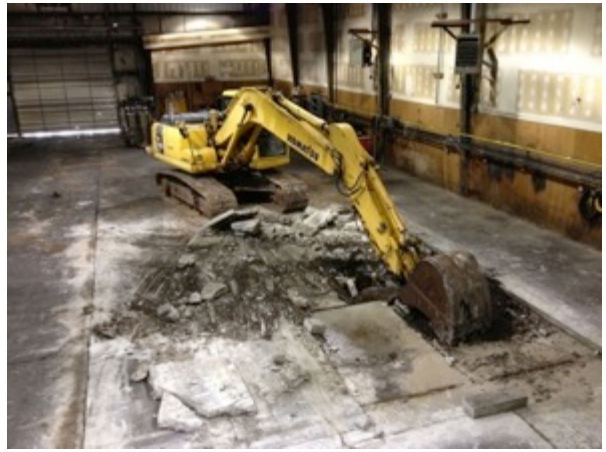

CLC Rig Components

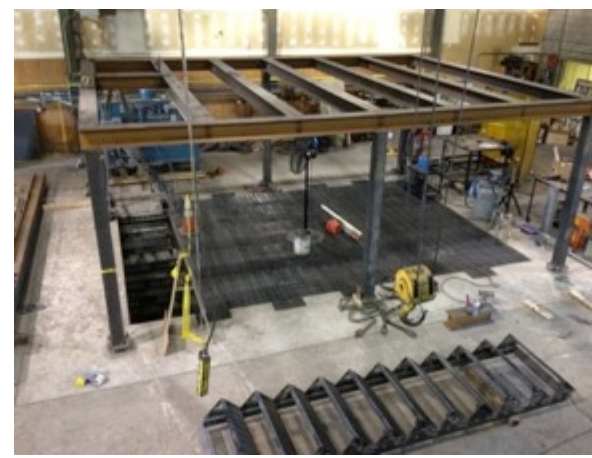
UofU 220 kW CLC PDU





CLC PDU Construction Progress





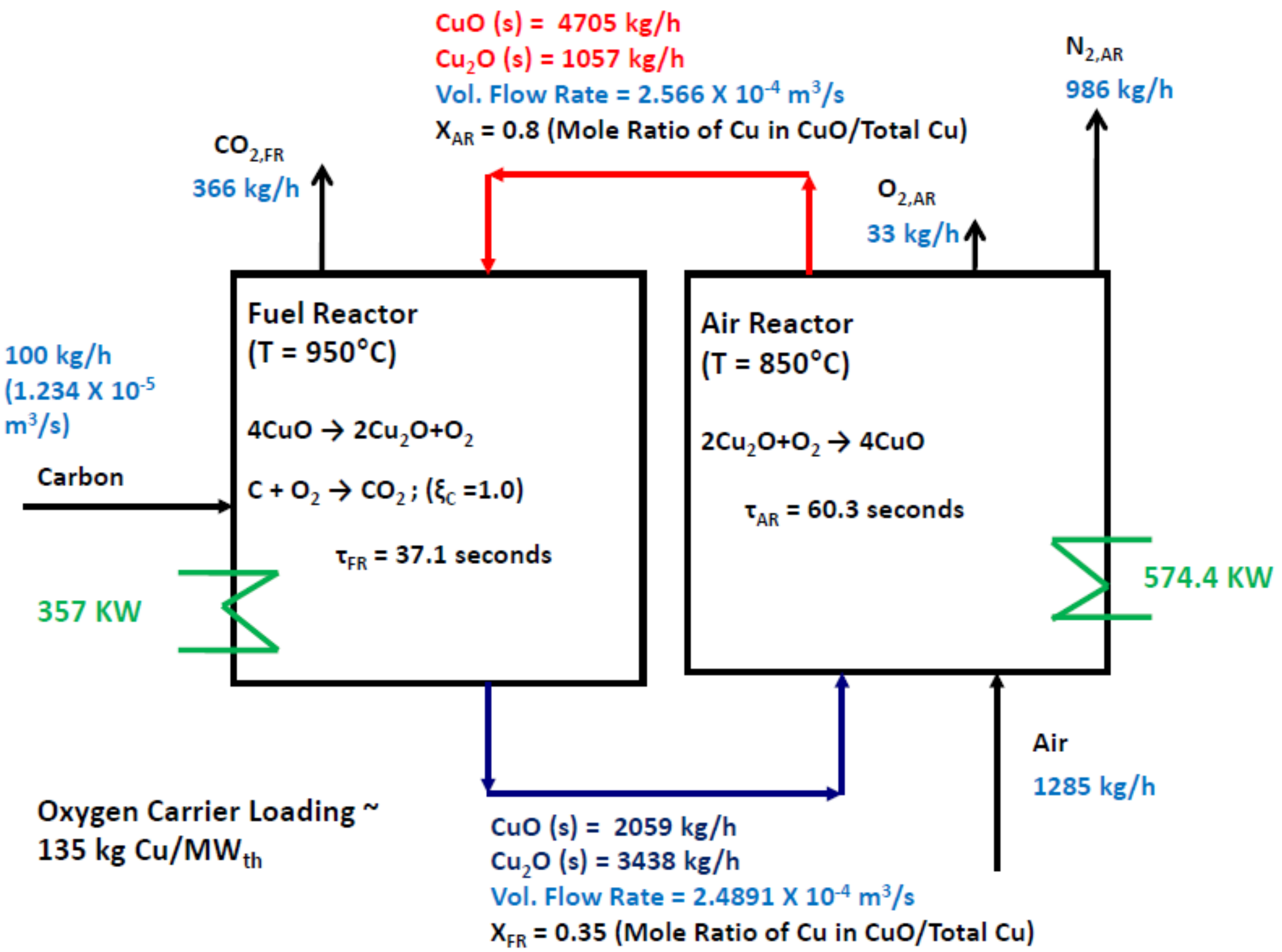
UofU 220 kW CLC PDU

Area 3:

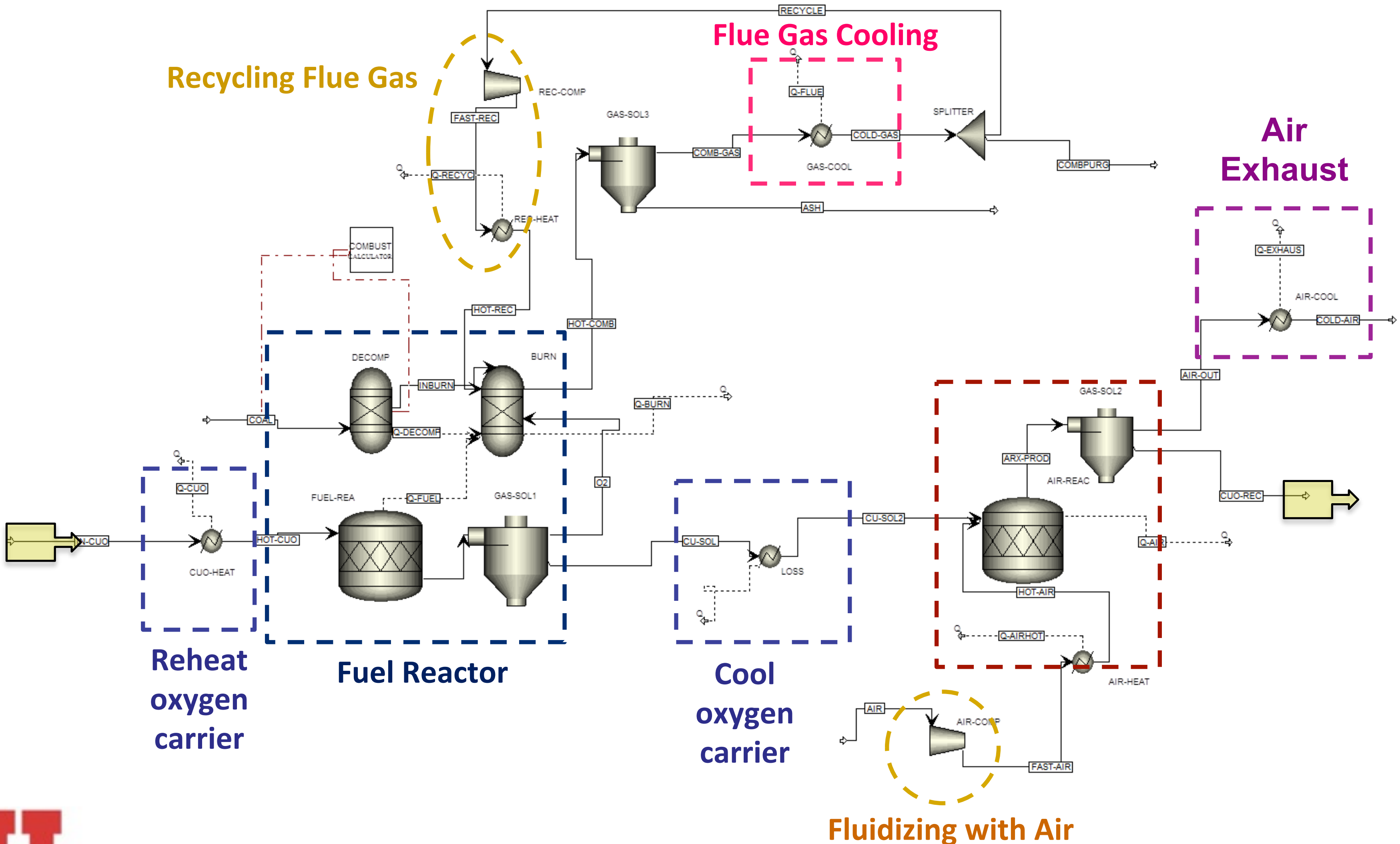
Reactor simulation and process modeling

System Modeling – Early Analysis

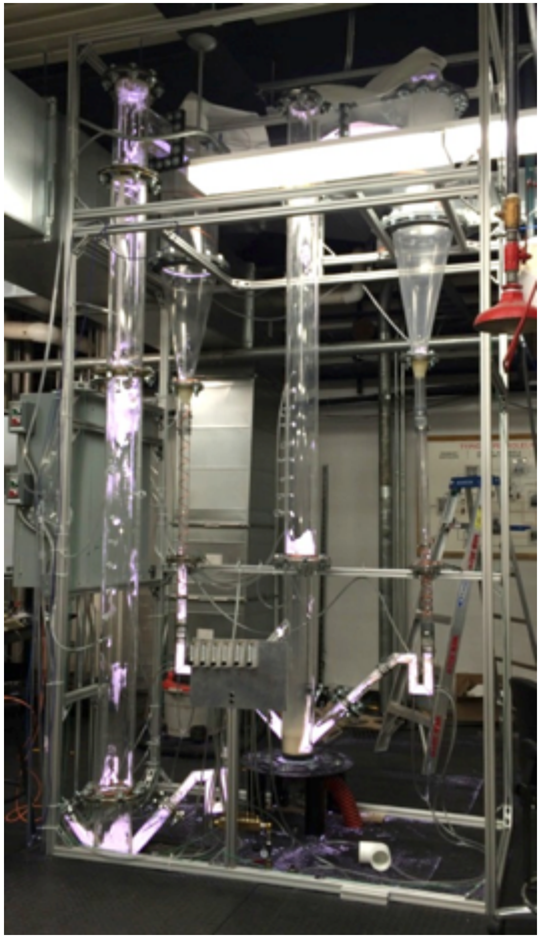
(Basis: 100 kg/h carbon input)

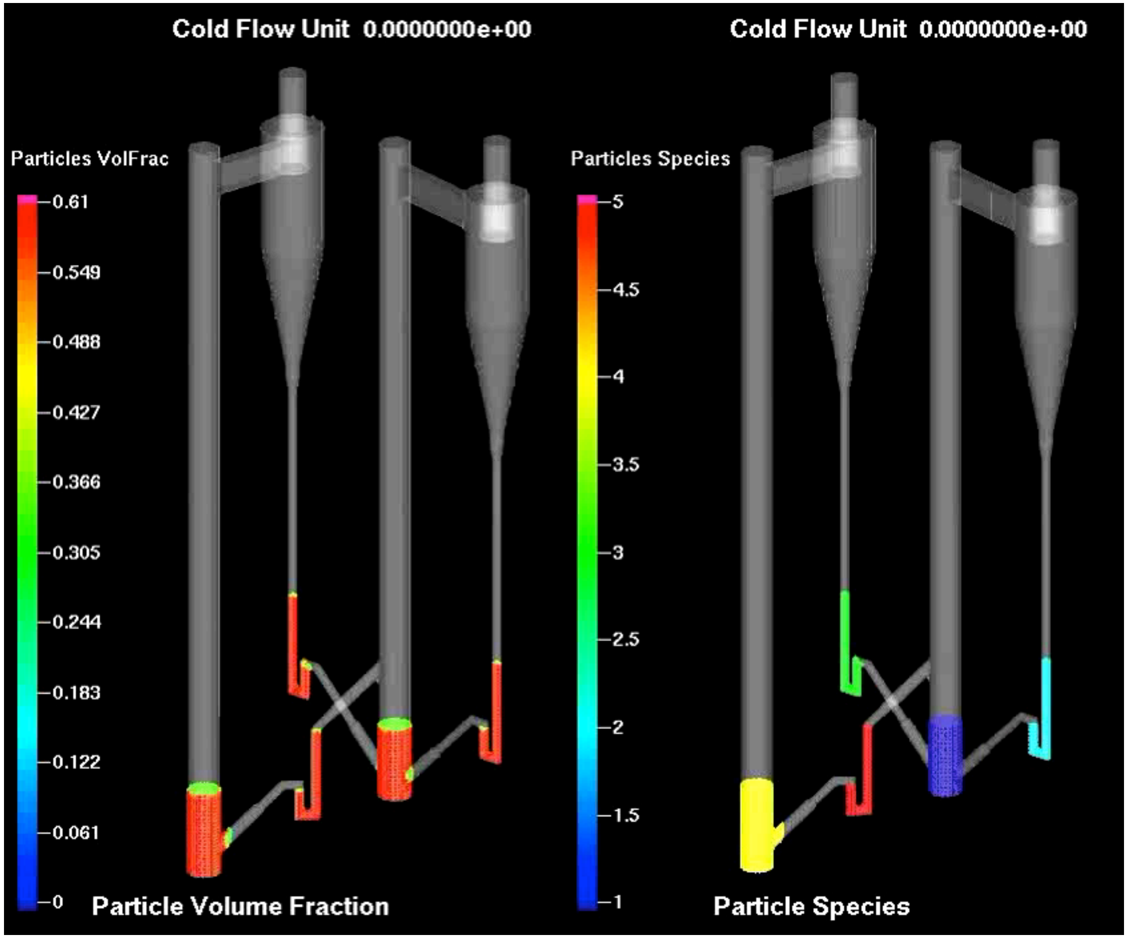


Aspen Plus Simulation

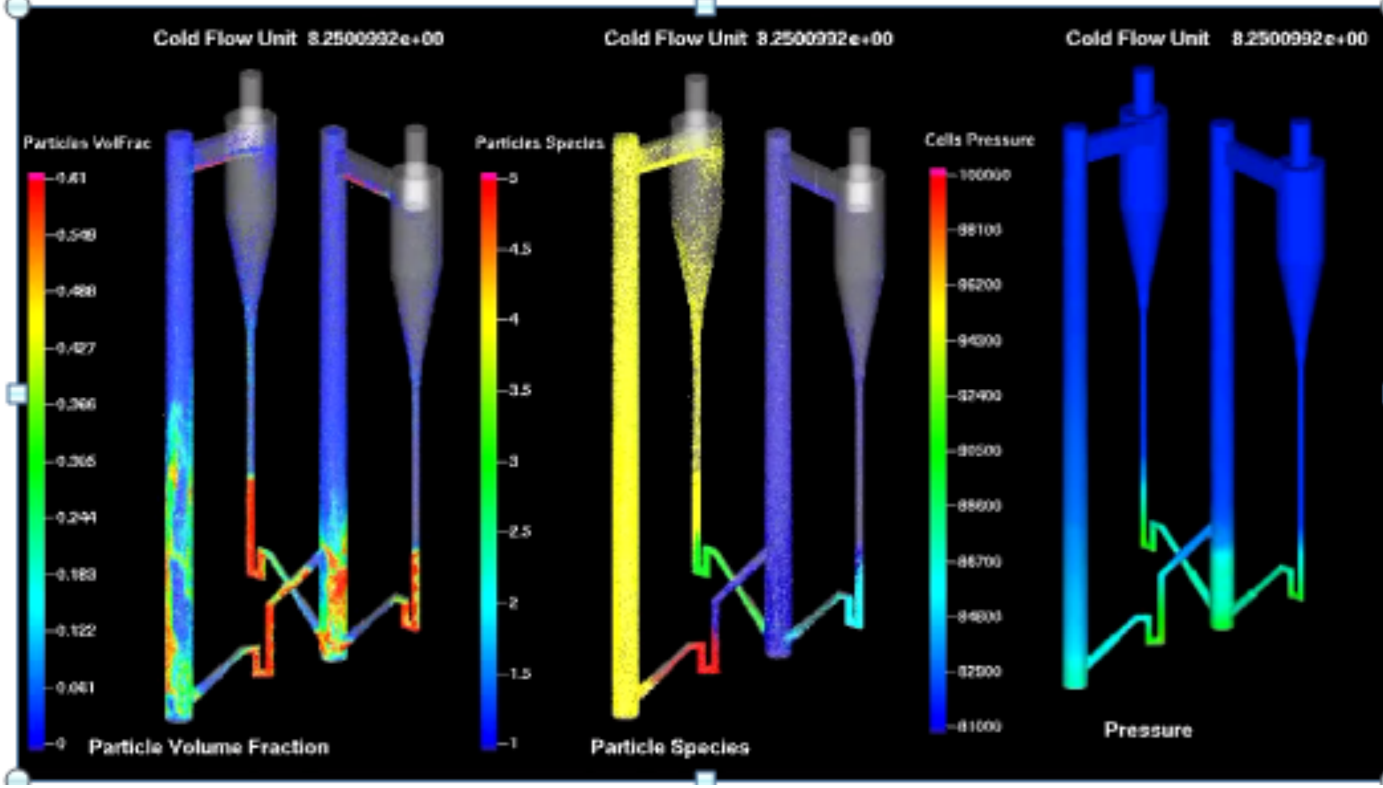


UofU CLC PDU Reactor Modeling





Hydrodynamic Studies: Cold-Flow Unit



- Air reactor fluidizing velocity of 2.39 m/s (91 scfm)
- Fuel reactor fluidizing velocity of 1.94 m/s (71 scfm)

- Determine circulation rates
- Determine pressure profiles
- Determine particle residence time
- Determine bed mass and other operating parameters

Outline

- Background – Chemical Looping Combustion
- Chemical Looping R&D at the University of Utah
- Project Details
  - Project objectives
  - Technical approach
  - Project structure
  - Project schedule
  - Project budget
  - Project management plan
- Current Status

Project Objectives

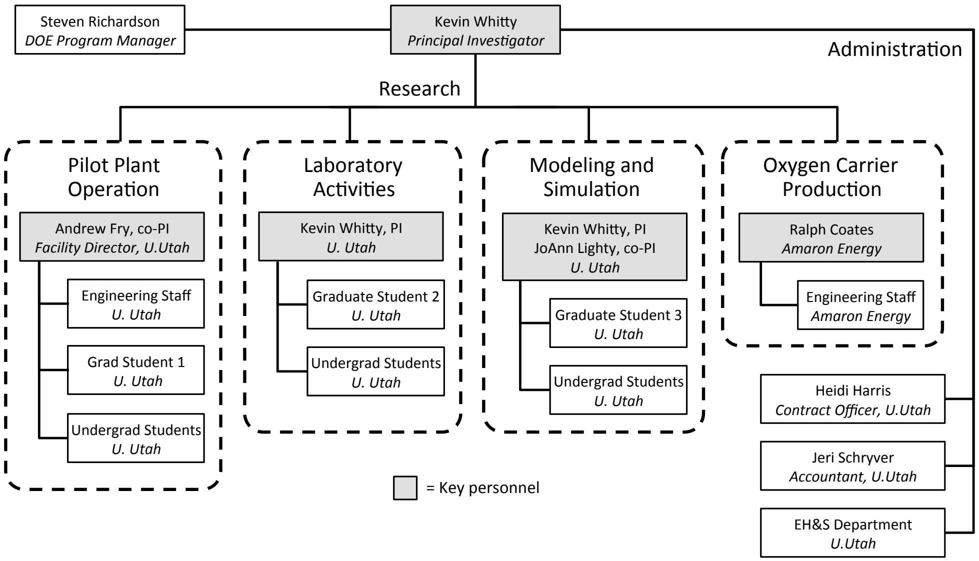
- Primary objective: Advance development of chemical looping with oxygen uncoupling (CLOU) to pilot scale
- Specific objectives
  - Evaluate performance of CLOU processing of U.S. coals in a pilot scale system over a range of conditions with focus on carbon conversion and CO_2 capture
  - Scale up and production of low-cost CLOU oxygen carriers
  - Design robust carbon stripper to maximize carbon conversion and CO_2 capture
  - Develop modeling and simulation tools for improving understanding of CLOU process, troubleshooting, optimization and scale-up

Technical Approach

- Overall objective is to advance CLOU to pilot scale
- Four technical tracks
  1. Operation and evaluation of pilot-scale process development unit (PDU) for CLOU
     - CO_2 capture efficiency
     - CO_2 purity
  2. Evaluation of carbon conversion and carbon stripper design
  3. Process modeling and reactor simulation
  4. CLOU oxygen carrier production scale-up and evaluation

Project Structure

- Four technical tracks
- Eight technical tasks
  - 4 per year each following one technical track
  - In addition, one management task
- Two organizations
  - University of Utah
  - Amaron Energy



Interaction and Goals

Rotary Kiln and Oxygen Carrier Development

Physical Properties
- Specific heat
- Thermal conductivity
- Densities
- Voidage at close pack
- Conversion of SiC to Si

Kinetic Parameters

Reactor Operation and Performance

- Heat Loss
- Exhaust gas composition
- Conversions
- Optimization of loopseals and cyclones
- Effect of carrier attrition
- Circulation rates

Carbon Conversion and Stripper Design

Design
- Size
- Temperature
- etc.

Process Modeling with ASPEN Plus
- Material & Energy Balances
- Autothermal calc.

CFD Simulations
- Hydrodynamics
- Kinetics
- Optimization

Energy Utilization

Scale-Up
10 MW
100 MW

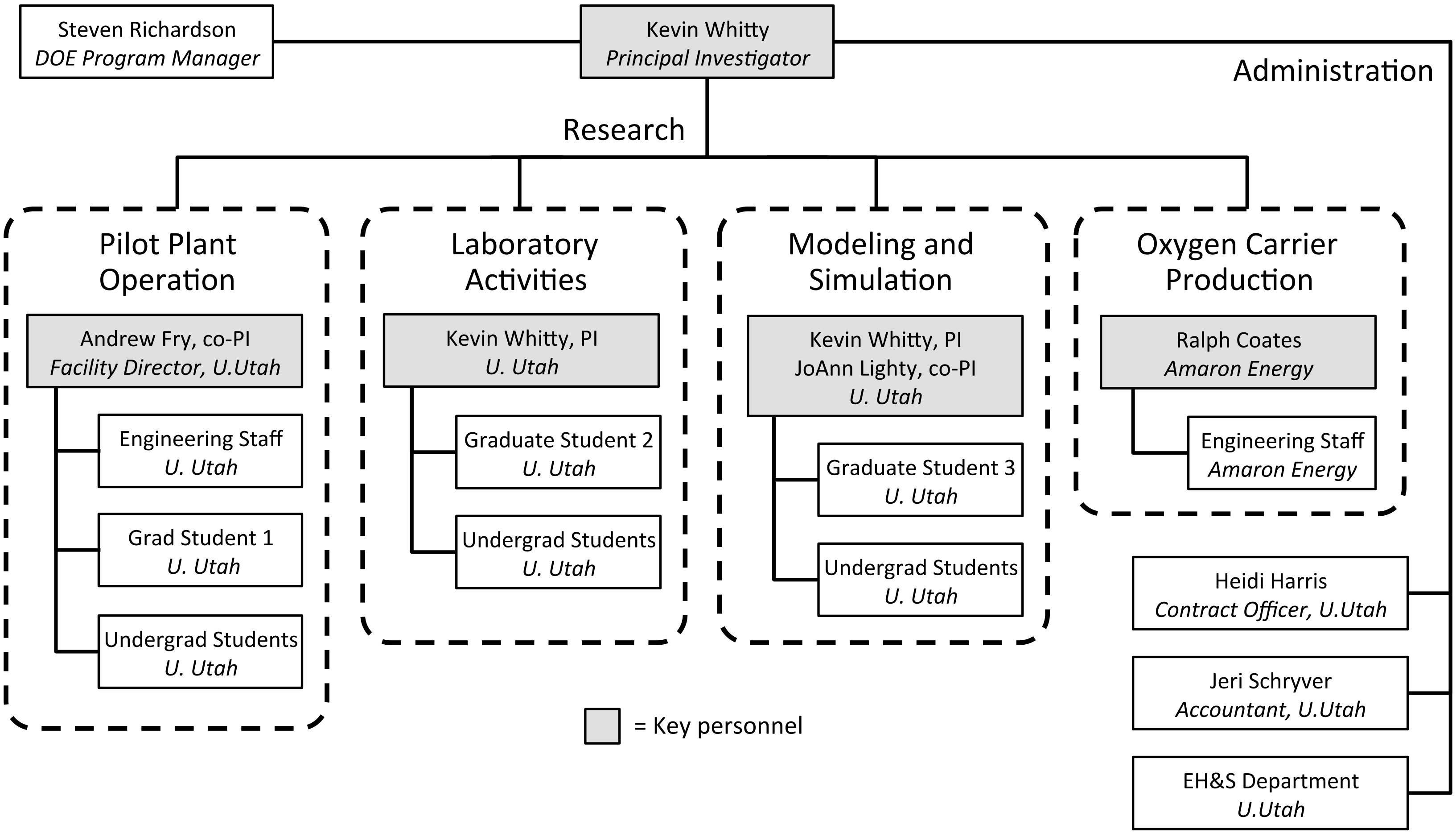
Project Structure – Tasks

1. Project management
2. Construction of rotary kiln
   - 2.1 Design/construction
   - 2.2 Refine procedure for kiln-based CLOU OC production
   - 2.3 Initial production of CLOU carrier
3. Construction and preliminary testing of pilot-scale CLC system
   - 3.1 Completion of CLC PDU construction
   - 3.2 Verification of pilot subsystems
   - 3.3 CLC in non-CLOU mode
   - 3.4 Initial assessment of CLOU performance
4. Evaluation of carbon conversion in CLOU environment
   - 4.1 Lab-scale evaluation of carbon conversion and properties
   - 4.2 Characterization of char carried over from fuel reactor
5. CLOU system modeling
   - 5.1 CLOU process modeling
   - 5.2 Computational simulation of dual-bed CLOU reactor

Project Structure – Tasks Year 2

6. Production and characterization of CLOU carrier particles
   - 6.1 Production of CLOU carrier for pilot system
   - 6.2 Characterization of CLOU oxygen carrier
7. Evaluation of CLOU performance and CO_2 capture at pilot scale
   - 7.1 Parametric testing of CLOU
   - 7.2 Optimization of CLOU operation
8. Carbon stripper design and operation
   - 8.1 Design and simulation of carbon stripper
   - 8.2 Carbon stripper fabrication and installation
   - 8.3 Evaluation and optimization of carbon stripper
9. Design of 10 and 100 MW_{th} CLOU reactors
   - 9.1 Simulation and validation of dual bed CLOU reactor
   - 9.2 Design of 10 and 100 MW reactors

Project Organization



Project Schedule

TASK	Q1	Q2	Q3	Q4	Q5	Q6	Q7	Q8
Task 1 - Project management and planning	M1.1	M1.2			M1.3			
Task 2 - Construction of rotary kiln CLOU carrier production facility								
2.1 - Design/construction of rotary kiln for oxygen carrier production		M2.1						
2.2 - Refine procedure for kiln-based CLOU carrier production								
2.3 - Initial production of copper-based CLOU oxygen carrrier								
Task 3 - Preliminary testing of CLOU performance at pilot scale								
3.1 - Completion CLC PDU construction		M3.1						
3.2 - Verification of pilot subsystems and circulation rate								
3.3 - Chemical looping combustion in non-CLOU mode								
3.4 - Initial assessment of CLOU performance in pilot system				M3.2				
Task 4 - Evaluation of carbon conversion in CLOU environment								
4.1 - Lab-scale evaluation of carbon conversion and char properties								
4.2 - Characterization of char carried over from pilot fuel reactor								
Task 5 - CLOU system modeling								
5.1 - CLOU Process modeling								
5.2 - Computational simulation of dual-bed CLOU reactor								
Task 6 - Production and characterization of CLOU oxygen carrier particles								
6.1 - Production of CLOU oxygen carrier for pilot system								
6.2 - Characterization of CLOU oxygen carrier particles								
Task 7 - Evaluation of CLOU performance and CO_2 capture at pilot scale								
7.1 - Parametric testing of CLOU								
7.2 - Optimization of CLOU operation								
Task 8 - Carbon stripper design and and operation								
8.1 - Design and simulation of carbon strippper								
8.2 - Carbon stripper fabrication and installation							M8.1	
8.3 - Evaluation and optimization of carbon stripper performance								
Task 9 - Simulation and scale-up of integrated CLOU reactor								
9.1 - Simulation and validation of dual-bed CLOU reactor								
9.2 - Design and simulation of large scale CLOU reactors								M9.1

Project Budget

- Total budget: $2,350,400
  - 80% DOE
  - 17% UofU cost share
  - 3% Amaron cost share
- $353,000 subcontract
  - Amaron Energy
  - includes $71k cost share
- Breakdown (approx)
  - 33% salaries
  - 18% equipment
  - 21% supplies, fuel, utilities, facility fee
  - 28% overhead
- One 24 month budget period

Institution	Govt. Share	Cost Share	**Total**
University of Utah	1,597,665	399,416	**1,997,081**
Amaron Energy	282,655	70,664	**353,319**
Total	1,880,320	470,080	**2,350,400**
Share percentage	80%	20%	100%

Estimated Project Costing Profile

Baseline Reporting Quarter	Q1	Q2	Q3	Q4	Q5	Q6	Q7	Q8	Q9
Period Start	09/01/15	10/01/15	01/01/16	04/01/16	07/01/16	10/01/16	01/01/17	04/01/17	07/01/17
Period End	09/30/15	12/31/15	03/31/16	06/30/16	09/30/16	12/31/16	03/31/17	06/30/17	08/31/17
Baseline Cost Plan									
Federal Share	110,730	274,658	195,221	226,875	226,875	214,126	205,006	198,926	195,886
Non-Federal Share	67,702	121,864	22,567	6,770	6,770	53,532	51,252	49,732	48,972
Total Planned	**178,432**	**343,323**	**244,026**	**283,594**	**283,594**	**267,658**	**256,258**	**248,658**	**244,858**
Cumulative Baseline Cost Plan									
Federal Share	110,730	385,388	580,609	807,484	1,034,359	1,248,486	1,453,492	1,652,418	1,848,304
Non-Federal Share	67,702	189,566	212,134	218,904	225,674	279,206	330,457	380,189	429,160
Total Planned	**178,432**	**521,755**	**765,781**	**1,049,375**	**1,332,969**	**1,600,627**	**1,856,885**	**2,105,543**	**2,350,400**

Project Management Plan

I. Executive Summary
II. Organization and Structure
III. Risk Management
IV. Milestone Log
V. Funding and Costing Profile
VI. Project Timeline
VII. Success Criteria at Decision Points

Project Management Plan: Risk Management

Description of Risk	Probability (Low, Moderate, High)	Impact (Low, Moderate, High)	Risk Management Mitigation and Response Strategies
Technical Risks:			
Unsuccessful production of oxygen carrier	Low	High	(1) Target lower Cu loading (2) Produce smaller batches
Plugging/fouling of pilot reactor or feed system	Low	Moderate	(1) Regular cleaning (2) Installation of e.g. cleaning jets (3) Redesign of affected components
Excessive attrition/loss of oxygen carrier	Low	Moderate	(1) Increase production of carrier material (2) Reduce load/circulation rate (3) Identify alternate materials
Resource Risks:			
Unavailability of lab-scale experimental systems	Low	Moderate	(1) Organized scheduling of equipment (2) Availability of similar (analytical) equipment.
Management Risks:			
Project costs exceed budget	Low	High	(1) Regular monitoring of finances, EOR system (2) Selective reduction in force
Loss of key personnel	Low	Moderate	(1) Multiple PI's familiar with all areas of project (2) Replace with next-best-suited candidate

Project Management Plan: Milestone Log

Task Number	Milestone Description	Planned Completion	Actual Completion	Verification Method
1	M1.1 Updated project management plan	09/30/2015	09/29/2015	Project Management Plan file
1	M1.2 Kickoff meeting	10/31/2015		Presentation file
3.1	M3.1 Completion of construction of pilot scale CLC system	12/31/2015		Photograph in quarterly report
2.1	M2.1 Fabrication of oxygen carrier production rotary kiln	03/31/2016		Photograph in quarterly report
3.4	M3.2 First pilot testing with CLOU oxygen carrier	07/31/2016		Data presented in quarterly report
1	M1.3 Updated project management plan	09/30/2016		Project Management Plan file
8.2	M8.1 Installation of carbon stripper into CLC pilot plant	04/30/2017		Photograph/discussion in quarterly report
9.2	M9.1 Simulation of 100 MW dual bed CLOU system	09/30/2017		Data presented in quarterly report

Project Management Plan: Success Criteria at Decision Points

- "Go" for Task 3.3 (pilot operation in non-CLOU mode)
  - Steam flow controllable 75-150 kg/hr
  - Air flow controllable 150-300 kg/hr
  - Ability to preheat steam to min 400°C
  - Ability to preheat air to min 400°C
  - Ability to circulate solids min 1200 kg/hr
- "Go" for Task 3.4 (pilot operation in CLOU mode)
  - Non-CLOU operation at min temp 850°C for 4 continuous hrs
  - 10 hours of CO_2 & O_2 measurements from fuel and air reactors
  - Minimum production of 150 kg of oxygen carrier with minimum 20% CuO
- "Go" for Task 7.1 (parametric testing of CLOU)
  - Minimum 50 hrs operation of PDU with at least 20 hours in CLOU mode
  - Minimum 10 successful measurements of solid carbon in coal, oxygen carrier from reactors and bag house particulate
  - Min 300 kg of Cu-based carrier available
- "Go" for Task 9.2 (design/simulation large CLOU reactors)
  - Simulation of PDU with min 3 carrier circulation rates and 3 coal feed rates, with min 30 seconds simulated steady state operation
  - Incorporation of heat transfer and kinetics
  - Comparison of simulated PDU to actual PDU for at least 3 different conditions

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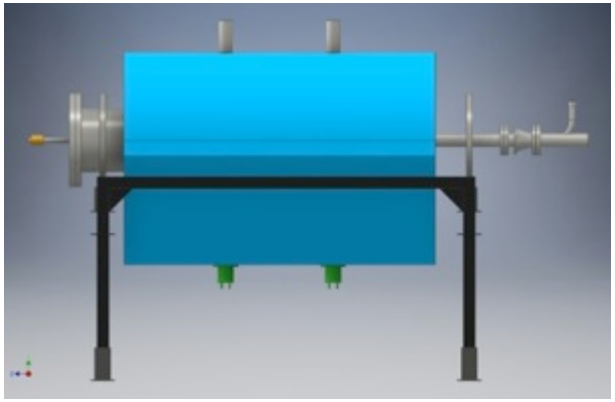
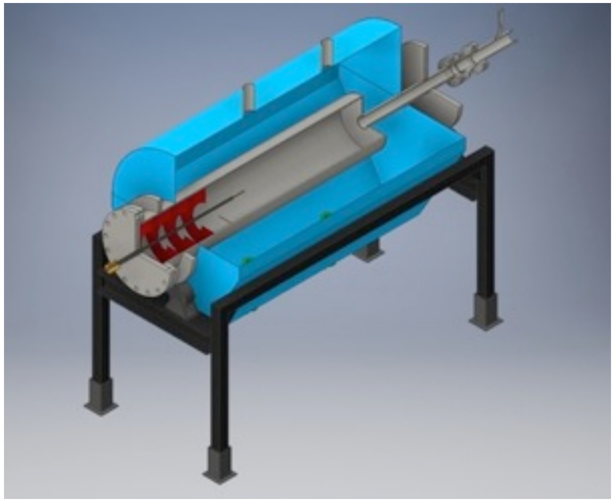
Status: Oxygen Carrier Production

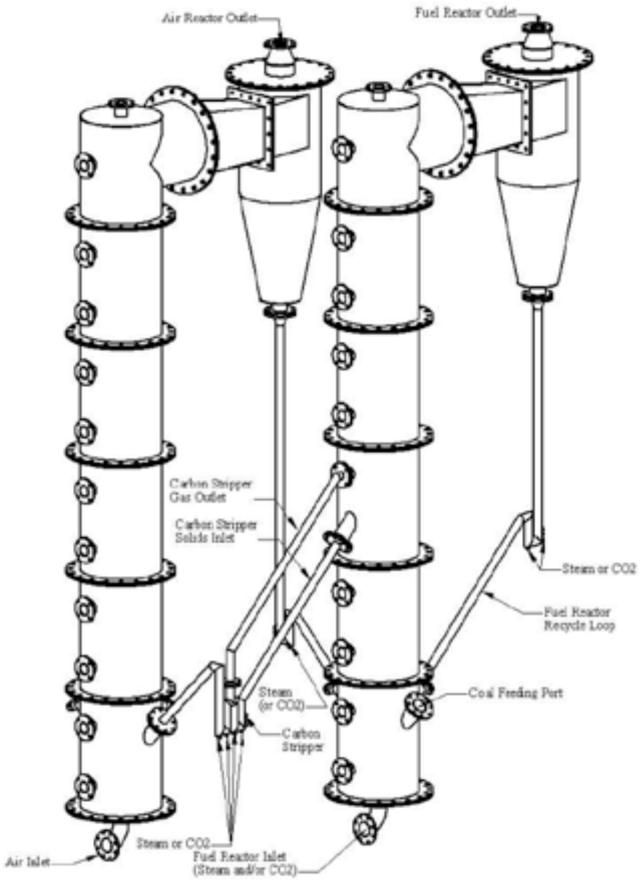
- Parametric optimization of CuO-on-SiC procedure underway
  - Number of addition cycles
  - Calcining time and temperature
- Large-scale kiln design complete (Amaron Energy)
  - Indirectly heated by two NG burners
  - Approx 70 kg of carrier per batch
  - Production procedure based on UofU development
- Bench-scale kiln design complete
  - Electrically heated
  - Approx 8 kg per batch
  - Suitable for 10 kW reactor
- 250 kg of $CuO(NO_3)_2 \cdot 3H_2O$ ordered and received





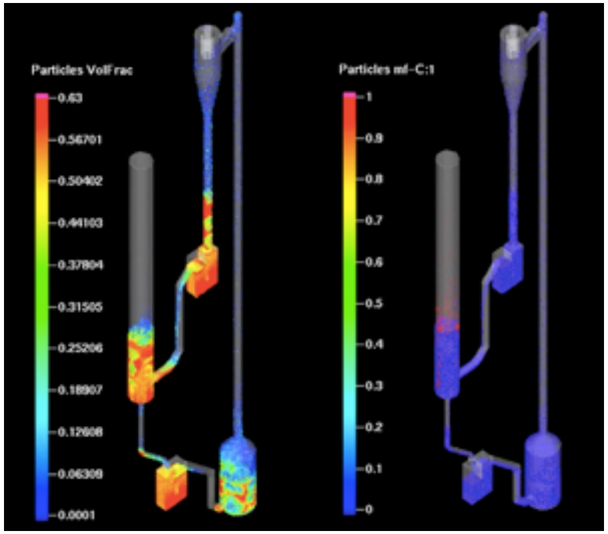
Status: Reactor Operation and Evaluation

- Pilot-scale PDU
  - Electric preheaters installed
  - Duct burner preheat chamber designed, built, installed
  - Plenum and distributor completed and installed for both reactors
  - Air reactor / duct burner blower installed
  - Utility and steam supply lines installed
  - Instrumentation and control system in progress
- Ilmenite oxygen carrier ordered (1 ton)
- Bench-scale (10 kW) system upgrades nearly complete



Status: Reactor Simulation and Process Modeling

- **Reactor simulation**
  - Have negotiated license agreement for Barracuda with CPFD
    - University of Utah CPFD's first Academic Center of Excellence
    - Unlimited licenses
  - Cold flow model evaluation ongoing
  - Incorporating reaction kinetics
  - Simulating 10 kW and PDU reactors
- **Process modeling**
  - Updated Aspen model
  - Evaluated inter-reactor heat flow and preheat/cooling demand



CLOU - AR Temp	940	945	950	955	960	965	970	975
delTemp (°C)	-10	-5	0	5	10	15	20	25
Q Air Reactor (kW)	403.41	345.92	288.32	230.63	172.83	114.93	56.93	-1.18
Q Air Preheat (Preheat to 400 °C) (kW)	-104.47	-104.47	-104.47	-104.47	-104.47	-104.47	-104.47	-104.47
Q Fuel Reactor (kW)	-51.97	3.78	59.64	115.59	171.65	227.81	284.07	340.43
Q Flue Recycle Preheat (Preheat to 675 °C) (kW)	-150.81	-150.81	-150.81	-150.81	-150.81	-150.81	-150.81	-150.81
Q AR Exhaust (kW)	256.31	258.05	259.79	261.53	263.27	265.01	266.76	268.5
Q FR Exhaust (kW)	353.16	353.16	353.16	353.16	353.16	353.16	353.16	353.16
Q Total (kW)	705.63	705.63	705.63	705.63	705.63	705.63	705.64	705.63
Q AR/Q Air Preheat (kW)	298.94	241.45	183.85	126.16	68.36	10.46	-47.54	-105.65
Q FR/ Q Flue Recycle Preheat (kW)	-202.78	-147.03	-91.17	-35.22	20.84	77	133.26	189.62
Q AR/Q Air Preheat (kW)	298.94	241.45	183.85	126.16	68.36	10.46	-47.54	-105.65
Q Fuel Reactor (kW)	-51.97	3.78	59.64	115.59	171.65	227.81	284.07	340.43
Q Air Reactor (kW)	403.41	345.92	288.32	230.63	172.83	114.93	56.93	-1.18
Q FR/ Q Flue Recycle Preheat (kW)	-202.78	-147.03	-91.17	-35.22	20.84	77	133.26	189.62

University of Utah CLC Group