Chemical Looping with Oxygen Uncoupling Systems Studies

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NATIONAL ENERGY TECHNOLOGY LABORATORY

2018 NETL CO_2 Capture Technology Project Review Meeting

U.S. DEPARTMENT OF ENERGY

Objectives

- Develop Reference coal-based CLC power plant reactor model and process simulations
- Estimate power plant performance and cost
- Estimate power plant component performance and cost sensitivities to key design parameters
- Guide research and development

Design Basis

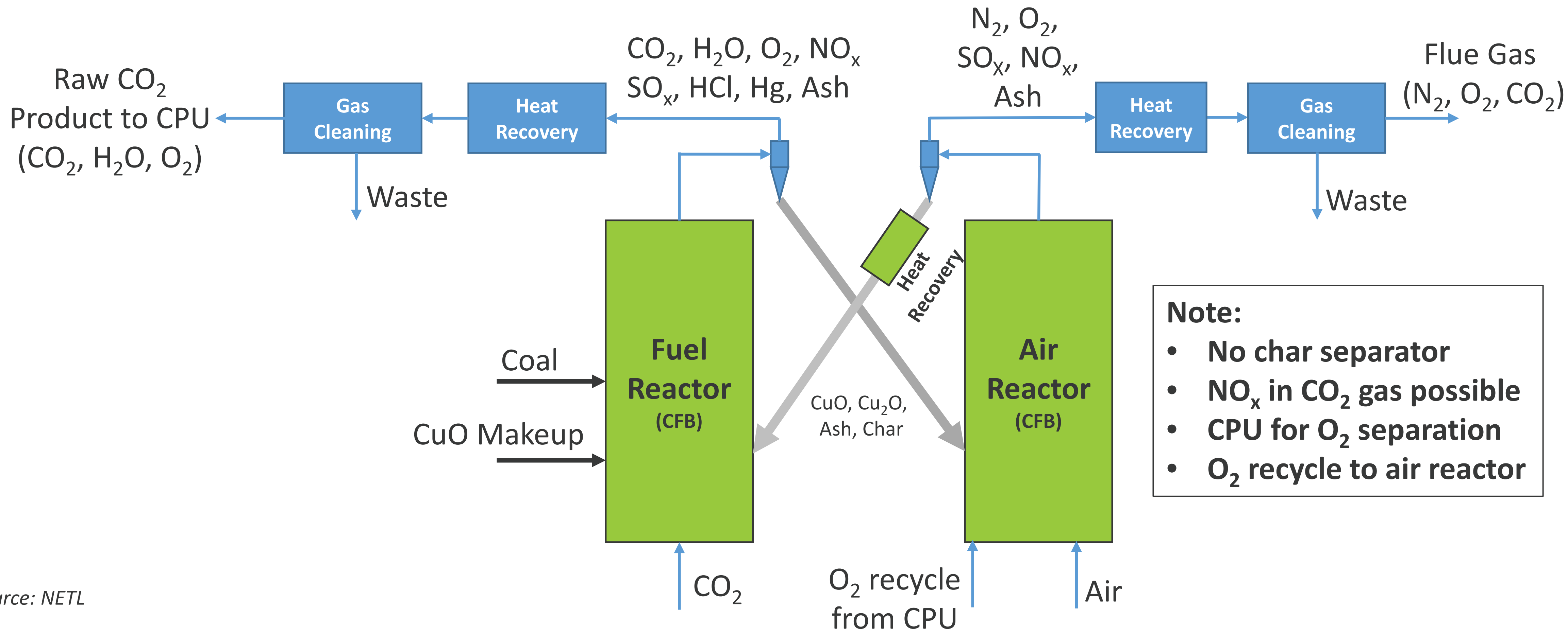
- Atmospheric, circulating fluidized bed CLC design
- Generic Midwest US site
- 550 $MW_{e,net}$
- ISO conditions
- Coal: Illinois #6
- Steam conditions: 3500 psig/1100 °F/1100 °F
- At least 90% carbon capture
- CO_2 product purity at least 95 mol%
- CO_2 product delivery pressure: 2200 psig
- Major equipment performance and cost assumptions consistent with the NETL Bituminous Baseline report*
  - Costs in June 2011$

Cost and Performance for Fossil Energy Plants, Volume 1a: Bituminous Coal and Natural Gas to Electricity, Rev3, DOE/NETL-2015/1723 (2015)

CLOU General Basis

- **CLOU oxygen carrier (OC): CuO supported on inert TiO_2 (52.6 wt% CuO)**
  - Apparent particle density 131 lb/ft^3
  - Particle mean diameter 278 µm
  - Minimum fluidization velocity 0.084 ft/s
  - Transition velocity to fast, circulating bed fluidization 22 ft/s
  - Reported literature kinetics
- **Gas-solids contactor type: CFB**
- **Process configuration:**
  - No char/OC separator
  - Excess oxygen in the fuel reactor off-gas
  - Low-temperature phase separation of fuel reactor off-gas excess oxygen in the CO_2 purification unit (CPU)
  - Recycle of CPU-separated oxygen to the air reactor

CLOU Process Concept



Note:
- **No char separator**
- **NO_x in CO_2 gas possible**
- **CPU for O_2 separation**
- **O_2 recycle to air reactor**

Source: NETL

Reference CLOU Plant Fuel Reactor Operating Conditions

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	CLOU Ref	CLC (Fe_2O_3) *
Temperature (˚F)	1744	1745
OC inlet rate (1,000 lb/hr)	25,772	97,727
Inlet CuO conversion to Cu_2O (%)	3.6	6.8 as Fe_3O_4
Outlet CuO conversion to Cu_2O (%)	71.1	68.7 as Fe_3O_4
Char carbon gasified (%)	98.0	96.0
Off-gas heat recovery (MMBtu/hr)	656	772
Off-gas composition to CPU (mole%)		
O_2	2.1	0
H_2 and CO	0	0.05
CO_2	65.1	50.5
H_2O	31.3	48.2
N_2	0.56	0.5

- CLOU fuel reactor off-gas contains excess O_2 requiring purification to meet 10 ppmv specification
- CLC (Fe_2O_3) fuel reactor off-gas contains excess CO requiring purification to meet 35 ppmv specification

Guidance for NETL's Oxycombustion R&D Program: Chemical Looping Combustion Reference Plant Designs and Sensitivity Studies, DOE/NETL-2014/1643 (2014)

Reference CLOU Plant Air Reactor Operating Conditions

	CLOU Ref	CLC (Fe_2O_3)*
Temperature (˚F)	1553	1800
Air feed rate (1,000 lb/hr)	4,560	4,898
In bed heat recovery rate (MMBtu/hr)	0	0
Off-gas heat recovery (MMBtu/hr)	1,250	1,644
Solids heat recovery (MMBtu/hr)	2,764	2,571
Off-gas composition (mole%)		
O_2	3.5	3.6
CO_2	0.8	0.8
H_2O	1.2	1.8
N_2	92.8	92.7
Ar	1.1	1.1

The CLC air reactor temperature is considerable higher than the CLOU air reactor, with several performance and cost consequences of secondary importance

Guidance for NETL's Oxycombustion R&D Program: Chemical Looping Combustion Reference Plant Designs and Sensitivity Studies, DOE/NETL-2014/1643 (2014)

Reference Plant Power Breakdown

	CLOU Ref (kW)	CLC (Fe_2O_3) (kW)[1]	PC Plant B12B[2]
Steam turbine generator power	635,653	641,430	641,500
Auxiliaries			
Solids handling	5,050	5,370	5,700
Fans	14,712	15,069	16,160
Emissions control	3,464	3,703	3,855
Pumps	10,530	11,370	9,100
CPU	51,747	56,053	35,690
BOP	2,000	2,000	2,000
ST auxiliaries	400	400	400
Transformer losses	2,460	2,520	2,380
Total auxiliaries	90,363	96,185	91,285
Net power	545,290	545,245	550,215
Net plant efficiency (%, HHV)	35.6	33.3	32.5

- The CLC process uses a char/OC separator with zero power consumption
- CLOU and CLC use a CPU for fuel reactor off-gas compression and purification
- The power plant efficiency, within the estimate uncertainties, favors CLOU and CLC technologies over conventional PC power generation

[1]*Guidance for NETL's Oxycombustion R&D Program: Chemical Looping Combustion Reference Plant Designs and Sensitivity Studies*, DOE/NETL-2014/1643 (2014)
[2]*Cost and Performance for Fossil Energy Plants, Volume 1a: Bituminous Coal and Natural Gas to Electricity, Rev3, DOE/NETL-2015/1723 (2015)*

Reference Power Plant Cost Breakdown

	CLOU Ref ($/kW)	CLC (Fe_2O_3) ($/kW)[1]	PC Plant B12B[2]
Coal handling	90	94	95
Coal prep & feed	43	45	45
Feedwater & Misc BOP	171	178	204
CLC (vessels, fans, piping)	153	165	1,779
All HRSGs, ducting & stack	371	275	
CPU	333	367	179
Gas cleanup	345	355	359
Steam turbine generator	323	329	324
Cooling water system	137	145	113
Ash handling	29	31	35
Accessory electric plant	171	174	170
Instrumentation & control	58	58	58
Improvements to site	31	31	33
Buildings & structures	124	124	130
Total	**2,379**	**2,370**	**3,524**

- CLOU and CLC (with zero cost for char/OC separation) have comparable plant capital costs
- The estimated CLOU equipment cost for coal combustion, HRSG, and CO_2 capture is >1,000 $/kW less than the conventional PC plant equivalent equipment cost
- The CLC-related equipment cost is only about 6% of the total power plant cost; development should focus on reliability and performance of this equipment and not on size reduction
- More effort is needed to understand the designs and costs of HRSGs, fans, gas cleaning, and CPU

[1] *Guidance for NETL's Oxycombustion R&D Program: Chemical Looping Combustion Reference Plant Designs and Sensitivity Studies*, DOE/NETL-2014/1643 (2014)
[2] *Cost and Performance for Fossil Energy Plants, Volume 1a: Bituminous Coal and Natural Gas to Electricity, Rev3, DOE/NETL-2015/1723 (2015)*

Reference Power Plant COE Breakdown

	CLOU Ref ($/MWh)	CLC (Fe_2O_3) ($/MWh)[1]	PC Plant B12B ($/MWh)[2]
Capital	49.0	48.9	72.2
Fixed	11.8	11.5	15.4
Variable	22.6	16.5	14.7
Fuel	28.1	30.1	30.9
Total	111.4	107.0	133.2

CLOU oxygen carrier makeup: 1% of coal feed rate @ $3,000 per ton
Fe_2O_3 oxygen-carrier makeup: 1% of coal feed rate @ $2,000 per ton

- Given the uncertainties in the screening analysis, the COE for CLOU and CLC should be considered nearly identical
- The CLC COE would increase if the char/OC system cost were included
- For the assumptions applied, the CLOU and CLC power plants have large COE advantage over the conventional PC power plant (17-20% reduction)
- Both the CLOU and the CLC COEs increase quickly with increasing makeup costs

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Key Sensitivity Parameters

Cost sensitivity parameters:

- CuO-based OC price (1 – 10 $/lb)
- OC makeup rate (0 – 5% of coal feed rate)

Operating condition sensitivity parameters (development guidance):

- Fuel reactor temperature
- Fuel reactor off-gas O_2 content
- Fresh OC CuO composition (wt%)
- OC conversion in fuel reactor

Cost Sensitivity Parameters: OC Price and Makeup Rate

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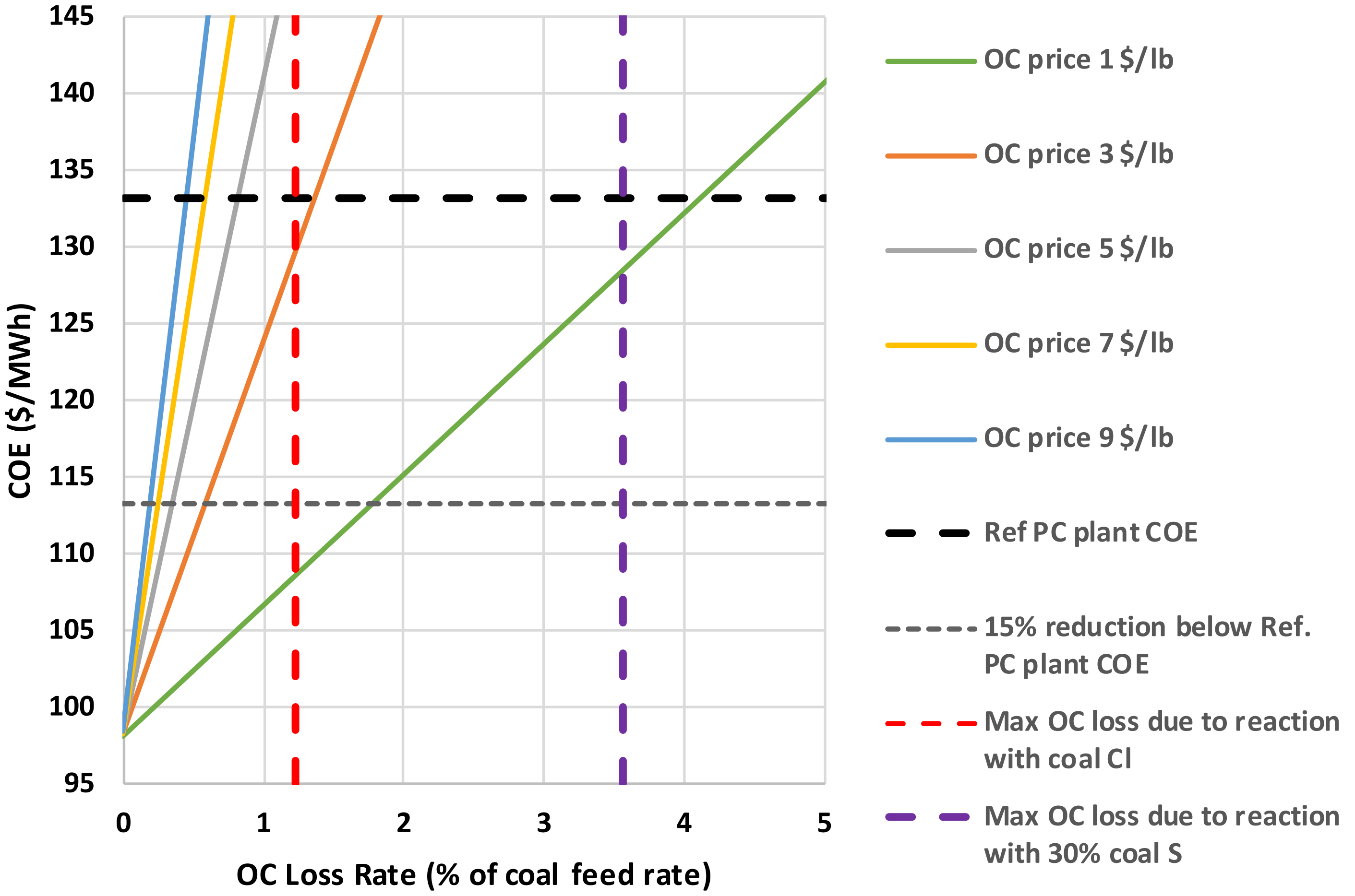
- **OC reactivity may degrade due to thermal sintering of CuO/Cu_2O, reaction of CuO with the inert support (TiO_2), and reaction of CuO with coal contaminants (e.g., HCl, SO_2, alkali metals, coal ash)**
  - Bulk sintering of CuO and Cu_2O initiated at 980 and 900˚F (Tammann temperature)
  - Reaction of CuO with support forms compounds with reduce equilibrium O_2 partial pressure
  - Reaction of CuO with HCl may be non-regenerable
  - Reaction of CuO with SO_2 may be only partially regenerable in the air reactor
- **OC material may be lost due to attrition and elutriation of generated fines, and losses of OC particles with coal ash waste drained from the fluid beds**

Sensitivity Parameters: Reference Plant OC Price and Makeup Rate



Source: NETL

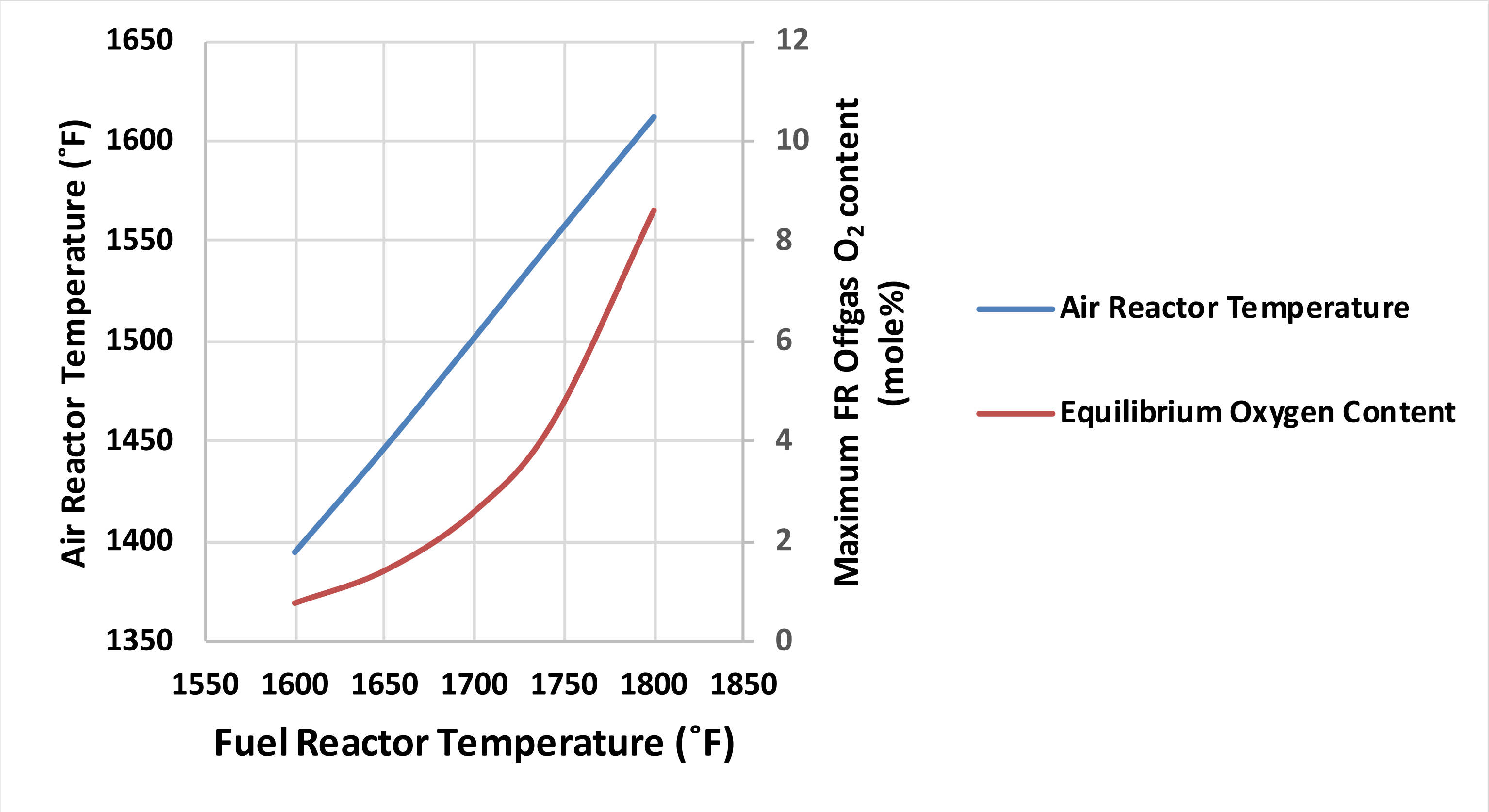
- With low OC price (1 to 2 $/lb), loss rate must be < 1 to 2% of coal feed rate for COE representing a significant reduction relative to the conventional PC plant COE
- With high OC price (7 to 9 $/lb), loss rate must be < 0.2% of coal feed rate
- Non-regenerative reactions with HCl and S could limit the cost potential of the CLOU power plant

Development Guidance: Fuel Reactor Off-gas O_2 Level

FR off-gas O_2 content (mole%)	3.5	2.1	1.05	0.45
Fuel reactor temperature (˚F)	1744	1744	1744	1744
Air reactor temperature (˚F)	1555	1553	1551	1551
OC circulation rate (millions lb/hr)	26.0	25.4	25.1	24.8
Fuel reactor vessel height (ft)	62.0	62.1	62.2	62.2
Fuel reactor shell diameter (ft)	41.3	40.7	40.3	40.1
Air reactor vessel height (ft)	36.7	36.8	36.9	36.9
Air reactor shell diameter (ft)	54.7	54.6	54.6	54.6
Air reactor vessel ΔP (psi)	1.0	1.0	1.0	1.0
Moving bed HX diameter (ft)	56.2	55.6	55.3	55.0
Moving bed HX height (ft)	41.3	41.5	41.6	41.7
Plant efficiency (%)	35.8	36.0	36.0	36.0
Total cost CLOU equip (millions $, BEC)	285.6	280.9	277.2	274.1

- The fuel reactor off-gas oxygen content has little impact on the characteristics and COE of the CLOU power plant
- Note that the moving bed heat exchanger conceptual design has dimensions comparable to the fuel and air reactors

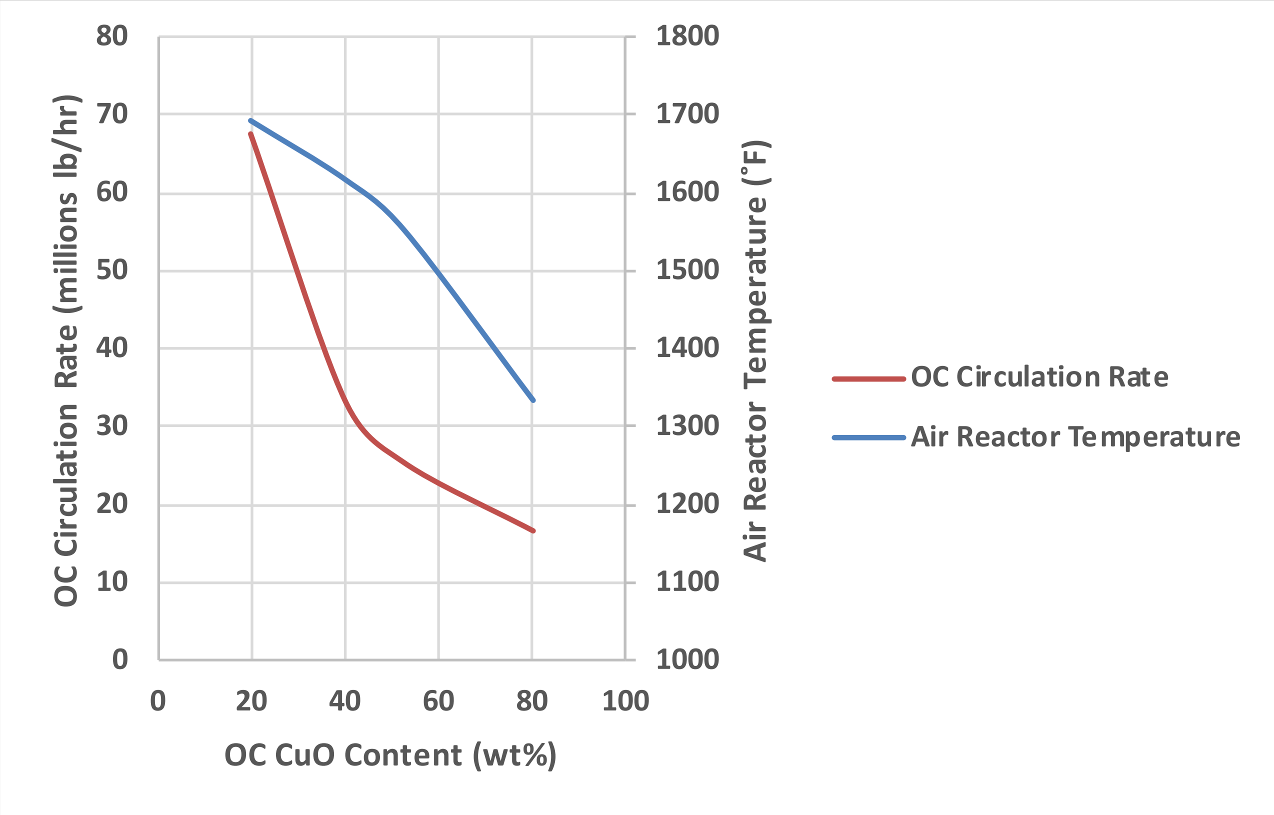
Development Guidance: Fuel Reactor and Air Reactor Temperature



Source: NETL

- The maximum fuel reactor off-gas oxygen content is equal to the equilibrium oxygen content; actual off-gas oxygen content may be as high as 50% of this value
- Should operate at the highest temperature where OC reactivity degradation is observed to be low when exposed to an actual coal gas environment

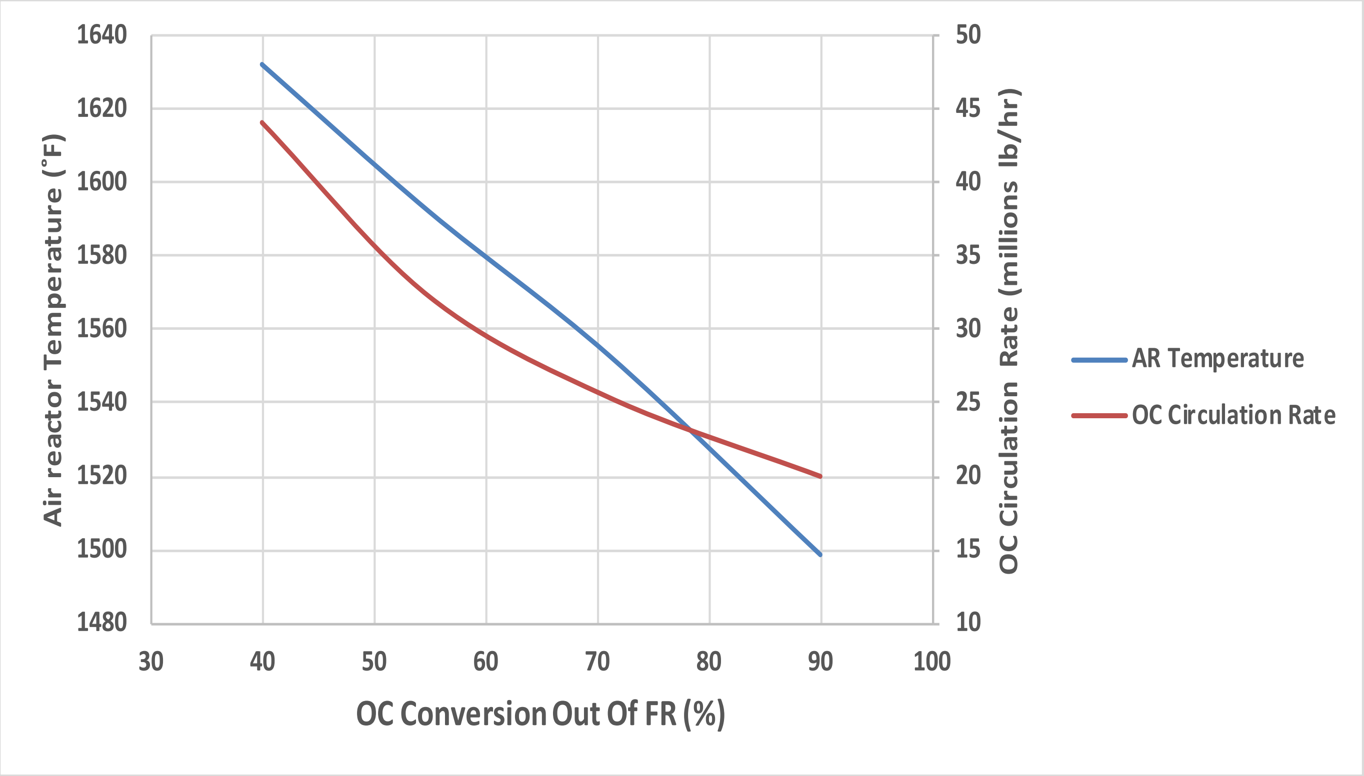
Development Guidance: OC CuO Content



Source: NETL

OC CuO content (wt%)	20	40	52.6	80
Particle density (lb/ft^3)	102.8	118.4	131.0	169.6
Air reactor temperature (˚F)	1693	1618	1553	1335
Solids HRSG outlet temp (˚F)	1623	1409	1184	361
OC circulation rate (millions lb/hr)	67.6	33.4	25.4	16.6
Fuel reactor vessel height (ft)	72.3	63.4	62.1	64.7
Fuel reactor shell diameter (ft)	40.7	41.3	40.7	38.9
Air reactor vessel height (ft)	39.0	36.4	36.8	39.6
Air reactor shell diameter (ft)	54.6	56.3	54.6	51.2
Air reactor vessel ΔP (psi)	2.1	1.2	1.0	0.9
Moving bed HX diameter (ft)	102.0	67.0	55.6	39.7
Moving bed HX height (ft)	53.6	41.0	41.5	137.3
Plant efficiency (%)	35.6	36.0	36.0	36.1
Total cost CLOU equip (millions $, BEC)	294	282	281	335

Development Guidance: Fuel Reactor OC Conversion



Source: NETL

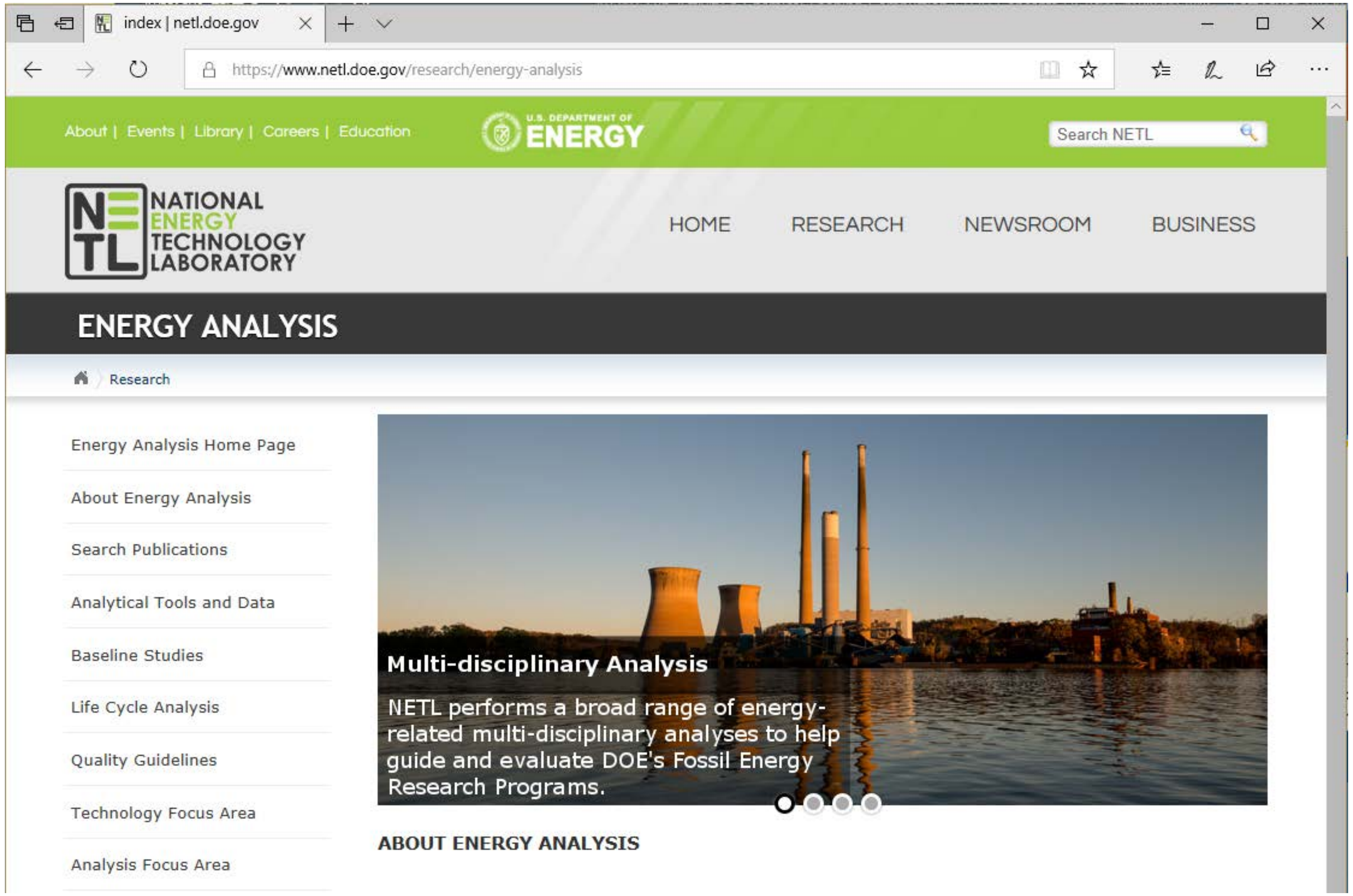
OC CuO conversion (%)	40	55	71.1	90
Air reactor temperature (˚F)	1632	1592	1553	1499
OC circulation rate (millions lb/hr)	44.1	32.3	25.4	20.0
Fuel reactor vessel height (ft)	56.2	58.6	62.1	68.6
Fuel reactor shell diameter (ft)	40.8	40.8	40.7	40.7
Air reactor vessel height (ft)	35.8	36.6	36.8	37.1
Air reactor shell diameter (ft)	51.0	55.0	54.6	54.4
Air reactor vessel ΔP (psi)	1.6	1.2	1.0	0.8
Moving bed HX diameter (ft)	73.2	62.6	55.6	49.5
Moving bed HX height (ft)	42.0	39.6	41.5	43.5
Plant efficiency (%)	35.7	35.8	36.0	35.9
Total cost CLOU equip (millions $, BEC)	281	280	281	282

Conclusions

- **CFB, CuO-based CLOU is superior to CFB, Fe_2O_3-based CLC in that it eliminates the development challenge of char/OC separation technology needed for CFB, Fe_2O_3-based CLC**
- **The current estimated power plant efficiency for CFB, CuO-based CLOU (35.6% HHV) is higher than for a conventional PC power plant with capture (32.5% HHV)**
- **The current estimated COE for CFB, CuO-based CLOU with $1.5/lb price and 1% makeup rate for OC (111 $/MWh) is 17% lower than the COE for a conventional PC power plant with capture (133 $/MWh)**
- **The CLOU developer has significant latitude in the selection of OC properties (composition and particle size), and fuel reactor and air reactor operating conditions that can result in CLOU power plants with acceptable performance and cost:**
    - Fuel reactor temperature (1600 to 1800˚F)
    - Fuel reactor off-gas O_2 content (0.5 – 4 mole%)
    - Fresh OC CuO content (20 – 80 wt%)
    - OC conversion in fuel reactor (50 – 90% conversion to Cu_2O)
- **Achieving low OC cost (integrated price and make-up requirement) represents a priority objective**
- **The focus of continued development of the chemical looping equipment should be on its operability and reliability rather than its size/cost reduction (~6% of Total Plant Cost)**

Stay tuned…

http://www.netl.doe.gov/research/energy-analysis



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