Coal Transformation: Clean Coal

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Overview

- Background
  - Environmental Concerns
  - Legislation

- What is Oxy-Fuel?
  - Background
  - Previous studies
  - Technical issues

- Proposed Solutions & Motivation
  - IGCC
  - Oxy-Fuel
  - Scrubbing
  - Economics estimates

- Purdue Combustion Studies Beginning
  - Constant volume or pressure Combustion
  - Pressurized Systems
  - Future areas?
    - Chemical Looping
    - Aluminum combustion with CO_2

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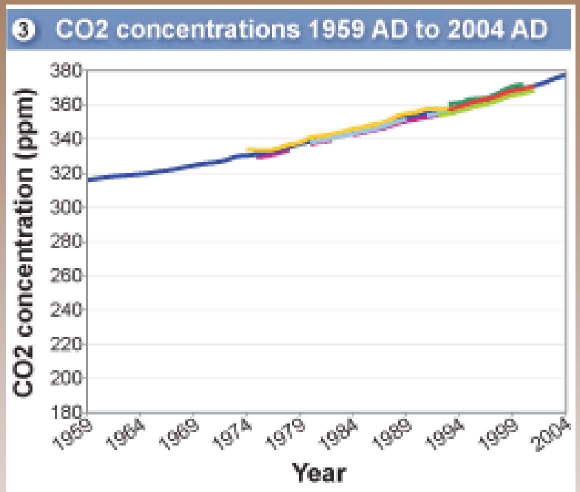
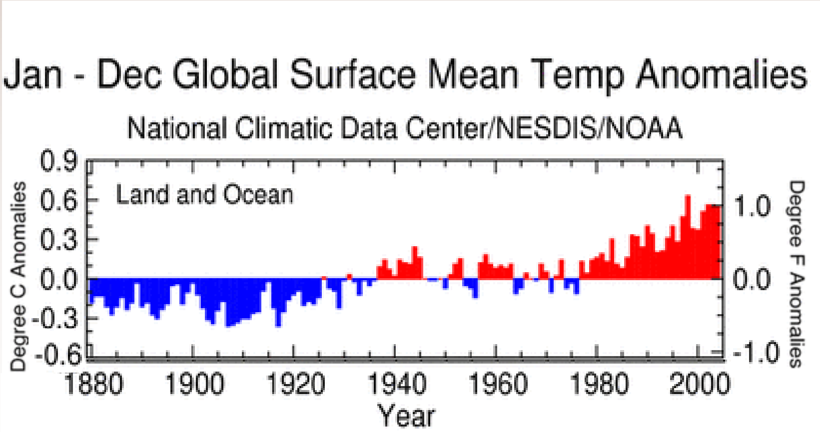
Background

- Environmental Concerns
  - "Greenhouse Effect" has led to 1^{o}F average increase over 20 years
  - Current rate is 0.32^{o}F per decade
  - NO_x contributes to Acid Rain and "greenhouse effect"





Source: www.epa.gov

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Background

- Legislation
  - President's Clear Skies Initiative
    - Reduce NO_x 67% from 2000 levels and SO_2 73% from 2000 levels by 2018
  - Greenhouse Gas (GHG) Intensity
    - Reduce intensity (tons gas/ $M GDP) 18% by 2012
  - International Kyoto Protocol
    - UN rule to reduce GHG emissions 5% by 2012
    - Binding to countries who ratified (>55% of world emissions)

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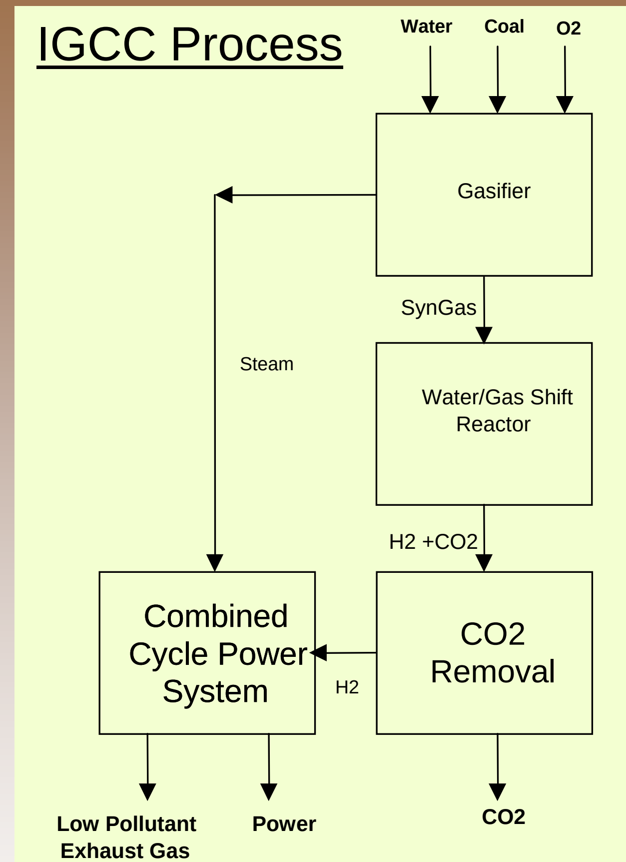
Proposed Solutions

- Longer Term
  - Nuclear
  - Alternative Energy
    - Renewable
      - Wind, Solar, Biofuels

→ Coal will be used in foreseeable future
  - **Coal is the most abundant domestic fuel and it remains the lowest cost fuel for power generation**
- Increase Efficiency
  - Ultra Super-Critical Pulverized Coal
  - Integrated Gasification Combined Cycle (IGCC)
    - Higher Efficiency
    - Produces usable hydrogen



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Nearer Term Options for Clean Coal

- Three approaches are presently seen as the front runners:
  - **Oxygen combustion**
    - Concentrates CO_2
    - Reduces NOx
  - **Amine (or others) scrubbing** for new or existing plants
    - Extracts the CO_2 from the flue gas using a regenerable sorbent-catalyst such as monoethanolamine (or MEA)
  - **IGCC**
    - Concentrates CO_2
    - Produces multi-use syngas
  - "*Some current studies show oxygen combustion as the least costly while others lean toward IGCC, indicating that the jury is still out.*" (Williams et al., BR-1779, 2006)

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Economics of Clean Coal

- Many uncertainties still exist when comparing costs of new technologies
  - Scales
  - Availability of Technology
  - Repair costs
  - Lost Energy Costs
  - Disposal/salvage Costs
- However, taking published studies on cost data and comparing to real world numbers, the following calculations result:

Method	Capital Costs ($/MW)	Annual Cost ($/ {year * MW})	Total cost (400 MW) ($ for year 1)
Amine	$899,297	$257,496	$462,717,326.84
Oxyfuel	$966,663	$220,878	$475,016,480.26
IGCC	$1,483,840	$192,750	$670,636,013.14

Notes:

1) **All numbers in $US 2006**
2) **Amine & Oxyfuel are retrofit costs, IGCC is new plant**
3) **20 years is the assumed life of retrofitted plant**

References:

Smith LA, Gupta N, Sass BM, Bubenik T, Byer C, Bergman P. “Engineering and economic assessment of carbon dioxide sequestration in saline formations.” Journal of Energy and Environmental Research 2002; 2:5–22.

Singh D, Croiset E, Douglas PL, Douglas MA. “Techno-economic study of CO2 capture from an existing coal-fired power plant: MEA scrubbing Vs. O2/CO2 recycle combustion.” Energy Conversion Management 2003;44:3073–91.

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Economics of Clean Coal

- What does this mean to Indiana?
  - Costs of revamping “The Big 10” estimated
  - 50 years assumed as life of plant
  - Retrofits include boiler and turbine refurbishment at 50 years from original boiler install

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Economics of Clean Coal

Without fuel costs

	Design Output (MW)	*Amine Retrofit Cost*	*Oxyfuel Retrofit Cost*	*IGCC Replacement Cost*
Gibson	3340	$16,520,853,638	$10,630,647,234	$15,811,025,710
Tanner's Creek	1099	$5,436,053,338	$3,497,928,536	$5,202,490,196
Rockport	1300	$6,430,272,374	$4,137,677,067	$6,153,992,043
Schahfer	2200	$10,881,999,402	$7,002,222,729	$10,414,448,072
Petersburg	1880	$9,299,163,125	$5,983,717,605	$8,899,619,262
Clifty Creek	1300	$6,430,272,374	$4,137,677,067	$6,153,992,043
Cayuga	1193	$5,901,011,494	$3,797,114,416	$5,647,471,159
Merom	1080	$5,342,072,434	$3,437,454,794	$5,112,547,235
Stout/Harding St.	1185	$5,861,440,587	$3,771,651,788	$5,609,600,439
Wabash River	668	$3,304,170,728	$2,126,129,447	$3,162,205,142

With fuel costs

	Design Output (MW)	*Amine Retrofit Cost*	*Oxyfuel Retrofit Cost*	*IGCC Replacement Cost*
Gibson	3340	$47,729,813,638	$41,839,607,234	$37,145,275,710
Tanner's Creek	1099	$15,705,109,338	$13,766,984,536	$12,222,352,696
Rockport	1300	$18,577,472,374	$16,284,877,067	$14,457,742,043
Schahfer	2200	$31,438,799,402	$27,559,022,729	$24,466,948,072
Petersburg	1880	$26,865,883,125	$23,550,437,605	$20,908,119,262
Clifty Creek	1300	$18,577,472,374	$16,284,877,067	$14,457,742,043
Cayuga	1193	$17,048,403,494	$14,944,506,416	$13,267,758,659
Merom	1080	$15,433,592,434	$13,528,974,794	$12,011,047,235
Stout/Harding St.	1185	$16,934,080,587	$14,844,291,788	$13,178,787,939
Wabash River	668	$9,545,962,728	$8,367,921,447	$7,429,055,142

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Economics of Clean Coal

- What if 50 years isn't realistic?
  - Assume Boiler and turbine retrofits are not necessary

	Design Output (MW)	Amine Retrofit Cost	Oxyfuel Retrofit Cost	IGCC Replacement Cost
Gibson	3340	$15,904,217,953	$14,294,657,503	$14,612,800,710
Tanner's Creek	1099	$5,233,154,350	$4,703,541,496	$4,808,223,946
Rockport	1300	$6,190,264,473	$5,563,788,848	$5,687,617,043
Schahfer	2200	$10,475,832,185	$9,415,642,666	$9,625,198,072
Petersburg	1880	$8,952,074,776	$8,046,094,642	$8,225,169,262
Clifty Creek	1300	$6,190,264,473	$5,563,788,848	$5,687,617,043
Cayuga	1193	$5,680,758,089	$5,105,846,228	$5,219,482,409
Merom	1080	$5,142,681,254	$4,622,224,582	$4,725,097,235
Stout/Harding St.	1185	$5,642,664,154	$5,071,607,527	$5,184,481,689
Wabash River	668	$3,180,843,591	$2,858,931,501	$2,922,560,142

With fuel / 15 years

	Design Output (MW)	Amine Retrofit Cost	Oxyfuel Retrofit Cost	IGCC Replacement Cost
Gibson	3340	$20,204,406,622	$17,983,325,321	$17,831,725,710
Tanner's Creek	1099	$6,648,096,670	$5,917,267,823	$5,867,385,196
Rockport	1300	$7,863,990,601	$6,999,497,880	$6,940,492,043
Schahfer	2200	$13,308,291,787	$11,845,304,104	$11,745,448,072
Petersburg	1880	$11,372,540,254	$10,122,350,780	$10,037,019,262
Clifty Creek	1300	$7,863,990,601	$6,999,497,880	$6,940,492,043
Cayuga	1193	$7,216,723,683	$6,423,385,362	$6,369,236,159
Merom	1080	$6,533,161,423	$5,814,967,469	$5,765,947,235
Stout/Harding St.	1185	$7,168,329,894	$6,380,311,529	$6,326,525,439
Wabash River	668	$4,040,881,324	$3,596,665,064	$3,566,345,142

With fuel / 20 years

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Economics of Clean Coal

- If IGCC somewhat cheaper (for 50 years & many assumptions), why oxy-fuel?
  - Cost of retraining operators for IGCC not included
    - IGCC operation is more complex
  - Air separation units purchased for Oxy-fuel retrofit could be used later on IGCC replacements
    - Can lower future necessary capital funds
  - IGCC startup costs much larger
    - Oxy-fuel capital is 65% less
    - IGCC technology and experience improving, so oxy-fuel retrofit followed at some point by IGCC replacement may be better in some cases
  - If oxy-fuel boiler & turbine are upgraded to higher performance (efficiencies), less fuel would be used and the system would be more competitive with IGCC
    - For example, could utilize higher temperatures from oxygen combustion instead of using recycled flue gases to match original design

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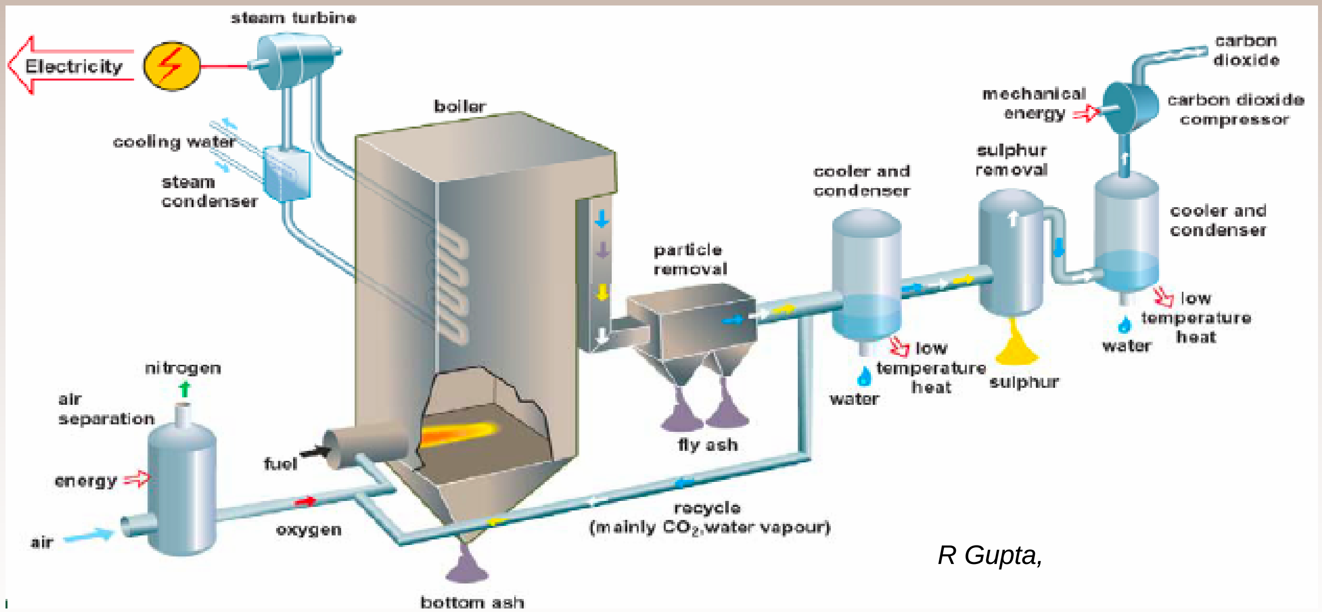
What exactly is oxy-fuel?

- Oxy-Fuel
  - Pure oxygen as oxidizer
  - Reduces or eliminates NOx
  - Increases CO_2 concentration
    - Easier to recover
  - ***Can be used in retrofit coal plants***



R Gupta,

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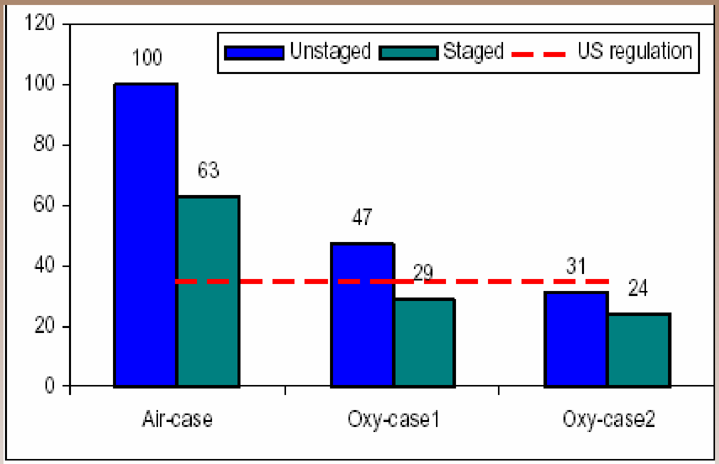
Previous Oxy-Fuel Studies

- Pollutants
  - NO_x reduced
    - Can be further reduced
  - CO_2 concentrated >90%



(a) NOx emissions, normalised assuming the baseline value in air-case is 100. Dash line is US regulation 65 mg/MJ

Oxy-fuel combustion in GHG Context – Status of Research, Technology and Assessment
R Gupta, CRC for Coal in Sustainable Developement
Univ of Newcastle Australia
Advanced Coal Workshop, Brigham Young University, Provo,Utah, 15-16th March 2005

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Previous Oxy-Fuel Studies

- Flame and Heat Transfer
  - Instabilities observed
    - Can be overcome by increasing O_2, but increases cost
    - Can this be overcome by recycling hot exhaust (flue) gas (RFG)? Are optimized ignition and combustion possible?
  - Heat Transfer changed
    - No NO_x, N_2, less CO to carry heat to boiler
      - Transport properties changed
    - Can likely be made to matched air burning with RFG
    - Avoids changing plant electrical output

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Previous Oxy-Fuel Studies


Jupiter Oxy-Fuel plant; Hammond, IN

- Retrofit
  - Most necessary technology is mature
    - Optimization should be only changes
  - Must find a place for CO_2
    - No current large scale market
    - Must sequester and store
  - Can be adapted to future technological advances
    - IGCC using air separation unit from oxy-fuel retrofit
  - Pilot Studies already done
    - Companies such as Air Liquide and Alstom

We are collaborating with Jupiter Oxygen Corporation, who is retrofitting 25 MW plant in Orville, Ohio; as well as developing an oxy-fuel pilot plant in Hammond, IN

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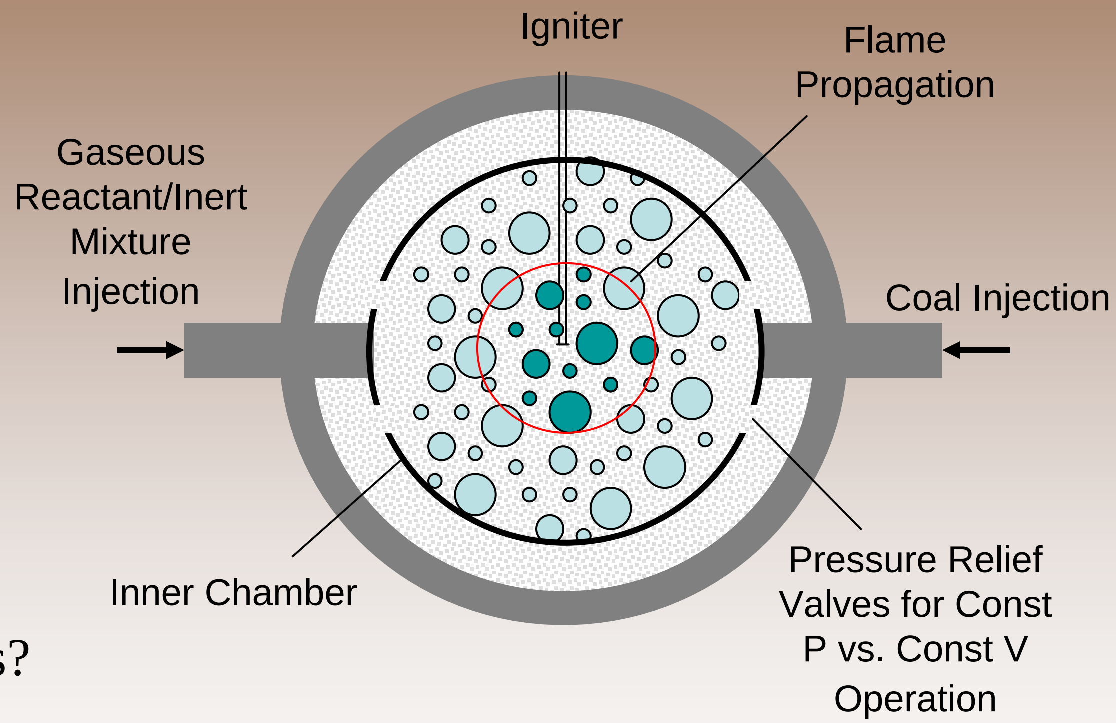
Studies Beginning at Purdue

- Constant volume or pressure ignition and combustion
  - Flame and ignition characterization studies
  - Pollutant concentrations
  - RFG/O_2% optimization
  - Comparisons with Jupiter pilot reactor
  - Indiana coals considered
- Pressurized studies
  - Control flame instabilities?
  - Future technology areas?
    - IGCC pressurized syngas
    - Chemical looping

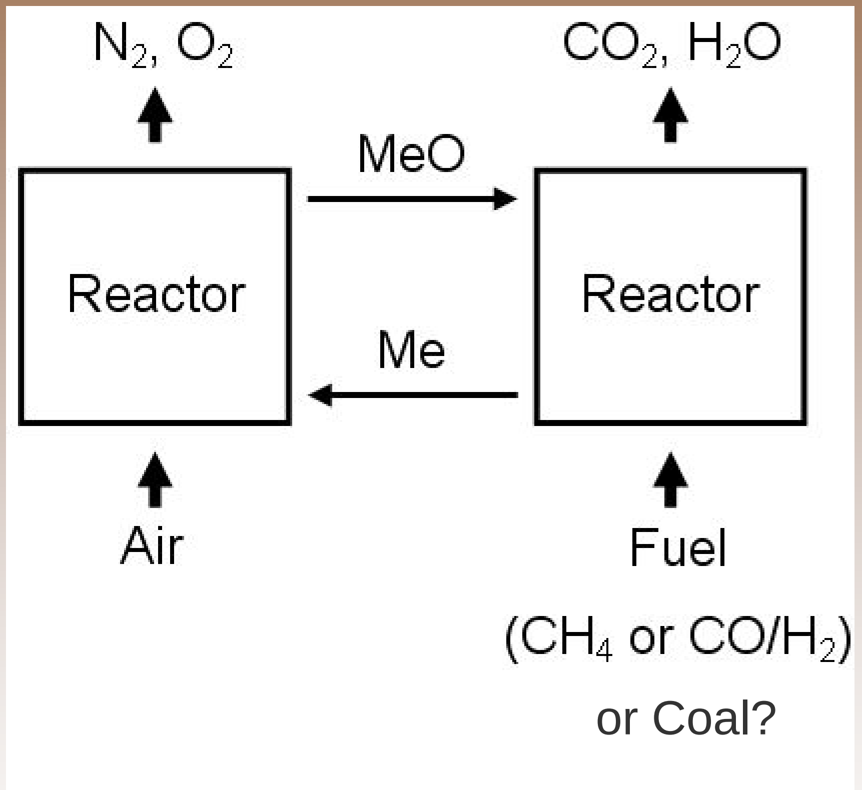
Funding from Indiana CCTR



Can hot RFG stabilize O_2/CO_2/Coal flame with lower O_2 concentration?

Some Future Areas

- Chemical Looping Combustion (CLC)
  - Uses metal oxides to provide oxygen for Oxy-Fuel
  - Potentially cheaper than cryogenic
  - Will pulverized coal work with CLC?
  - Survivability of cycled metal
- Can CO_2 be used as oxidizer instead of air?
  - For example, Al and Mg can burn with CO_2 as the oxidizer
  - Eliminates need for sequestration
  - Produces heat (could drive additional power generation) and CO that could be used to make alcohol fuel
  - Optimize for CO or C(s) products?



Note: MeO = Metal Oxide

Me = Metal