March 13, 2003

Greenhouse Gas Emissions Control by Oxygen Firinig in Circulating Fluidized Bed Boilers

John L. Marion
ALSTOM

Greenhouse Gas Emissions Control by Oxygen Firing in Circulating Fluidized Bed Boilers

presented at

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ALSTOM Power Inc.

&

Scott Klara

DOE National Energy Technology Laboratory

Outline of Talk

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- CO2 Mitigation from Fossil Power
- Oxy-fuel firing strategy
- Oxy-fuel fired CFB
- Study Cases
- Testing results
- next steps

Technology Response: CO_2 Mitigation Options -for Power

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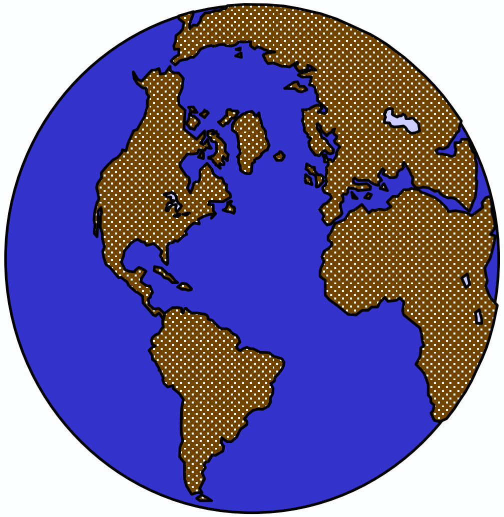
- Conservation
- Increase efficiency
  - [of fossil fuel energy conversion]
- Fuel Switch
  - nuclear
  - renewables
  - natural gas



- CO_2 Sequestration
  - Capture
  - Sequestration

Needed in the long run if we continue to use fossil fuels and commit to CO2 emissions stabilization

Technology Response:
CO_2 Capture Approaches-for Power

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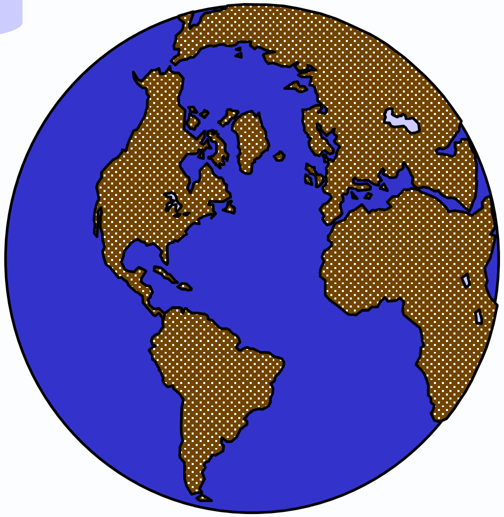
- Post Capture
  - Adsorption
  - Absorption
- Oxy-fuel Firing
  - external oxygen supply
  - integrated membrane-based
  - oxygen carriers
- Decarbonization
  - reforming (fuel decarbonization)
  - carbonate reactions (combustion decarbonization)

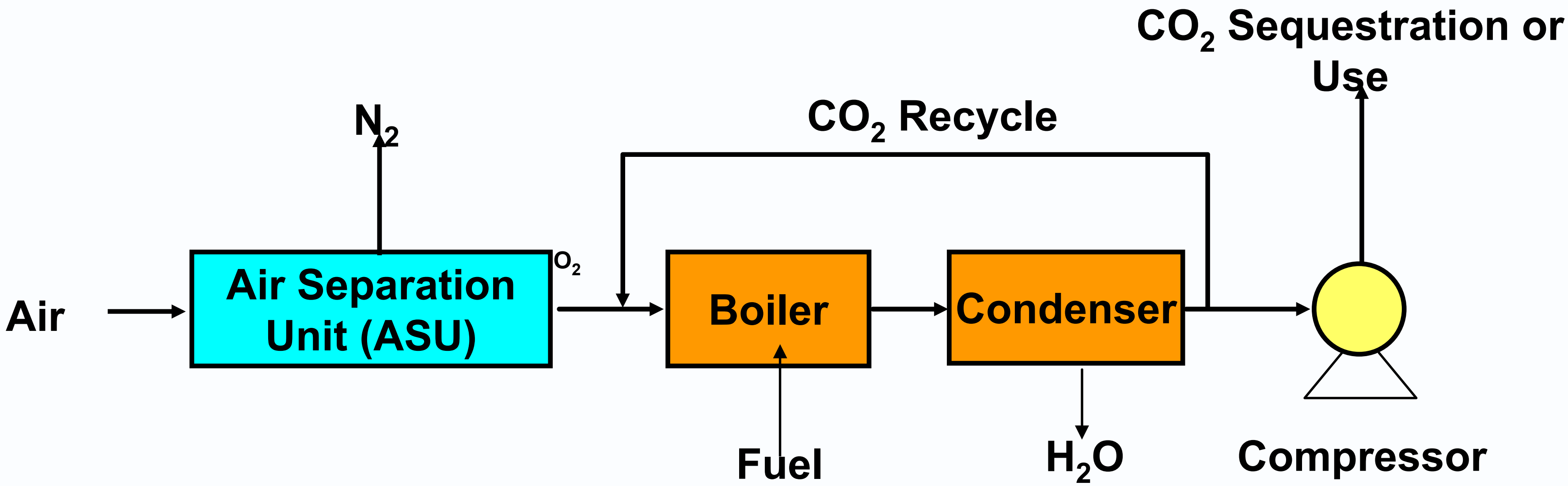
FOCUS OF TALK



Innovative technology options just now emerging

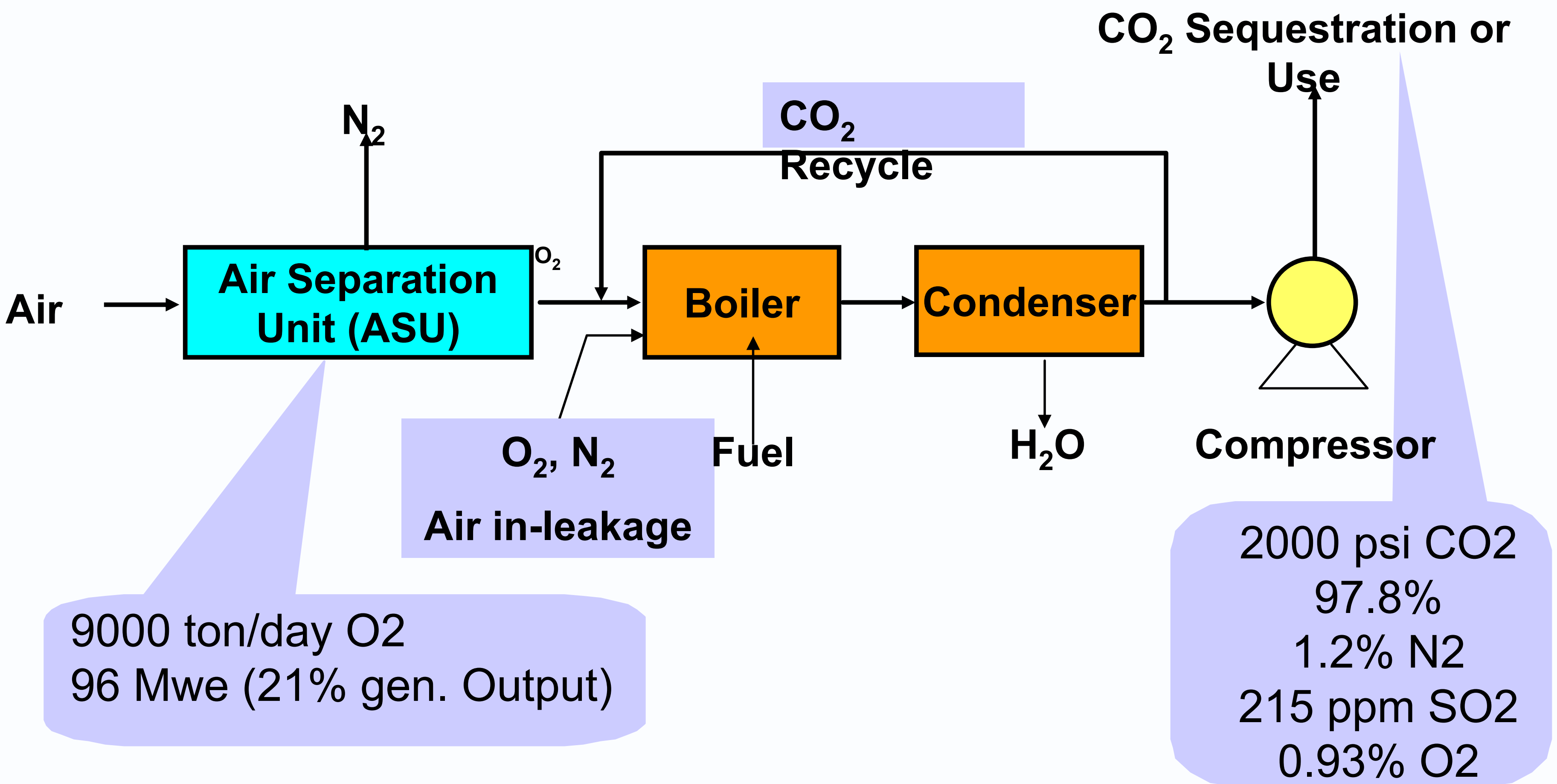
CO_2 Capture by Oxy-fuel Combustion

Coal Combustion in O_2/Recycled Flue Gas (with High CO_2 Concentration) without CO_2 Separation



CO_2 Capture by Oxy-fuel Combustion

COMPLICATIONS!!



CO_2 Liquefaction for Pure CO_2

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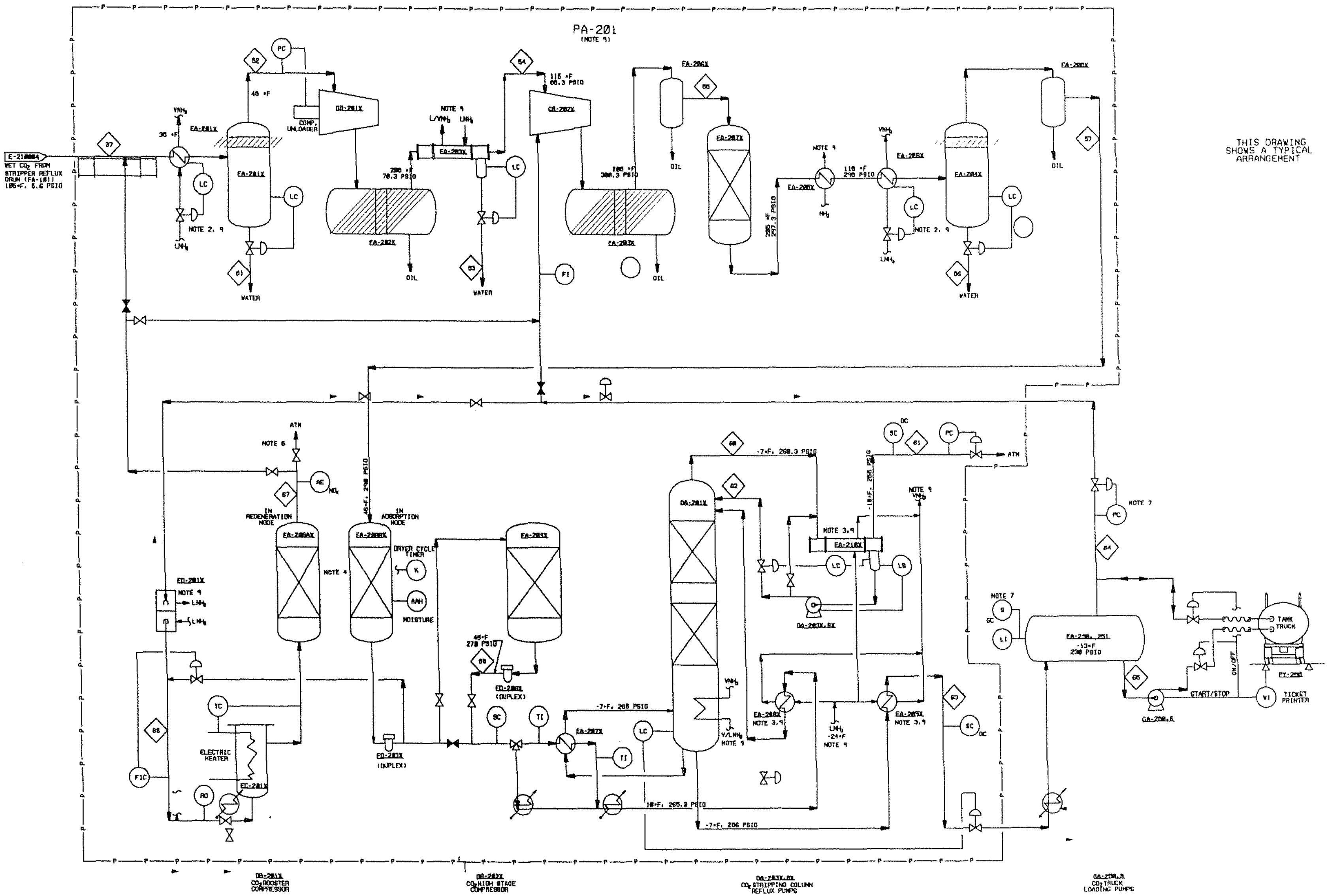

Oxygen Fired CFB

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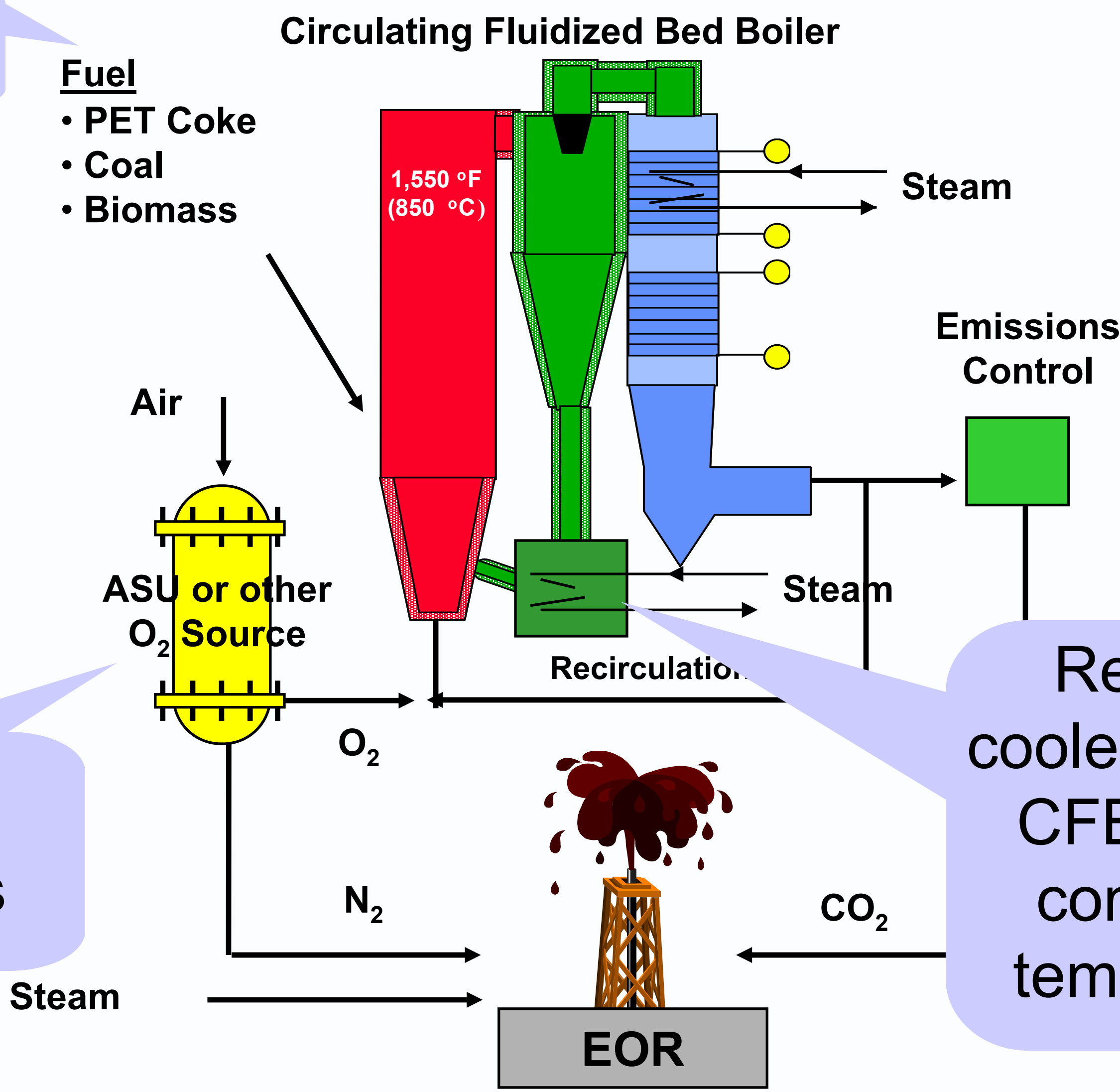
Fuel Flexible

Future - O2 Membranes

Recycled cooled solids in CFB control combustor temperature



"Greenhouse Gas Emissions Control By Oxygen Firing in Circulating Fluid Bed (CFB) Boilers"

Study of nine (9) alternate novel CO2 capture from combustion systems technologies and comparison to three (3) IGCC cases - coal and petcoke fired

US DOE cofunded

ALSTOM Power
Parsons (A/E)
ABB Lummus
Praxair
Plasma

Project Objectives

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To determine if carbon dioxide can be recovered at an avoided cost of $10/ton (or less) of carbon avoided, using a newly constructed coal fired plants

- ☐ Performance and economic analyses of an existing design 210-MWe air-fired CFB plant to provide Base Case information
- ☐ Design an O_2-fired CFB, for the same steam cycle parameters as Base Case CFB, and carry out performance and economic analyses
- ☐ Design several other advanced "CFB-based" and novel CO2 capture plants for the same steam cycle parameters and carry out performance and economic analyses.
- ☐ Performance and economic analyses of IGCC cases for comparison (with and without CO_2 capture). These cases will be based upon prior DOE and Parsons study, but will be modified to allow comparison with the Base Case including similar thermal fuel input
- ☐ Bench and Pilot Testing of Promising Case(s)

Cases Studied: All ~ 210 MWe Gross)

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Case 1: Base Case Circulating Fluid Bed (CFB) Boiler

Conventional Air-Fired CFB without CO_2 Capture.
Provides Reference Point for Performance & Economic Analyses of Cases 2-7

Case 2: New Compact O_2-Fired CFB with CO_2 Capture, Purification, Compression and Liquefaction

Same Thermal Input But Smaller Boiler Island than Case 1. Oxygen Is from a Cryogenic ASU Plant. CFB Plant Provides Concentrated CO_2 Flue Gas.
Implication: Cost Savings on Boiler Island and On CO_2 Processing Equipment

Case 3: New Compact O_2-Fired CFB with Flue Gas Compression and Liquefaction

Same as Case 2, But Without CO_2 Purification. Flue Gas Compression and Liquefaction for Sequestration Only.
Implication: Gas Processing System Cost Reduction from Case 2

Cases Studied: All ~ 210 MWe Gross

Case 4: O_2-Fired Circulating Moving Bed (CMB) with CO_2 Purification, Compression and Liquefaction

Same as Case 2, But Uses Advanced Boiler Design Concepts.

Implication: Further Boiler Cost Savings Compared to Case 2

Case 5: Air-Fired CMB with High Temperature Regenerative Carbonate Process

Air-Firing and Carbonate Regeneration at Higher Temperatures Than Steam Cycle Temperatures:

Implication: Advanced Novel Concept Eliminates Energy Penalty for CO_2 Capture

Case 6: Case 2 or 4, Integrated with Oxygen Transport Membrane (OTM)

OTM is a More Efficient Method for O_2 Production Than Conventional Cryogenic ASU As Was the Case with Cases 2 & 4.

Implication: Potential Reduction of Energy Penalty by About One-third.

Case 7: Indirect Combustion of Coal via Chemical Looping

Utilizes a Solid Oxygen-Carrier (e.g., Fe_2O_3), Which Oxidizes the Fuel Into H_2O and CO_2, Condensing H_2O Then Yields a Virtually Pure CO_2 Stream

Cases Studied - these 250 MW gross

Case 8: Present Day Integrated Gasification Combined Cycle (IGCC)
Conventional Operating IGCC (Single Train F-Class Gas Turbine) Without CO_2 Capture. Provides a Reference Point for Performance and Economic analyses of Cases 9 and 10

Case 9: Present Day IGCC With Shift Reaction and CO_2 Capture, Compression, and Liquefaction
Same as Case 8, But With Scrubbing Equipment for CO_2 Capture, Compression, and Liquefaction

Case 10: Future (2015) IGCC With Shift Reaction and CO_2 Capture, Compression, and Liquefaction
Same as Case 9, But Applying the Most Advanced Thinking of Technology Breakthroughs (e.g., OTM for O_2 Production and H-Class Gas Turbine)
Implication Potential Reduction in Cost and Improvement in Performance of an IGCC Power Plant

Basic Work Steps for each Case

1) Develop Process Design

Material & Energy Balance (Gas side, Steam side)

Overall plant performance & CO2 emission summary

2.) Develop System / Component Specifications and Designs

3.) Develop Equipment Costs

Capital Costs

O&M Costs

4.) Develop Boiler and Plant Drawings

5.) Economic Evaluation

Cost of Electricity (COE)

CO2 Mitigation Cost

Case 1: Air-Fired CFB -- Boiler Island Equipment Scope Definition

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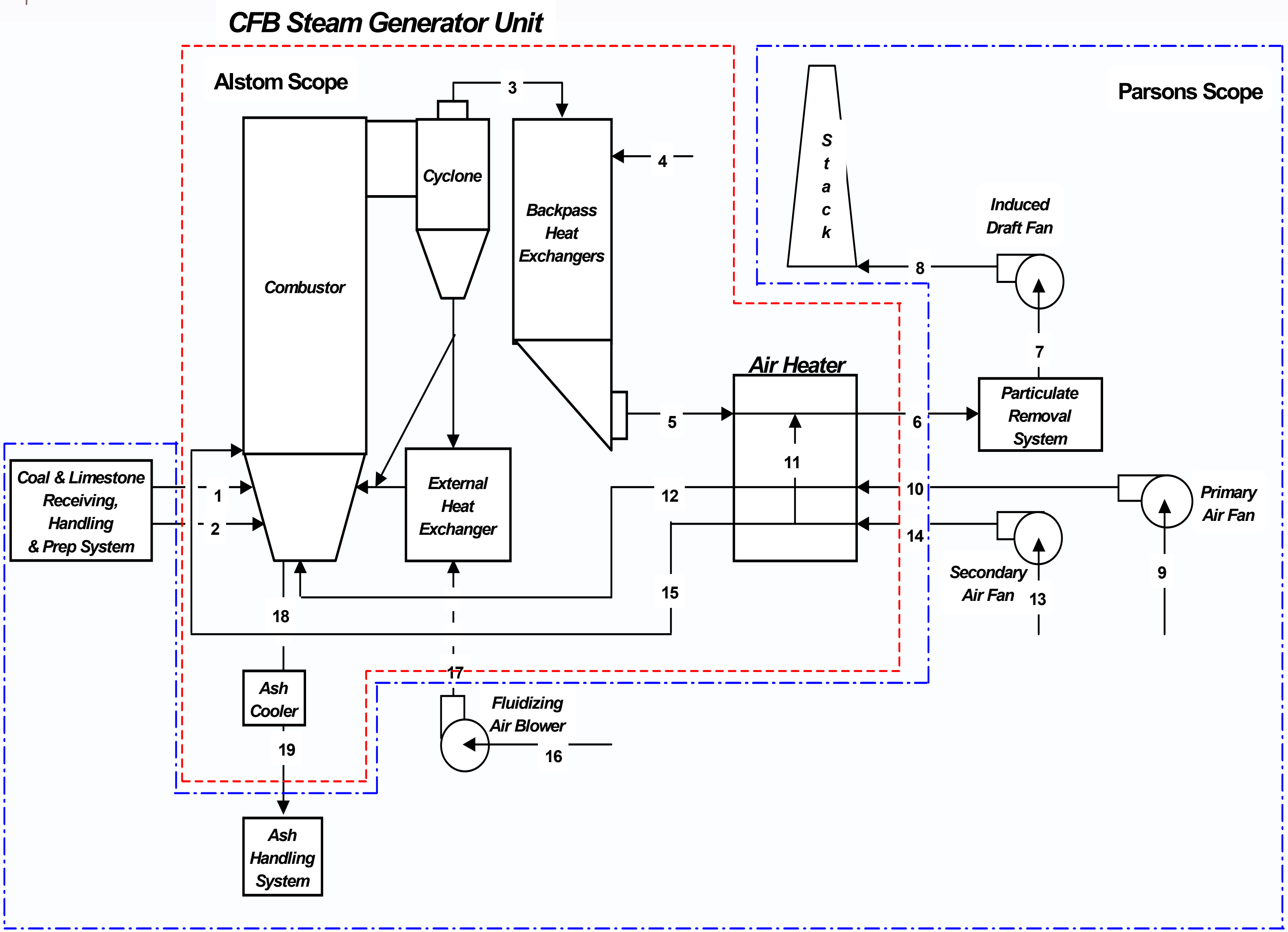

Case 2/3: Oxygen-Fired CFB -- Boiler Island Equipment Scope Definition

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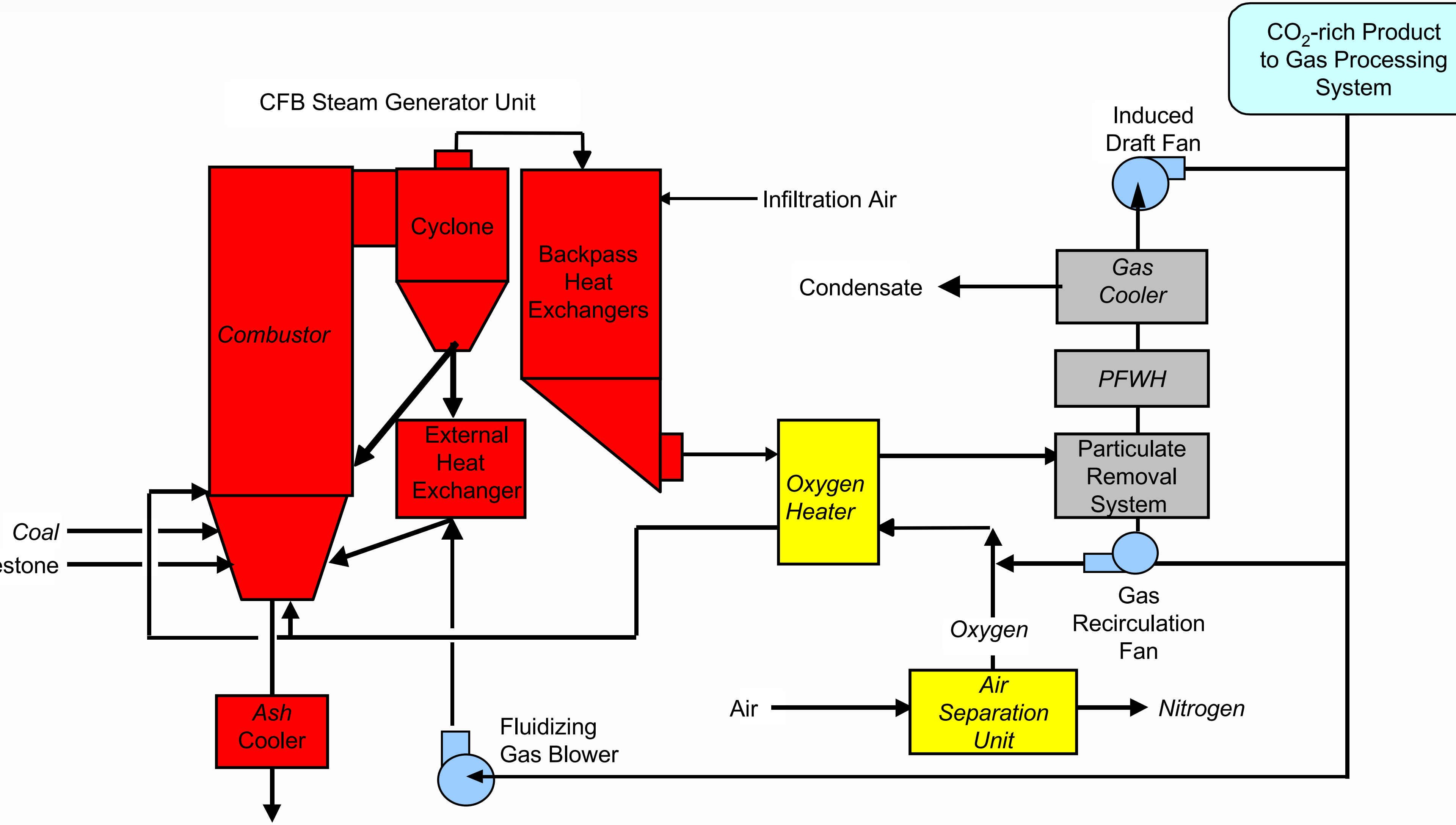
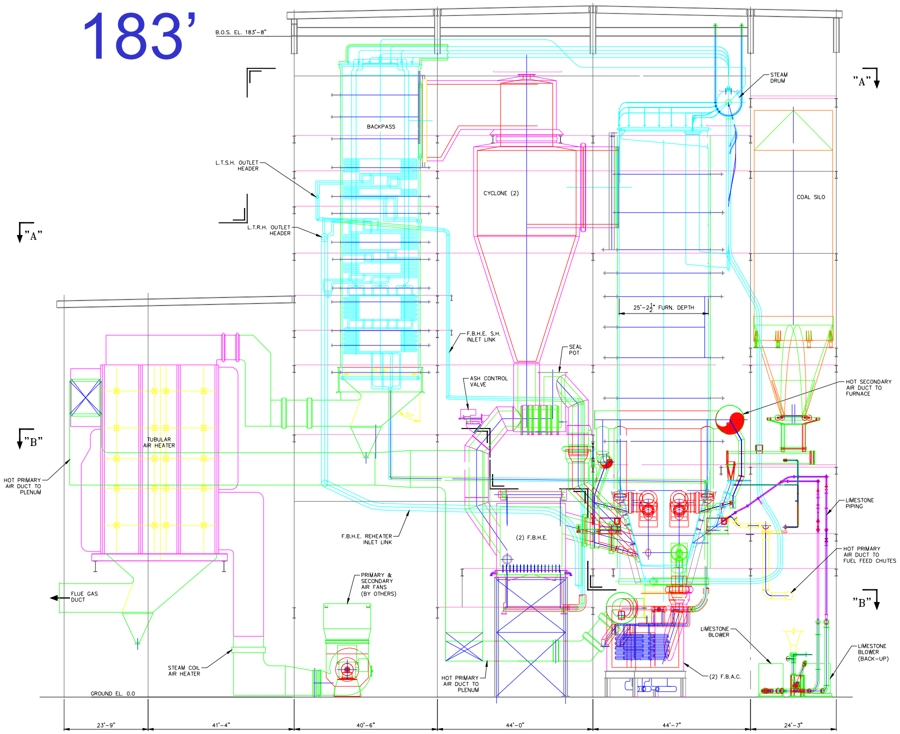


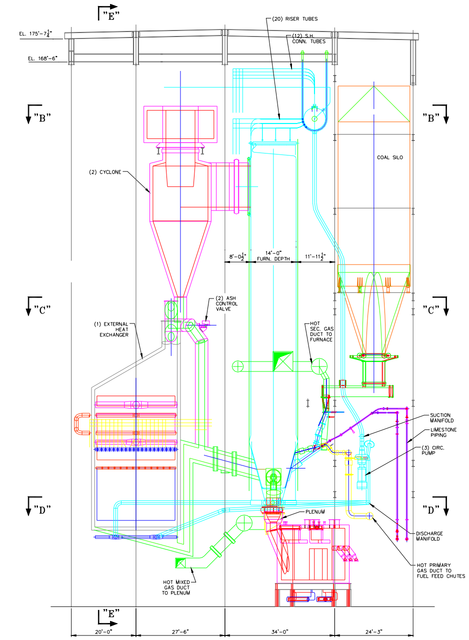
183’



← 220’ →

Air Fired CFB

156’

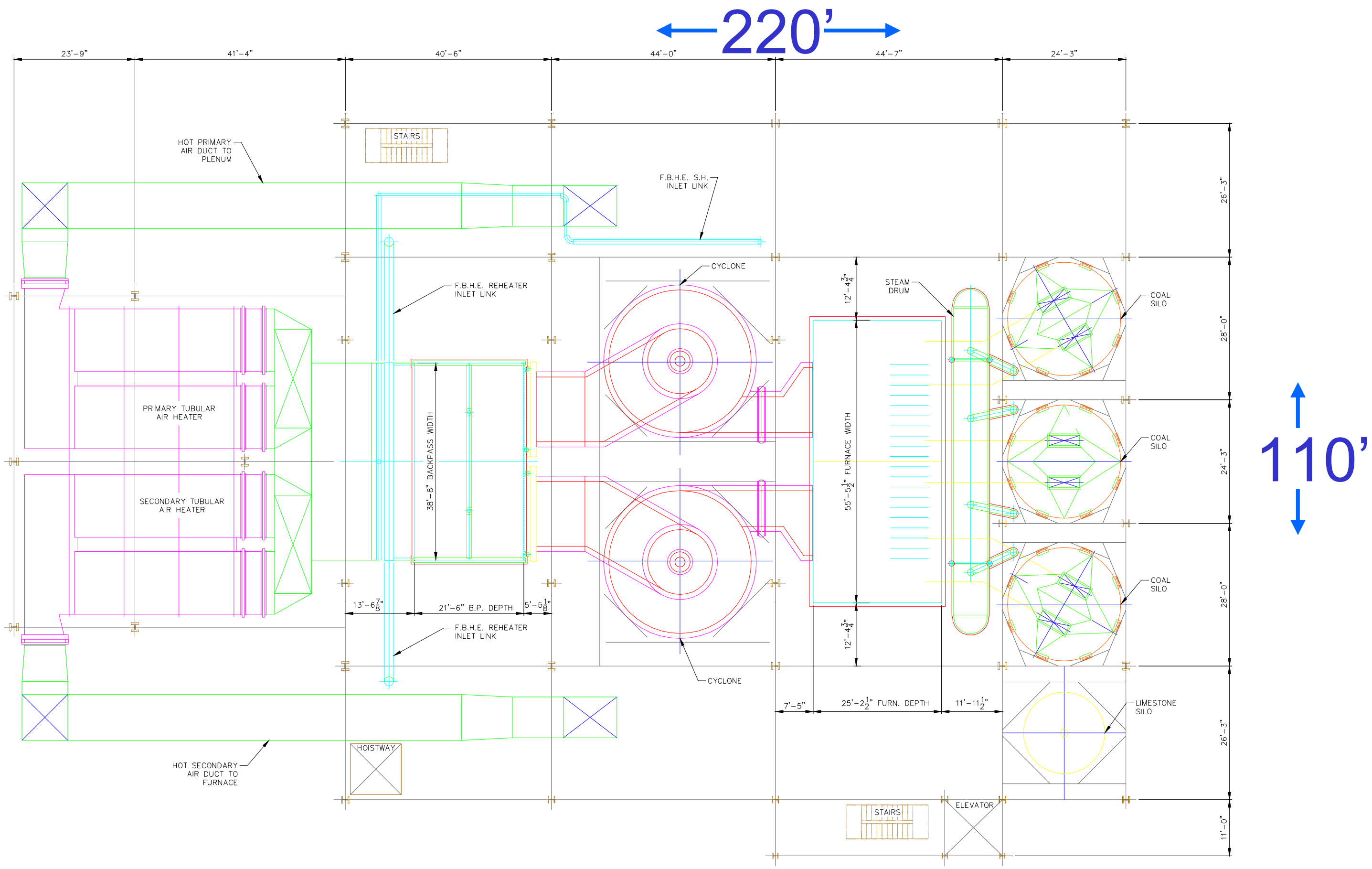


← 106’ →

Oxygen Fired CFB

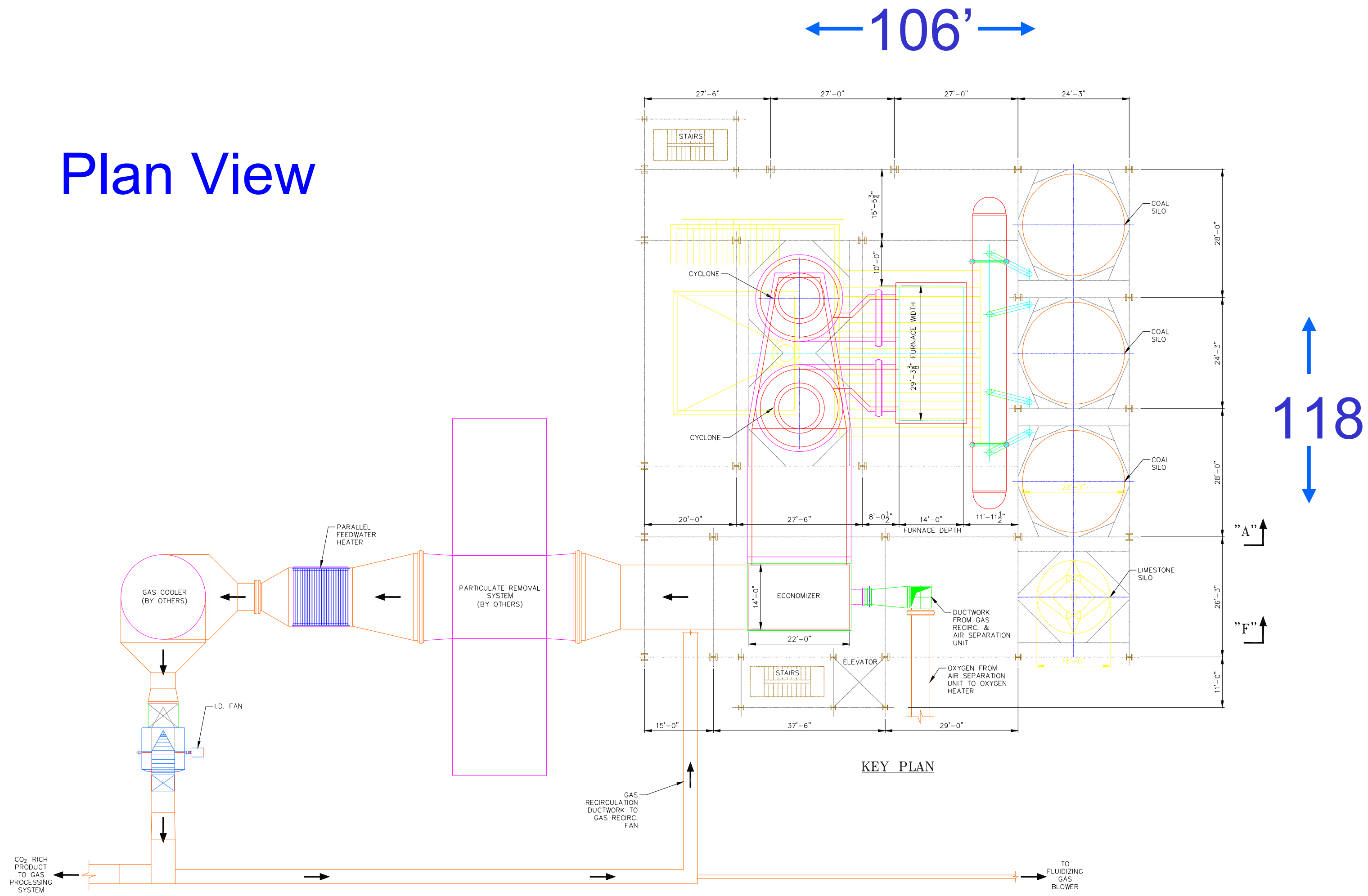
Air Fired CFB

Plan View

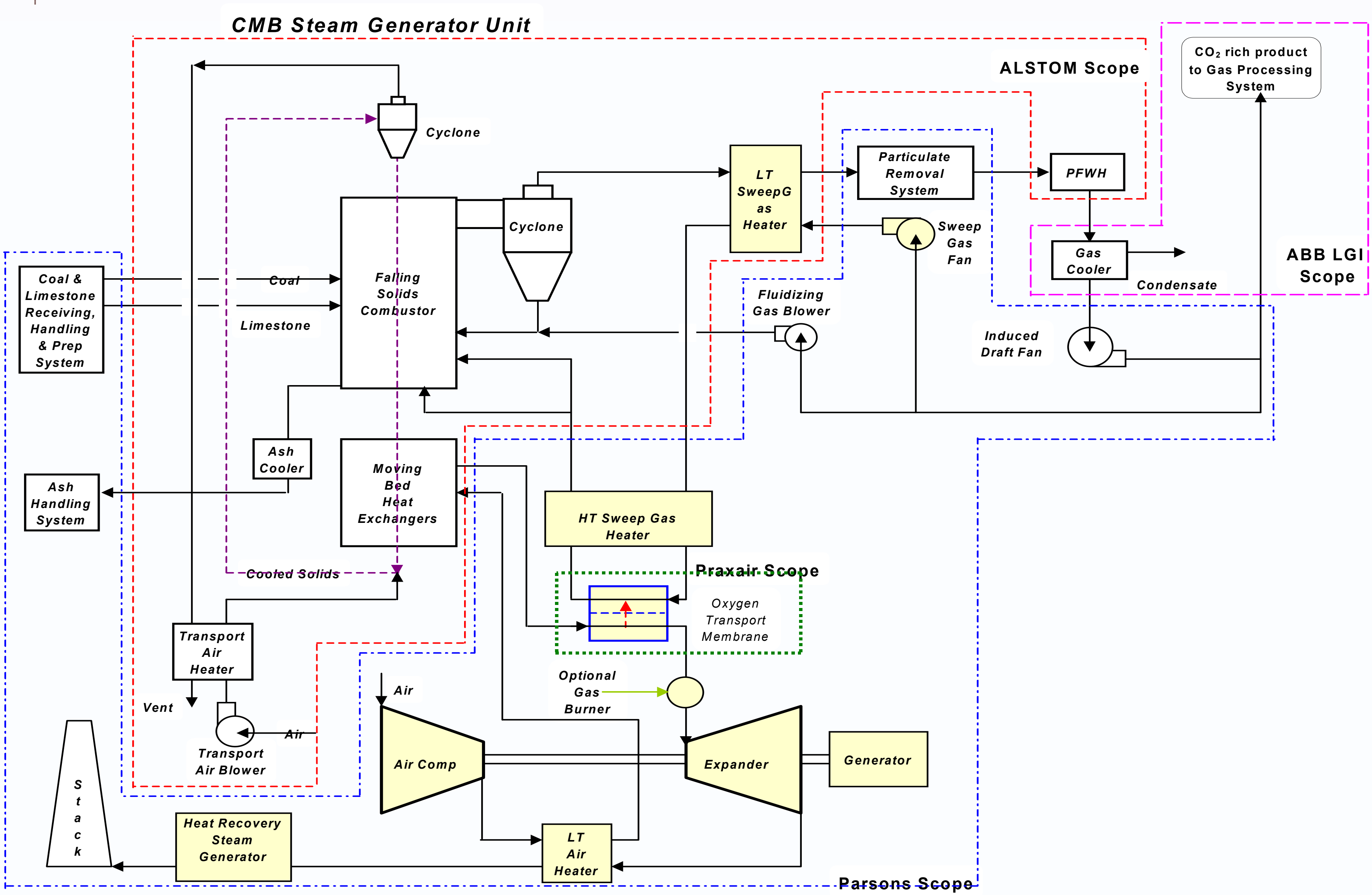


Oxygen Fired CFB

Plan View



Case 6: CMB Boiler Integrated with Oxygen Membrane System



Performance Comparison - Air (base case) to Oxy-fuel firing

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		Case 1 Air	Case 2 O2	diff
Boiler Efficiency	(fraction)	0.8948	0.9412	5%
Steam Turbine Heat Rate	(Btu/kwhr)	8002	8256	
Power Plant Auxillary Power	(kw)	15871	10071	-37%
Air Separation Unit Power	(kw)	0	37505	+
CO_2 Purification & Compression	(kw)	0	28996	+
Total Plant Auxillary Power	(kw)	15871	76572	382%
Generator Output	(kw)	209041	209907	0%
Net Plant Output	(kw)	193170	133335	-31%
Coal Heat Input (HHV)	(10^6 Btu/hr)	1855	1806	
Net Plant Heat Rate (HHV)	(Btu/kwhr)	9604	13576	
Net Plant Thermal Efficiency (HHV)	(fraction)	0.3554	0.2514	-29%
Carbon Dioxide Emissions	(lbm/kwhr)	2.000	0.170	-92%

Performance Comparisons - Air to All Oxy-fuel firing Cases

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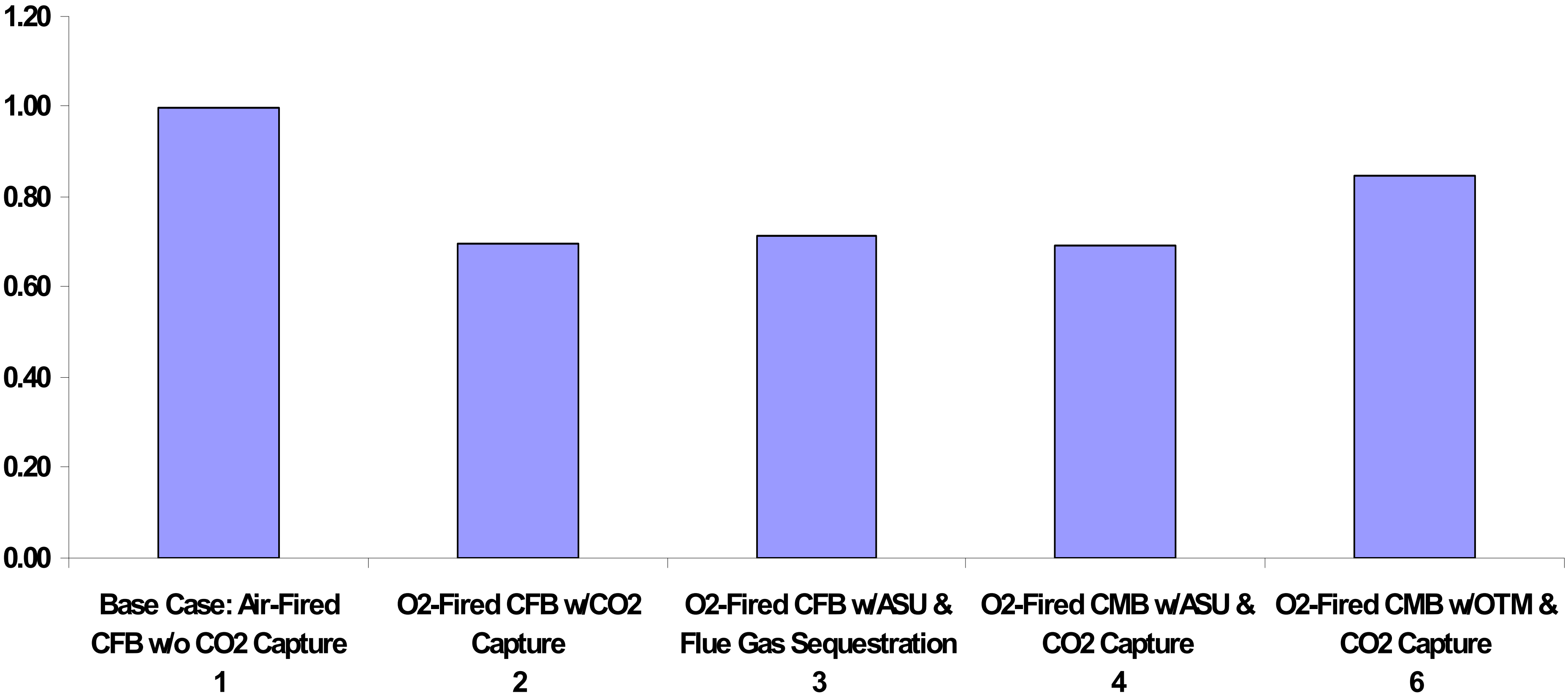
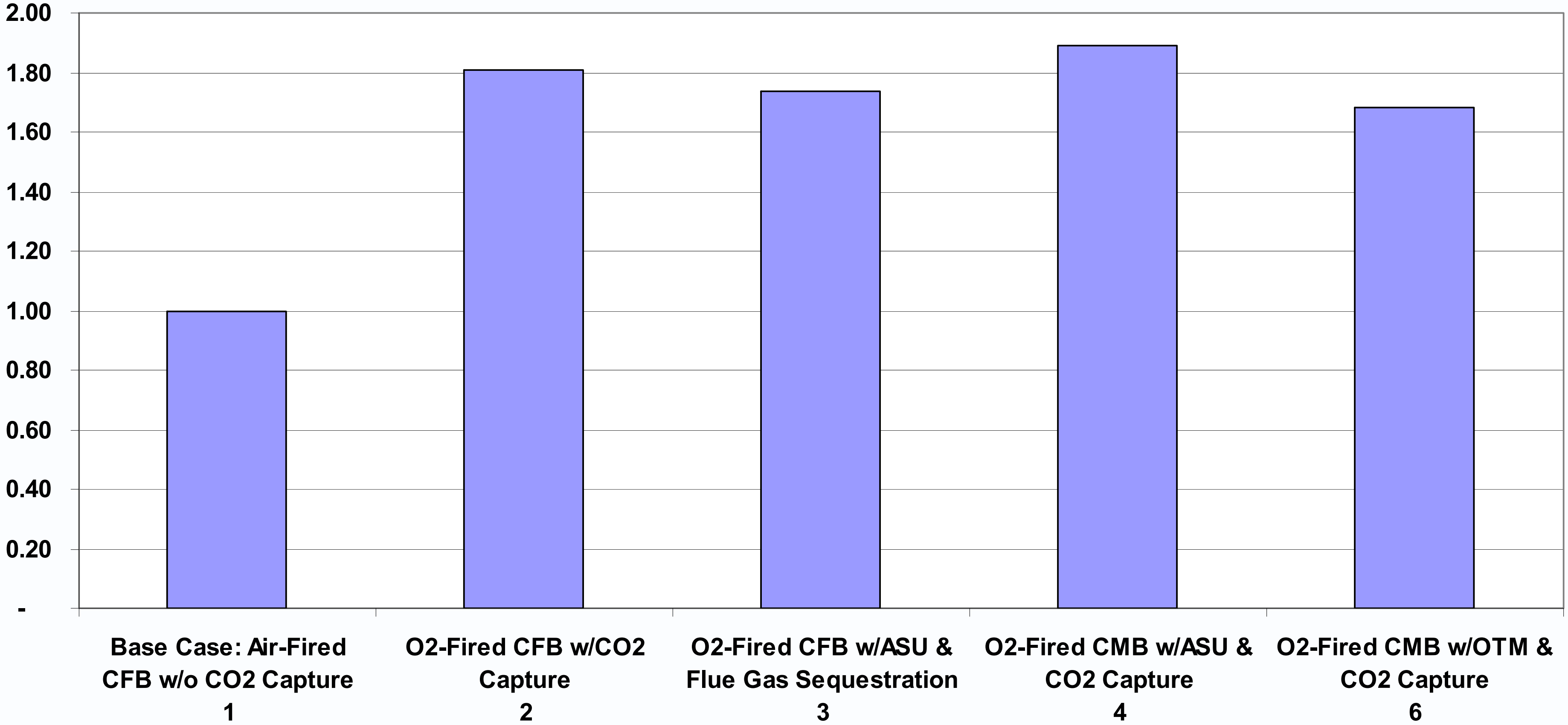
		Case 1 Air	Case 2 O2	Case 3 dirty CO2	Case 4 CMB	Case 6 OTM
Boiler Efficiency	(fraction)	0.8948	0.9412	0.9412	0.9366	0.9404
Steam Turbine Heat Rate	(Btu/kwhr)	8002	8256	8256	8275	8758
Power Plant Auxillary Power	(kw)	15871	10071	10687	10101	14570
Air Separation Unit Power	(kw)	0	37505	37505	37800	0
CO_2 Purification & Compression	(kw)	0	28996	26364	27200	33434
Total Plant Auxillary Power	(kw)	15871	76572	74556	75101	48004
Generator Output	(kw)	209041	209907	209907	210056	233699
Net Plant Output	(kw)	193170	133335	135351	134955	185695
Coal Heat Input (HHV)	(10^6 Btu/hr)	1855	1806	1806	1820	2242
Net Plant Heat Rate (HHV)	(Btu/kwhr)	9604	13576	13492	13518	11380
Net Plant Thermal Efficiency (HHV)	(fraction)	0.3554	0.2514	0.2530	0.2525	0.2999
Carbon Dioxide Emissions	(lbm/kwhr)	2.000	0.170	0.035	0.180	0.150

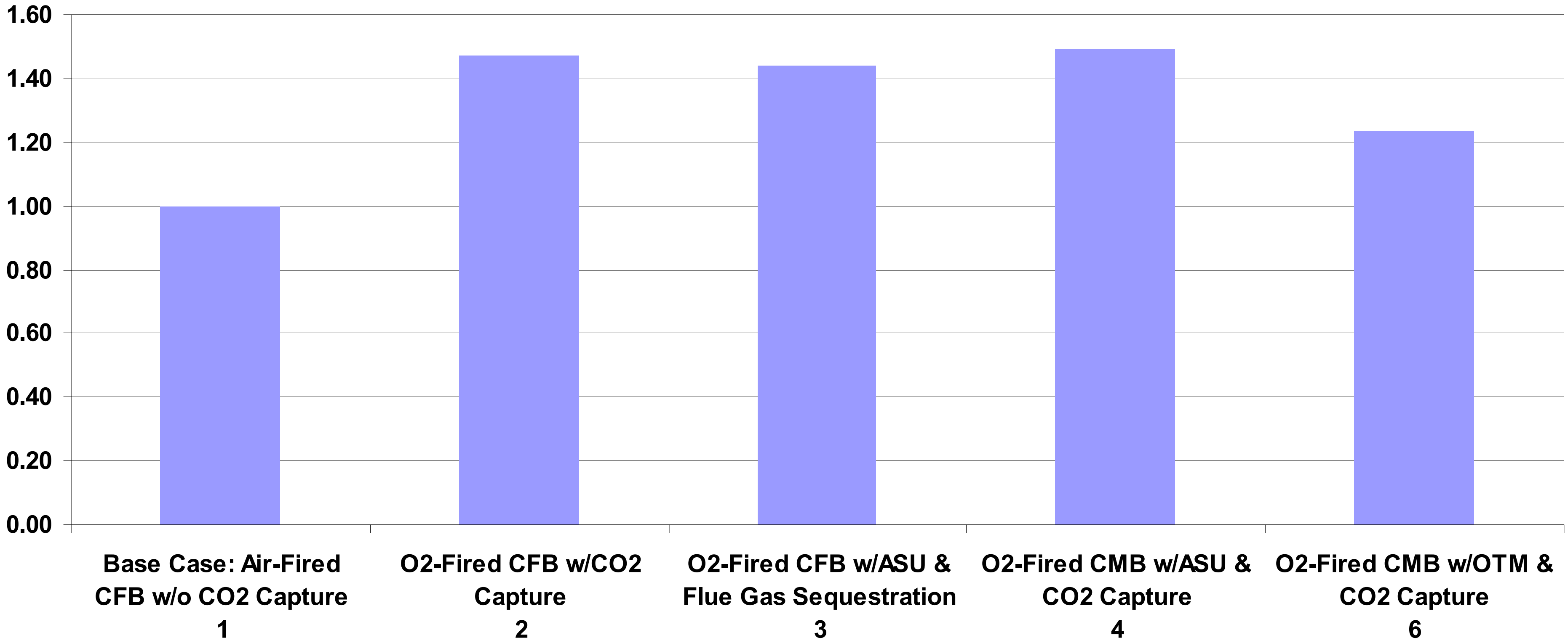
Relative Net Plant Thermal Eff, %(HHV) to base case



Relative Investment Costs ($/KW)



Relative Cost of Electricity (Cents/KW-hr)



Estimated Economics for an O2-Fired CFB Plant with CO_2 & N_2 Capture

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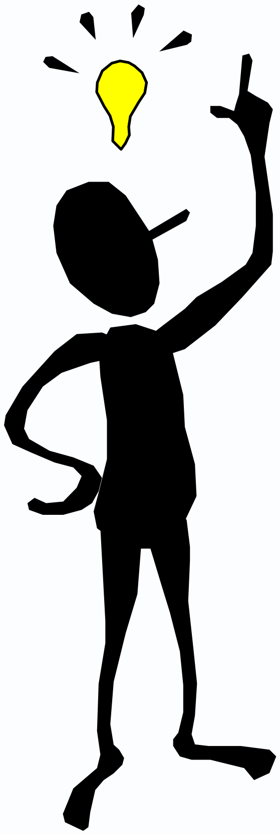
Assumptions :

- Fuel Costs
  - Coal : $1.32/MMBtu
  - Pet. Coke: $0.65/MMBtu

- CO_2 & N_2 & $CaCO_3$ Costs
  - CO_2 : $17/Ton
  - N_2 : $11/Ton
  - $CaCO_3$: $10/Ton

- Grid Electricity Cost : $0.04/kWh

- Plant Capacity Factor: 80% (7000 hrs./yr.)



Analysis :

- <u>Economics are viable</u>   expenses = revenues

Preliminary Economics of Oxy-Fuel CFB for EOR Application

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Coal : $1.32/MMBtu

Plant Without CO_2 Capture			
Gross Output		**210** MWe	
Aux Power, Fractional		**0.076**	
Net Output		194 MWe	
Plant With CO_2 Capture			
Gross Output		210 MWe	
Net Output, Fractional		**0.613** Fraction of gross	
Net Output		128.6 Mw	
Net Plant Heat Rate		**14079** Btu/kwhr	
Fuel Heat Input		1811 10^6 Btu/hr	
Limestone Usage		**0.13** lbm/kW-gross	
		14.1 Tons/hr	
Plant Cost With CO_2 Capture			
Power Plant Cost		**1100** $/kW-net w/o capture	
Oxygen Plant Cost		**148** $/lbm/hr CO2 captured	
Gas Processing System Cost		**149** $/lbm/hr CO2 captured	
Total Installed Plant Cost		2475 $/kW-net	
Annual Operating Time		**7000** Hrs/yr	
Annual Revenues & Outputs	(10^6 $/yr)		
Electricity	36.0	**0.04** $/kwhr	901
Carbon Dioxide	21.0	**17** $/Ton	**176**
Nitrogen	41.0	**11** $/Ton	**532**
TOTAL	**98.0**		
Annual Expenses	(10^6 $/yr)		
Capital Investment	63.7	**0.20** Capital Charge Rate (Frac of	
Fuel	16.5	**1.3** $/10^6$ Btu	
Limestone	1.0	**10** $/Ton	
Operating & Maintenance	16.8	0.0187 $/kwhr	
TOTAL	**98.0**		

Preliminary Economics of Oxy-Fuel CFB for EOR Application

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Petcoke : $0.65/MMBtu

Plant Without CO_2 Capture			
Gross Output		**210**	MWe
Aux Power, Fractional		**0.076**	
Net Output		194	MWe
Plant With CO_2 Capture			
Gross Output		210	MWe
Net Output, Fractional		**0.613**	Fraction of gross
Net Output		128.6	Mw
Net Plant Heat Rate		**14079**	Btu/kwhr
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Limestone Usage		**0.13**	lbm/kW-gross
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Power Plant Cost		**1100**	$/kW-net w/o ca
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Electricity	36.0	**0.04**	$/kwhr
Carbon Dioxide	21.0	**17**	$/Ton
Nitrogen	41.0	**11**	$/Ton
TOTAL	**98.0**		
Annual Expenses	(10^6 $/yr)		
Capital Investment	63.7	**0.20**	Capital Charge F
Fuel	8.2	**0.65**	$/10^6$ Btu
Limestone	1.0	**10**	$/Ton
Operating & Maintenance	16.8	0.0187	$/kwhr
TOTAL	**89.7**		

Oxygen Fired CFB Recommended for further testing:

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- It Is the Most Near-Term Solution, As it Uses Readily Available Commercial Technologies:
  - Oxygen Production by Cryogenic Air Separation
  - CO_2 Capture, Compression, and Liquefaction_
- Preliminary Economic Analysis Looks Viable for Commercial EOR Application:
  - CO_2 Sale for Oil Field Stimulation
  - N_2 Sale for Oil Field Pressurization
- Is A Required Intermediate Step Leading to the More Advanced Combustion Processes, e.g.:
  - Case 5 (Carbonate Regeneration)
  - Case 7 (Chemical Looping)

Bench-Scale Testing

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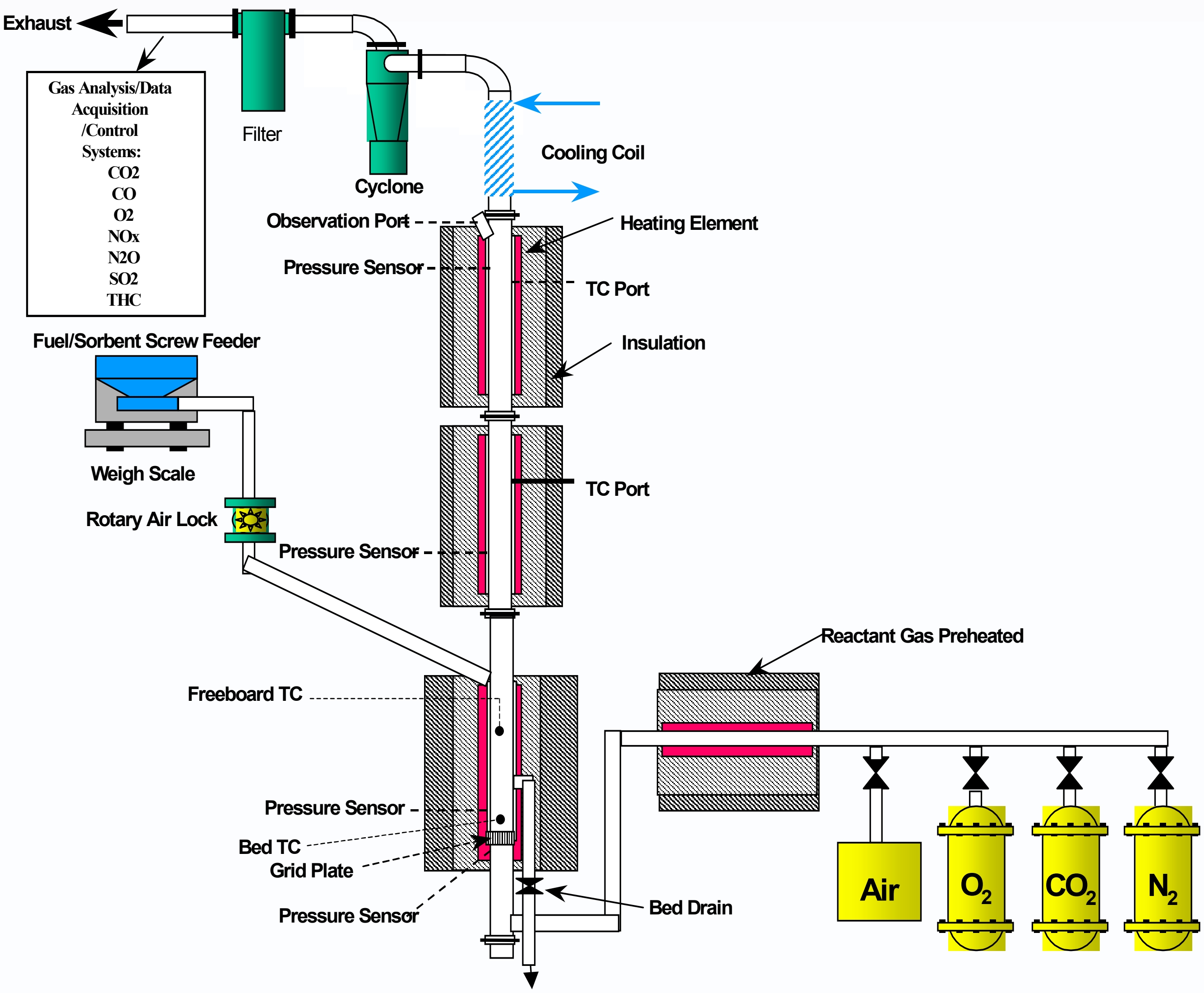
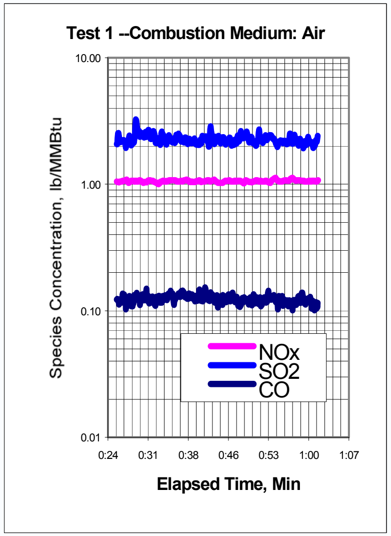
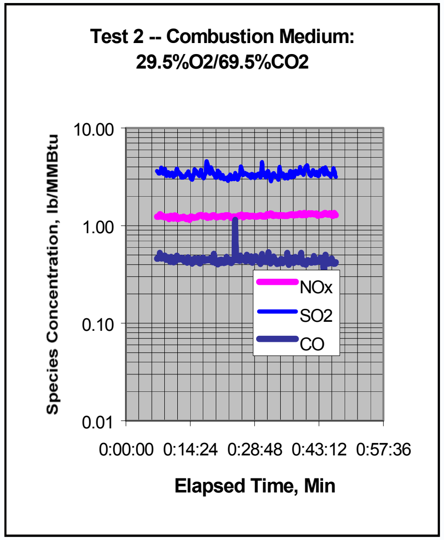
Four-Inch FBC Facility

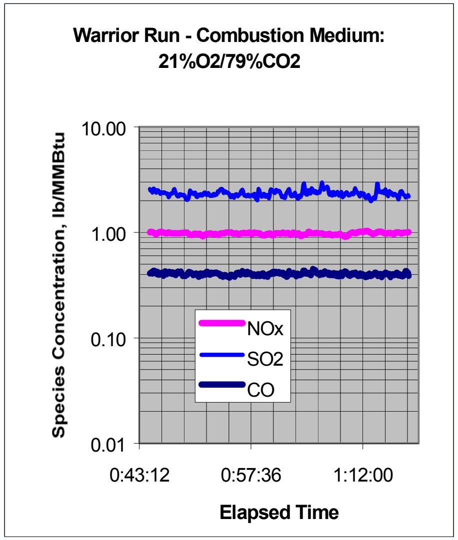


Oxy-fuel FBC Bench-Scale Testing:

- NOx Emissions Roughly Equal to or Less Than from Air Firing
- SO_2 Emissions Roughly Equal to Air Firing
- CO Emissions significantly Higher Than for Air Firing, Most Likely Due to High CO_2 in the Flue Gas, Which Hinders CO Oxidation to CO_2
- Burning the Base Case Coal in Up to 50%O_2/50%CO_2 Presented No Bed Agglomeration Problems, Provided That The Bed Was Fully Fluidized.



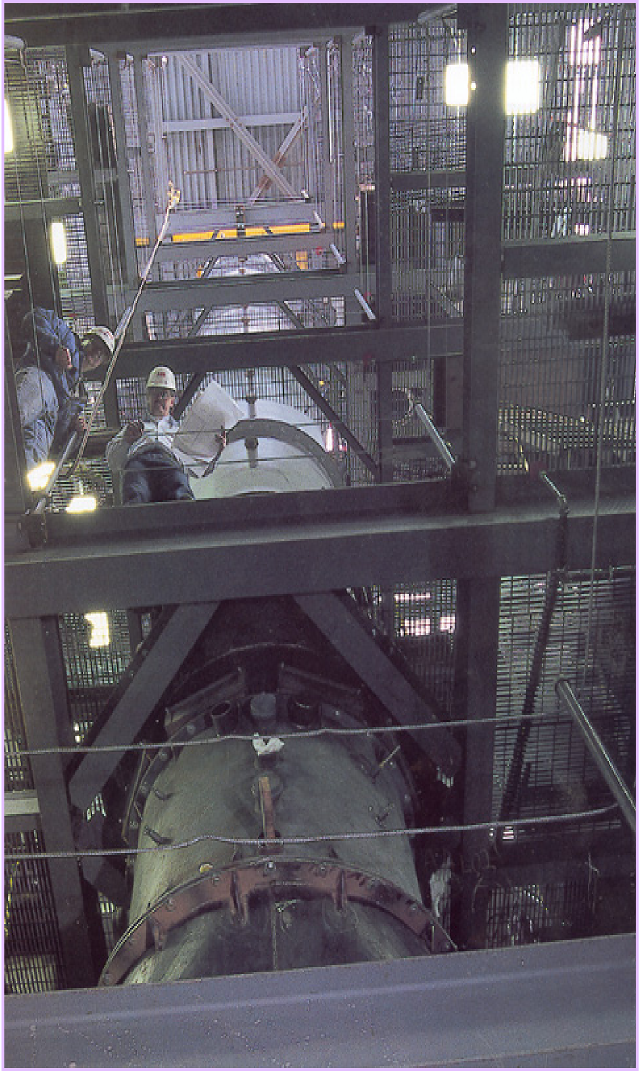




Pilot-Scale Testing

To Generate Detailed Technical Data Needed to Establish Advanced CFB Design Requirements and Performance When Firing Coals and Delayed Petroleum Coke at <u>~10 MMBtu/h</u> in O_2/CO_2 Atmospheres.

- Flue Gas Quality
- Bed Dynamics
- Heat Transfer to the Waterwalls
- Flue Gas Desulfurization
- NOx Emissions Reduction
- Other Pollutants' Emissions (N_2O and CO)
- Bed and Ash Characteristics (e.g., Potential Bed Agglomeration)



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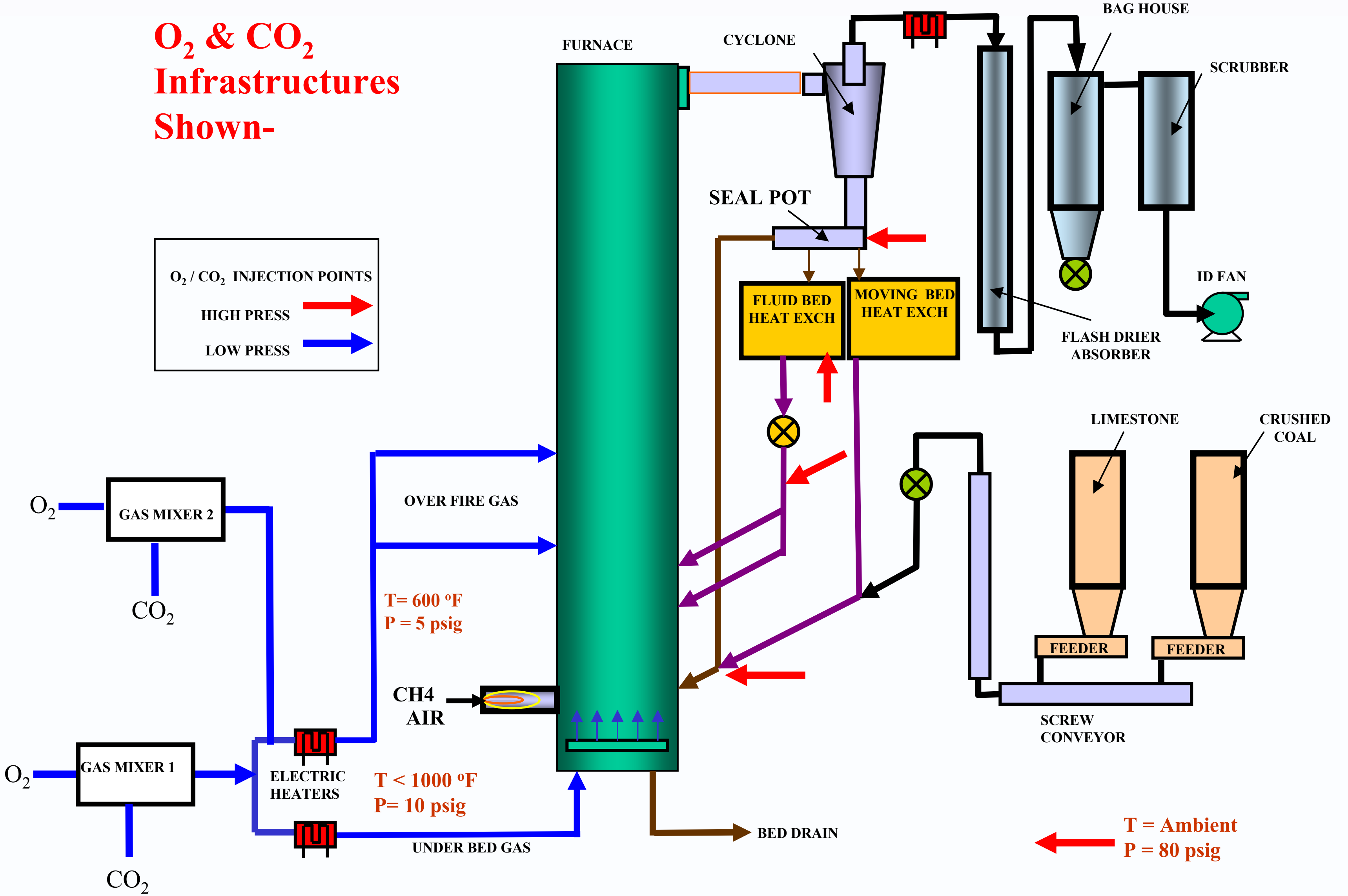
MTF Pilot-Scale Facility

O_2 & CO_2 Infrastructures Shown-



MTF Pilot-Scale Facility

Furn
Modific
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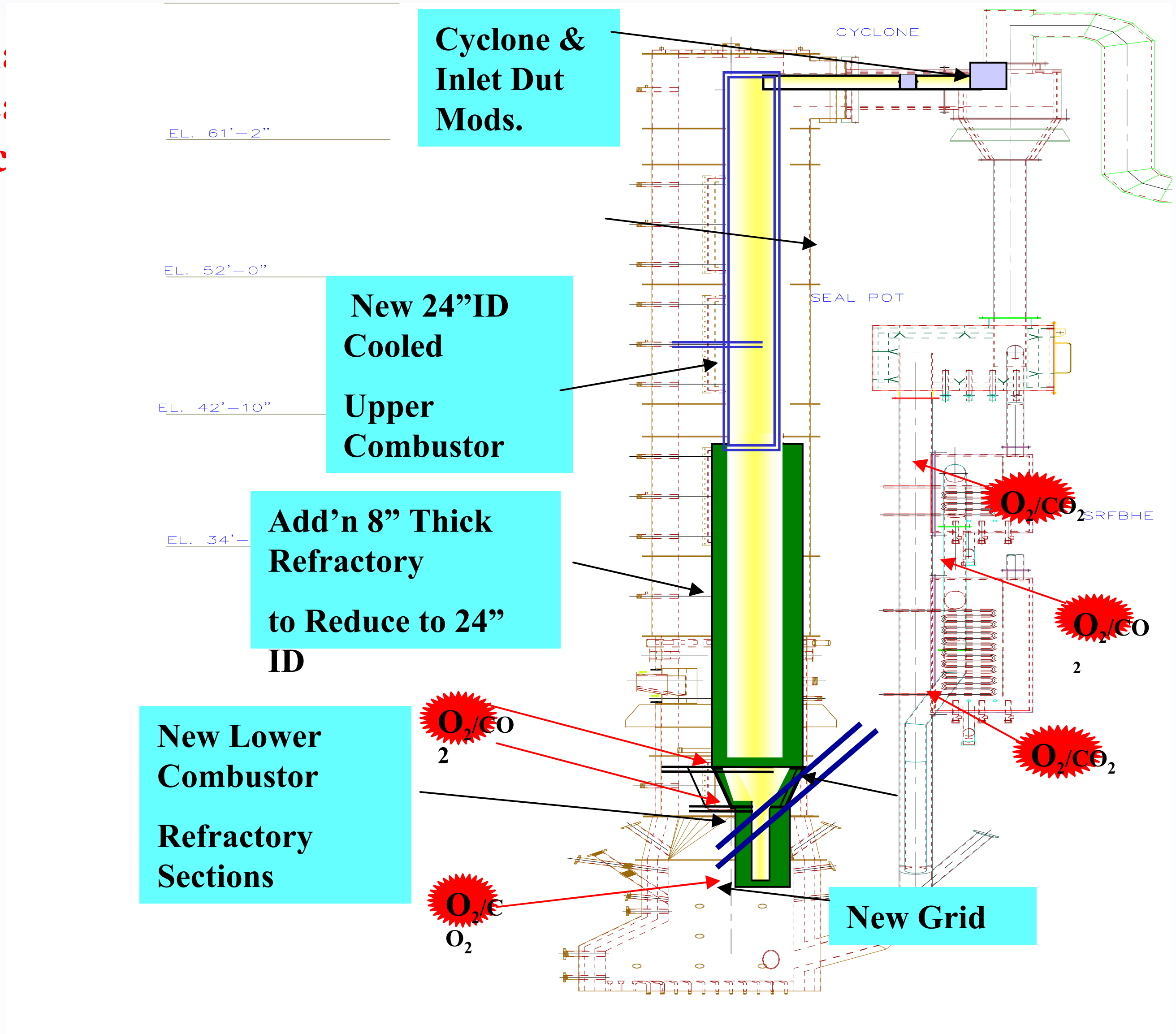

Conclusions

- Oxy-fuel Firing is a viable strategy for CO_2 capture

- Capital Costs are high and Efficiencies are low
  - breakthrough needed in oxygen production
  - CFB offers reduced cost and application to low quality fuels.

- In the long run more cost effective options for CO_2 capture and sequestration need development and verification.
  - IGCC
  - Chemical Looping

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Conclusions - OCDO/AEP Study of CO2 Capture Retrofit to Existing Coal Plant

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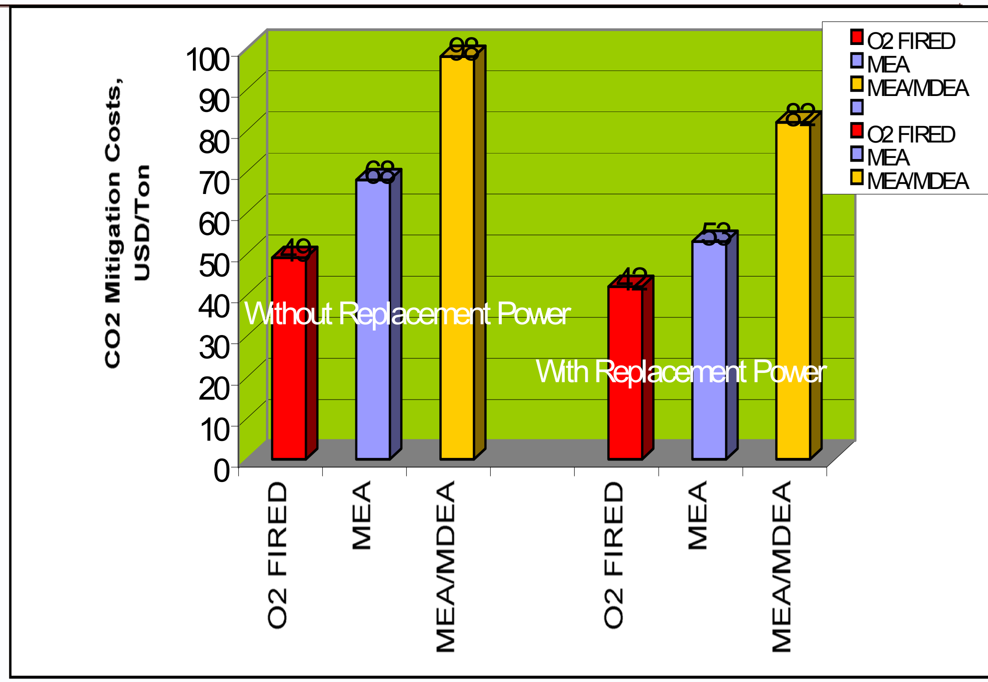
- No Major Technical Barriers
- Energy Requirements and Power Consumption are High,
- High Investment Costs (about 1000 to 2000 $/kW)
- Cost of Electricity increased by nearly 4 to 8 cents/kW-hr
- CO2 capture cost from 40 to 100 $/Ton CO2 avoided
- Oxygen fired boiler was more economic vs. amines



Parameter	Base Case	Concept 3A CO_2 Capture w/ MEA	Concept 3B Oxy-fired Boiler	Concept 3C CO_2 Capture w/ MEA/MDEA
Plant Eff., % HHV	35	20	24	21
Net Power Output, MWe	434	250	291	313
CO_2 Emissions, lbm/kWh	1.997	0.202	0.175	0.185
CO_2 Liquid Purity, %	N/A	99.95	97.80	99.97

Indirect Combustion via chemical Looping for CO2 Capture

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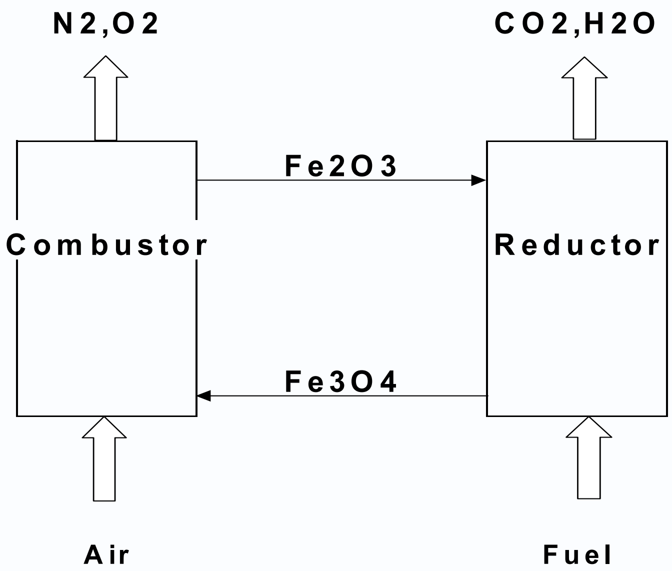

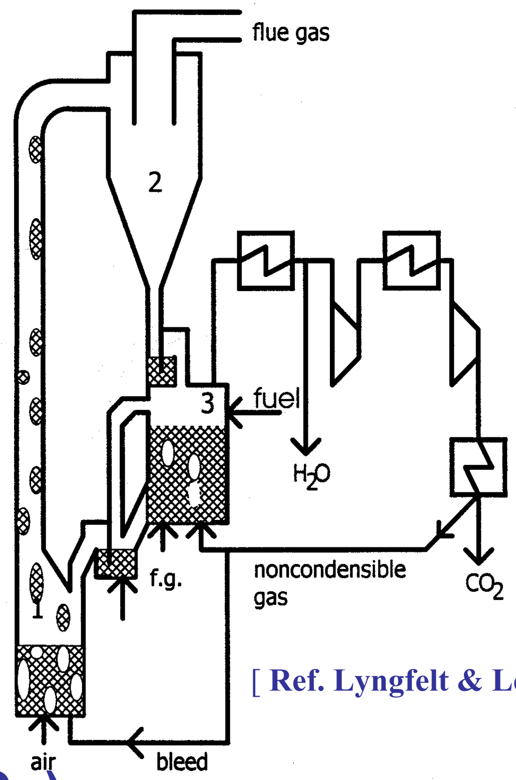

[Ref. Lyngfelt & Leckner]

- Atmospheric Pressure
- Oxygen carriers (Cu, Cd,Ni, Mn, Fe, Co)
- Potential combustion process with interconnected FBC's

Another innovative technology option

Work Breakdown Structure

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TASK 1
Preliminary Performance & Economic Analysis -- 10 Cases: Baseline, High O_2 Firing, Chemical Looping & IGCC

TASK 2
Bench-Scale Fluidized Bed Combustion (FBC) Experiments -- Bed Agglomeration and SO_2 Capture

TASK 3
Project Period I final Report -- Results/Recommendations

Stop Project

Decision Point (Define the Most Promising Concept)

Implement Budget Project Period II

Work Breakdown Structure -- Period II

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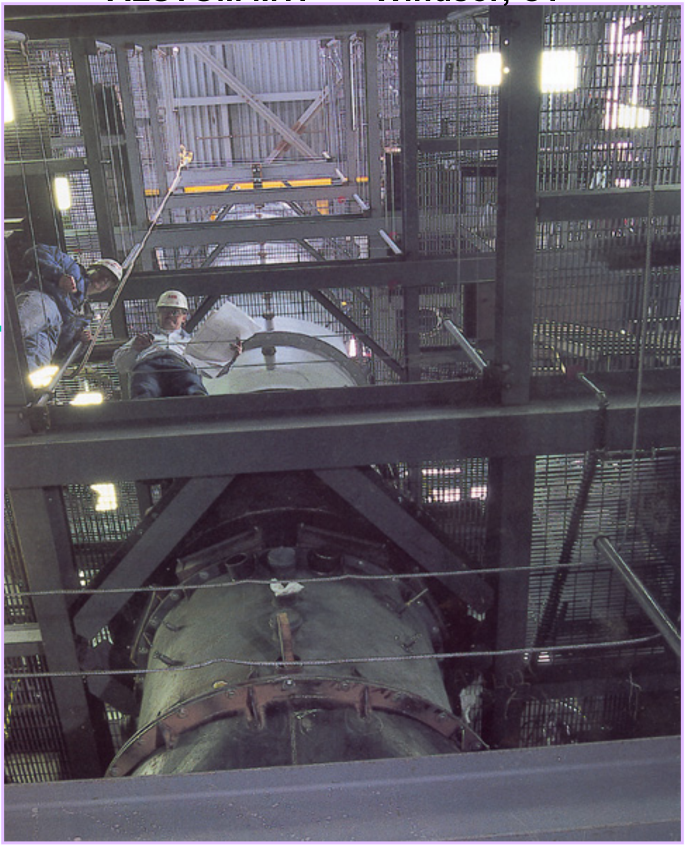

TASK 4
Pilot-Scale Testing (MTF) of Most Promising Concept (s) -- Detailed Combustion/Bed Dynamics Evaluation

TASK 5
Refined Performance & Economic Analysis of Most Promising Concept(s)

TASK 6
Period II Final Report -- Systems Performance & Economics