NATIONAL ENERGY TECHNOLOGY LABORATORY

# Operational Boundaries
## for
# Pulverized Coal Plant $CO_2$ Capture


**John J. Marano NETL Consultant**
**Jared P. Ciferno DOE-NETL**


***Carbon Capture 2020 Workshop***
***Washington, DC***

**October 5-6, 2009**

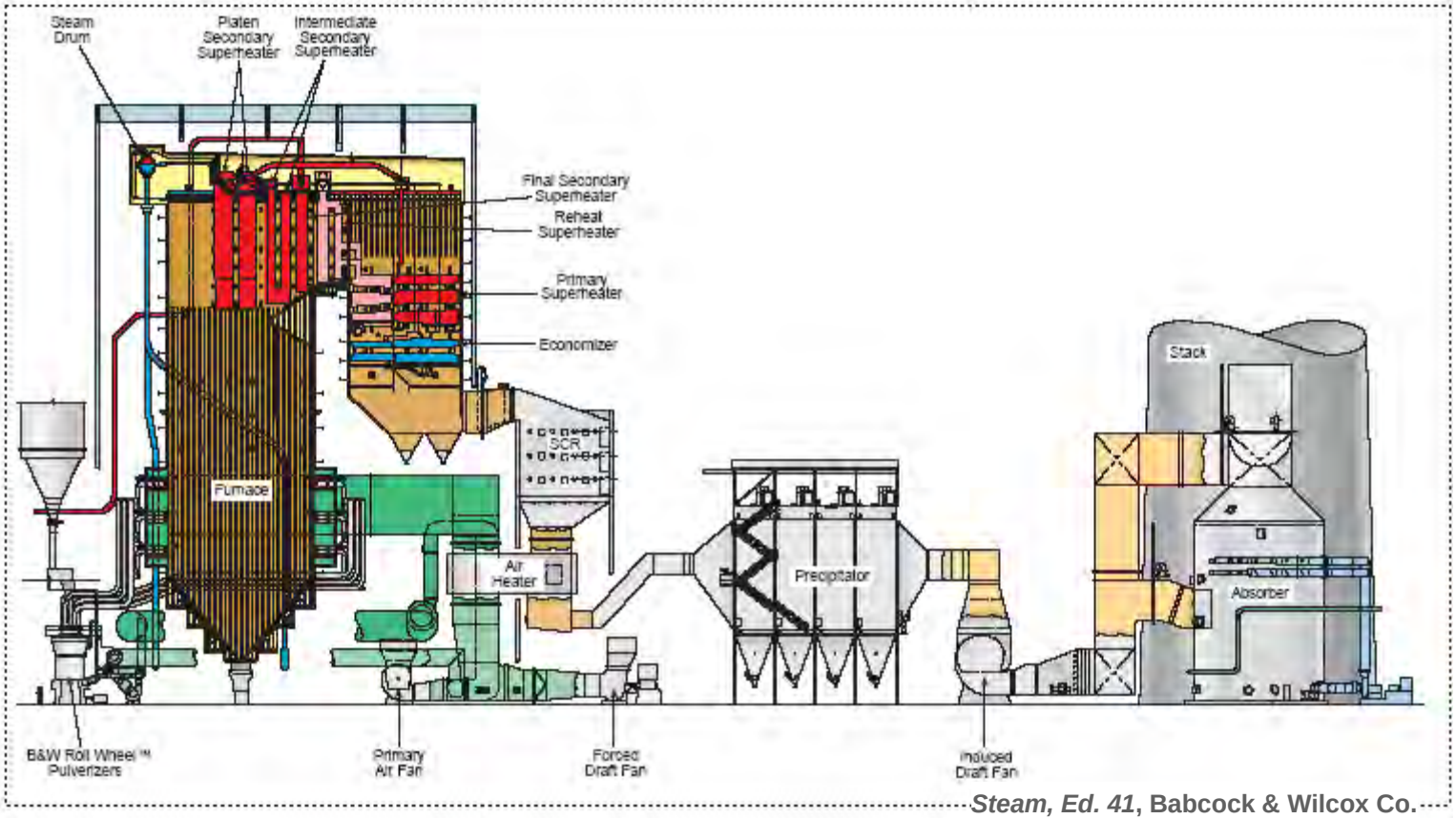
# Developing the right tools to do the job

- **The Existing Plants Emissions and Capture (EPEC) Program sponsors R&D on carbon capture from combustion-based power systems**
  - Post-Combustion
  - Oxy-Combustion
  - Chemical Looping
  - Carbon Dioxide Compression
- **NETL initiating quantitative analysis to establish R&D targets for these technologies**

# Purpose of this presentation

- To provide overview of conventional pulverized coal (PC) power plant
- To identify conditions that any capture technology will encounter if deployed in a PC plant
- To identify critical performance parameters for different types of $CO_2$ capture technologies
- To discuss how targets will be set for these parameters to ensure progress made toward meeting EPEC R&D Program objectives

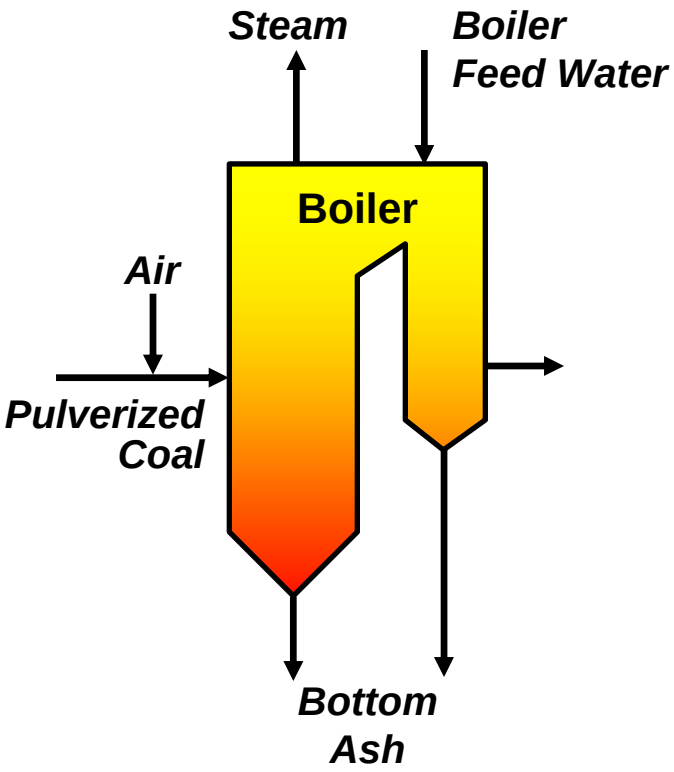
# Overview of PC Power Plant




*Steam, Ed. 41*, Babcock & Wilcox Co.

# PC Power Plant Walk-Through

## *The Boiler*



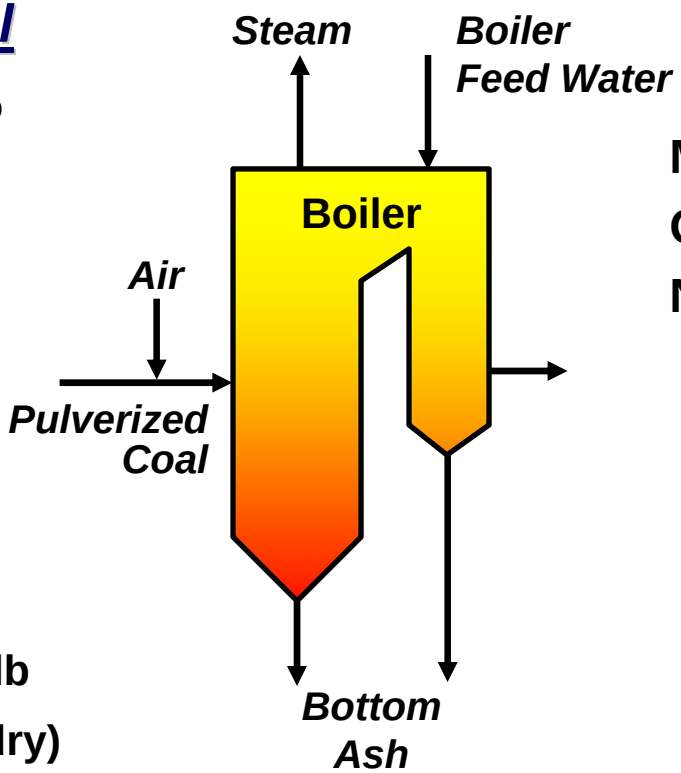

******Cost and Performance Baseline for Fossil Energy Plants, Vol.1*
**DOE/NETL-2007/1281, Aug. 2009 revised (@ *www.netl.doe.gov*)**

# PC Power Plant Walk-Through

## *The Boiler*

### ***Bituminous Coal***

| | |
|---|---|
| Moisture | 11 wt% |
| Carbon | 64 |
| Hydrogen | 4.5 |
| Nitrogen | 1.2 |
| Chlorine | 0.3 |
| Sulfur | 2.5 |
| Oxygen | 6.9 |
| Ash | 9.7 |
| HHV | 11.7 M Btu/lb |
| Hg | 0.15 ppm (dry) |




### ***Air***

| | |
|---|---|
| Moisture | 0.006 wt/wt dry air |
| $O_2$ | 20.95 vol% (dry) |
| $N_{2a}$ | 79.05 |

**5,250 TPD ≈ 0.2 MM SCFD**

**15% Excess Air**
**52,600 TPD ≈ 1,380 MM SCFD**

# PC Power Plant Walk-Through

## *The Boiler*

### *Bituminous Coal*

| | |
|---|---|
| Moisture | 11 wt% |
| Carbon | 64 |
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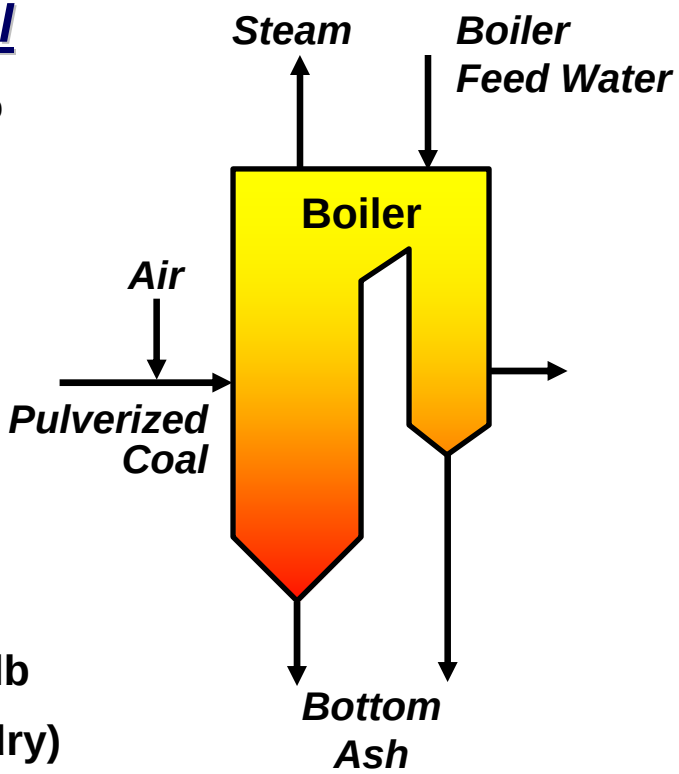



### *Flue Gas*

| | |
|---|---|
| $CO_2$ | 14.5 vol% |
| $H_2O$ | 8.7 |
| $N_{2a}$ | 74.1 |
| $O_2$ | 2.5 |
| SOx | 0.21 |
| NOx | 0.30 |
| PM | 7,100 ppmw |
| HG | 12 ppbw |

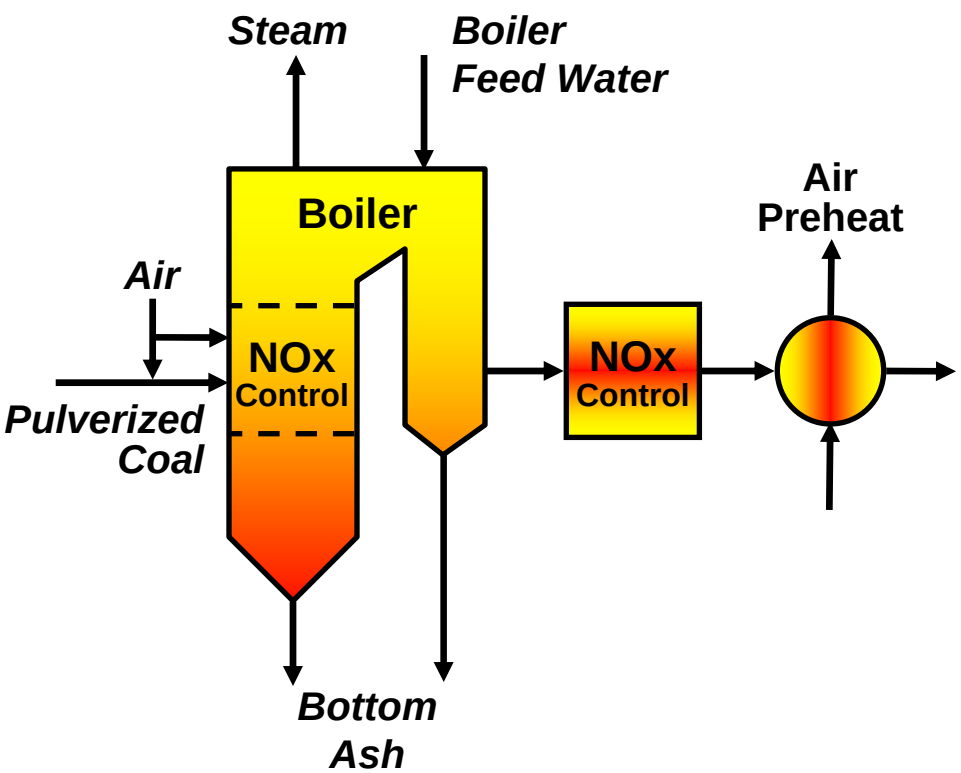
**5,250 TPD ≈ 0.2 MM SCFD**

**57,700 TPD ≈ 1,460 MM SCFD**

# PC Power Plant Walk-Through

## *NOx Control*

***2010 Air Regs***
0.070 lb NOx/MM Btu




### *Flue Gas*

| | |
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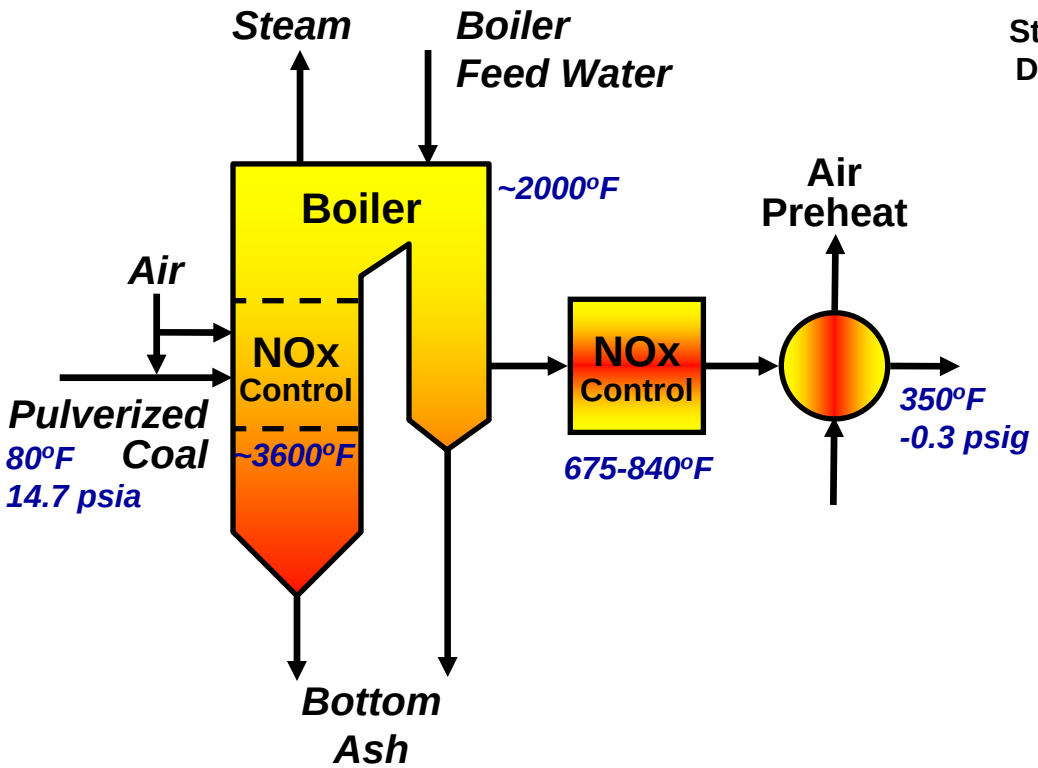
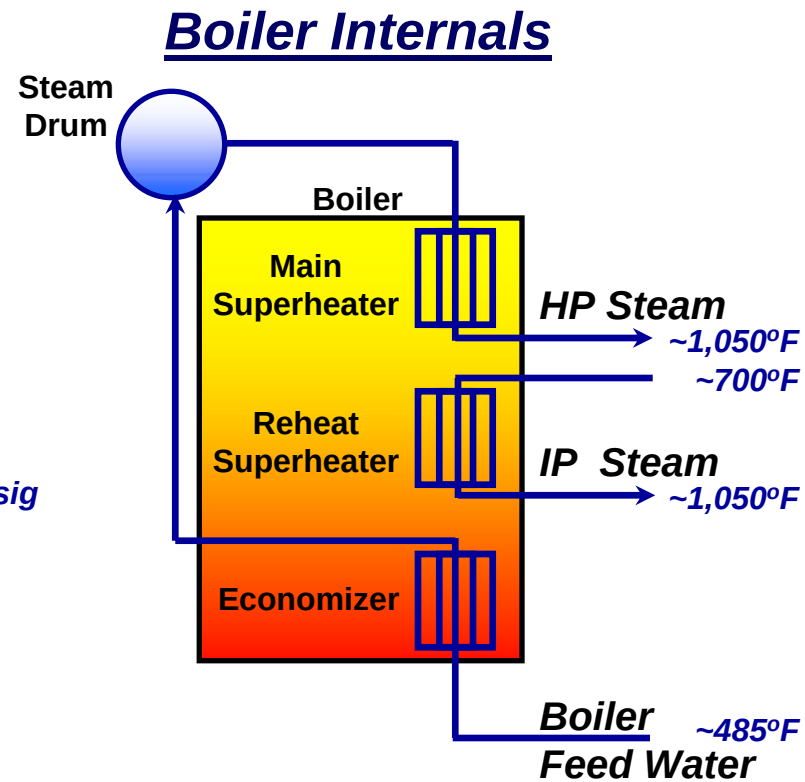
| $CO_2$ | 14.5 vol% |
| $H_2O$ | 8.7 |
| $N_{2a}$ | 74.1 |
| $O_2$ | 2.5 |
| SOx | 0.21 |
| NOx | 74 ppmv |
| PM | 7,100 ppmw |
| HG | 12 ppbw |

**NOx Reduction: 83% + 86% ⇒ 98% total**

**57,700 TPD ≈ 1,460 MM SCFD**

# Anatomy of a PC Boiler



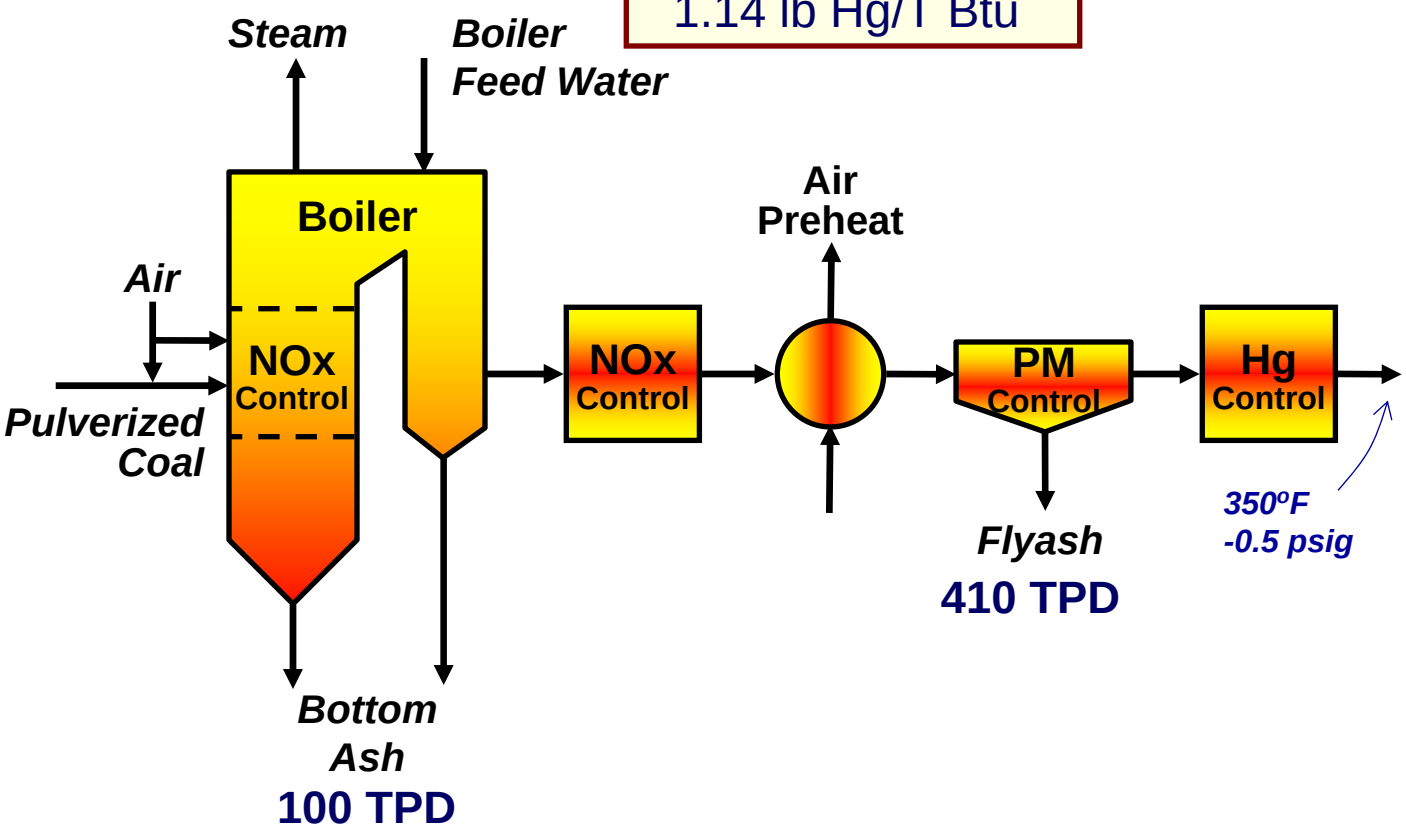




**Boiler Efficiency: 89%**

# PC Power Plant Walk-Through

## *PM & Hg Control*

***2010 Air Regs***
0.013 lb PM/MM Btu
1.14 lb Hg/T Btu




***Flue Gas***

| | | |
|---|---|---|
| $CO_2$ | 14.5 | vol% |
| $H_2O$ | 8.7 | |
| $N_{2a}$ | 74.1 | |
| $O_2$ | 2.5 | |
| SOx | 0.21 | |
| NOx | 74 | ppmv |
| PM | 9 | ppmw |
| HG | 1.2 | ppbw |

57,300 TPD
~1,460 MM SCFD

Ash Reduction: 20%

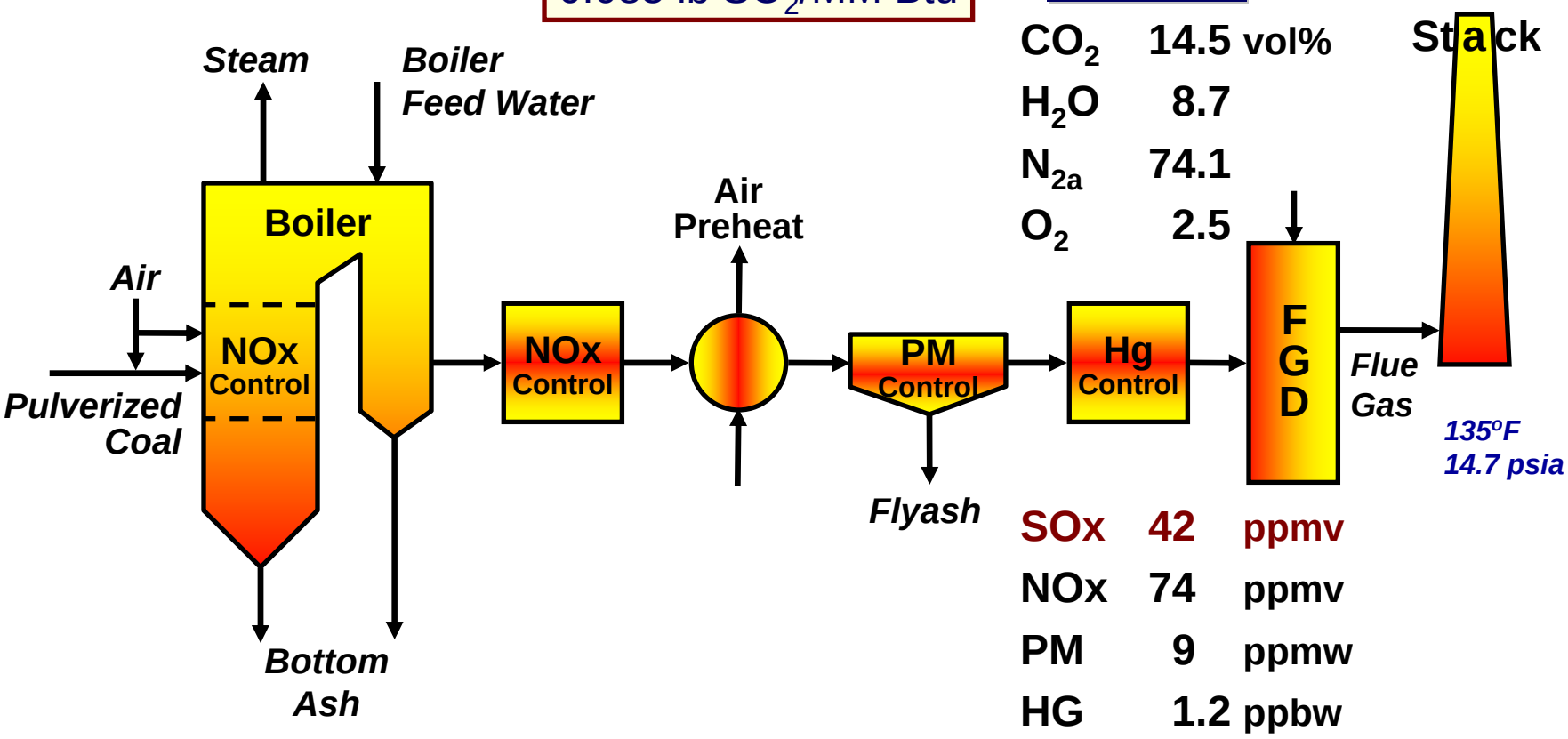
PM Reduction: 99.9%
Hg Reduction: 90%

# PC Power Plant Walk-Through

## *SOx Control*

***2010 Air Regs***
0.085 lb $SO_2$/MM Btu

**61,500 TPD**
**~1,630 MM SCFD**




***Flue Gas***

| | | |
|---|---|---|
| $CO_2$ | 14.5 | vol% |
| $H_2O$ | 8.7 | |
| $N_{2a}$ | 74.1 | |
| $O_2$ | 2.5 | |

| | | |
|---|---|---|
| SOx | 42 | ppmv |
| NOx | 74 | ppmv |
| PM | 9 | ppmw |
| HG | 1.2 | ppbw |

**SOx Reduction: 98%**

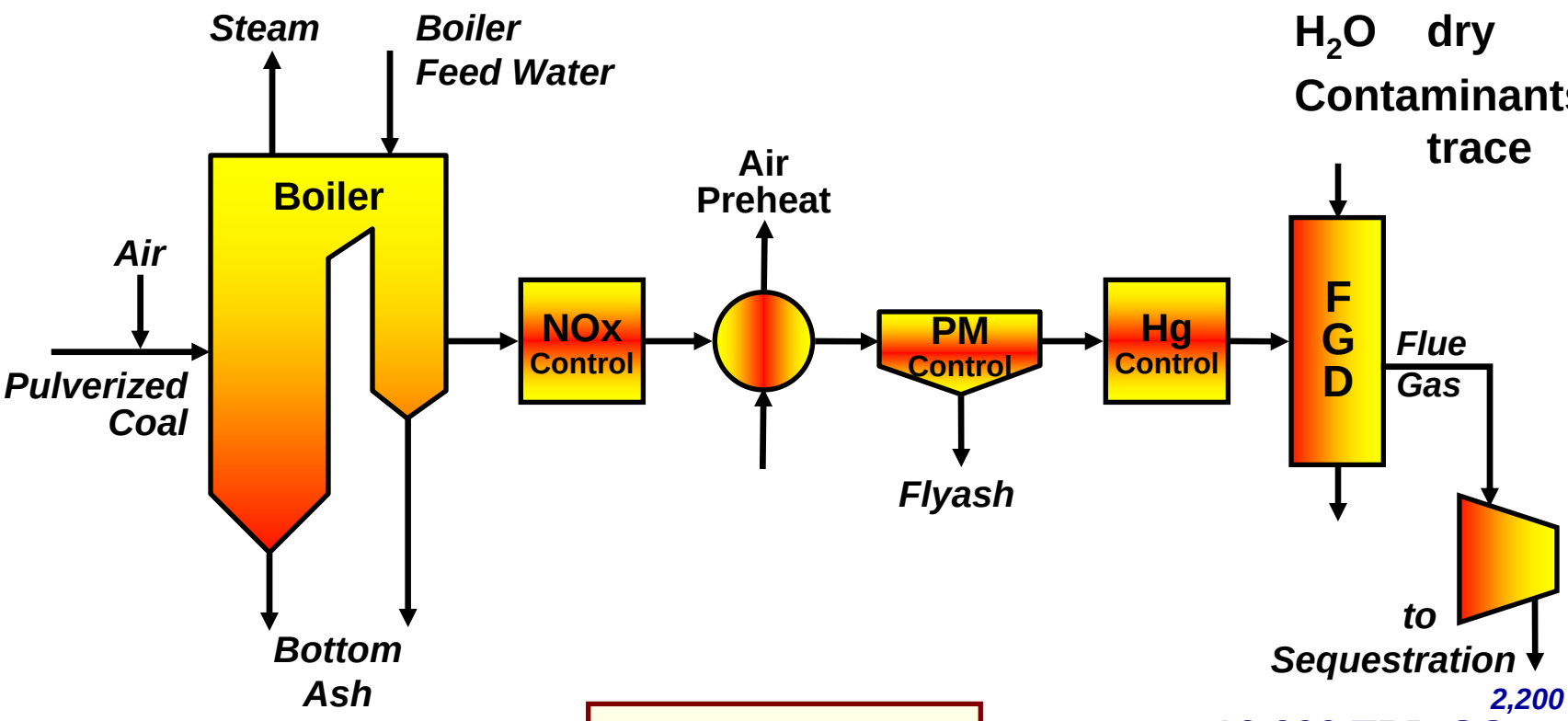
# PC Power Plant Walk-Through

## *$CO_2$ Capture*

***Air Regs***
*TBD*

***CCS Specs***

| | |
|---|---|
| $CO_2$ | 95+ vol% |
| $H_2O$ | dry |
| Contaminants | trace |

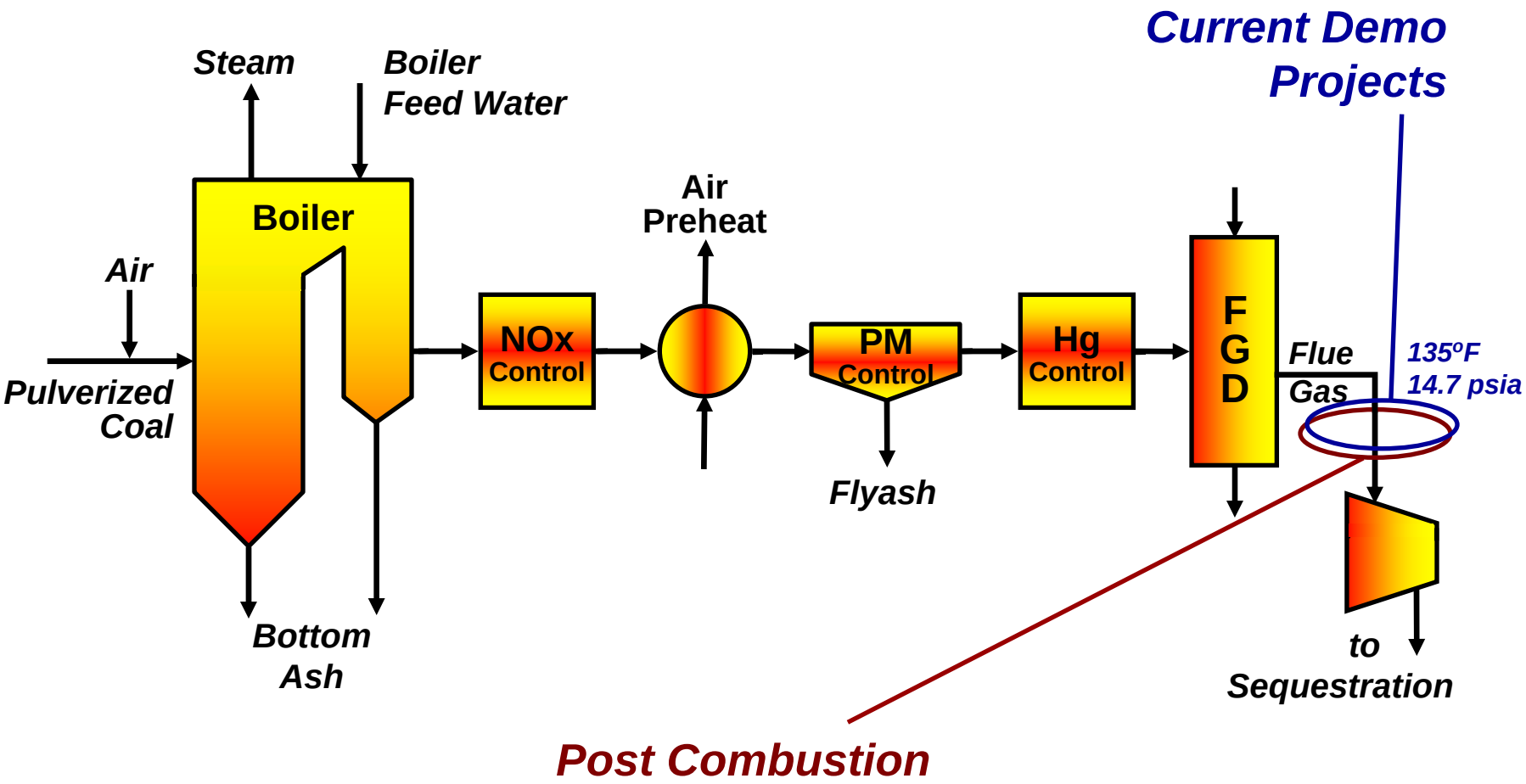



***DOE R&D Goal***
*>90% Removal*

**16,600 TPD $CO_2$**
**~290 MM SCFD**
**~0.81 MM ACFD**

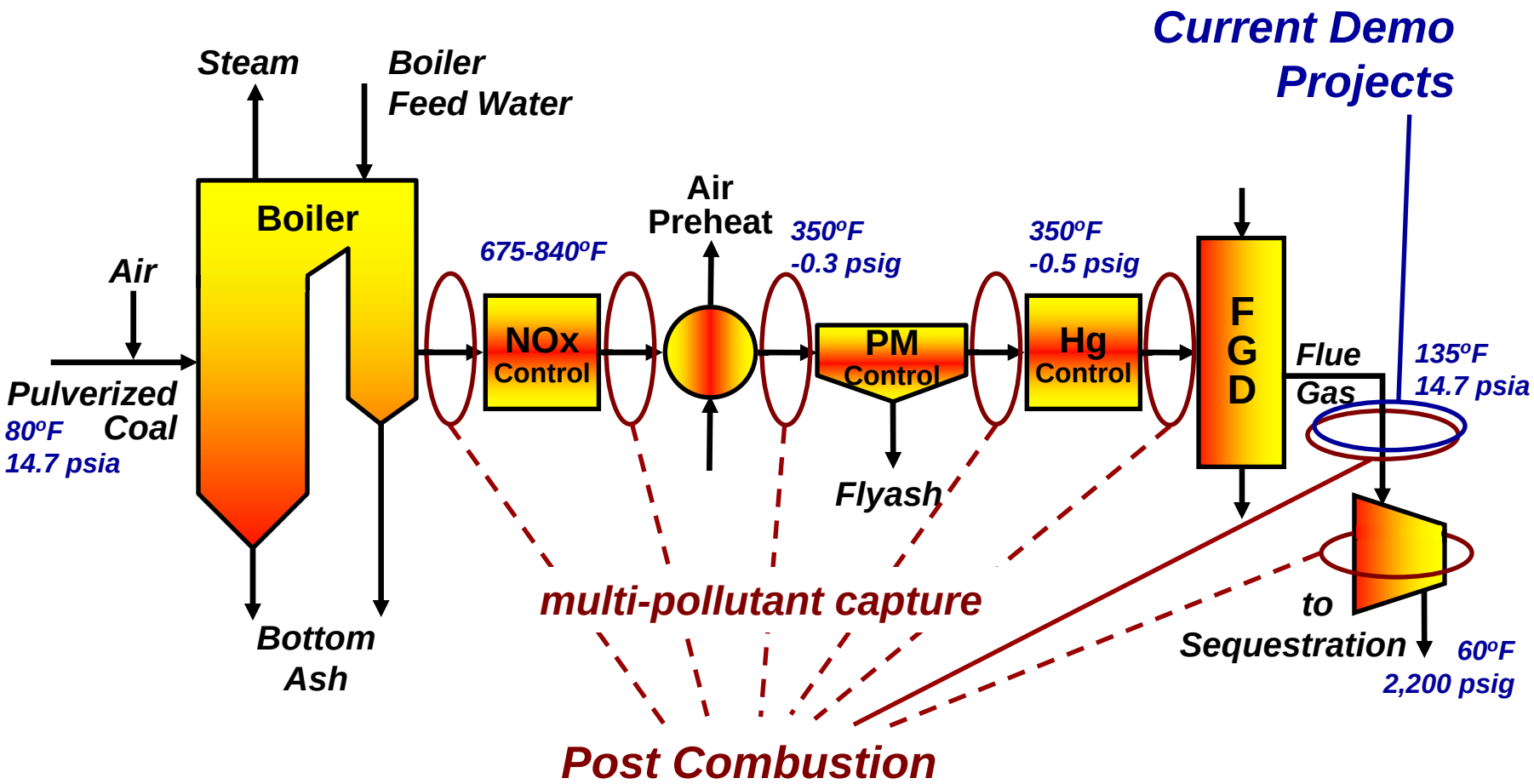
# $CO_2$ Capture Points

## *Post Combustion Capture*



# $CO_2$ Capture Points

## *Other Post Combustion Opportunities*

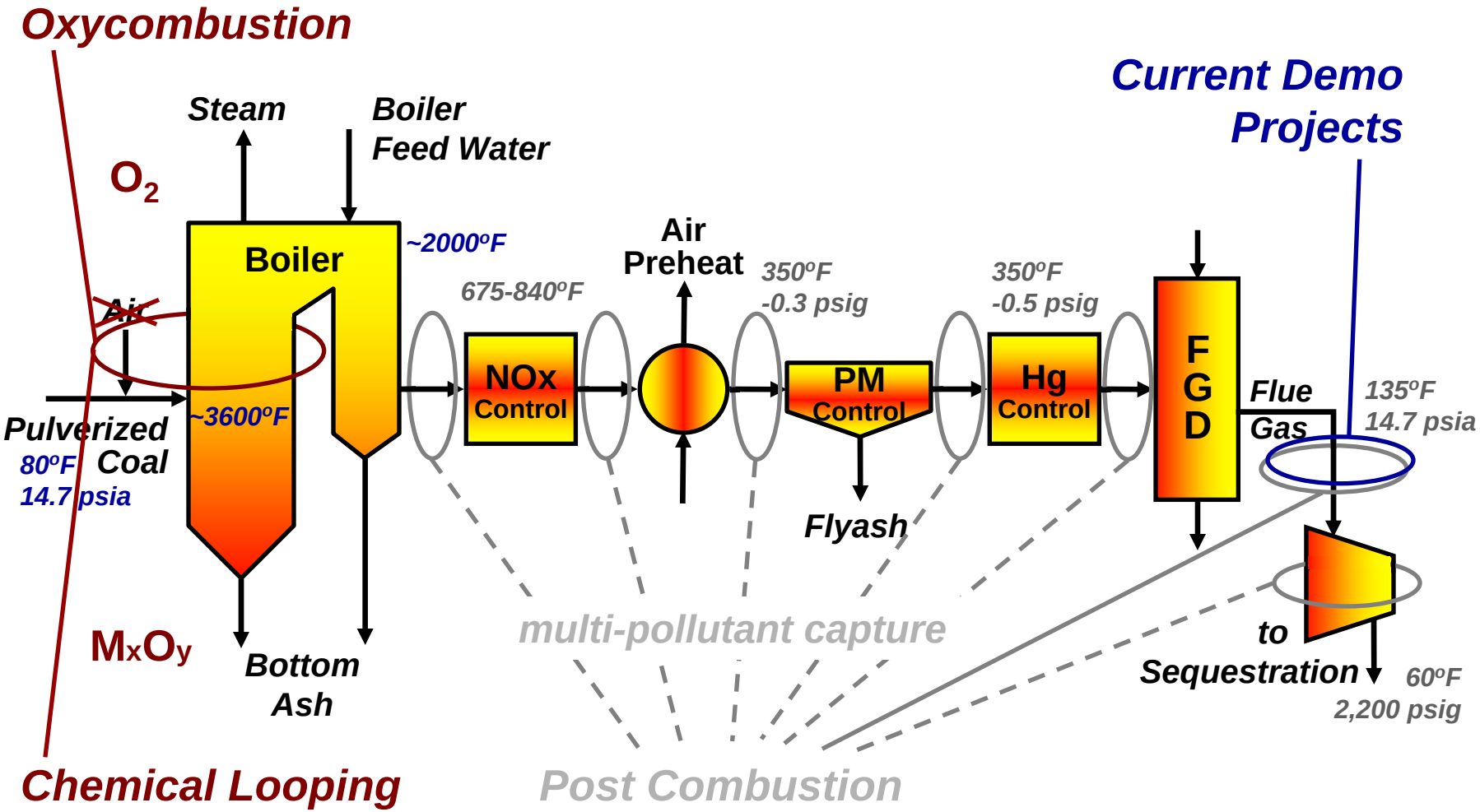


# Post Combustion Capture
## *System Characteristics*

- **Near atmospheric pressures**
  - except during $CO_2$ compression
- **Temperatures less than 350ºF to near ambient**
- **Dilute flue gas 10-15% $CO_2$**
- **Various levels of flue gas contaminants**
  - NOx, SOx, particulates, trace metals
- **Very large volumetric and mass flows**
  - greater than billion SCFD

# $N_2$ Rejection Points

## *Pre Combustion*



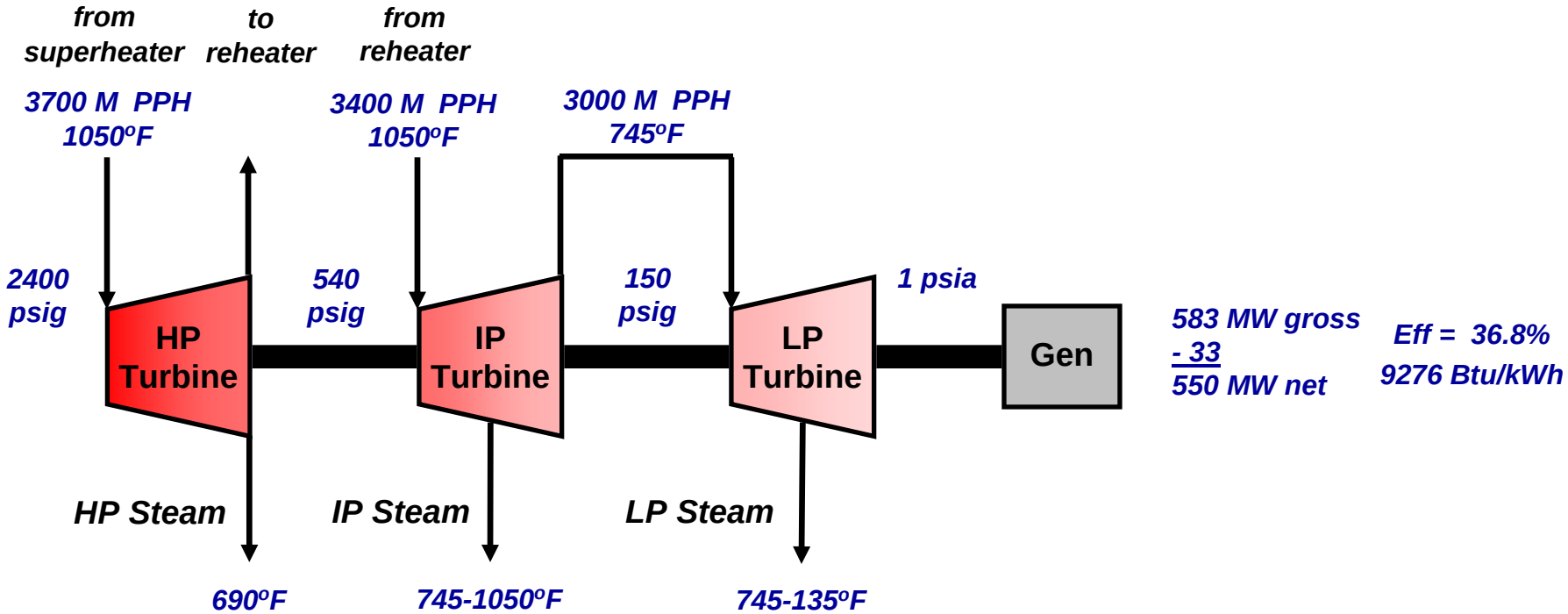
# Combustion & Pre Combustion

## *System Characteristics*

- **Near atmospheric pressures**
- **Temperatures**
  - approaching 4,000ºF in boiler
  - Ambient starting air
- **High levels of contaminants in boiler**
  - NOx, SOx, particulates, trace metals
- **Very large volumetric & mass flows**
  - roughly 5,000 TPD of coal
  - billion SCFD of air

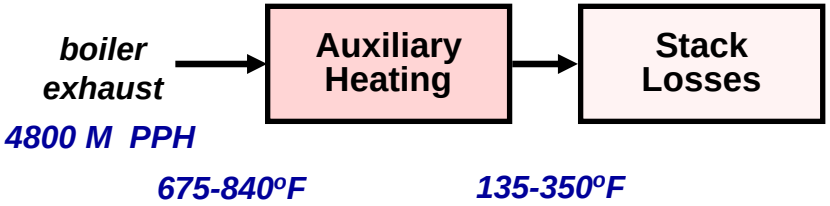
# Energy Availability

## *CCS Regeneration & Parasitic Loads*

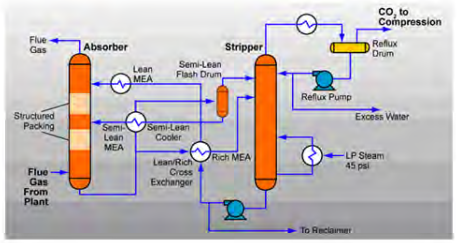


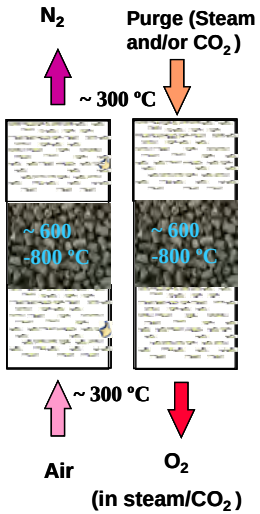

### *Steam Extraction Possibilities*

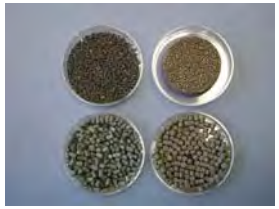
### *Waste Heat Possibilities*

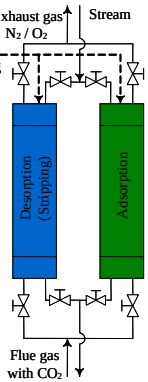


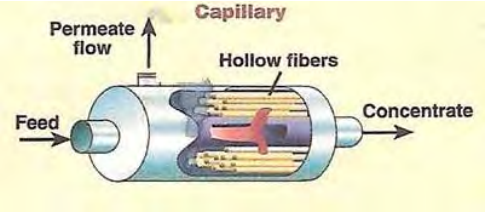
# $CO_2$ Capture Technologies

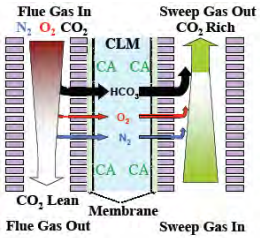


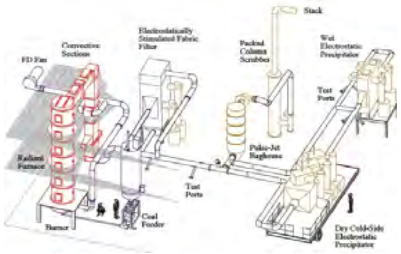


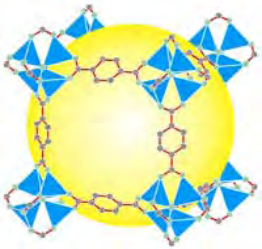



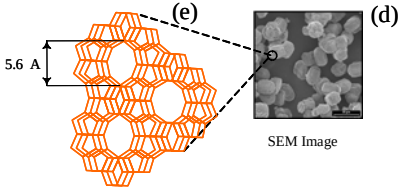


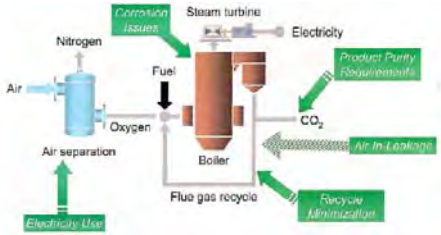



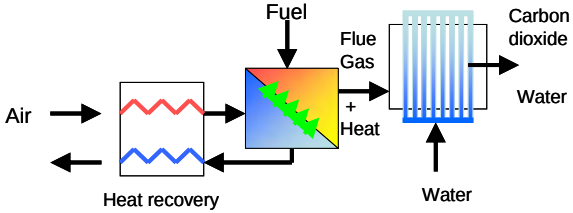



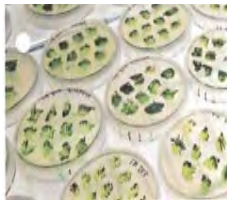


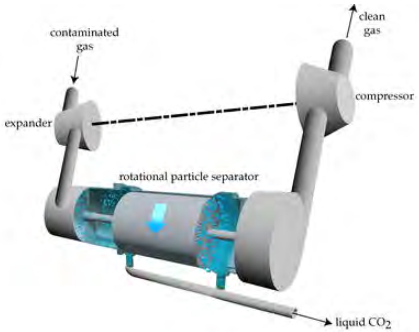



- **Reactive Purge**



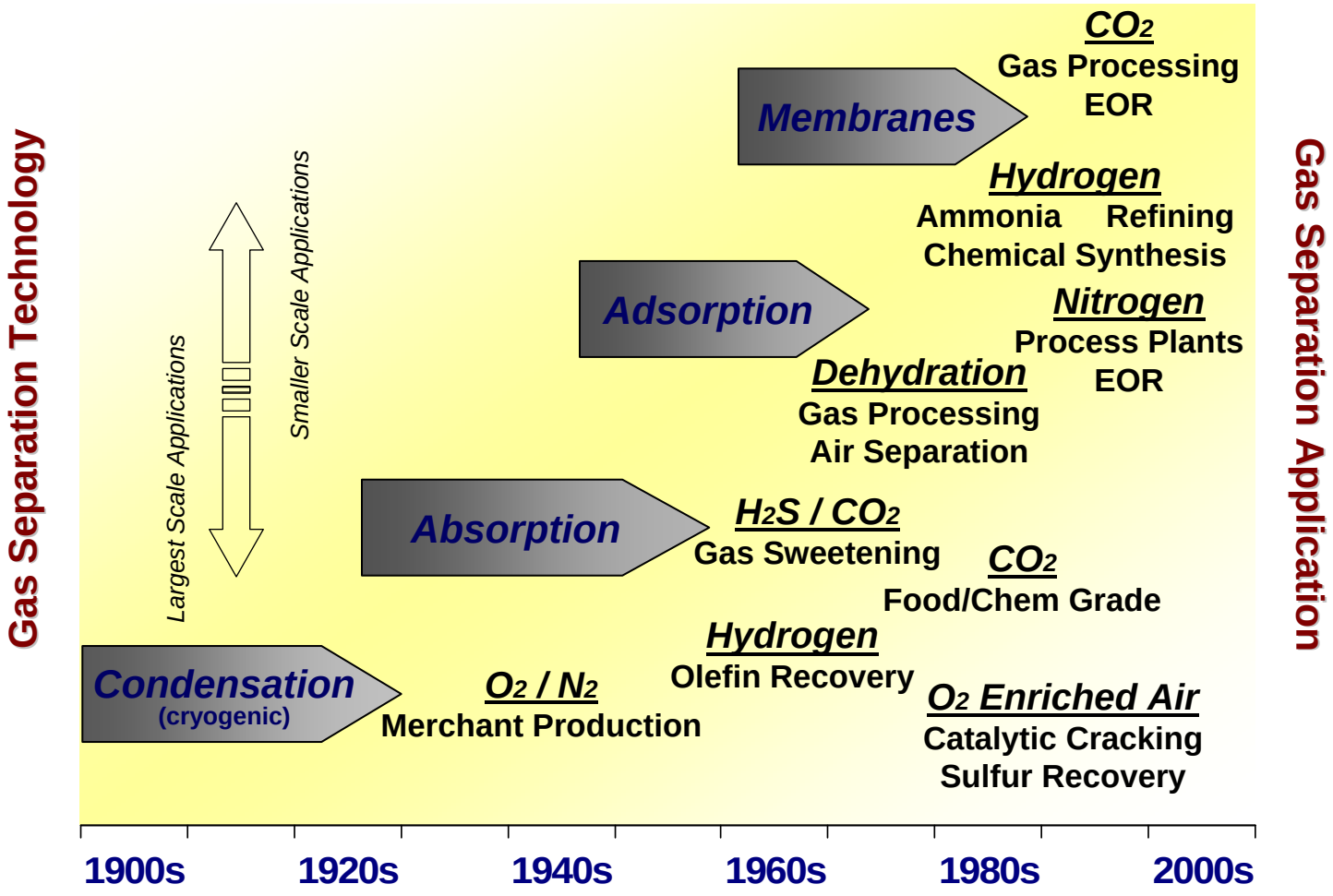


# Gas Separation Categories

1) Absorption into liquid
2) Adsorption onto solid
3) Permeation through dense membrane
4) Condensation to liquid or solid
5) Chemical conversion to another compound

# Industrial Gas Separations

## *Historical Evolution*



# Gas Separation Categories

## *Examples*

1) **Absorption into liquid**
   - i. *Physical*
     *e.g.* **dimethyl ethers of polyethylene glycol**
   - ii. *Chemical*
     *e.g.* **amine-based solvents**
2) **Adsorption onto solid**
   - i. *Physical*
     *e.g.* **zeolites**
   - ii. *Chemical*
     *e.g.* **immobilized amines**
3) **Permeation through dense membrane**
   - i. *Diffusion Controlled*
     *e.g.* **$CO_2$ in glassy polymer**
   - ii. *Adsorption Controlled*
     *e.g.* **$CO_2$ in rubbery polymer**
     *e.g.* **$O_2$ in doped ceramic (ITM)**
4) **Condensation to liquid or solid**
   - *e.g.* **refrigeration**
   - *e.g.* **direct expansion**
5) **Chemical conversion to another compound**
   - *e.g.* **$M_xO_y$ + Coal $\rightarrow$ M + $CO_2$**
   - *e.g.* **$CO_2$ + light $\rightarrow$ Biomass**

# Other Possible Gas Separations

## *Can these be made to work?*

6) **Permeation through porous membrane**

   *e.g.* ***Knudsen Diffusion or Molecular Sieving***

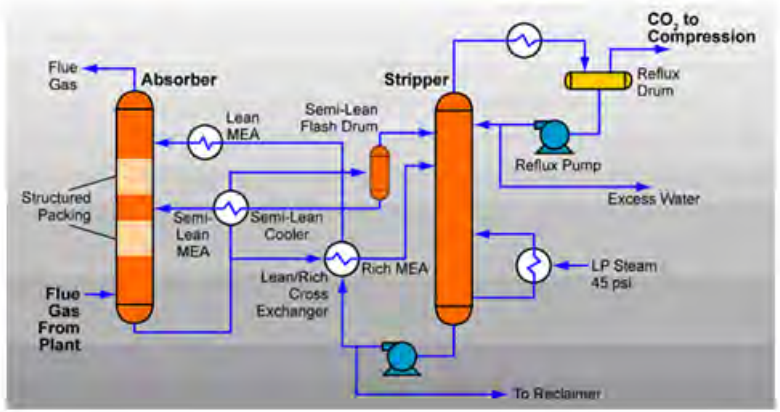
7) **Centrifugation**

   *e.g.* ***Molecular weight based separation***

8) **Chemical conversion to another compound**

   *e.g.* $CO_2 + H_2O \rightarrow$ ***Methanol***

# Absorption

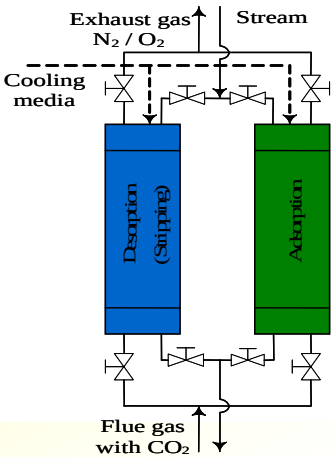



- **Commercial technology for $CO_2$ removal**
- **Fast kinetics & high selectivity**
- **Effective at low $CO_2$ partial pressures**
- **Ease of heat management**
- **Economies of scale**

**Challenges:**

- significant parasitic heat requirement for regeneration
- significant parasitic power requirement for circulation of solvent
- solvent losses
- high costs

# Adsorption

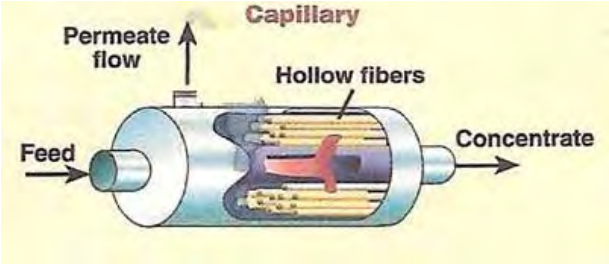



- **High capacity & selectivity, fast kinetics**
- **Effective at low $CO_2$ partial pressures**
- **Chemical Looping shares many characteristics with adsorption**

**Challenges:**

- significant parasitic heat requirement for temperature-driven regeneration
- significant parasitic power requirement for pressure-driven regeneration
- difficult heat management
- complex designs: cyclical fixed bed or moving bed operations
- trade-off between $CO_2$ purity and recovery
- economic scale-up
- high costs

# Gas Separation Membranes

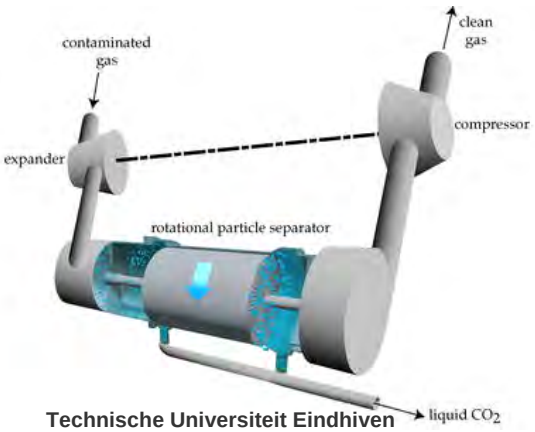



- **Applicable to $CO_2/N_2$ or $O_2/N_2$ separations**
- **Membranes are compact and modular**
  - can be placed in more than one location
- **Currently:**
  - require clean, dry feed gas
  - operate at temperatures less than about 150ºC (300ºF)
  - uncompetitive at scales exceeding <100 MM SCFD

**Challenges:**

- require feed compression or permeate vacuum pressures
- existing membranes deliver $CO_2$ (or $O_2$) at low pressures and $N_2$ at near feed pressure
- complex designs required to deliver high-purity and recovery
- economic scale-up
- selectivity

# Condensation




- **Cooling & condensation to separate $CO_2$ from $N_2$**
- **Resulting high-purity solid $CO_2$ stream easily liquefied & pumped up to sequestration pressures**
- **Currently being developed for gas processing & EOR applications**
- **May be applicable to multi-pollutant control**

**Challenges:**

- minimizing initial flue-gas compression
- maximizing recovery of refrigeration/energy of expansion
- separating solid/liquid from continuous gas phase

# Oxycombustion & Chemical Looping

- **Approaching 100% $CO_2$ capture**
- **May be applicable to multi-pollutant control**

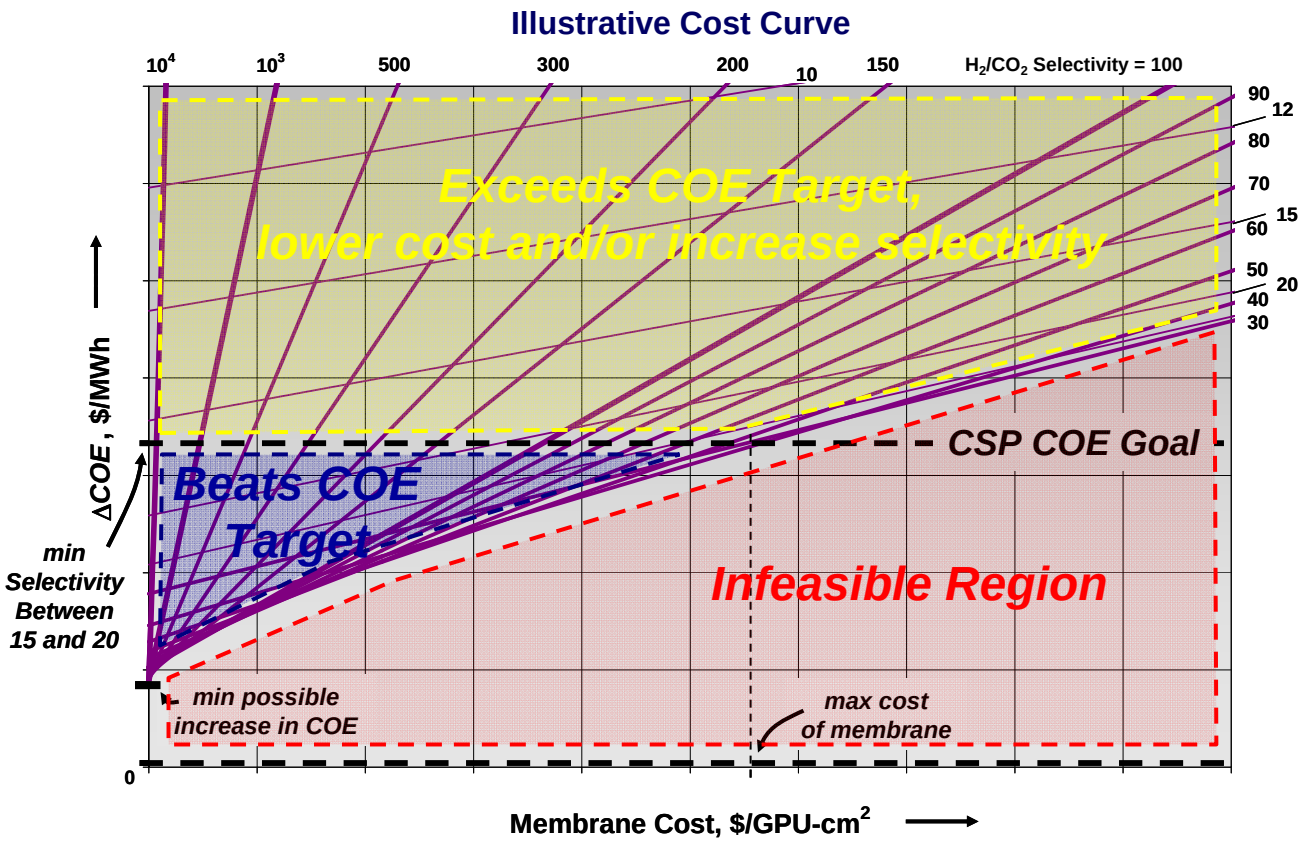
**Challenges:**

- oxycombustion requires $CO_2$ recycle to lower combustion temperature
- retrofit to existing plants could be quite difficult
- high parasitic energy requirements
- high costs

# Comparison to PC Application

| | Effective Dilute Gas | Effective Low Pres | Economies of Scale | Retrofit Difficulty |
|---|---|---|---|---|
| Absorption | yes | yes | yes | variable |
| Adsorption | yes | yes TSA<br>no PSA | limited | variable |
| Membranes | no | No | limited | variable |
| Condensation | yes | no | yes | possibly difficult |
| Oxy-Combustion | N/A | yes | yes | difficult |
| Chemical Looping | N/A | yes | yes | difficult |

# R&D Goals & Technology Targets



# EPEC R&D Goals for CCS

- **Minimum 90% carbon capture**
  - not limiting for many candidate technologies
- **COE increase of no more than 35%**
  - Baseline* subcritical PC plant w/o CCS **6.40** ¢/kWh
  - Goal for future plant with CCS **+ 2.24**

    **8.64** ¢/kWh

***Cost and Performance Baseline for Fossil Energy Plants, Vol.1***
**DOE/NETL-2007/1281, Aug. 2009 revised (@ *www.netl.doe.gov*)**

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  - Goal for future plant with CCS **+ 2.24**
    **8.64** ¢/kWh
  - Baseline PC plant with SOTA capture +5.48 ¢/kWh
    - 86% increase in COE over baseline plant w/o CCS
    - Allocated between: Capture, Compression, Transportation, Storage & Monitoring

# Specific Program Objectives*

***OBJECTIVE 1* - Lower Specific Capital Costs of CCS**

***OBJECTIVE 2* - Lower Specific Operating Costs of CCS**

***OBJECTIVE 3* - Improve Energy Efficiency of CCS**

***OBJECTIVE 4* - Lower Specific Retrofit Costs**

***OBJECTIVE 5* - Increase On-Site Steam & Power Generation**

******Existing Plants - Emissions and Capture Program Goals***

**DOE/NETL-2009/1366, April 2009 (@ *www.netl.doe.gov*)**

# Specific Program Objectives*

***OBJECTIVE 1* - Lower Specific Capital Costs of CCS**

***OBJECTIVE 2* - Lower Specific Operating Costs of CCS**

***OBJECTIVE 3* - Improve Energy Efficiency of CCS**

***OBJECTIVE 4* - Lower Specific Retrofit Costs**

***OBJECTIVE 5* - Increase On-Site Steam & Power Generation**

***Reduce Direct Costs of CCS System***

*Includes items related to capital & operating costs for 90% $CO_2$ capture when added to new PC plant*

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***OBJECTIVE 3* - Improve Energy Efficiency of CCS**

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***OBJECTIVE 5* - Increase On-Site Steam & Power Generation**

***Reduce Indirect Costs of CCS System***

*Includes costs associated with modifications to new PC plant design to accommodate CCS system*

*a.k.a. 'energy penalty'…'make-up power' '…'parasitic or auxiliary load'*

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***OBJECTIVE 5* - Increase On-Site Steam & Power Generation**

***Reduce extra costs associated with retrofit to existing plant***

***Make up by adding supplemental plant capacity***

# EPEC R&D Goals for CCS

- **Minimum 90% carbon capture**
- **COE increase of no more than 35%**

***How do we translate these into R&D targets ?***

| | Quanitative Technology Specific Metrics | | |
|---|---|---|---|
| Has not demonstrated potential to ever be meet or exceed capture goal | | | |
| May have potential for meeting goals, more fundamental work required | | | |
| Has definite potential, exceeds performance of new PC plant w/SOTA CC | | | |
| Has definite potential, exceeds EPEC goals for new PC plant w/SOTA CC | | | |

# Target Development Methodology

## *Steps*

*Heuristics* — **Screen Technology Integration Options (1)**

*Spreadsheet models* — **Model Capture Technology (2)**

*Aspen & Spreadsheet models* — **Simulate PC Plant w & w/o CC (3)**

*Economic Spreadsheet EPRI TAG* — **Economic Analysis (4)**

*Graphical Representation* — **Establish Technology R&D Targets (5)**

1. **Integrate in PC plant at location(s) where technology's operating envelope matches process conditions**

2. **Based on these conditions, model capture technology to determine selectivity required to meet $CO_2$ capture target**
   - determine relationship to loading and regeneration energy

3. **Process simulator used to model baseline PC plant w/o capture**
   - results used to estimate equipment performance and parasitic loads with $CO_2$ capture

4. **Simulation results used in economic model to determine technology cost required to meet EPEC Program goal for COE**

5. **Establish quantitative application-specific R&D targets for selectivity and specific cost of capacity**
   - provide qualitative guidance on how to achieve R&D targets

# Parameters for Developing Targets

| Technologies | Key Metrics | | | |
|---|---|---|---|---|
| | Specific Cost of Capacity | Specific Capacity | Specific Regen Energy | Selectivity |
| Absorption | $\frac{\{\$/m_{solv}\}}{\{m_{CO2}/m_{solv}\}}$ | $\{m_{CO2}/m_{solv}\}$ | $\{\Delta H_{abs}/m_{CO2}\}$ | $\frac{\{v_{CO2}/m_{solv}\}}{\{v_{N2}/m_{solv}\}}$ |
| Adsorption (&Chem Looping) | $\frac{\{\$/m_{sorb}\}}{\{m_{CO2}/m_{sorb}\}}$ | $\{m_{CO2}/m_{sorb}\}$ | $\{\Delta H_{ads}/m_{CO2}\}$ | $\frac{\{v_{CO2}/m_{sorb}\}}{\{v_{N2}/m_{sorb}\}}$ |
| Membranes Flue Gas / Air | $\frac{\{\$/A_{mem}\}}{\{P_{CO2\ or\ O2}\}}$ | $\{P_{CO2\ or\ O2}\}$ | N/A | $\frac{\{P_{CO2}\}\ or\ \{P_{O2}\}}{\{P_{N2}\}}$ |

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## *Other Important Considerations*

- Mass & Heat Transfer
- Reaction Kinetics
- Effects of Gas Contaminants
- *P-T* Operating Envelope
- Stability
- Durability & Maintainability
- Retrofitability to Existing PC Plants
- Toxicity & Enviro Profile

# Application of EPEC R&D Targets

## *Guidelines for Assessing Progress*

| | Selectivity | Specific Cap & Reg | Specific Cost of Capacity |
|---|---|---|---|
| Has not demonstrated potential to ever be meet or exceed capture goal | $<T_S$ | N/A | N/A |
| May have potential for meeting goals, more fundamental work required | $>T_S$ | $>T_C$ & $<T_R$ | N/A |
| Has definite potential, exceeds performance of new PC plant w/SOTA CC | $>T_S$ | N/A | $<T_\$$ (baseline) |
| Has definite potential, exceeds EPEC goals for new PC plant w/SOTA CC | $>T_S$ | N/A | $<T_\$$(goal line) |

- **Selectivity target relates most closely to 90% capture goal**
- **Specific Cost of Capacity target relates most closely to COE goal**
  - trade-off between specific capacity & specific costs
- **During more fundamental stages of R&D costs very uncertain**
  - substitute $T_C$ & $T_R$ for $T_\$$

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# Closing Thoughts

1) **Start by trying to match technologies to PC plant process as it is, and not vice versa**
2) **Look for new R&D opportunities in areas that are not already over populated**
3) **Don't discount "crazy" ideas if you have novel new insight or approach**
4) **Focus initially on key performance metrics**
   - if results look promising & progress is made, transition to cost and other criteria