ENG 505
ENERGY SURETY AND SYSTEMS

Coal

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Outline of Presentation

- Brief Biographical Note
- Coal Fundamentals
- Conventional Coal Utilization Technologies
- Future Coal Utilization Technologies
- Coal Utilization – Complex Systems Issues and Analysis
- Coal Research at Sandia
- Summary
- Q & A

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Brief Biographical Note: Chris Shaddix

- B.S., Mech. Engring, UC Davis
- PhD, MAE, Princeton University; thesis on combustion chemistry
- NRC Postdoc – NIST, Center for Fire Research
- Sandia: Combustion Research Facility, since 1995
  - Recently promoted to DMTS
  - Wide array of research on coal and biomass combustion and gasification, soot formation, boiler measurements, laser diagnostics, oxy-fuel combustion
- Current Projects:
  - Oxy-fuel combustion and gasification of coal
  - Li-ion battery failure plume diagnostics and ignition properties
  - Down-hole oxy-fuel combustion for EOR

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Fundamentals

- What is coal, and what differentiates coals
- Where is coal mined and used
- What kind of coal and how much is there in the U.S.
- How much coal is currently being mined in U.S.
- How is coal transported and used in U.S.

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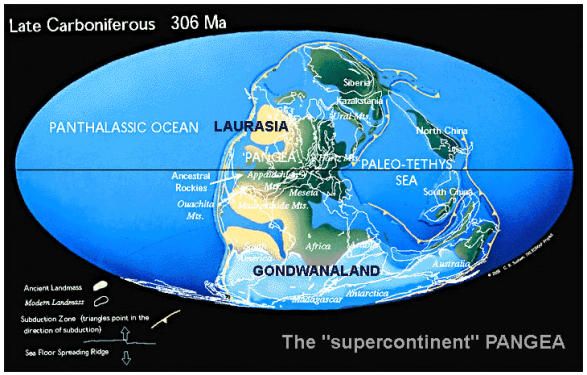
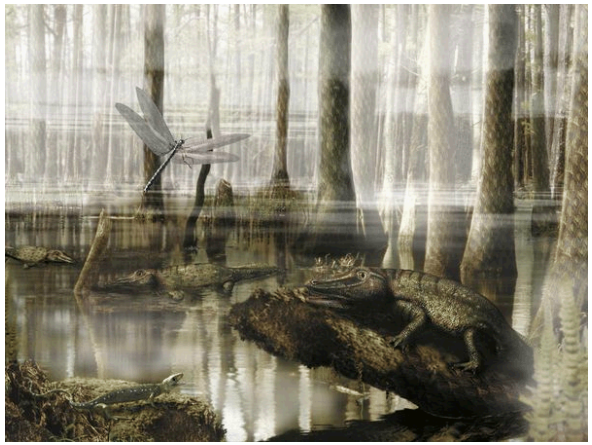
Where did coal come from?

- coal = organic sedimentary rock
- derived from buried bogs of accumulated plant matter
- coal deposits date from 2 – 400 million years ago
- Carboniferous Period (300 million years ago) resulted in extensive, thick bituminous coal seams from conifers growing in thick forest swamps on Pangea





Carboniferous swamp

South Africa coal seam

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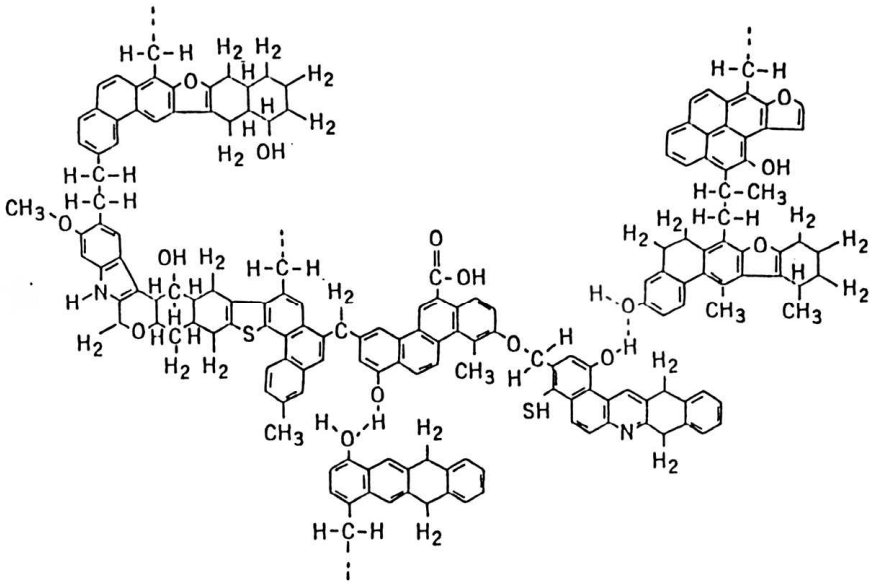
What is coal?

- Chemically, coal is a complex, branched, cross-linked macromolecular matrix
- Aromatic carbon backbone
- Includes varying levels of heteroatoms (O, N, S, Cl)
- Includes varying levels of mineral matter mixed in with organics (Si, Al, Ca, Fe, Na, K, Ti, P, . . . Hg)



Idealized molecular structure of a bituminous coal

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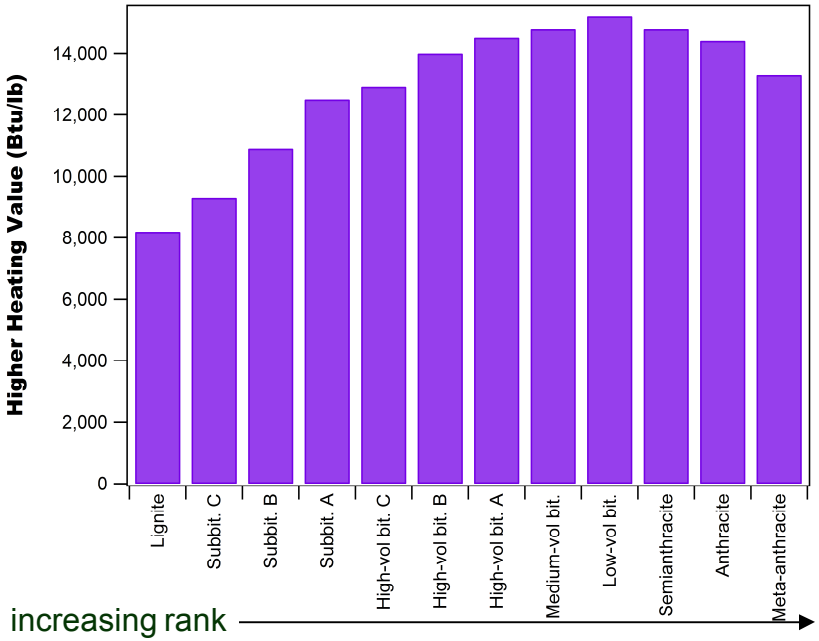
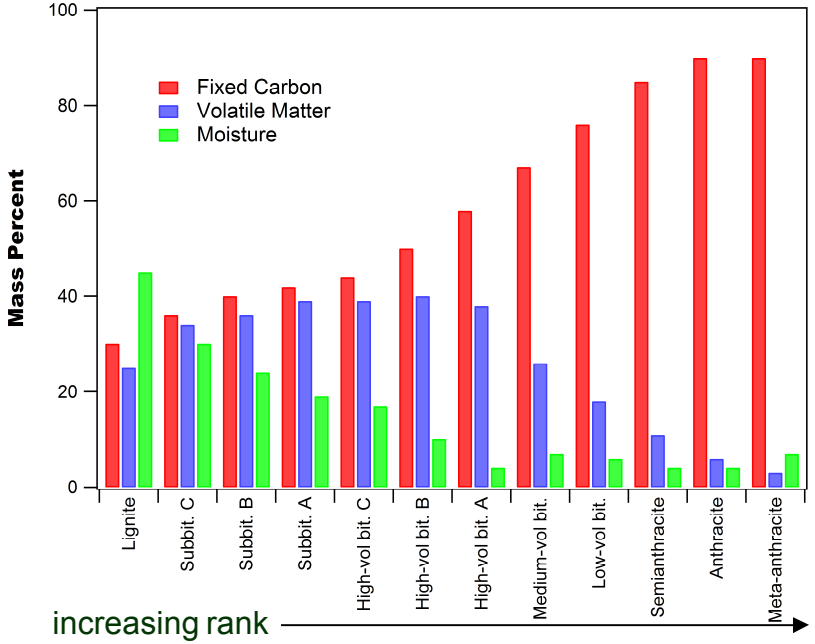
How is coal characterized?

- Coal is generally characterized by its “rank” and by its concentration of undesirable entities: moisture, ash, S, Hg, etc.
- For all but the highest rank coals, the “rank” correlates with the energy density of the coal (heating value) and tends to correlate inversely with moisture content





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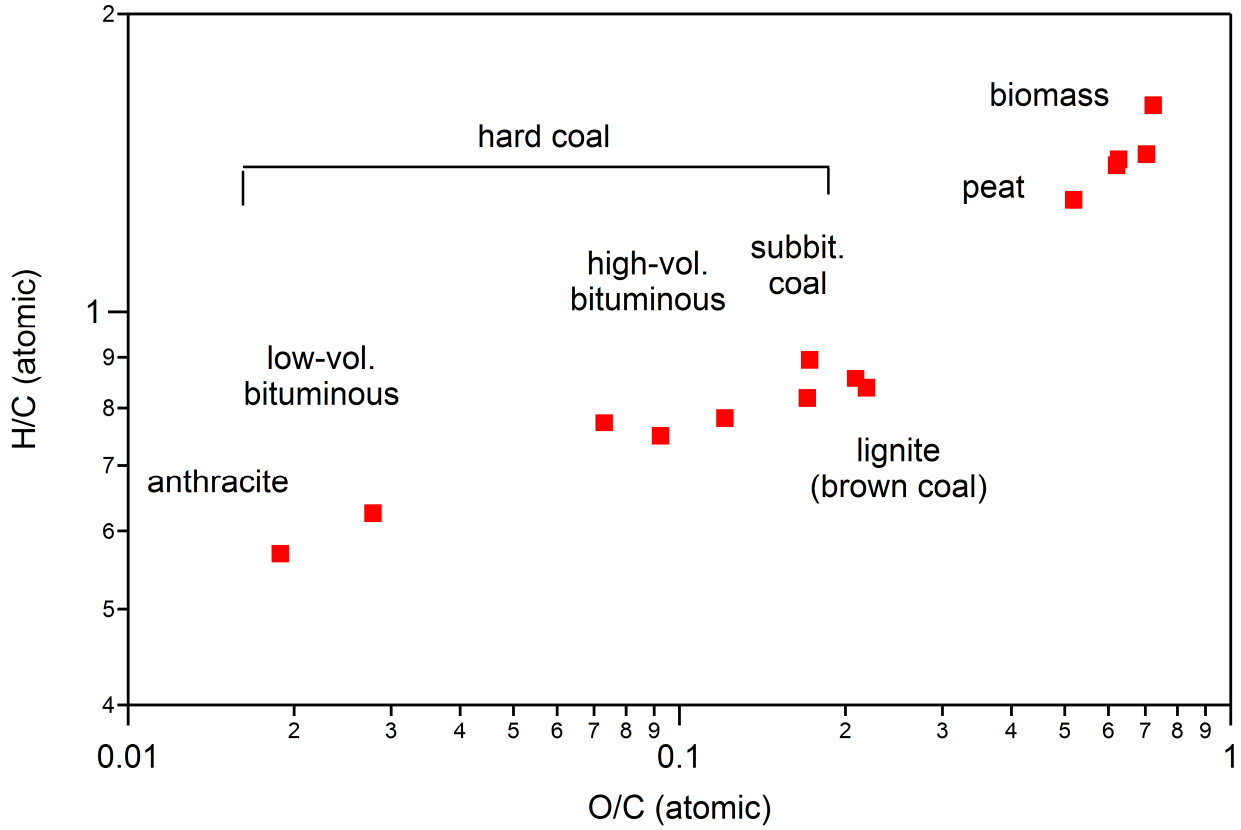
What causes different coal ranks?

How long you leave the coal in the oven!

Van Krevelen Diagram of Coalification



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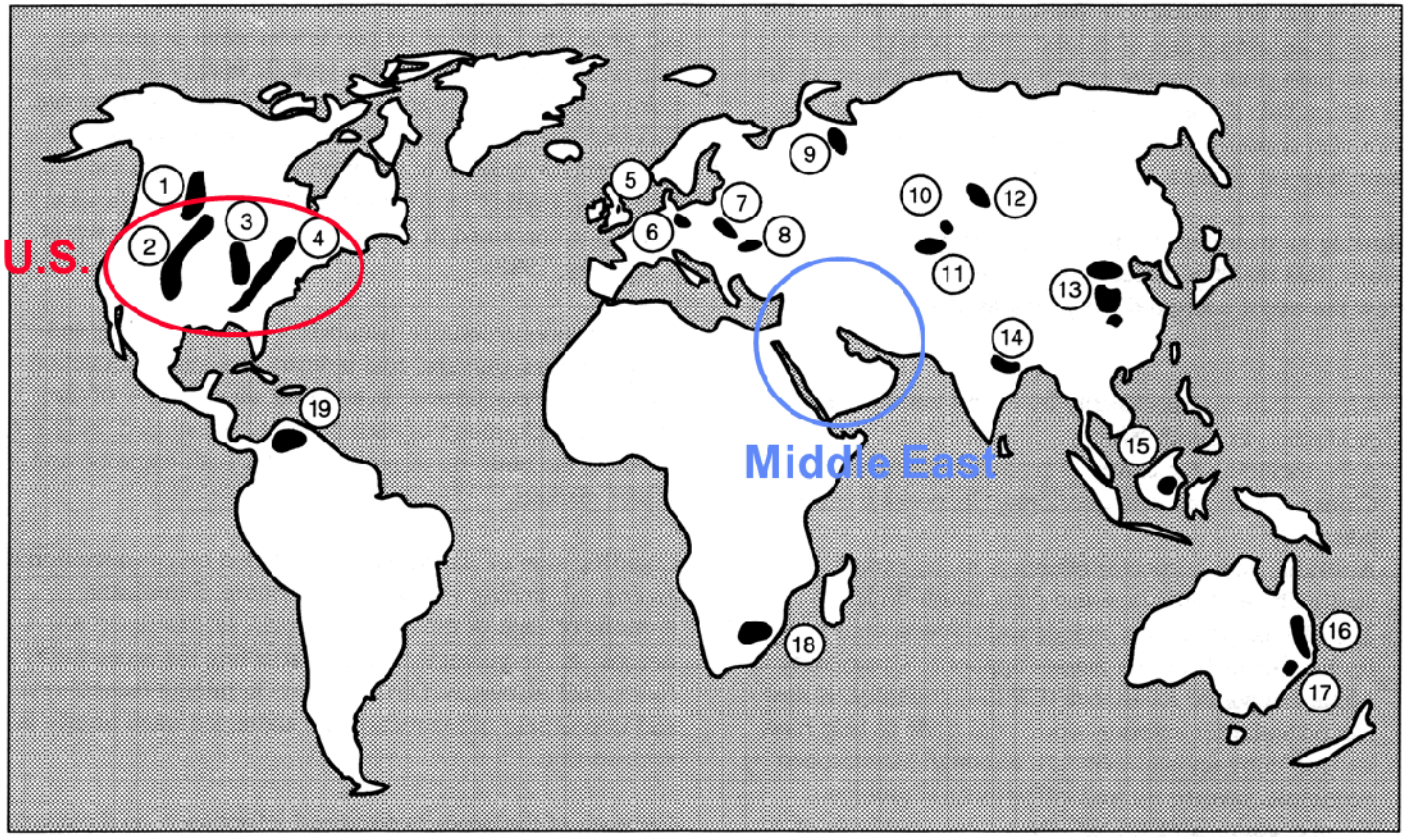
Worldwide Distribution of Coal



1	Western Canada	8	Donetsk	15	Kalimantan
2	Western USA	9	Pechora	16	Bowen
3	Illinois	10	Ekibastuz	17	Sydney
4	Appalachian	11	Karaganda	18	Karoo
5	East Pennine	12	Kuznetsk	19	Northern Colombia/Venezuela
6	Ruhr	13	China		
7	Upper Silesia	14	Raniganj/Jharia		

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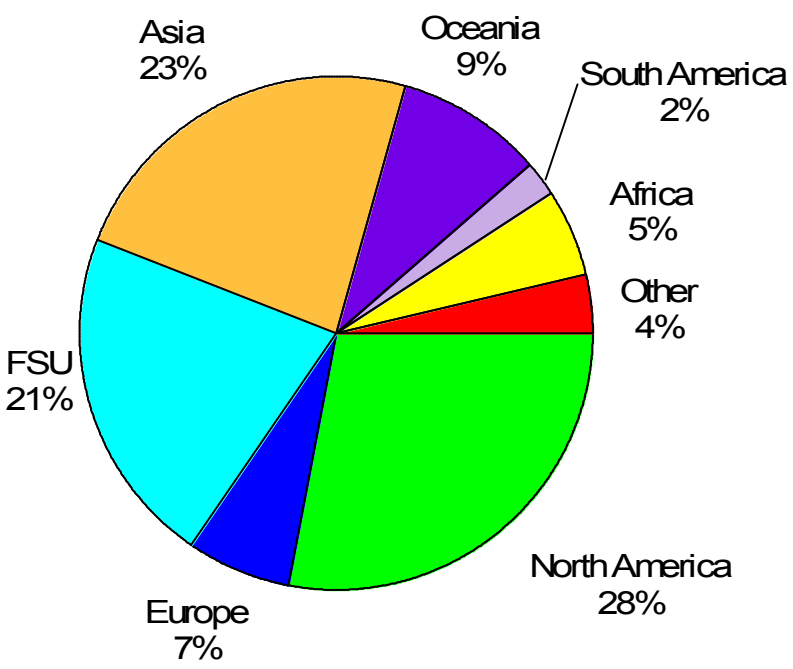
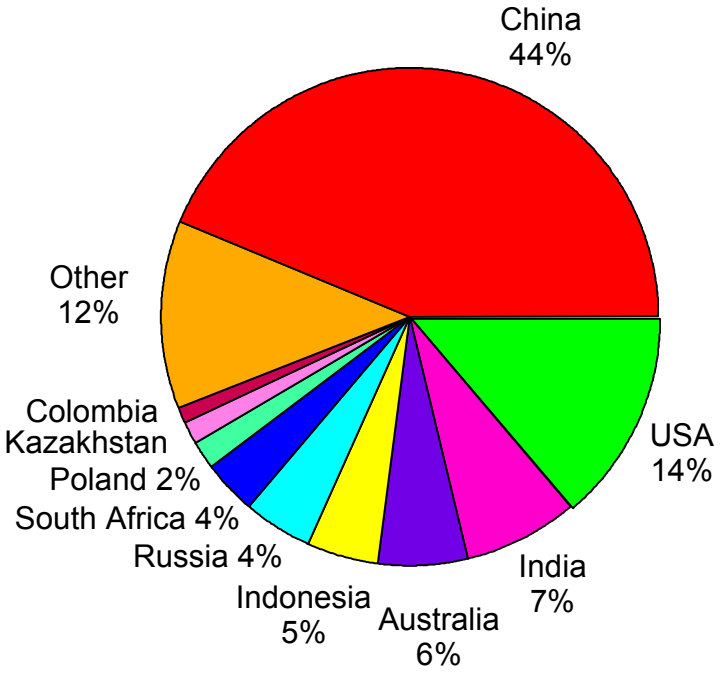
How much coal is there and where is it being produced?

Coal Reserves by Region
(~ 1000 B tonnes total)



Coal Production by Country (2010)
(7.2 B tonnes total)



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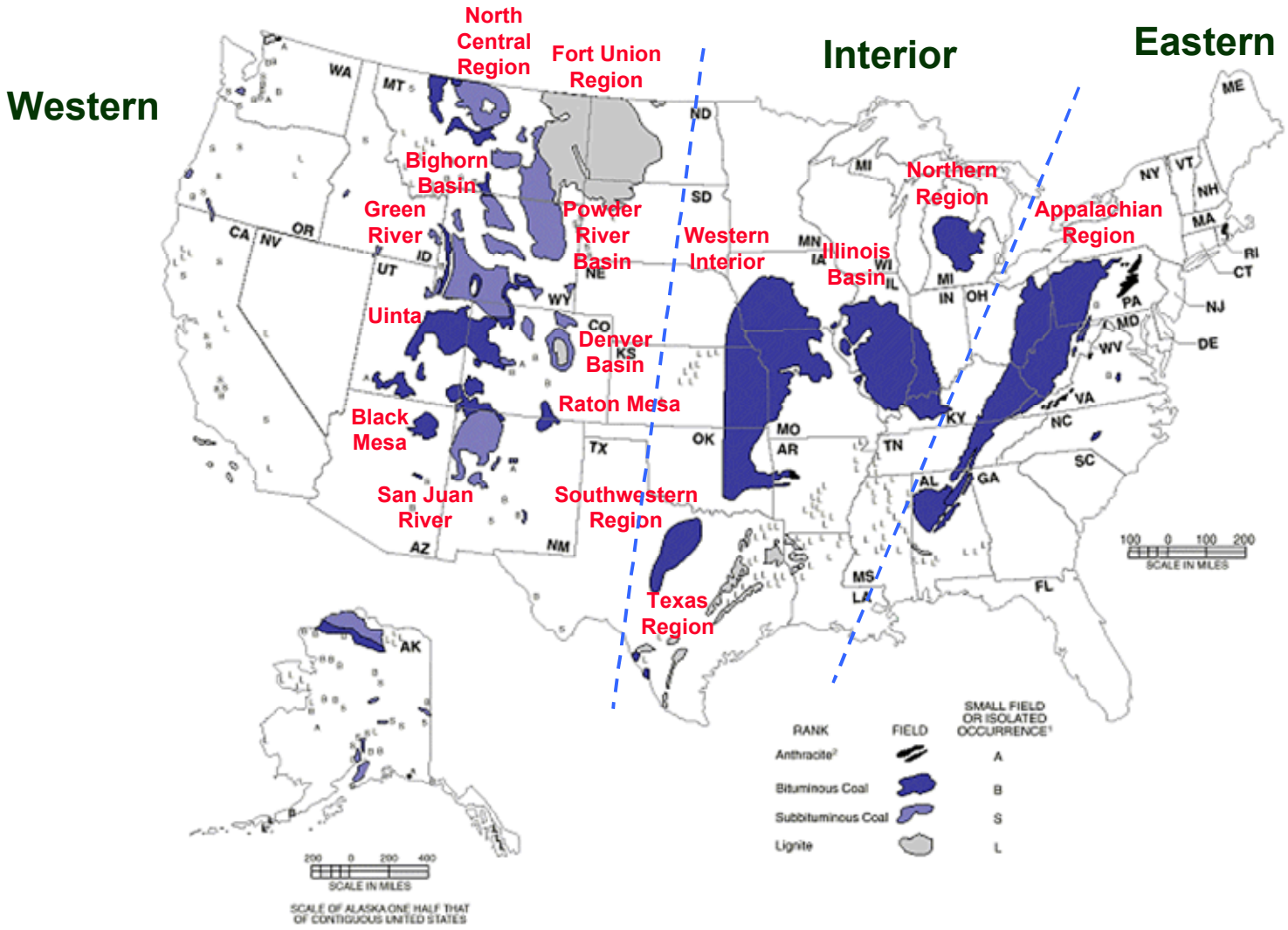
U.S. Coal Deposits



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U.S. Coal Reserves (Recoverable*)

Reserves by Region		Top Reserves by State	
	Mt		Mt
Western	131,000	Montana	68,000
Interior	61,000	Wyoming	36,000
Eastern	46,000	Illinois	34,000
		West Virginia	16,000
Total U.S.	238,000	Kentucky	13,000
		Pennsylvania	11,000

* “recoverable” reserves typically are ~ ½ of “demonstrated” reserves

U.S. reserves can maintain current extraction rate for ~ 200 years

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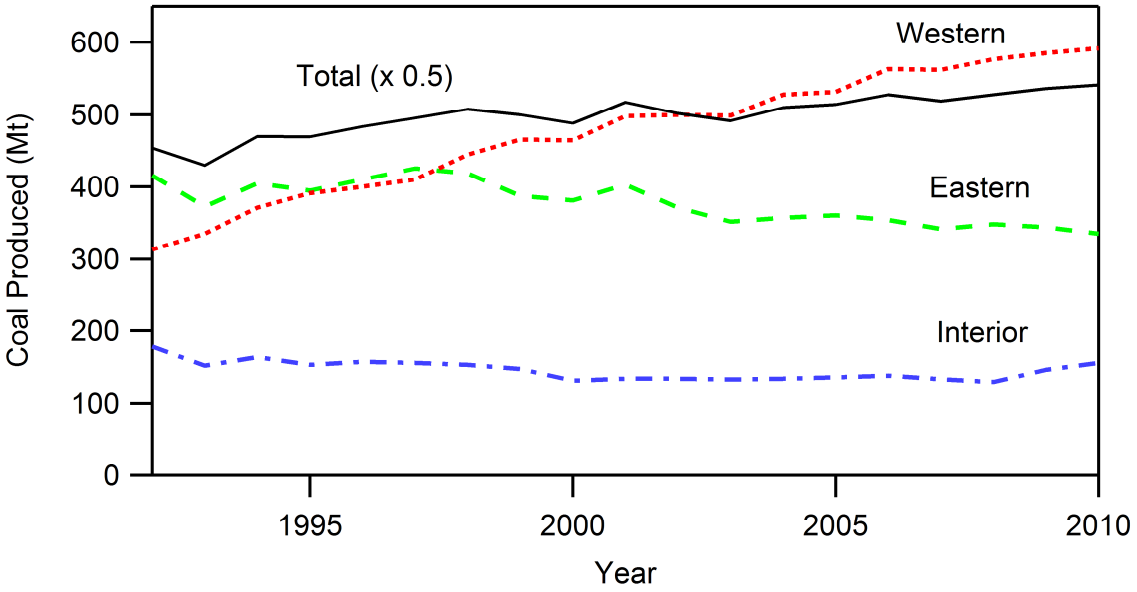
U.S. Coal Production



trends reflect 'fuel switching' to meet 1990 Clean Air Act Amendments, specifically for SO_2 emissions

- Western Coal
  - subbituminous
  - low S
  - surface mined
  - thick seams (PRB – 40 ft)

Eastern Coal

- bituminous
- low to high S
- underground and surface mined
- Thin seams (3 – 10 ft)

- Interior Coal
  - similar to Eastern, but high S and high Cl (IL seam)

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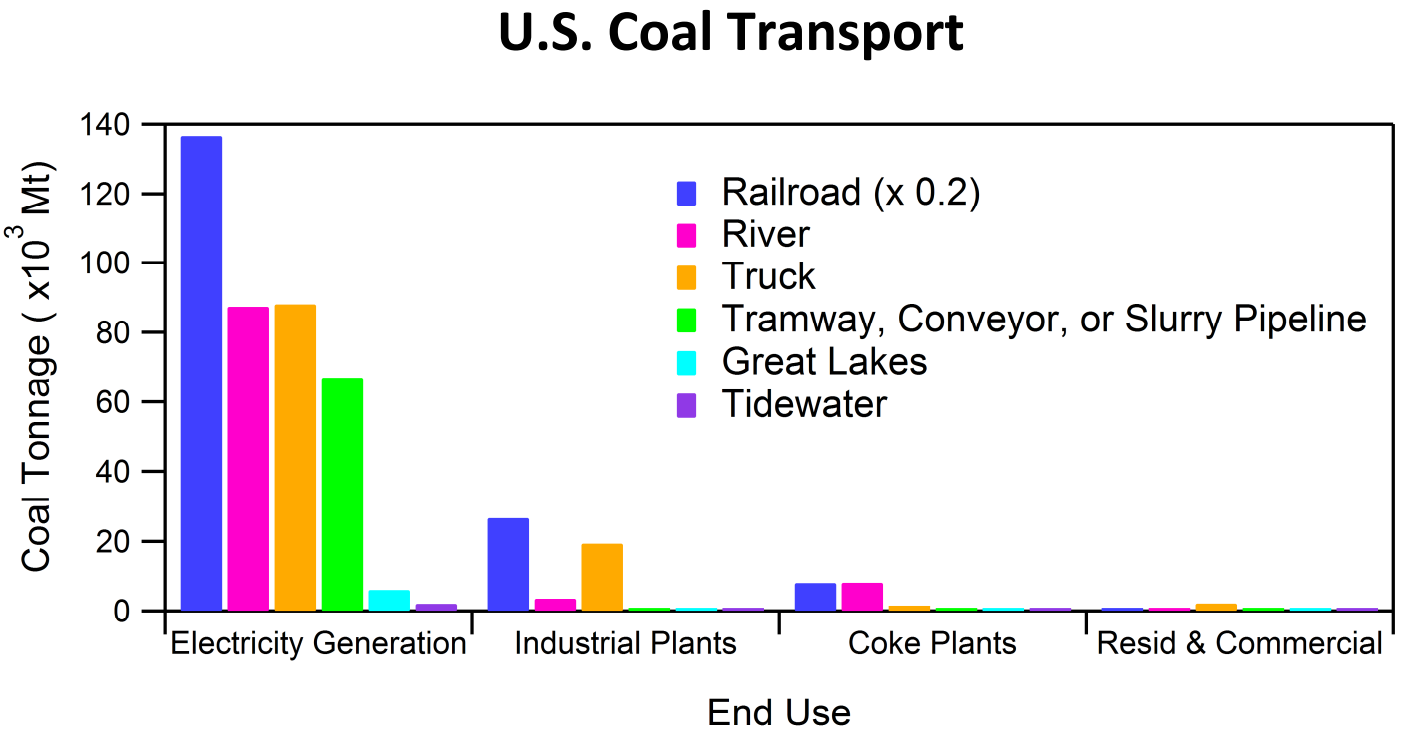

- Use of coal for power plants dominates in U.S.
- Predominant mode of transport is rail (100-car 'unit trains'), with cost of $1 – $2 per 100-ton-mile (cost is tied to oil price)
- Barge transport (esp. Mississippi and Ohio Rivers) is cheapest

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Conventional Coal Utilization Technologies

- Pulverized coal powerplant
- Fluidized bed powerplant
- IGCC

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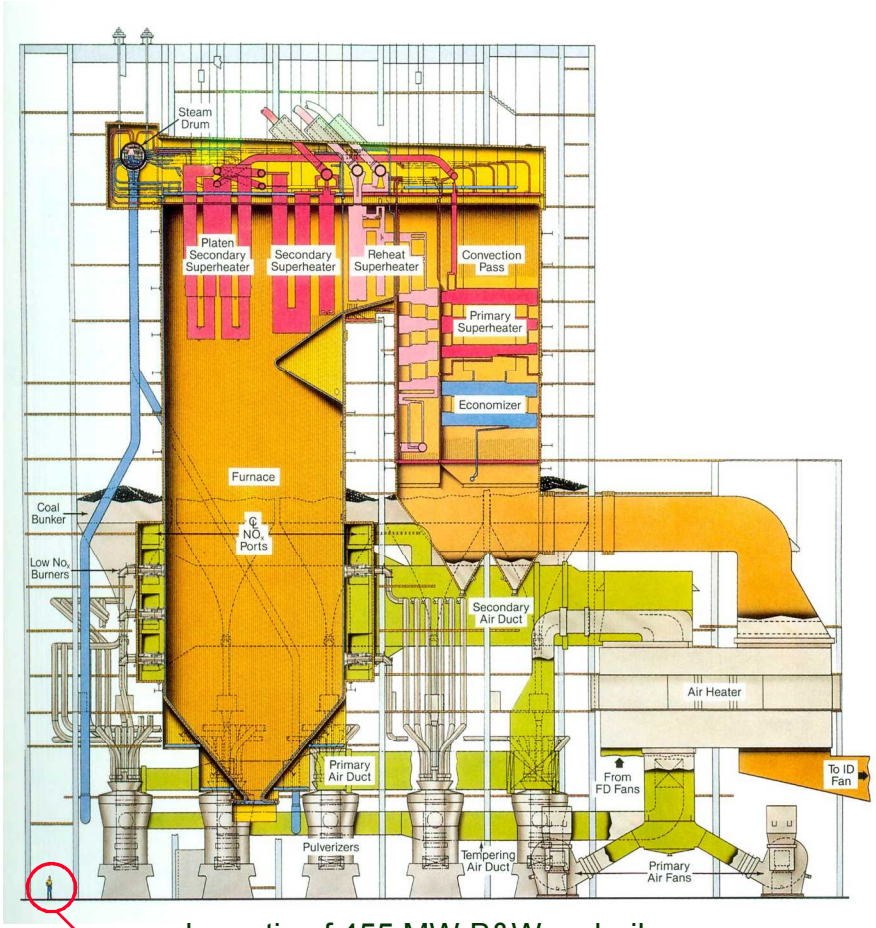
PC Boiler

- coal dried and ground to ~ 50 μm
- high-intensity entrained particle combustion with dozens of burners mounted on furnace walls
- typ. large boiler sizes (600 MW)
- can attain 43+% thermal efficiency (USC steam, 660 °C)
- U.S. fleet averages ~ 30 years old, has mean thermal efficiency of 32%
- In U.S. most boilers use low-NOx burners and/or addition of N reagent (ammonia or urea)



schematic of 455 MW B&W pc boiler

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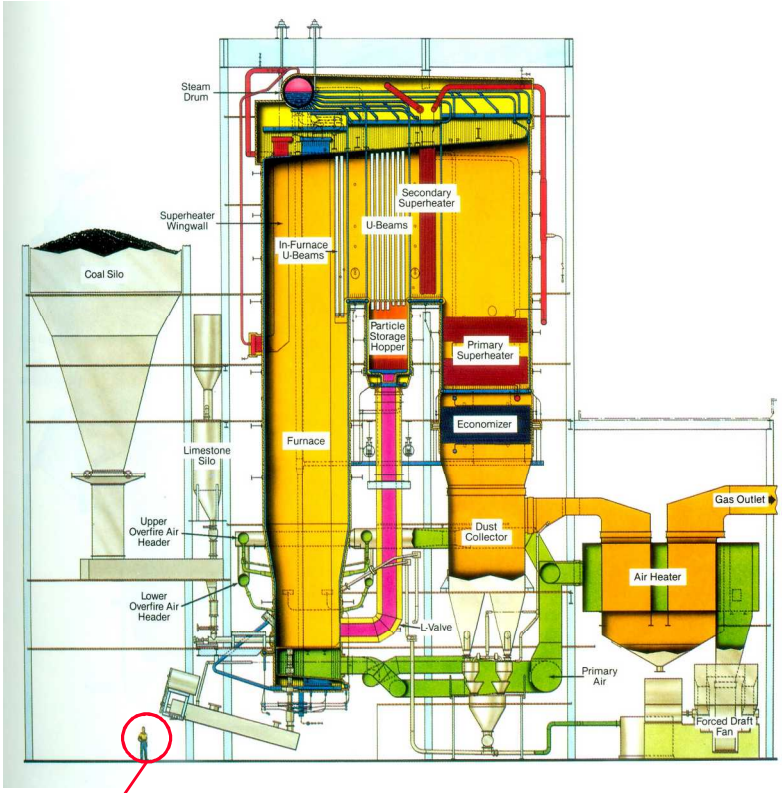
Fluidized Bed Boiler

- coal ground to 3-6 mm in size
- particles burnt in suspension
- long residence time (good for low-quality fuels)
- relatively low temperature, 850°C (low NOx)
- allows use of sorbents (limestone or dolomite) for sulfur and volatile metal capture
- can be built to operate at pressure
- limited thermal efficiency, limited scalability



schematic of circulating fluidized bed (CFB) boiler

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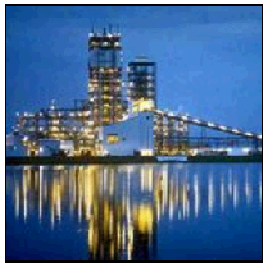
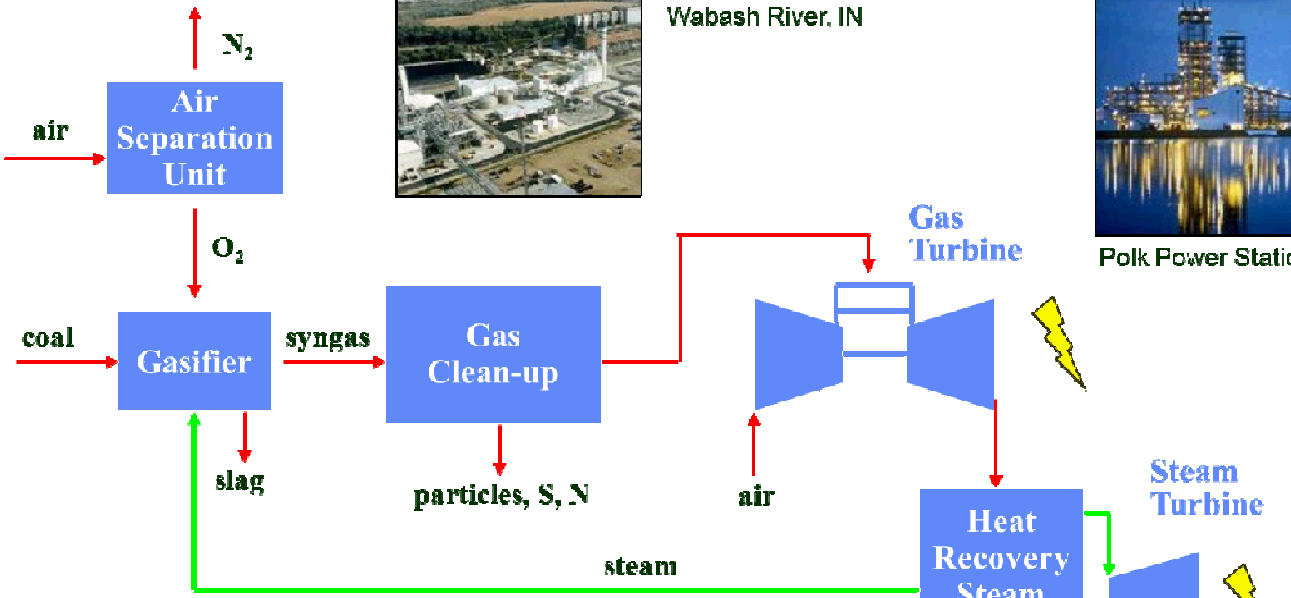
Integrated Gasification Combined Cycle (IGCC)

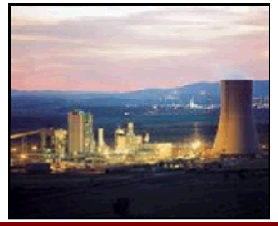
- 4 plants in operation around world (another one being built in China), all with significant government cost-share

Wabash River, IN



Polk Power Station, FL





Puertollano, Spain

Future Coal Utilization Technologies

- Oxy-Fuel Combustion
- IGCC w/ Carbon Capture
- PC Boiler with Amine Capture
- Chemical Looping Combustion

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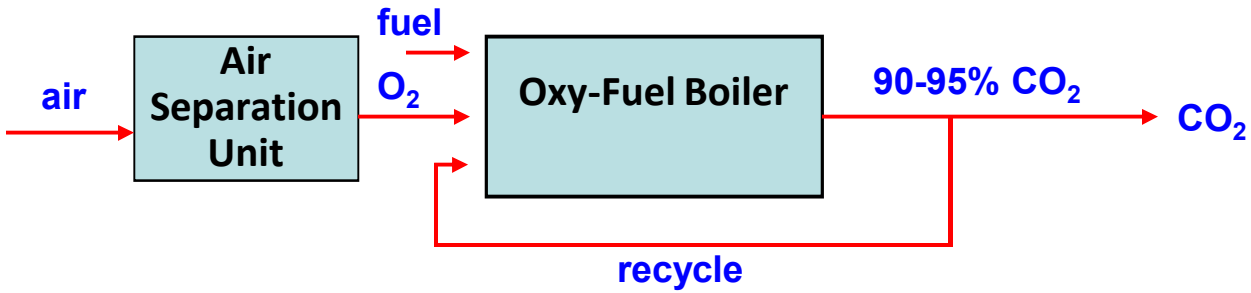
Oxy-Fuel Combustion

- One of the more promising options for carbon capture when using coal for power production:



- can be retrofitted to existing boilers
- modest modification of existing technology
- concurrent emissions reductions

- Pilot-scale (30 MW_{th}) plant has been operating in Germany for two years
- Small demo-scale (30 MW_e) plant now starting up in Australia
- U.S. FutureGen 2 plant would be oxy-fuel (300 MW_e)

Schwarze Pumpe Pilot Plant, Germany

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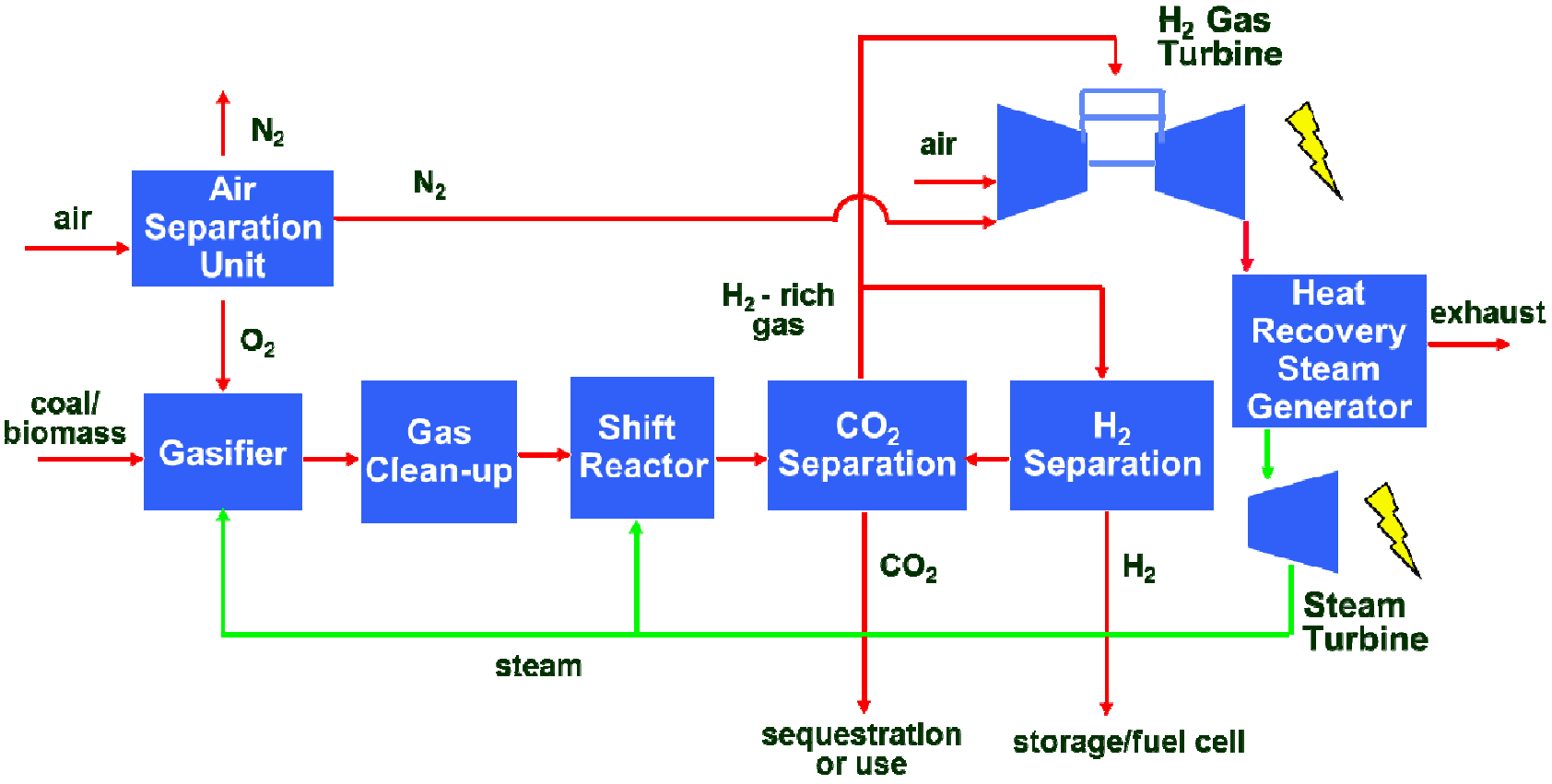
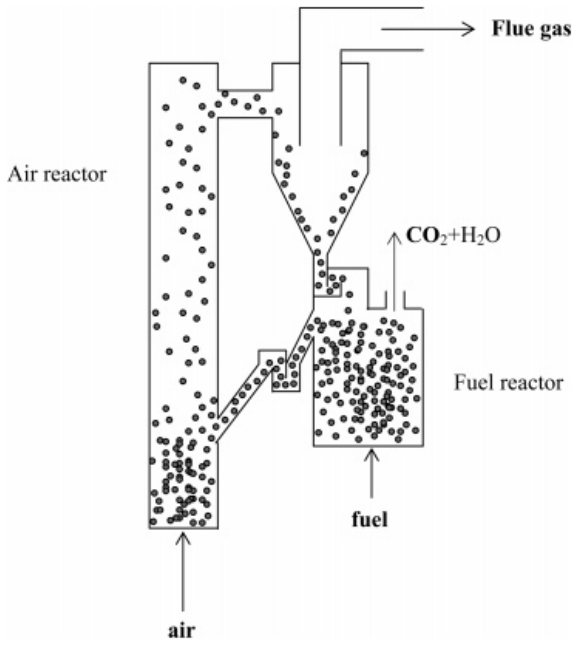
IGCC with Carbon Capture

- Relatively modest change to conventional IGCC
- Was basis for original FutureGen concept in U.S.



Chemical Looping Combustion

- Primary additional cost and efficiency loss for oxy-fuel combustion (and to some extent for IGCC) is in O_2 generation
- Current state-of-the-art for large-scale O_2 production is cryogenic separation
- Chemical Looping combustion avoids this costly step by using metal oxide carrier(s) and having separate oxidation and reduction reactors
- Primary metal-oxide systems being investigated are Fe_2O_3/Fe_3O_4, Mn_3O_4/MnO, Cu_2O/Cu



Schematic of Potential CLC Reactor

Recall: What is a Complex System?

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- A **complex system** is a system composed of interacting elements that as a whole exhibit one or more properties (behavior among the possible properties) not obvious from the properties of the individual parts
- Common Attributes
  - Multiple interacting phenomena
  - Heterogeneous element
  - Non-linear dynamics and effects
  - Adaptive behavior
  - Elements with memory
  - Large network of elements or nested complexity

Recall: Approaches to Complex Systems

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- Mathematics
- Physical-Cyber-Behavior
- Threat and Risk
- Systems Engineering
- Sandia Software Tools
- Sandia Disciplines

These represent approaches or resources that an analyst or engineer may apply to a systems engineering challenge. They are not intended to be a complete set, just one chosen to add structure to this course.

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Relevant Complex Systems Type to Coal Utilization

- Coal powerplant 'Availability' and Mathematics approach to system analysis
- Cost-of-Electricity (COE) strongly weighted by availability (baseload power)
- Increasing complexity of powerplants (IGCC, emission control technologies, etc., leads to reduced powerplant availability from component failures)
- Push by government and industry to develop equipment sensors and apply advanced systems modeling to identify weak points and proactively perform maintenance
  - Fault Tree Analysis
  - Non-linear Dynamic Systems
  - Stochastic Methods (random sensor failure)

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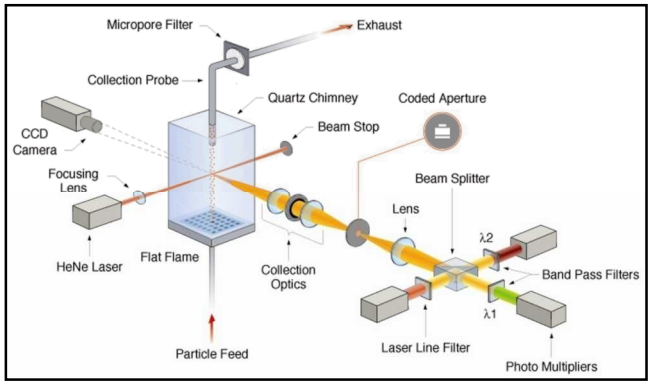
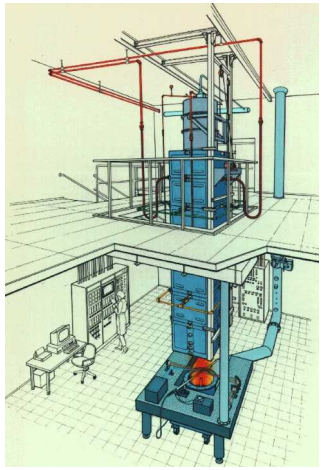
Coal Research/Capabilities at Sandia

- Coal combustion/gasification research has been performed at Sandia's CRF since its inception in 1979; Nancy Jackson led work on coal liquefaction in 1980's to early 1990's
- 3 laboratories focused on coal/biomass combustion and gasification research





- Current research program emphasizes oxy-fuel combustion and gasification 'science', with a focus on development of accurate process submodels for use in CFD

Summary

- Coal is characterized by its ‘rank’
- Coal is distributed in many countries in the world – led by U.S.
- Coal is largest single source of electrical generation in U.S.
- Increasingly stringent SO_2 emission regulations have led to shift in coal production to western U.S.
- Currently, coal is predominantly burned in large pulverized coal boilers
- Gasification technology has been demonstrated, but higher costs and reduction in availability have deterred adoption
- Several options available for true ‘zero emission’ coal utilization, but come with a price and a need to sequester the CO_2

THANK YOU!

QUESTION & ANSWER SESSION

Contact me if you have further questions:
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