Oxy-Combustion of Coal – Needs, Opportunities and Challenges

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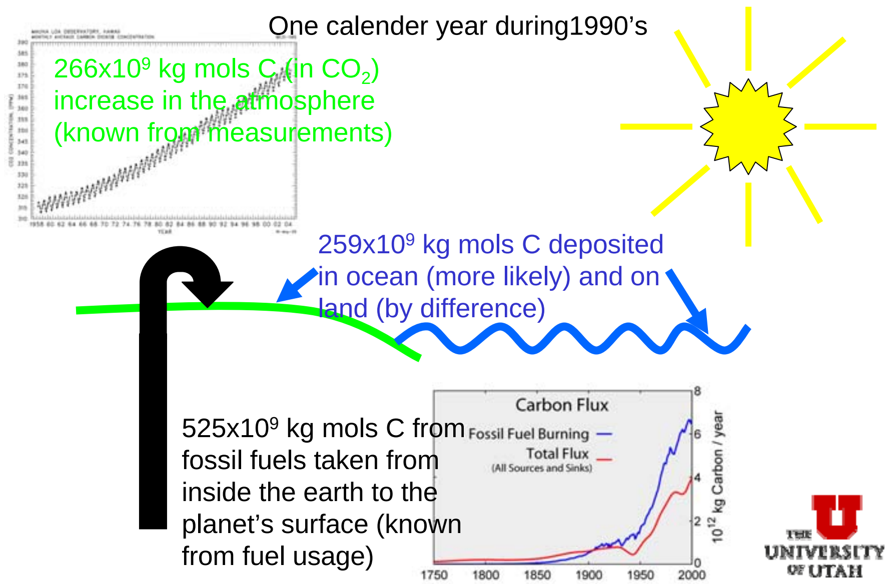
Scope of this presentation

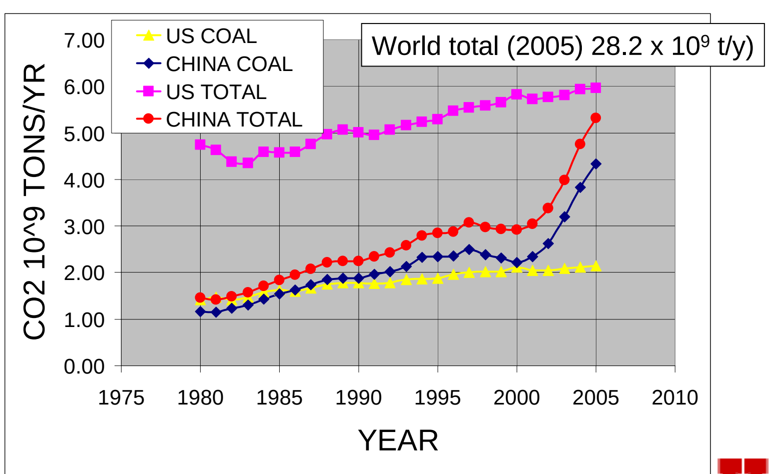
- Identify problem and potential role of oxy-coal combustion
- Focus on pulverized coal configurations rather than on circulating fluid bed combustors, and other systems
- Identify current state of the technology and critical research issues.

Motivation: typical annual dislocation of carbon originally within the earth.

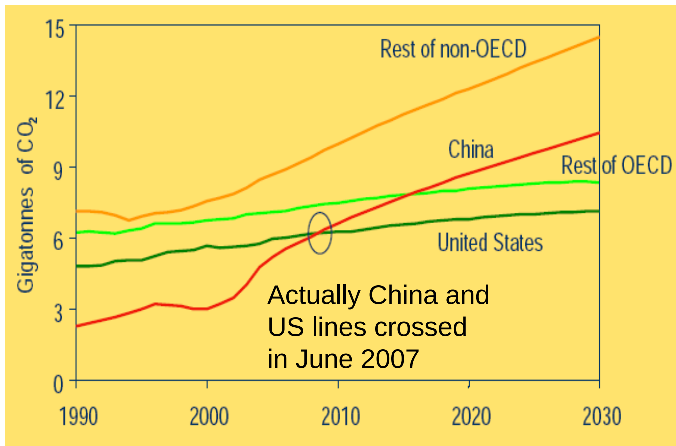


Coal and total CO_2 emissions

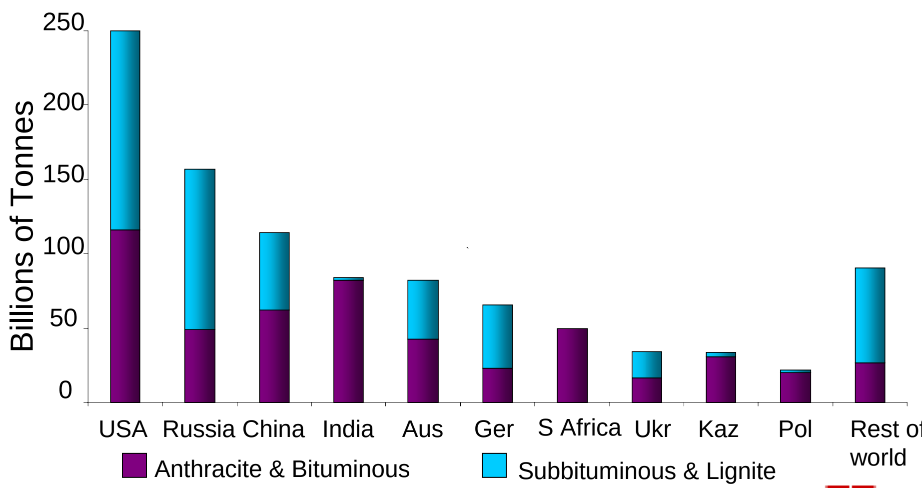
Historical - US and China



CO_2 emission projections, all sectors.



However, coal is abundant



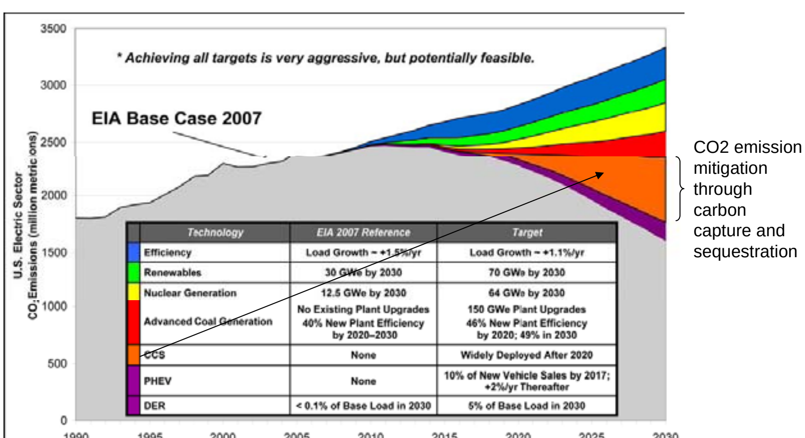
Source: 2003 BP World Energy Outlook.

The problem

- Increasingly large amounts of carbon are currently being transported out of the ground, onto the surface and into the atmosphere (as CO_2) of the earth.
- A preponderance of peer reviewed scientific opinion suggests that consequences of this will have profound effects on global climate change.
- The US and China are major emitters of CO_2.
- Coal combustion is a major source of carbon dioxide emissions, both in US and in especially in China.
- Electric power generation accounts for most of the coal combustion CO_2 in the US and in China.
- Ample supplies of coal are available for future energy use.
- "*We conclude that CO_2 capture and sequestration (CCS) is the critical enabling technology that would reduce CO_2 emissions significantly while also allowing coal to meet the world's pressing energy needs"* Deutch and Moniz 2007 *The Future of Coal Coal,* MIT

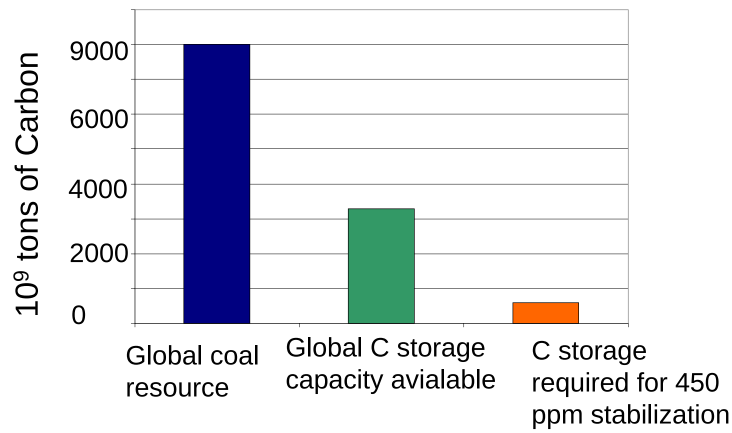
The power to reduce CO_2 emissions

Ref EPRI Technology Assessment Center 2007



Technology	EIA 2007 Reference	Target
Efficiency	Load Growth ~ +1.5%/yr	Load Growth ~ +1.1%/yr
Renewables	30 GWe by 2030	70 GWe by 2030
Nuclear Generation	12.5 GWe by 2030	64 GWe by 2030
Advanced Coal Generation	No Existing Plant Upgrades 40% New Plant Efficiency by 2020–2030	150 GWe Plant Upgrades 46% New Plant Efficiency by 2020; 49% in 2030
CCS	None	Widely Deployed After 2020
PHEV	None	10% of New Vehicle Sales by 2017; +2%/yr Thereafter
DER	< 0.1% of Base Load in 2030	5% of Base Load in 2030

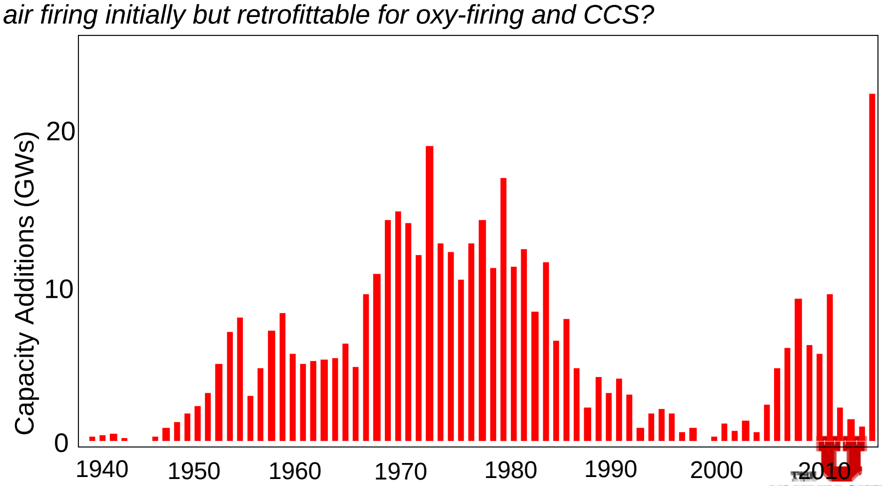
C storage capacity is abundant



Source: James Dooley, Pacific Northwest National Laboratory, Battelle, 2004

New coal plants built/planned

Many new coal-fueled power plants are currently being planned. These represent over 250 MMTPY of coal use. Therefore: short term focus to implement CCS for coal should be on NEW, EFFICIENT units designed for air firing initially but retrofittable for oxy-firing and CCS?



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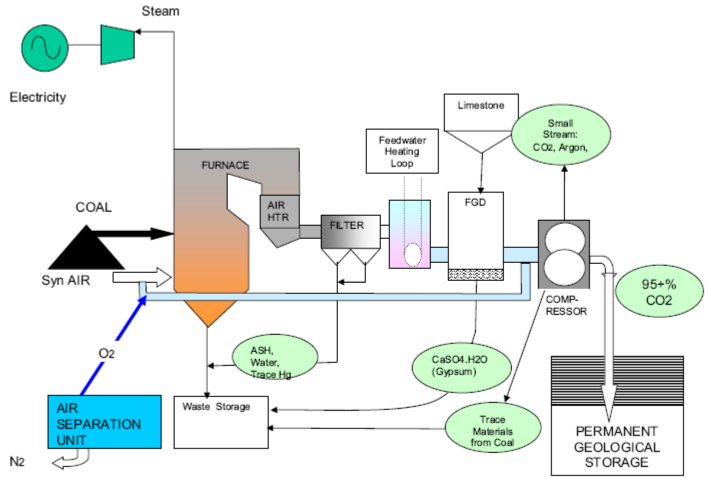
Oxycoal combustion: near-term application to efficient conventional boilers. (Stobbs, 2007)



SaskPower Oxyfuel Process

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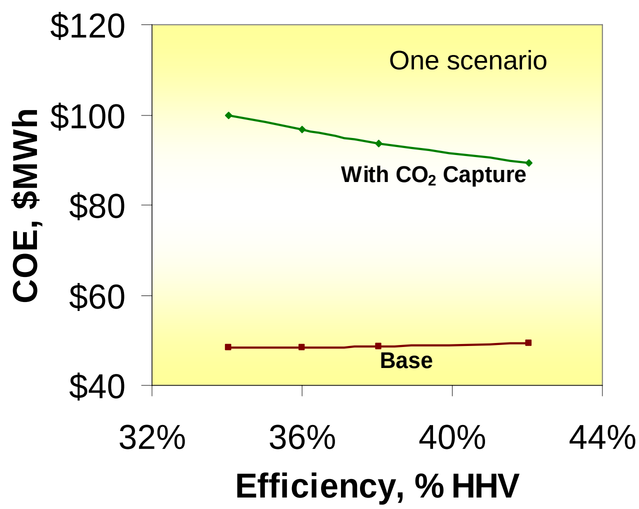
Is oxy-coal combustion economically viable?



Adapted from: Shah, Minish M., Electric Power 2007 Conference, Chicago, May 1-3, 2007

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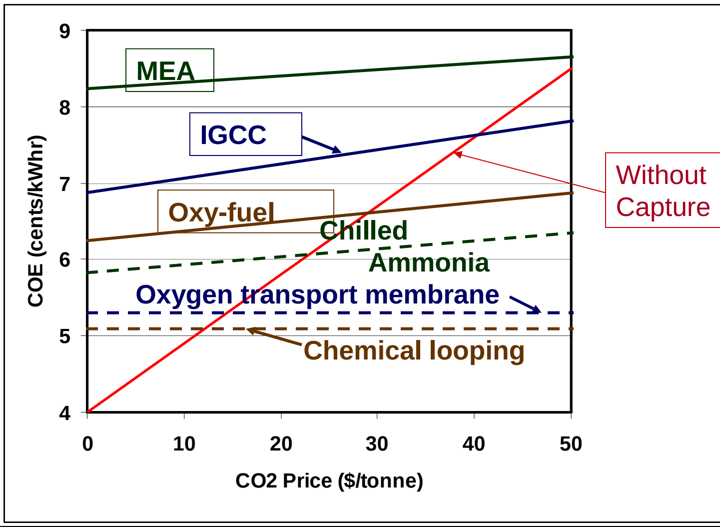
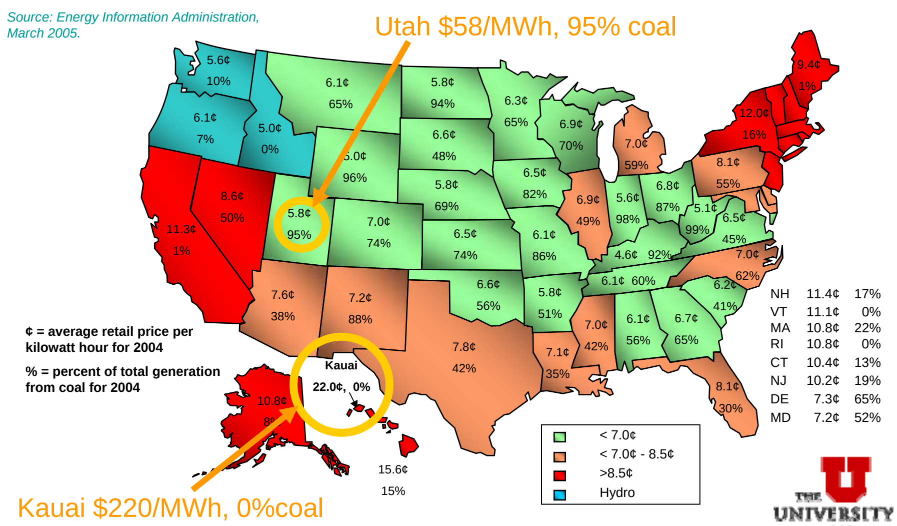
Another scenario for costs:

Variations depend greatly on assumptions *(Marion et al, 2004)*



Retail price of electricity (2004) and percentage from coal

Huge variations: Low – Kentucky at $46/MW-h; High – Island of Kauai, HI at $220/MW-h.



Oxy-coal combustion: Two over-arching issues

1. O_2 supply energy penalty
   – Current cryogenic technology can consume 15-20% of energy produced
2. Purity of CO_2 flue gas for sequestration
   – Is it a waste? Or a resource?
   – Regulatory and legal issues.
   – Does it have commercial value for tertiary oil recovery?
   – What impurities are allowed?
     • Corrosion during transportation to disposal site?
   – Technology for purification, if required.

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Oxygen supply

• Currently available
  – Air separation unit
  – Modest energy improvements
• Breakthroughs
  – Oxygen transport membranes
  – other

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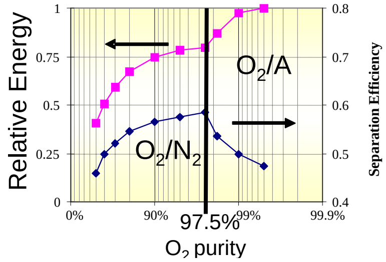
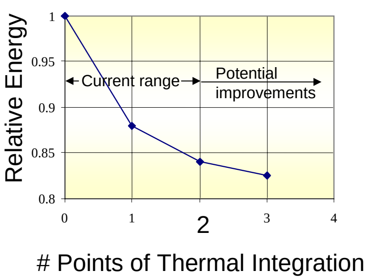
Oxygen supply energy penalty (near term)

Taken from Shah, M.M., 2006 Clearwater Conference

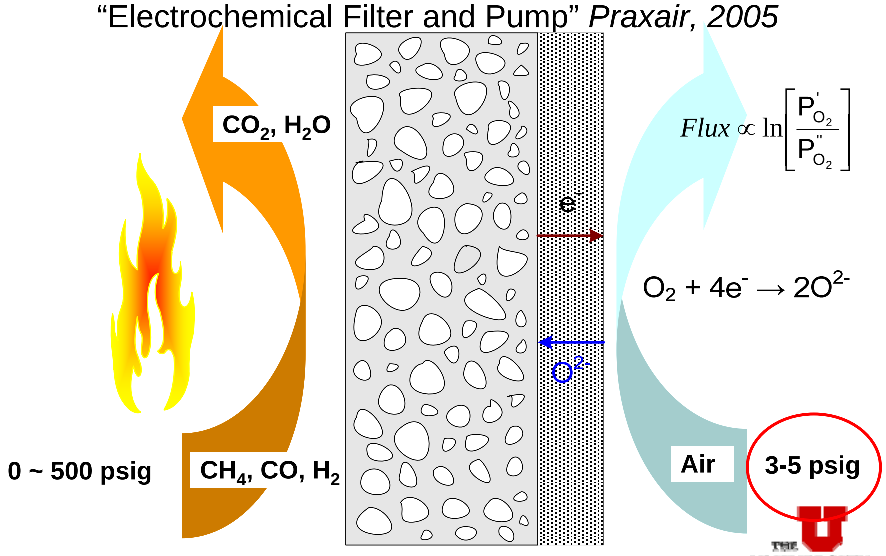




- ASU Cryogenic distillation
- Oxygen purity
  - At 97.5% O_2 purity sudden increase in energy requirements due to O_2/A separation.
- Points of thermal integration
  - ASU capacities > 5000 tpd might justify increased thermal integration to recover additional energy within ASU.

Example: Potential breakthrough: *Integrated* Oxygen Transport Membrane (OTM)

"Electrochemical Filter and Pump" *Praxair, 2005*



CO_2 purity: Technical issues

- What impurities can be removed during simple compression?
  - Moderate co-capture 100% SO_2, 15%NO_x (might require SCR)
  - Extreme co-capture (*Allam, Air Products, 2006*)
- SO_2 is converted to Sulfuric Acid, NO_2 converted to Nitric Acid:
  - $NO + NO + O_2 = 2NO_2$ (1) Slow
  - $2\ NO_2 = N_2O_4$ (2) Fast
  - $2\ NO_2 + H_2O = HNO_2 + HNO_3$ (3) Slow
  - $3\ HNO_2 = HNO_3 + 2\ NO + H_2O$ (4) Fast
  - $NO_2 + SO_2 = NO + SO_3$ (5) Fast
  - $SO_3 + H_2O = H_2SO_4$ (6) Fast
- Rate of Reaction 1 increases with Pressure to the 3rd power
  - only feasible at elevated pressure
- No Nitric Acid is formed until all the SO_2 is converted
- Hg, As and other trace metals dissolved in acid solution
- Pressure, reactor design and residence times, and NO concentration are important
- Can oxy-coal combustion operate with no APC technology required?
- Is high NO_x desirable for the reactions above to occur?

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Oxy-coal *combustion* research outputs

1. Enabling technology for retrofit in conventional, but new, high efficiency, air-tight, air-fired units that have been proven for air firing (short term).
2. Enabling technology for oxy-coal application to new units that were never planned for air firing, but "still look (somewhat) like boilers" (intermediate term)
3. Research for development of new technologies which do not look at all like current boilers (long term).

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Retrofit for existing, but efficient air fired units

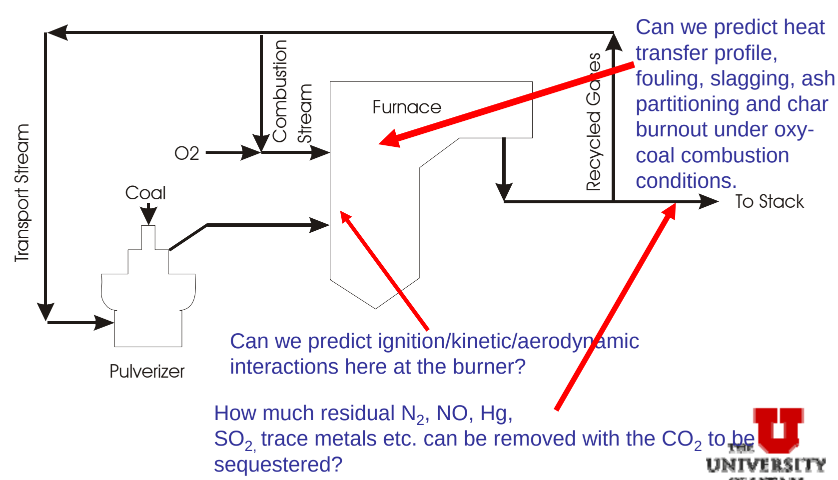
Short term applications

"not only looks like a boiler, but actually works like a boiler"

- Need for *simulations* which allow:
  1. Fiddle-free *validation* using comprehensive (heat transfer, temperature profile, O_2, CO_2, NO_x profiles, ash deposition, steam side properties) data from air-fired coal combustion units
  2. *Validated sub-models* for various oxy-coal combustion processes – heat transfer, ignition, burnout, ash etc.
  3. *Extrapolation* from air fired to oxy-combustion conditions

Oxy-Coal Combustion (short term):

Schematic of oxygen fired PC furnace with CO_2 recycle (*Sarofim et al, 2004*)



Retrofit issues: need for *validated* sub-models to extrapolate from air to O_2

- Heat transfer sub-model
  - Radiant zone
  - Convection zone
- Coal jet ignition sub-model
  - Chemistry
  - Burner aerodynamics and heat transfer
- Char burnout sub-model
- Ash partitioning sub-model
  - Deposition
  - Trace metals
- Combustion by-products
  - NO_x, SO_x, Hg
- Integrated furnace model
  - Calculation of heat transfer, species, temperature profiles in all furnace zones as function of recycle ratio. For heat transfer see *Payne, Chen, Wolsky, and Richter Combust. Sci. Technol, 67,1,1989*

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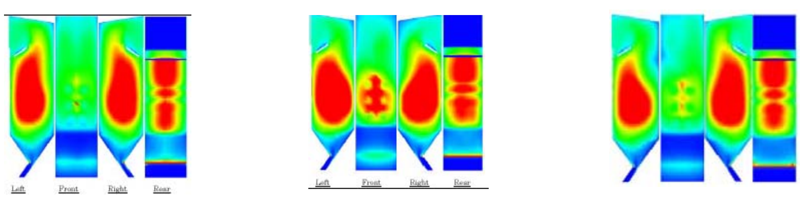
Heat transfer sub-model: radiant zone

Wall heat flux predictions (taken from *Wall,T.F. Symposium (International) on Combustion, Heidelberg, August 2007, calculations attributed to IHI)*



Air firing *30% O_2 – match T_{adb}* *26%O_2 – match heat transfer*

•Should we match adiabatic temperature (30% O2; R=0.7, R_{PRAX}=2.33) OR wall heat flux (26% O2; R=0.74, R_{PRAX}=2.85)?

• The high proportions of CO_2 and H_2O in the furnace gases result in higher gas emissivities

•The volume of gases flowing through the furnace is reduced

•The volume of flue gas (after recycling) is reduced by about 80%.

•Recycled gas species have higher concentrations in the furnace.

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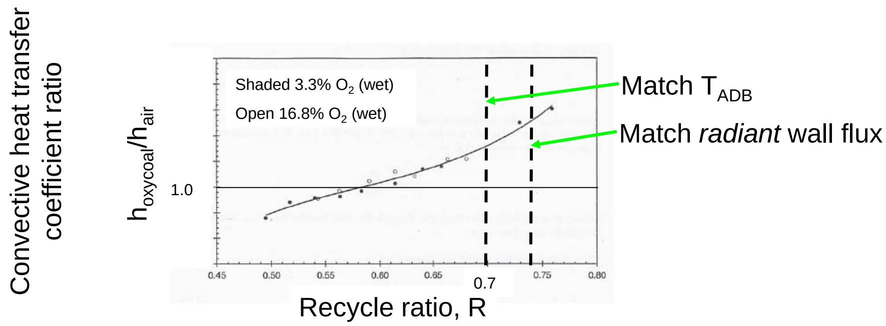
Heat transfer sub-model: convection zone



- Flue gas properties different from those of air (e.g. Prandtl Number). At R=0.7, 30%O_2, h_{oxy}/h_{air}=1.15 for convective pass (no ash deposit resistance). As recycle ratio decreases, *h* decreases to a value below the baseline air fired case. *(Woycenko, Ikeda, van de Kamp, 1994, "Combustion of Pulverized Coal in a Mixture of Oxygen and Recycled Flue Gas", IFRF Document #F98/y/1)*
- Volumetric flow rate of flue gases is decreased – both with T_{adb} match and radiant zone wall flux match.
- However, deposition of ash on heat transfer surfaces might be controlling
  - Needs validated ash partitioning model
  - Needs validated ash deposition model

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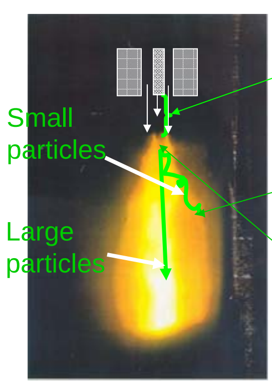
Coal jet ignition sub-model



•Standoff ignition distance depends on primary jet velocities, and P_{O2}, which becomes an independent variable under oxy-coal combustion

•Sub-model should capture observations that smaller particles preferentially migrate to jet edge. *Sinclair Curtis (2003)*. Implications on effects of secondary P_{O2}, also an independent variable.

•Pyrolysis behavior. *(Naredi and Pisupati, 2007, Penn State University)*
•Particle ignition. (*Shaddix and Molina, 2005, 2006, Sandia Labs)* Influence of gas properties which vary heat transfer to coal particle.

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Char burnout sub-models

- Contradictory results in the literature on effects of oxy-coal combustion, with CO_2 recycle, on char burnout times.
  - Increased burnout times (Alverez, 2005, Shaddix et al. 2006, 2007)
  - Similar burnout times (Liu et al., 2005), Borrego et al., 2007)
  - Decreased burnout times (Borrego et al. 2007)
- Need to untangle conflicting effects of
  - Residence time changes
  - Surface reaction effects of composition changes
  - Particle transport effects of composition changes
  - Coal composition and rank effects
  - Temperature profile changes.
- Need well defined, systematic, experimentation to validate existing char burnout models and identify the need for new ones.

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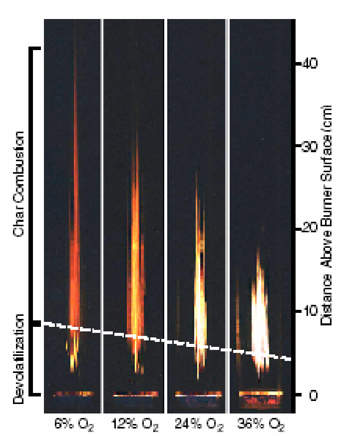
Char burnout sub model (contd.)



Taken from Murphy and Shaddix, 2006
Effect of O_2 concentration in N_2 on char combustion in flue gases. Expanded by Shaddix and Molina (2007) to explore effect of CO_2 bath.

- Possible influences of CO_2 vs N_2
  1. Effect of CO_2 on film diffusion of O_2 to char surface (20% slower).
  2. Effect of CO_2 heat capacity on peak *gas* temperature around boundary layer and on heat transfer back to particle
  3. Competition for available reaction sites for O_2
  4. Direct gasification of char by CO_2
- *Shaddix and Molina* *(Pittsburgh Coal Conference, Johannesburg, Sep 10-14, 2007)* showed at 12%O_2 and higher
  - Char particle temperature, $T_{p,}$ is lower (by 50-100K) in CO_2 hence combustion rate is lower.
  - But, *at given* T_p the burning rate unchanged
  - Postulate 1 above is main cause for CO_2 effect. (Even though film diffusion is not controlling it still has an effect).
  - Gasification reactions may play greater role for O_2<< 12%

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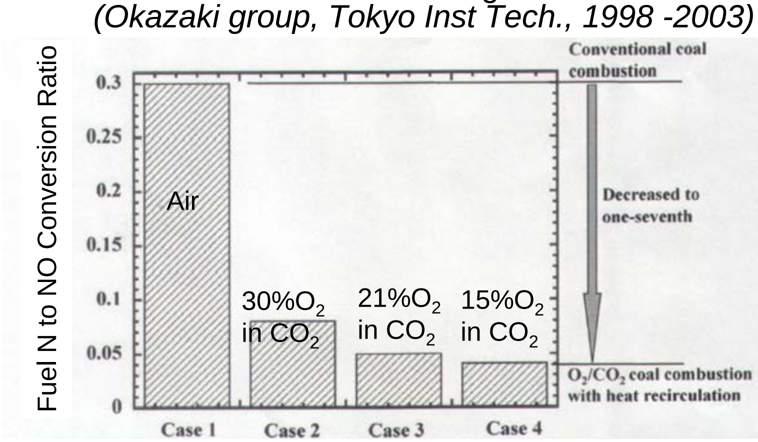
Ash partitioning and deposition sub -model

- Little information available on effect of oxy-combustion on size segregated ash aerosol compositions.
- Particle deposition and slag formation.
- Effects of high CO_2, SO_2, SO_3 and recycling of these species.
- Equilibrium analyses are available *(e.g. Weber et al, IEF-2, Julich, Germany, 2007)*
- Important for heat transfer sub-model
- Critical gap.

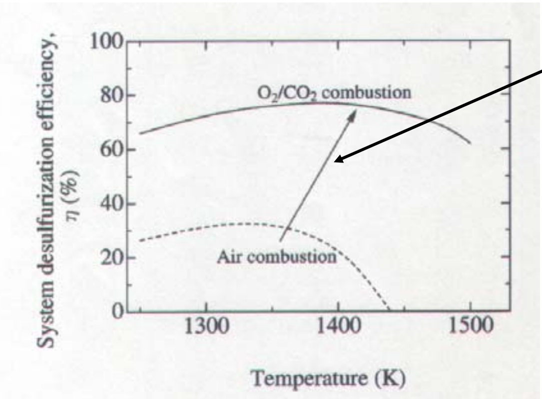
Combustion by-products sub-model: NO_x

- NO_x produced is very much less with recycle on a mass emission basis.
- Mechanism due to reburning and is well understood *(Okazaki group, Tokyo Inst Tech., 1998 -2003)*



Taken from Okazaki, K. Plenary lecture, 13th intl. Heat Transfer Conf., Sydney, August 2006

Combustion by-products sub-models – SO_x, Hg, other



Taken from Okazaki, K. Plenary lecture, 13th intl. Heat Transfer Conf., Sydney, August 2006

- SO_3 is potentially much higher.
- Sulfation of $CaCO_3$ is 4-6 times higher. *(Liu & Okazaki, 2003)* Mechanisms?
- Little data available on Hg, and trace metals
- Hypothesized chemistry (rates, mechanisms etc.) during compression/condensation needs to be validated *(Allam 2006, 2007)*

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Application to new units: Intermediate term

“Still looks like a boiler” *somewhat*.

- How to minimize (optimize, eliminate?) externally recycled CO_2 stream.
  - H_2O recycle/injection?
  - CANMET oxy-fuel R&D program (*Zangane, K., 57th Canadian Chemical Engineering Conference, Edmonton, October 28-31, 2007)*
- Draw on oxy-fuel experience for glass furnaces.
- Use internal recycle to diminish temperature peaks.
  - “Flameless combustion”?
- Identify critical barriers to implementation in boilers.
  - Materials
  - Directed O_2 injection.
- Need simulations
  - Aerodynamic/temperature predictions for internal recirculation caused by super fast jets
  - Heat transfer simulation to allow controlled cooling
  - Ash partitioning and deposition
  - Steam side system predictions
  - Validated components/modules

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New technologies: long term

Unlikely to look much like a current boiler.

- Integrated oxygen transport membrane applications.
- Chemical looping (using oxygen carriers)
  - Iron oxide based
  - Calcium sulfate/sulfite based
- Circulating fluidized bed
- Other

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Summary & conclusions

- Future use of coal requires CCS
- Oxy-coal combustion can play a role for new boilers, initially built to fire air, but with the potential for future retrofit (new, CCS ready boilers)
- Two overarching issues are O_2 supply and required CO_2 purity.
- In the short term *validated* simulations will be the key to allow retrofit with confidence.
- Simulation sub-models still require some development and validation, although much is already known.
- Intermediate term should focus on optimizing (eliminating?) flue gas recycle. Needs *validated* simulations.
- In the long term there are many competing concepts, ranging from chemical looping to integrated oxygen membranes. These units will not look much like boilers.

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