CO_2 Reduction by Oxy-Fuel Combustion: Economics and Opportunities

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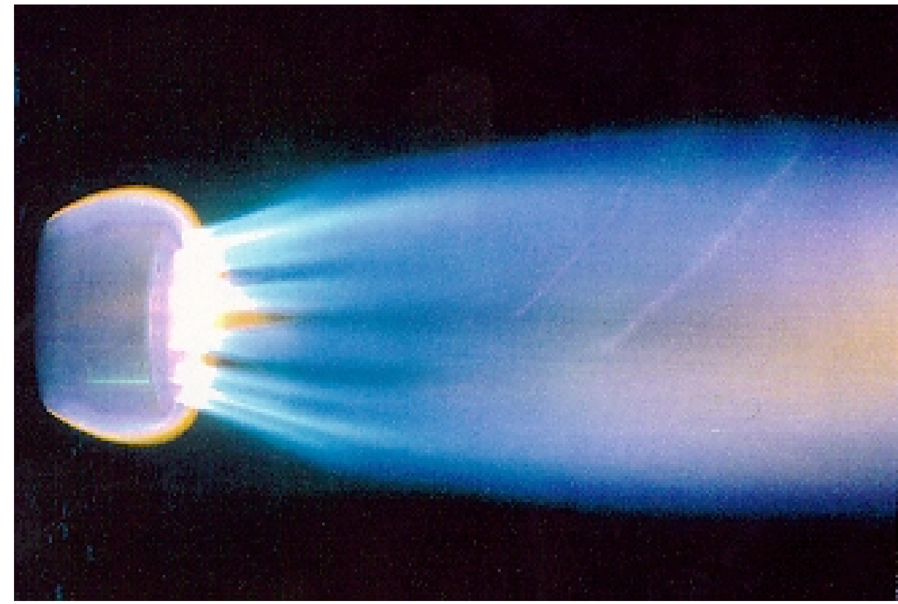
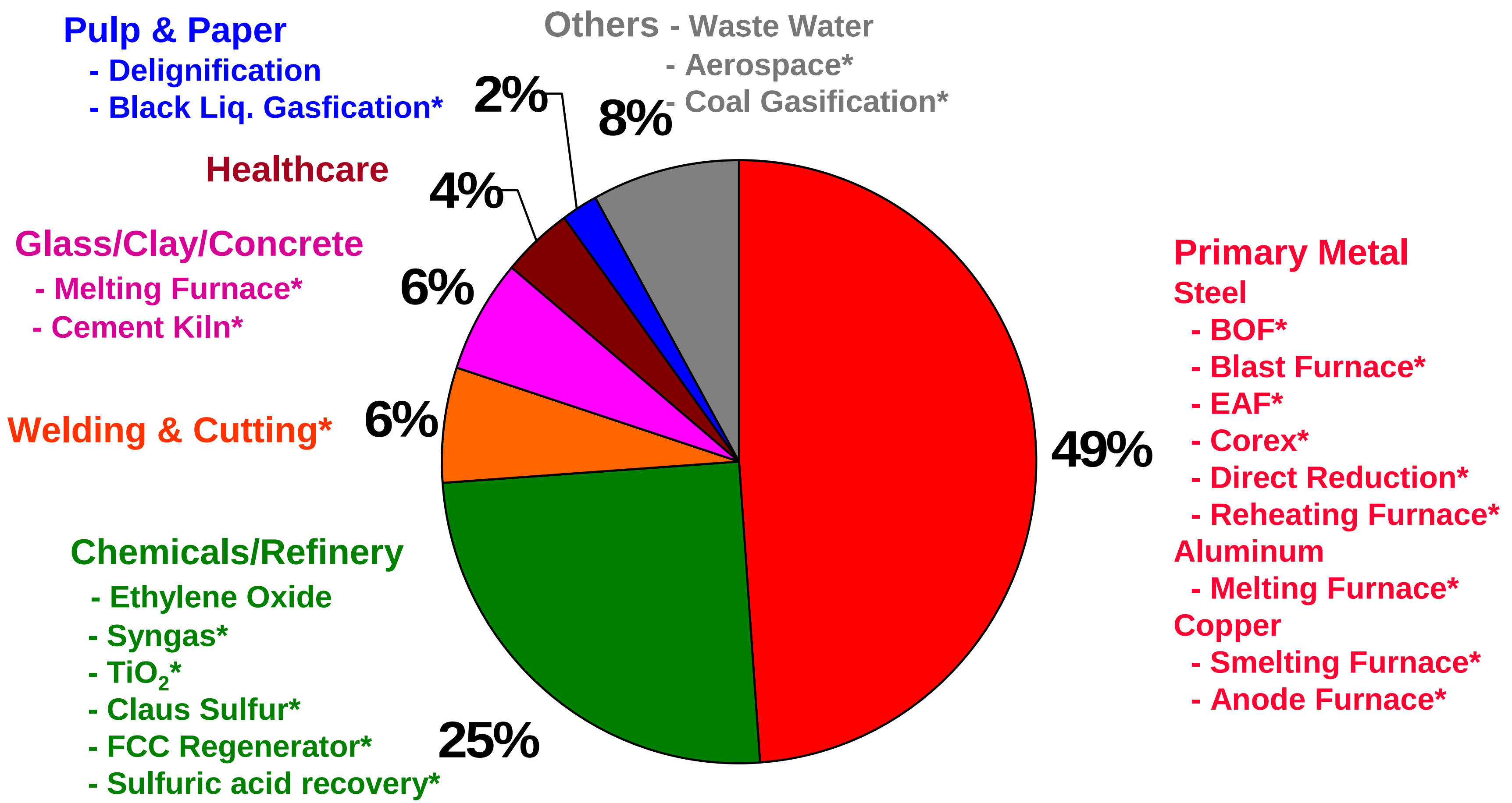


GCEP Advance Coal Workshop
Provo, Utah
March 15, 2005

Worldwide Oxygen Market and Applications

(Market Size $8.3B)



***** Most of oxygen is used for high temperature metallurgical processes and combustion applications***

Source: Salomon Smith Barney 2002

Oxy-Fuel Combustion
History of Applications Development

1

High Temp
Applications
1940-1950s

Welding
Cutting
Flame polishing

2

Productivity
Enhancement
O2 Enrichment
1960-1970s

Glass
Aluminum
Cement

3

Fuel Savings
Full Oxy-fuel
Combustion
1980s

Incineration
Steel
Copper

4

NOx
Reduction
1990-2000s

Glass Melting
(30% of US capacity)
Coal Fired boilers

5

CO2
Reduction
2010s ?

Power generation
-CO2 sequestration
IGCC
Oxy boilers

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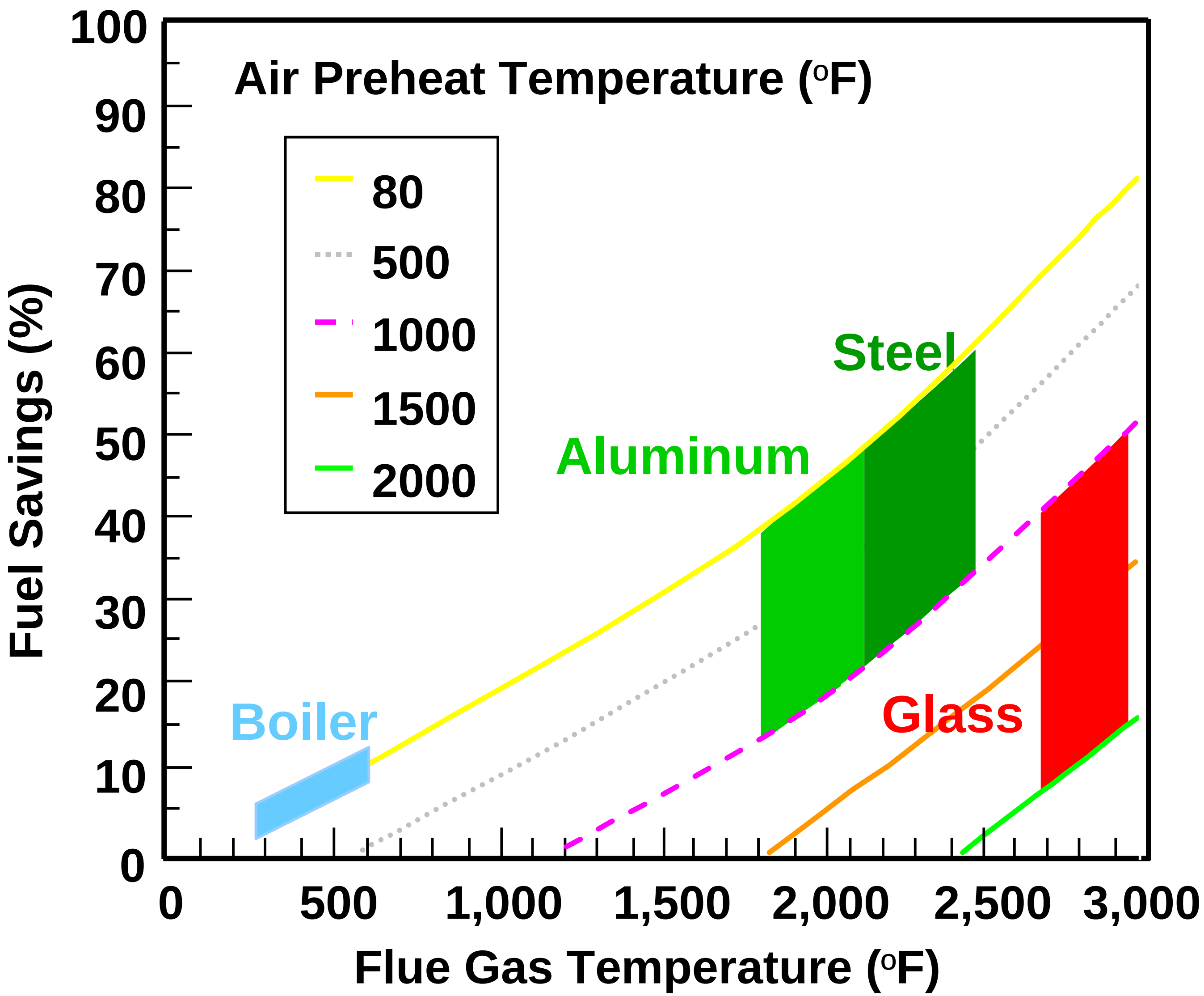
Methods to Reduce CO_2 Emissions by Oxy-Fuel Combustion

1. **Oxy-fuel combustion to improve fuel efficiency to reduce CO_2 emission**
   1. **Power required for oxygen production has to be considered.**
2. **Oxy-fuel combustion to produce flue gas with high CO_2 concentration for sequestration**
   1. **Oxy-fuel with FGR for retrofitting existing air fired furnaces**
   2. **Direct oxy-fuel firing**
3. **Oxy-fuel combustion to increase productivity to reduce specific fuel consumption and CO_2 emission**

Fuel Savings With 100% Oxy-Fuel Conversion
Fuel: Methane, 2% O_2 In Flue Gas



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Energy Required for Oxygen Production

Current technologies to produce 95% O2 purity requires

~200 Kwh/ton O2

2 MMBtu of fuel /ton O2 at 10,000 Btu/kwh (e=34%hhv)

1.2 MMBtu of fuel /ton O2 at 6,000 Btu/kwh (e=57%hhv)

To reduce net energy consumption in furnaces by oxygen combustion fuel savings of about 9 to 14% are required to compensate for the energy for oxygen production.

For Oxygen-CH4 Fired Power Plant

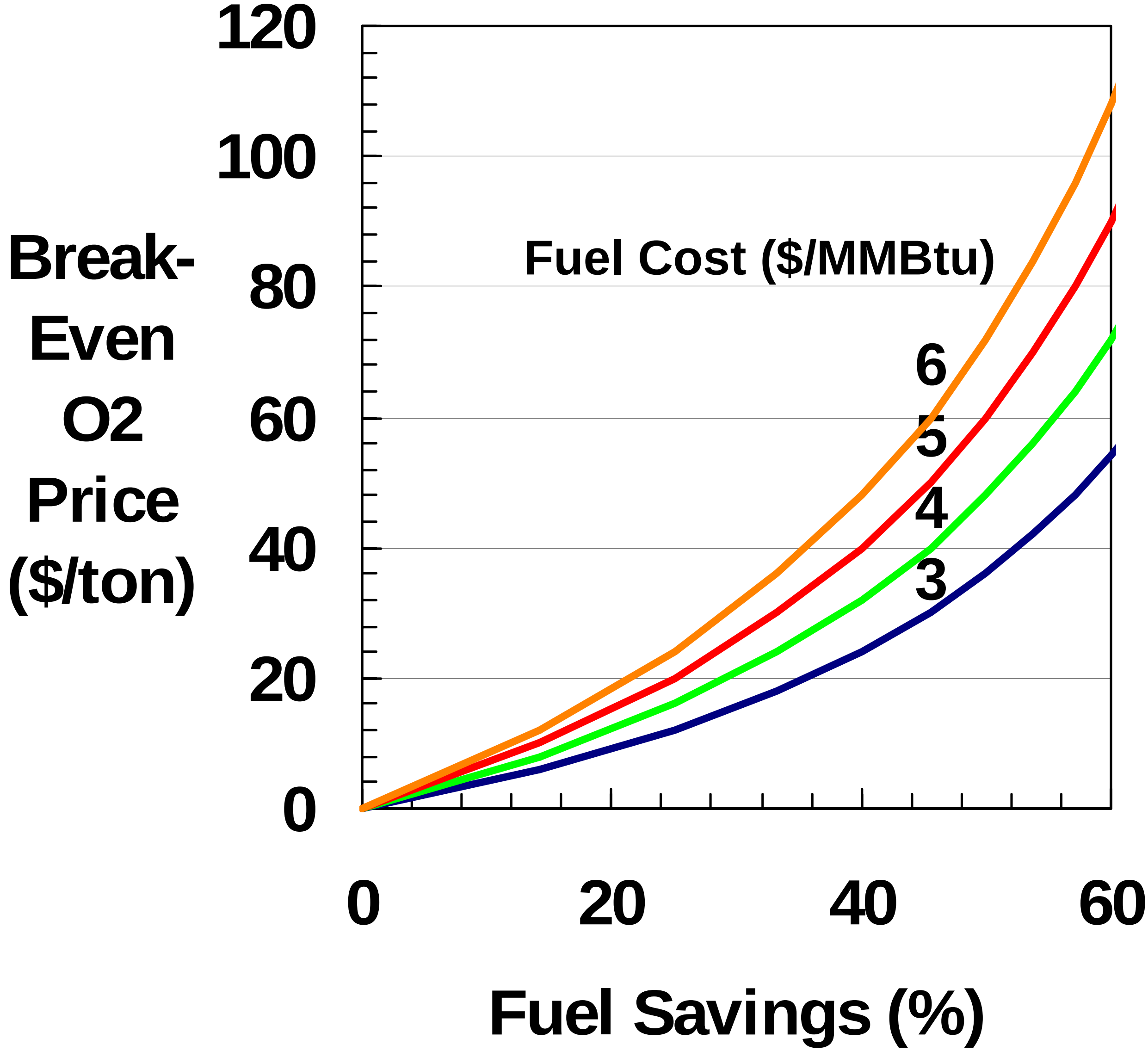
17% Of power output is consumed at e=34% hhv

10% Of power output is consumed at e=57% hhv

Fuel Savings and Break-Even Oxygen Price

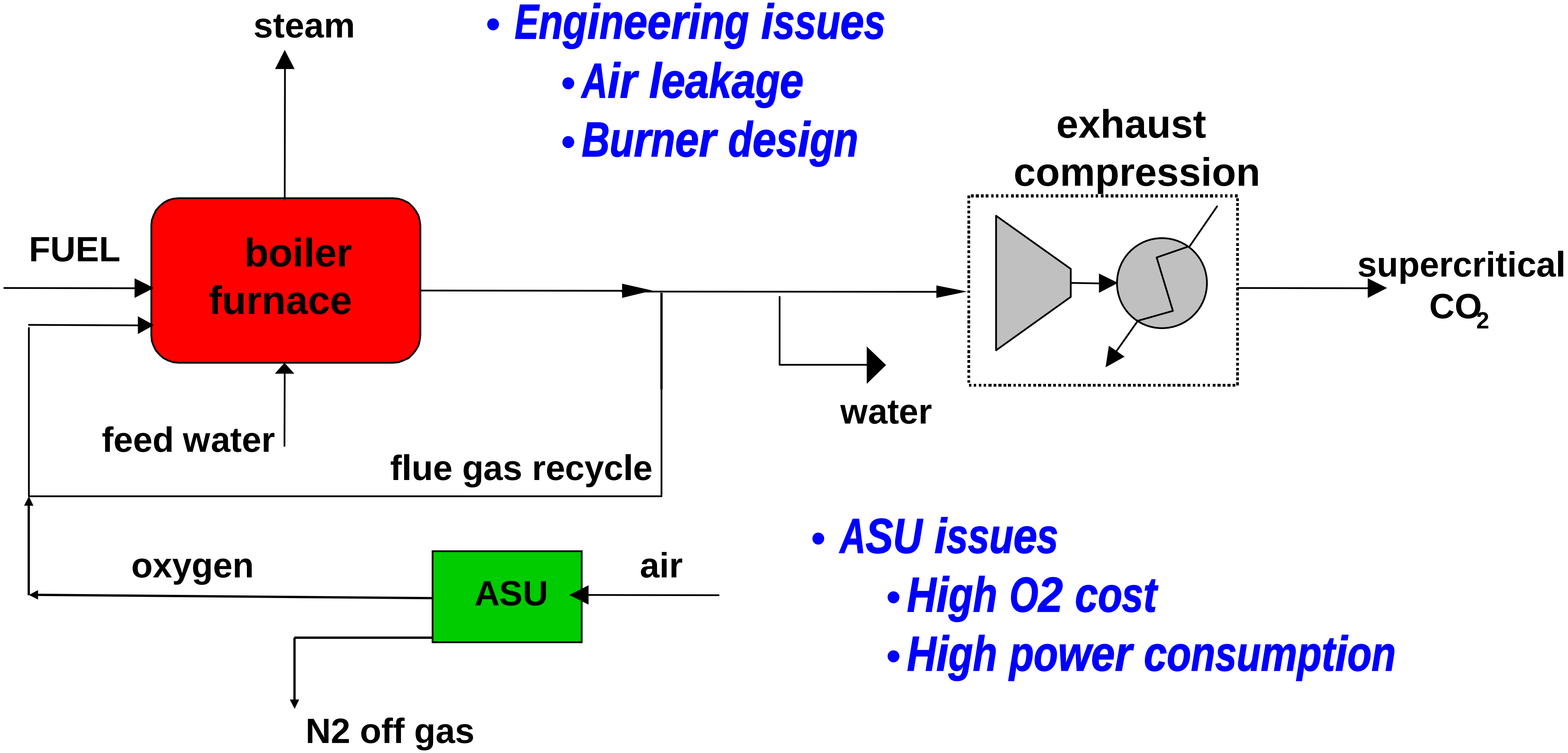
- ***Minimum fuel savings of 20% are required to pay the cost of oxygen. (without considering other oxy-fuel benefits)***

- ***Most current oxy-fuel applications save more than 20% fuel and result in net reduction in CO2 emissions***



Oxygen-Recycled Flue Gas Fired Boiler for CO_2 Sequestration (retrofit)

- *Technically feasible*
  - *Oxy-coal firing tested in pilot scales*
- *Engineering issues*
  - *Air leakage*
  - *Burner design*



- *ASU issues*
  - *High O2 cost*
  - *High power consumption*

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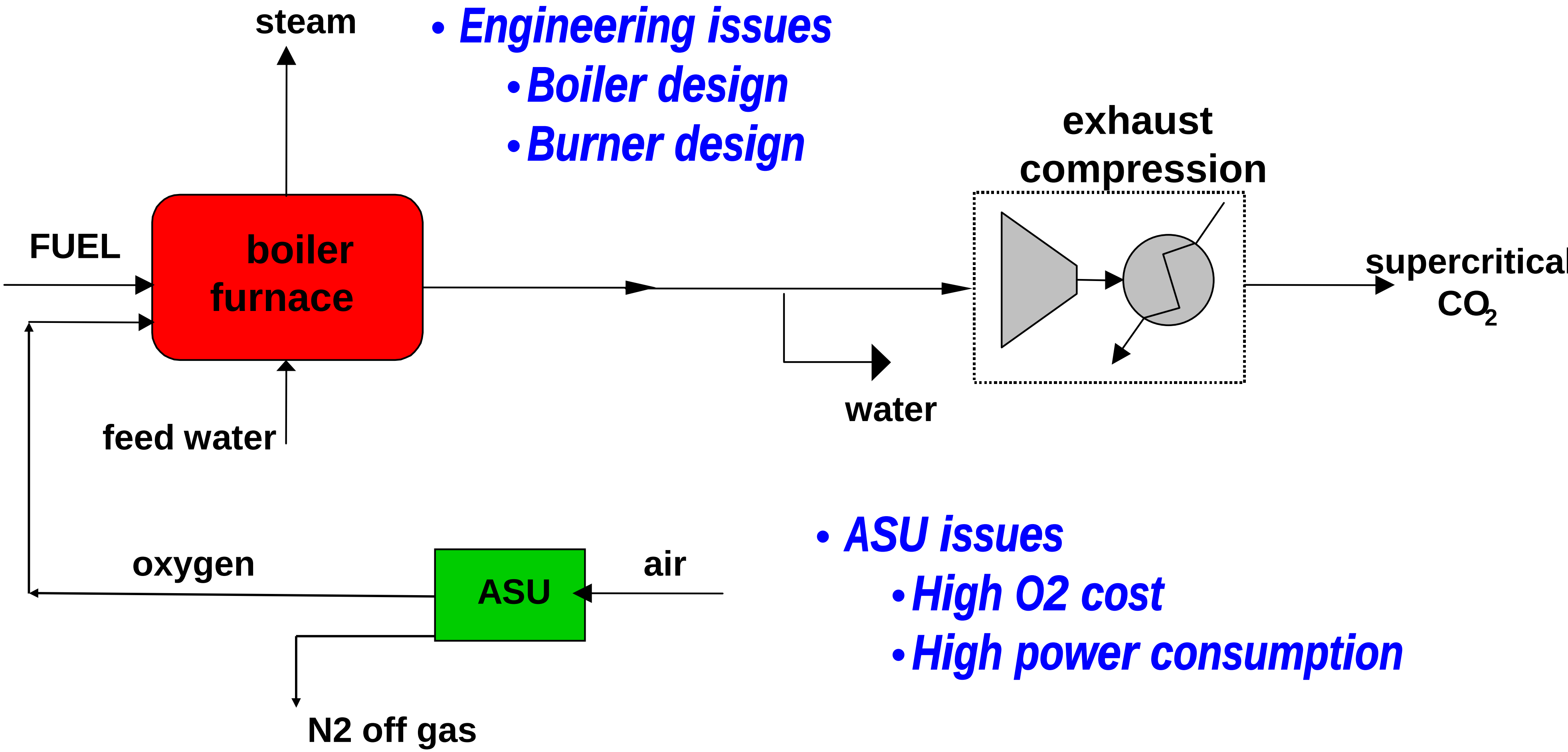
Direct Oxygen Fired Boiler for CO2 sequestration (new)

- *Technically feasible*
  - *Oxy-oil firing tested in a pilot-scale in Japan*
- *Engineering issues*
  - *Boiler design*
  - *Burner design*



- *ASU issues*
  - *High O2 cost*
  - *High power consumption*

Oxy-Fuel Combustion Technology – Current status and Issues

1. Technologies to control flame temperature and heat flux have been developed for most gas and oil-fired furnace applications

-> Oxy-fuel flames can be used in any air-fired furnaces

-> 30% of glass melting furnaces have been converted to oxy-fuel firing

2. Large NOx reduction has been demonstrated for both thermal and fuel NOx

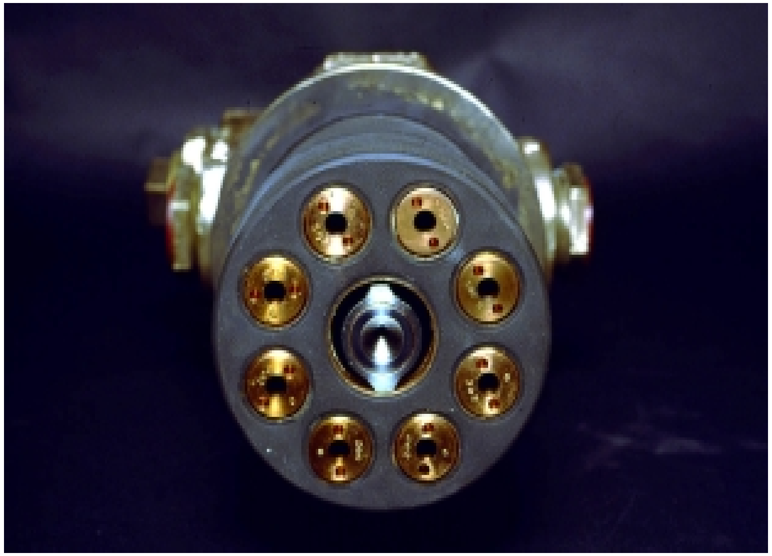
3. Limited experiences with oxy-coal burners

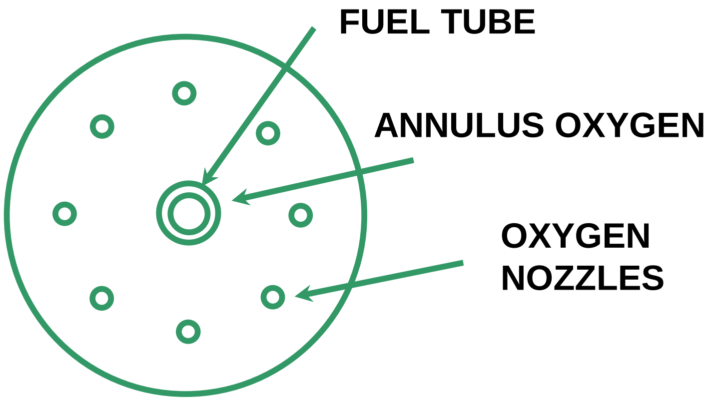
-> engineering issues remain on optimum burner configurations for O2 and RFG streams

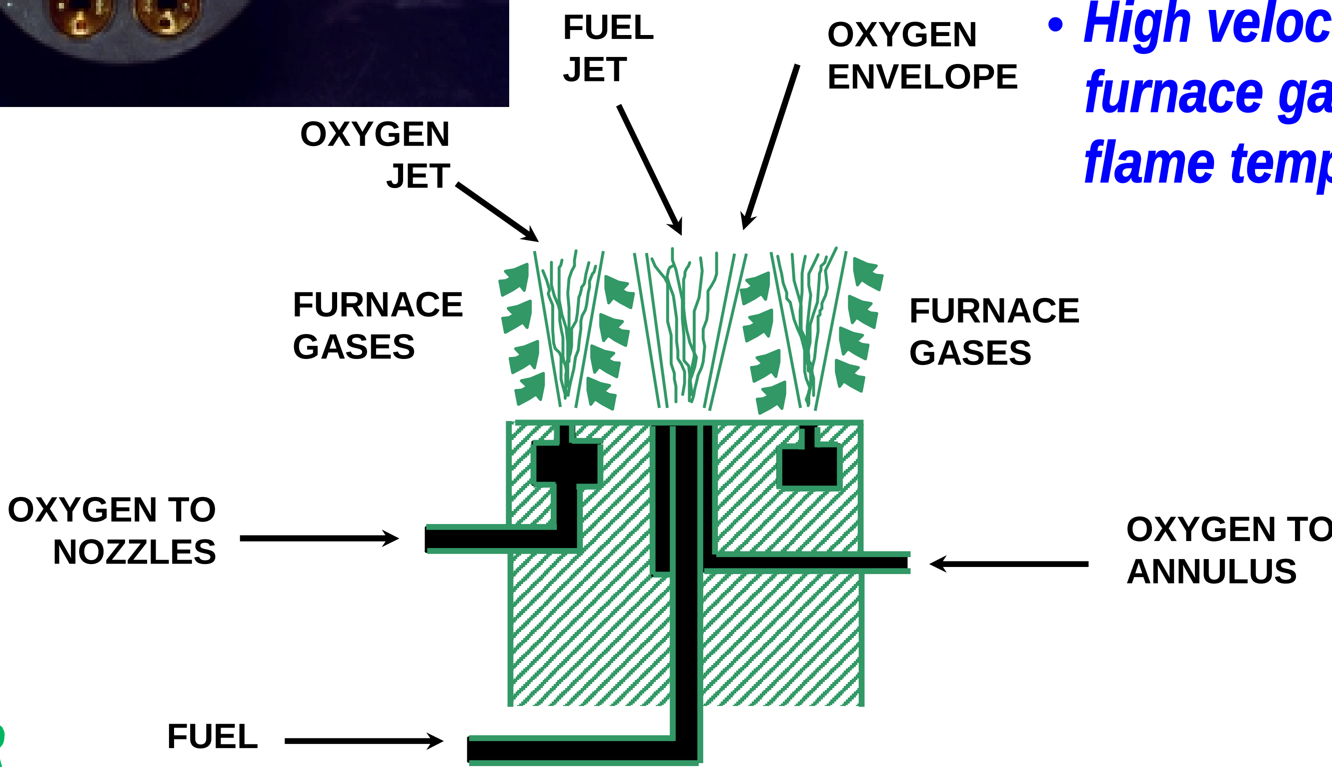
4. Limited fundamental data on coal combustion under oxygen atmosphere

Praxair "A" Burner

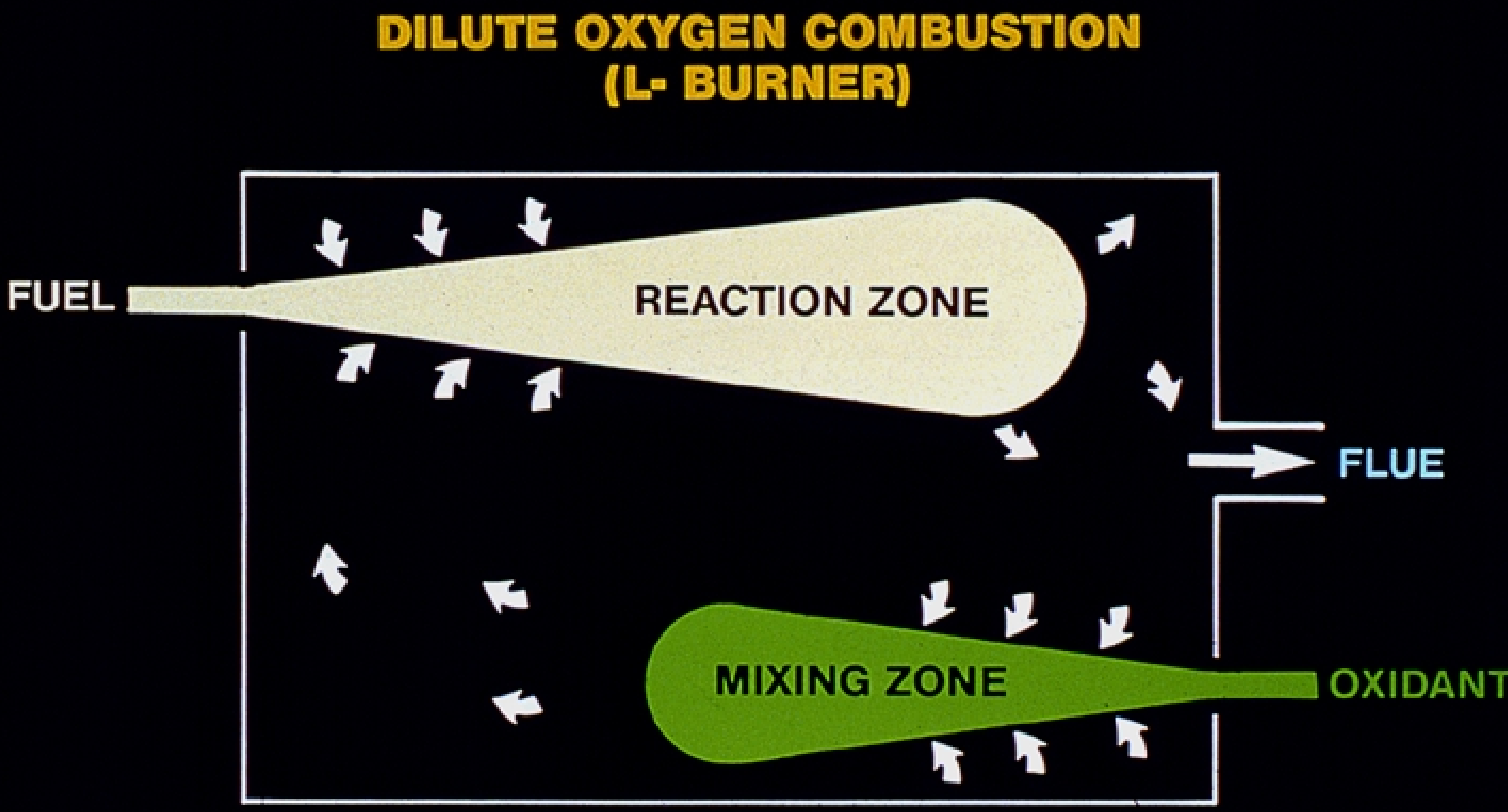
In-furnace FGR to control flame temperature and heat flux







- *High velocity O2 jets aspirate furnace gas and reduces the flame temperature*



High velocity fuel jet reacts with hot diluted oxygen (2-10%) in the furnace to achieve uniform heating and ultra low NOx

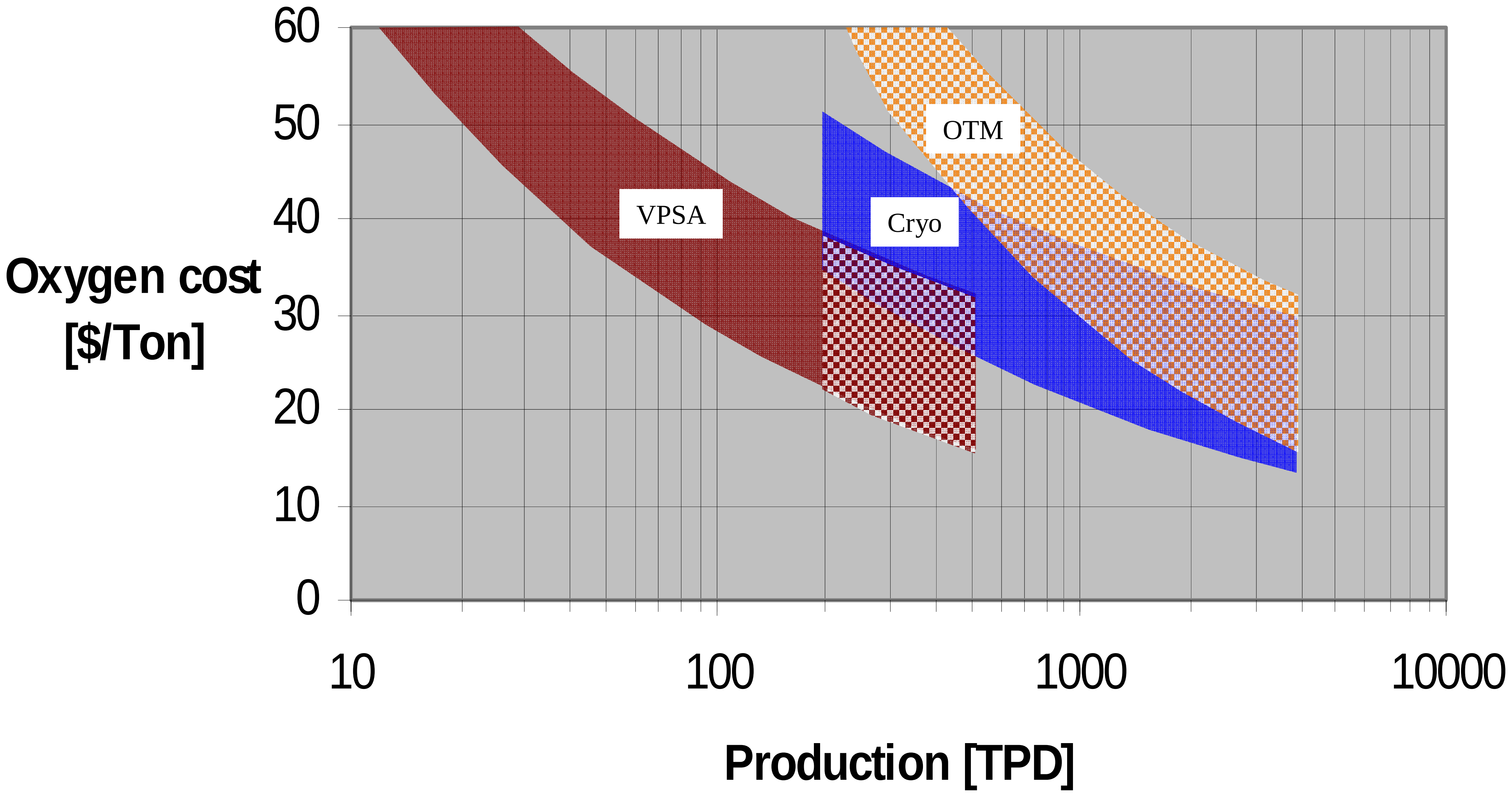
Oxygen Production Technologies

Cryogenic
- Uses low temperature distillation
- O_2 purities up to 99.9%

Vacuum Pressure Swing Adsorption (VPSA)
- Uses the adsorbent properties of zeolites
- Typical O_2 purities: 90-94 %

Ceramic Membranes (Oxygen Transport Membranes)
- Uses ceramic materials that are selective for oxygen ions at elevated temperature: O_2 purities 99+ %

Oxygen Production Costs vs. Plant Capacity



Power Required for Air Separation

Theoretical Energy Requirement to compress O_2 from 0.21 to 1 atm

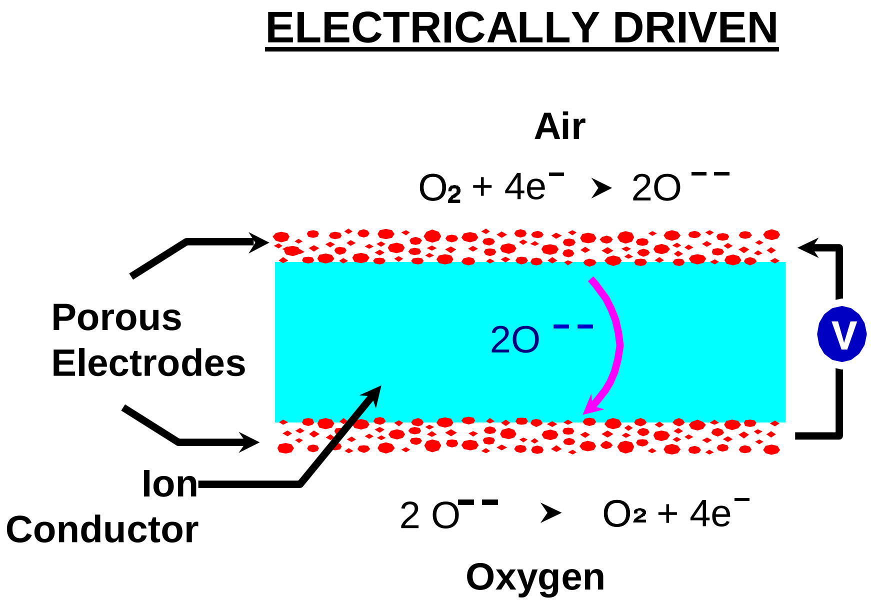
About 30 Kwh/ton O_2

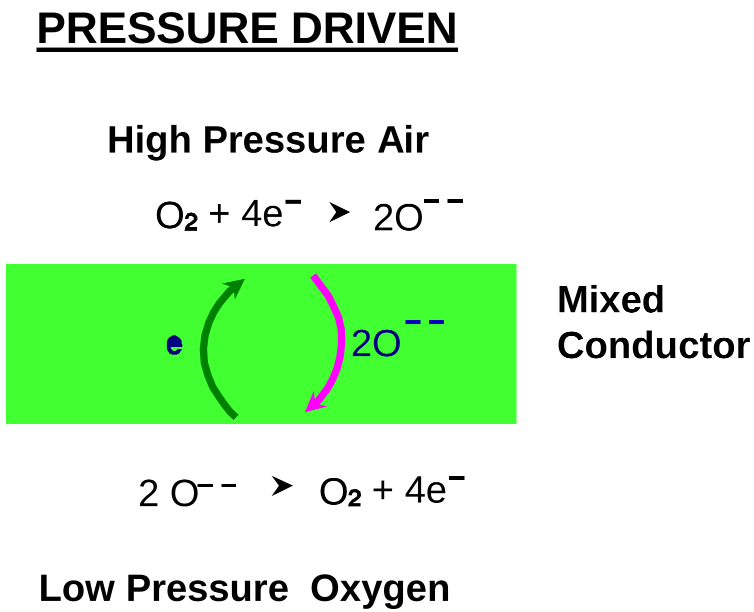
Current Cryo and VPSA For 90-95% O_2 Purity

About 200 Kwh/ton O_2

The current oxygen production technologies consume more than six times the theoretical energy requirement. Although the unit energy consumption to produce O_2 by cryogenic and VPSA processes continues to decrease, a step change technology is needed for CO_2 sequestration applications.

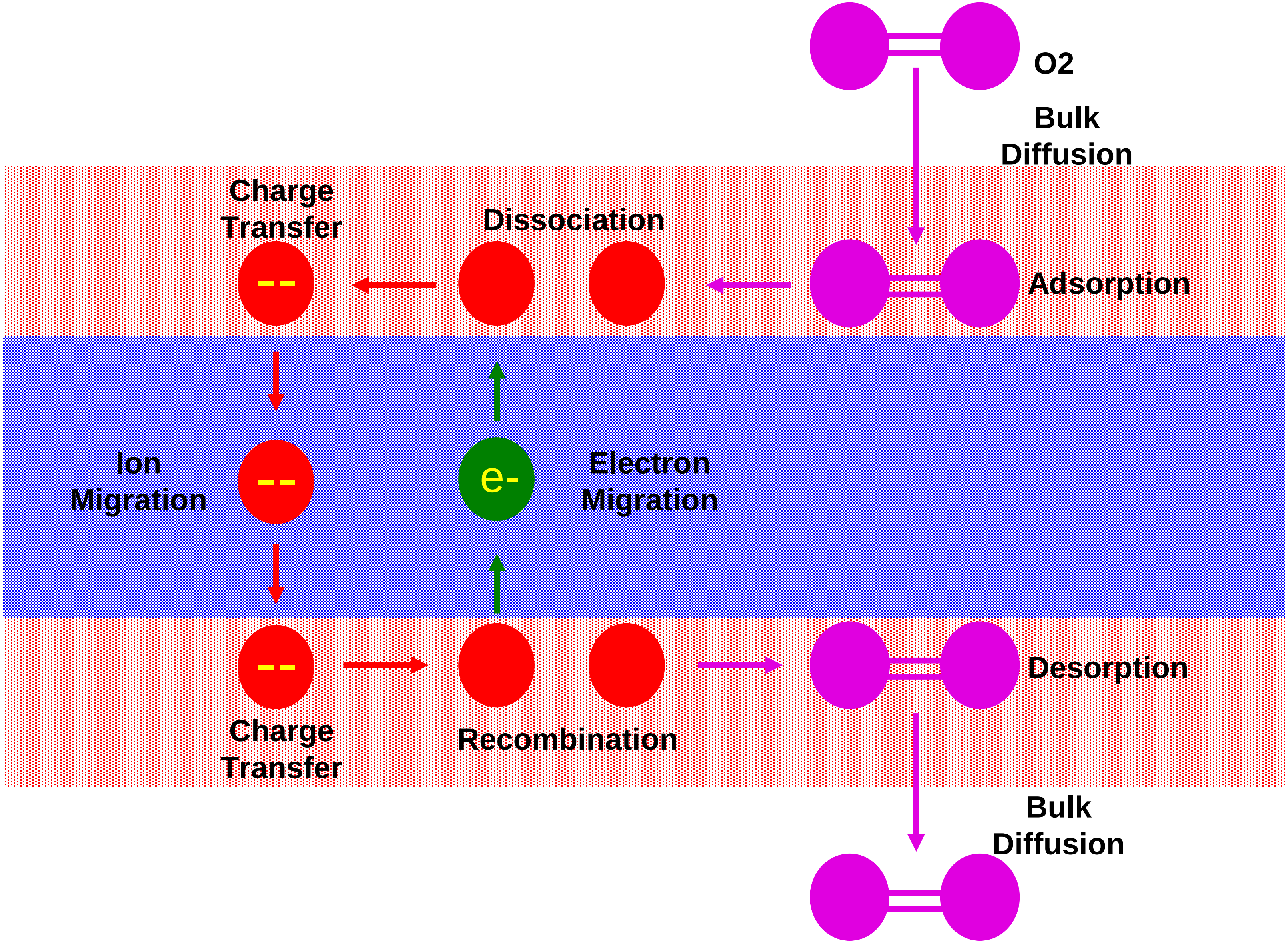
Oxygen Transport Membrane (OTM) Technology





OXIDES OF METALS
OXYGEN ION TRANSPORT
INFINITE O_2 SELECTIVITY
HIGH TEMP OPERATION (400-1000 ^oC)

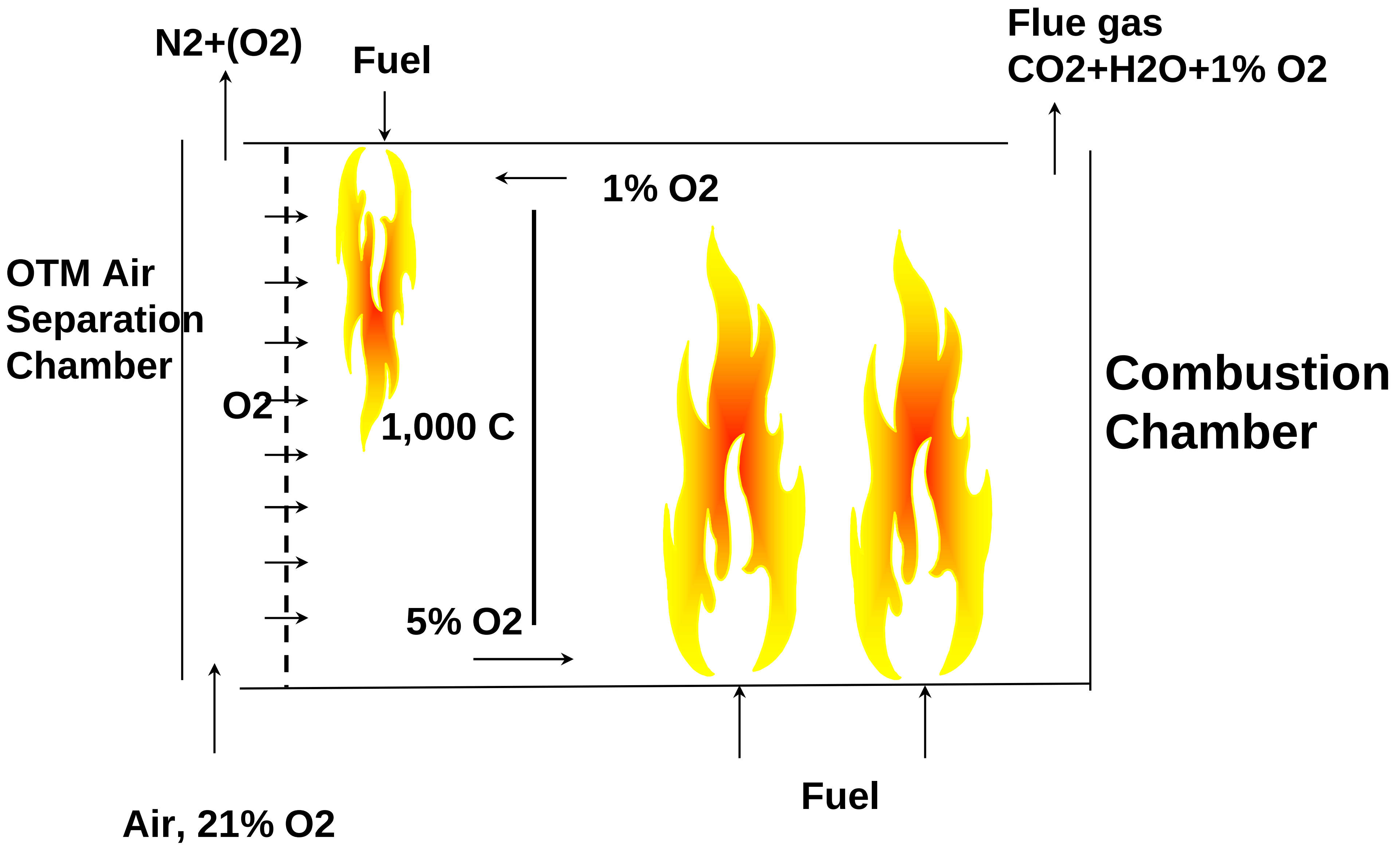
Mixed Conductor O2 Transport mechanism



O_2 Flux and Compression Requirements

- O_2 Flux Across OTM = C ln$(P_1/P_2)_{O_2}$
- $(P_1/P_2)_{O_2}$ = 3 Required for High O_2 Flux
  (Ideal compression power of 53 kwh/ton O2 at 80 F)
- Air compressed to 14.3 atm to produce pure O_2 at 1 atm
  (Ideal compression power of 250 kwh/ton O2 at 80 F), or
- Air at 1 atm and Dilute Oxygen Combustion at 7% O_2

OTM-Dilute Oxygen Combustion Concept



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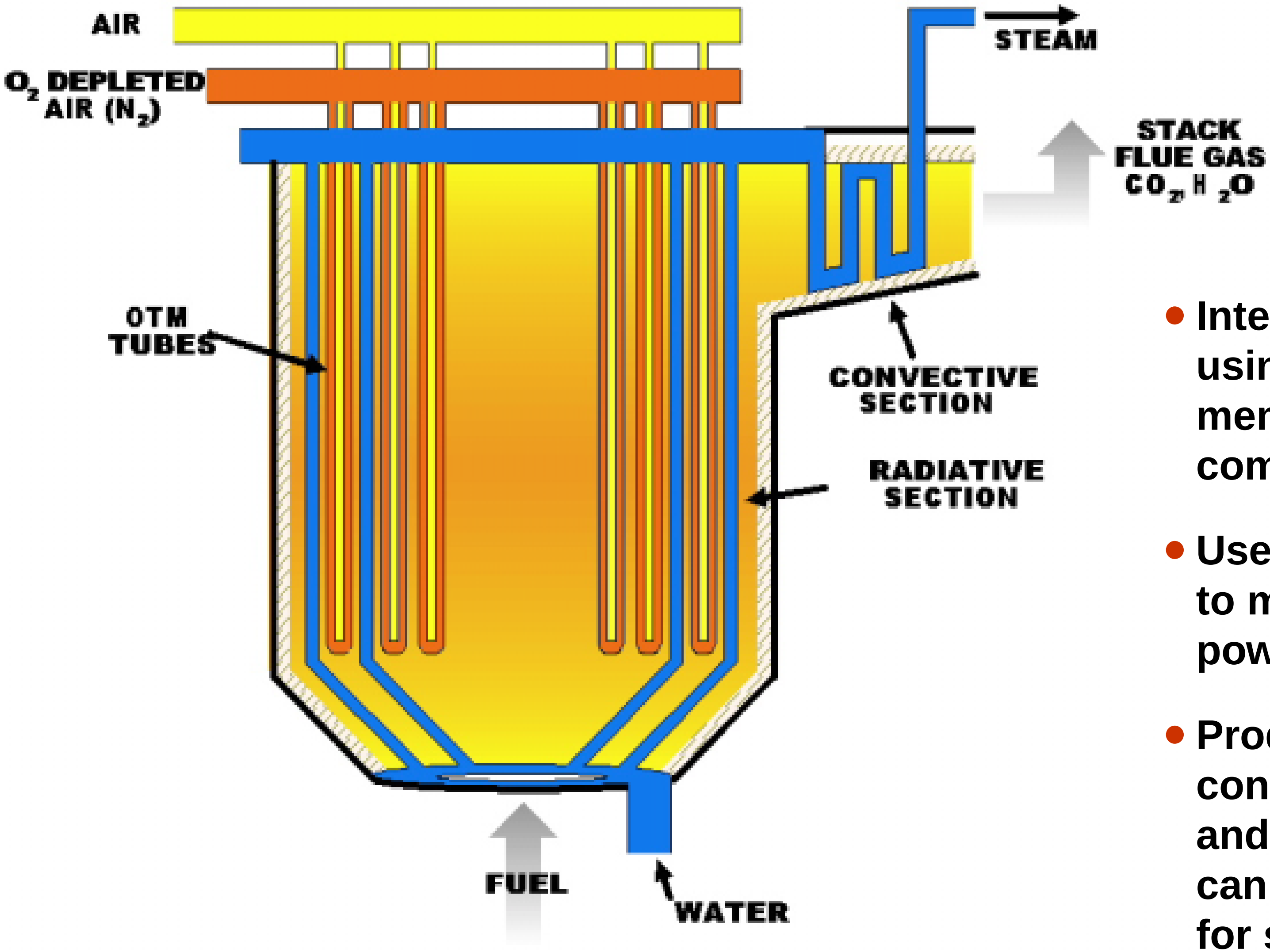
Praxair Advanced Boiler Concept



- Integrates air separation using oxygen transport membranes and combustion
- Uses chemical potential to minimize air separation power required
- Produces flue gas containing only CO_2, H_2O and inerts from fuel that can be readily cleaned up for sequestration.

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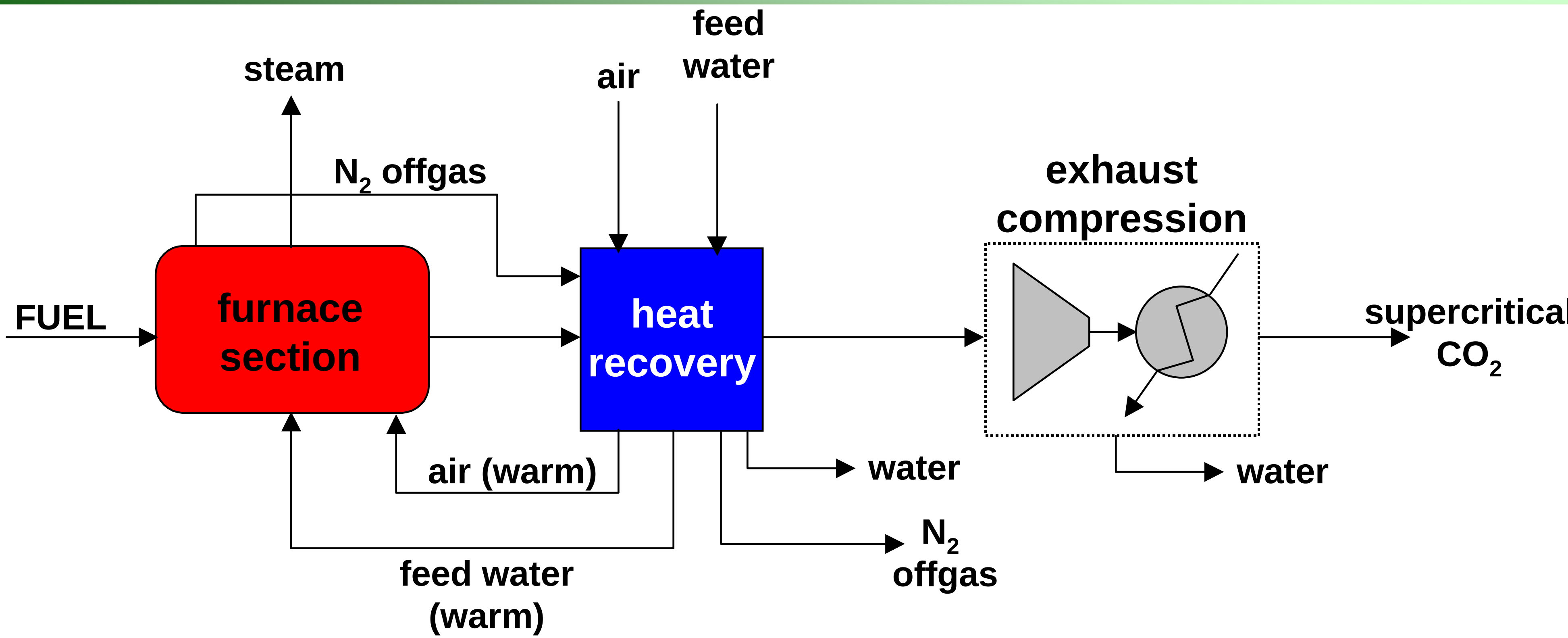
Conceptual NG Fired OTM Boiler Process



- **OTM boiler reduces air separation power by 90%**
- **High purity CO_2 exhaust reduces the cost of capture**
- **Cost of CO2 capture and compression \$3-\$5/ton CO2**

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Conceptual Coal-Fired OTM Boiler Process

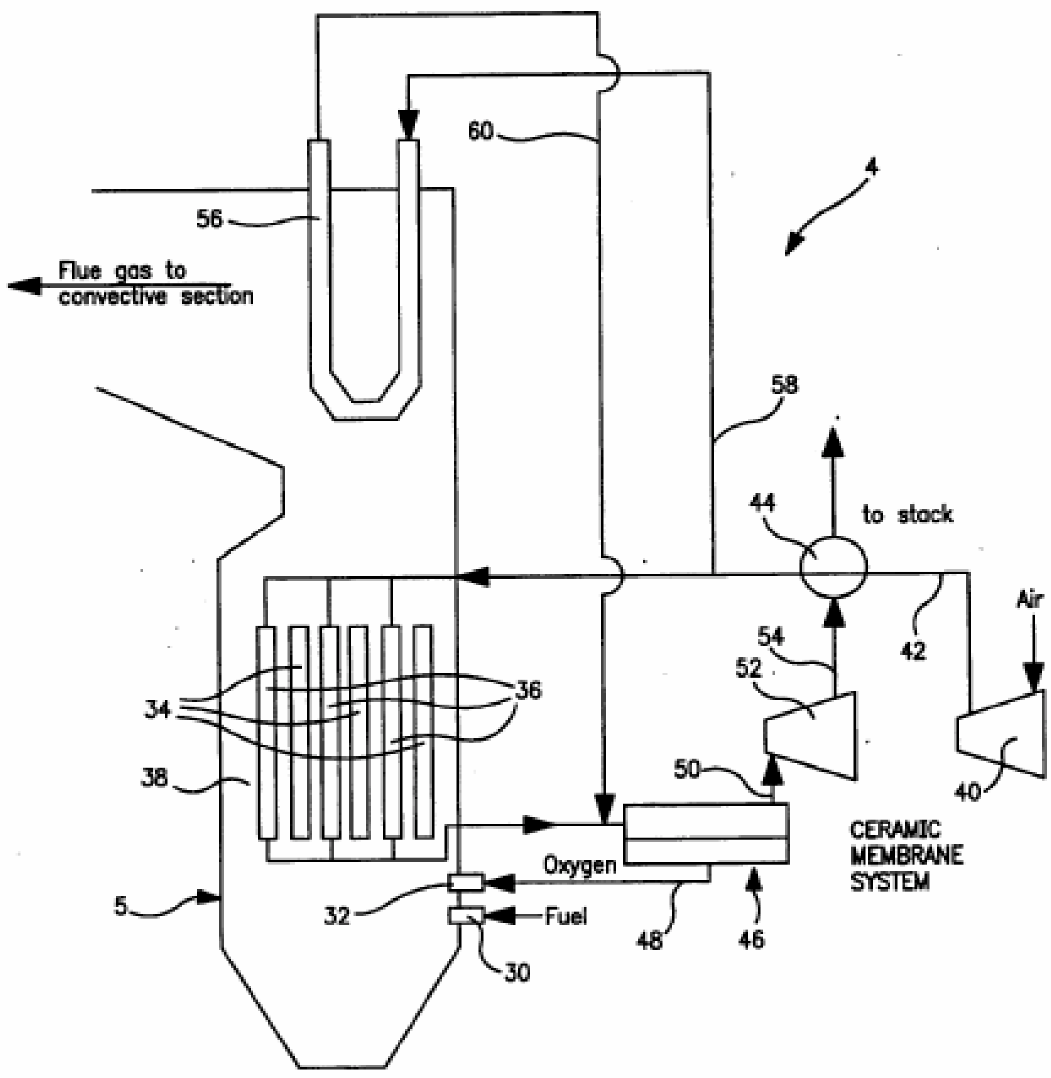

FIG. 2

- **Indirect compressed air heating and external OTM**
- **Hot compressed air topping cycle to boost power**

Oxy-Fuel Combustion Without Producing Pure O2 Appears Promising for CO2 Sequestration

1. **OTM-Dilute Oxygen Combustion Integration**

2. **Chemical Looping Combustion**

   Oxygen carried from air to fuel by metal oxides, sulfates, etc.

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Unit CO_2 Reduction Through Productivity Improvement by Oxy-Fuel Combustion

Example 1 – Steel Reheat Furnace

Baseline fuel consumption	1.5 MMBtu/ton
CO_2 emissions	174 lb/ton
Throughput increase	20%
Incremental fuel consumption	0.75 MMbtu/ton
CO_2 emissions	87 lb/ton

Example 2 – Gas Turbine Topping Cycle

- Generate power at an incremental heat rate of 4000 to 6000 Btu/kwh (57 to 85% HHV efficiency)
- No incremental CO_2 emissions
- Net Reduction of NOx Emissions

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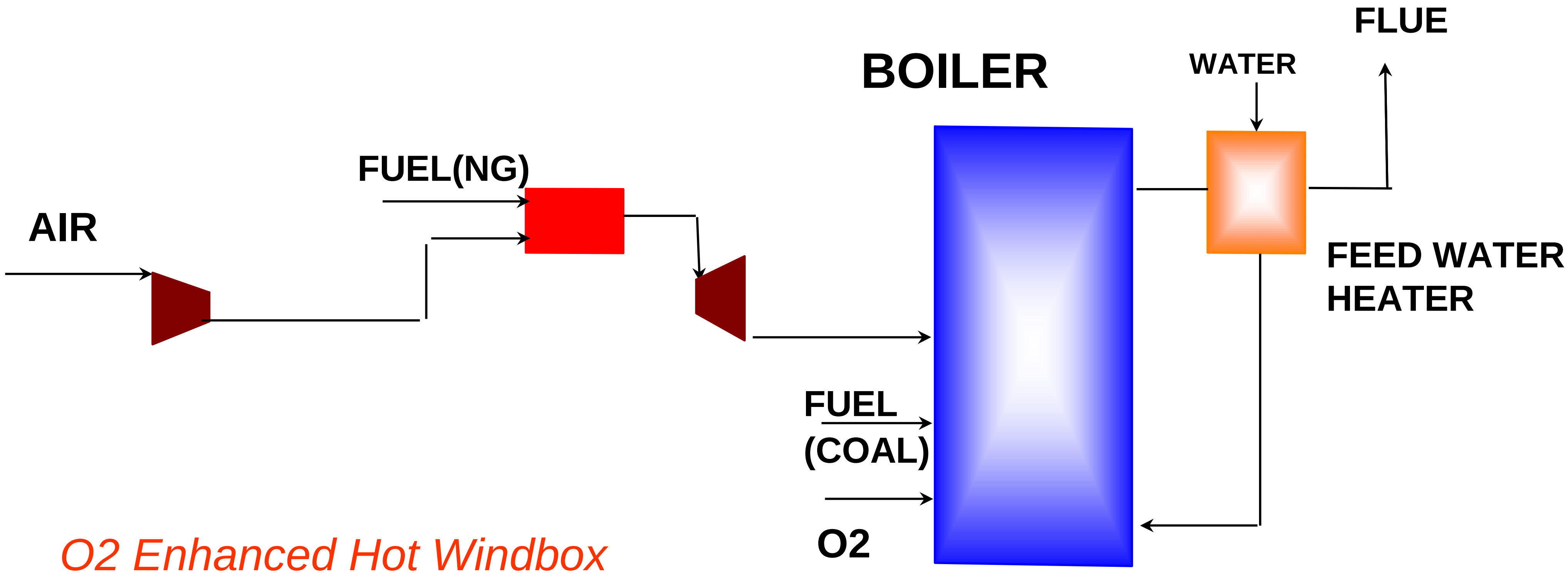
GAS TURBINE TOPPING CYCLE RETROFIT WITH O2 INJECTION



O2 Enhanced Hot Windbox

Incremental power at 4,000-6,000 Btu/kwh
No increase in total CO2
NOx reduction to 0.15 lb/MMBtu

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CO_2 Reduction By Oxy-Fuel Combustion - Summary

- 100% oxy-fuel firing of coal fired boilers is feasible for CO_2 sequestration.
  - Stand alone oxygen generation plant consumes 10 to 20% of the power plant output and is not economically attractive
- "Oxy-fuel combustion" without producing pure O_2 appears promising for CO_2 sequestration.
  - OTM-Dilute Oxygen Combustion Process
  - Chemical Looping "Combustion" Process
- Oxy-fuel combustion for retrofit applications offers viable near-term opportunities for CO_2 reduction
  - Oxy-fuel fired industrial furnaces
  - O_2 enhanced gas turbine topping cycle of PC fired boilers
- There are needs for experimental data on coal combustion under oxygen fired conditions