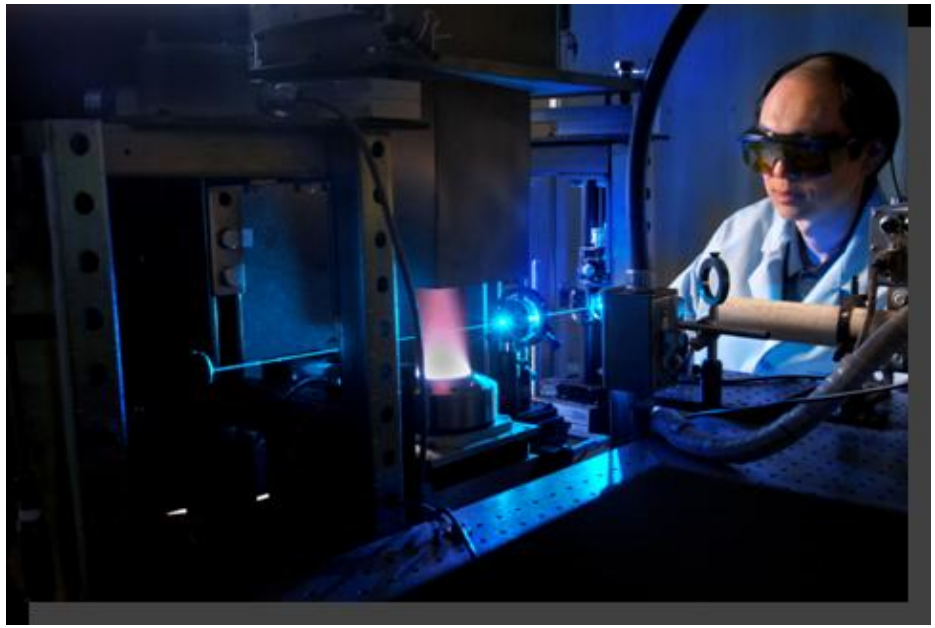
NATIONAL ENERGY TECHNOLOGY LABORATORY



U.S. DOE/NETL Office of Research and Development - Oxyfuel Combustion Progress Update – Thermofluids

E. David Huckaby

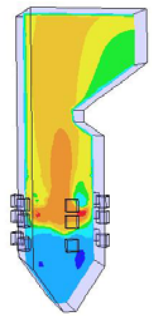
Research Group Leader – Device Scale Modeling

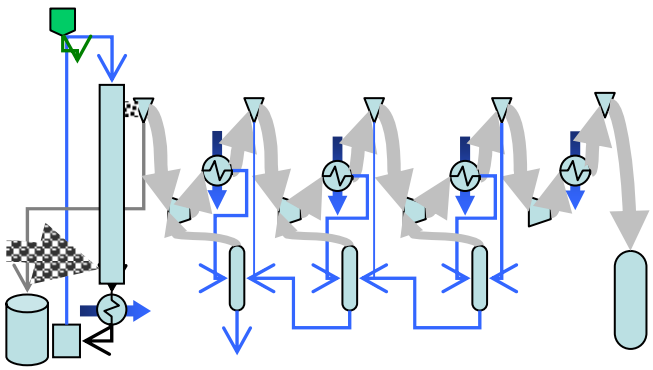
U.S. DEPARTMENT OF ENERGY

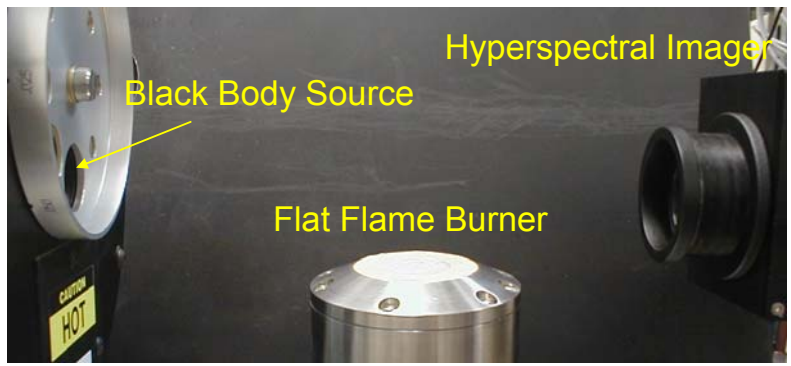
Introduction

Current ORD Projects in the Thermo-fluid area

- **System Modeling and Analysis**
- **Integrated Pollutant Recovery System**
- **Oxyfuel Boiler Experiments**
- **Laboratory Flame Experiments**
- **Computational Fluid Dynamics**







Systems Analysis

- **Approach**
  - apply standard power plant modeling software

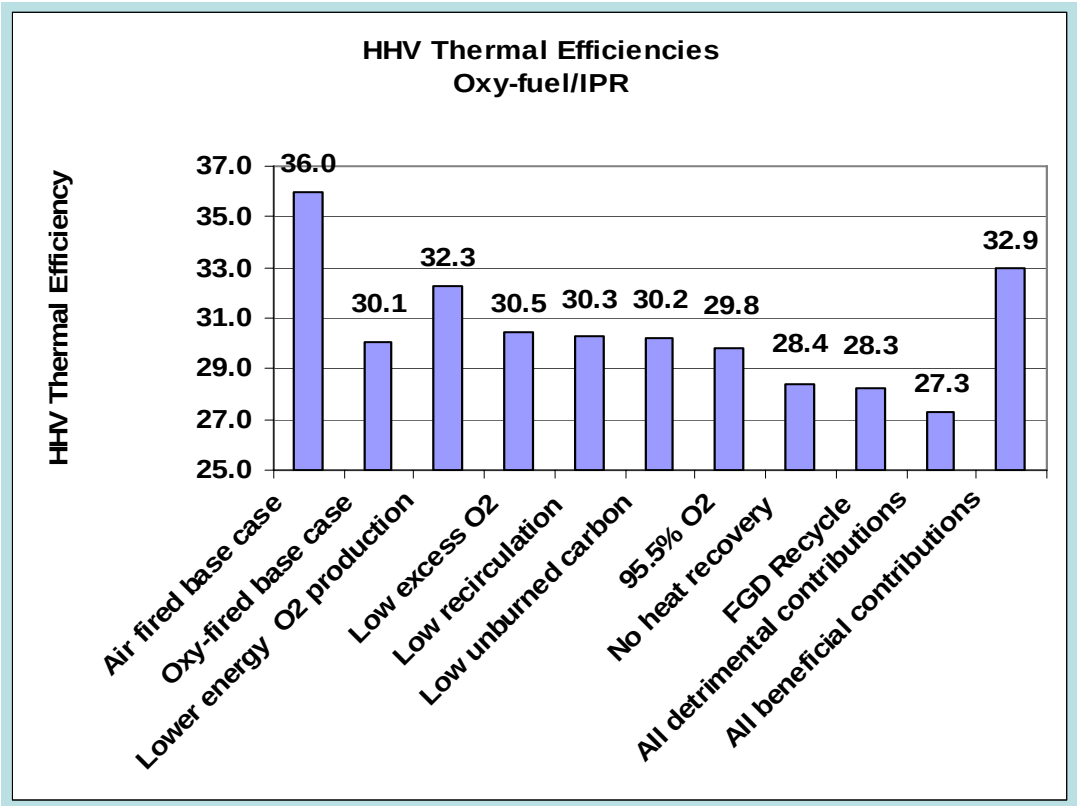
- **Applications & Objectives**
  - Oxy-fuel retrofit w/ IPR for existing power-plant:
    - engineering estimates at a component level
    - verified against existing heat balances at varying loads
  - Hammond Test Facility (Jupiter)
    - Measurements help to verify component design
  - Advanced oxy-fuel combustion greenfield plants
    - Predict behavior of power plant components when not restricted by existing equipment

Systems Analysis

- **Benefits**
  - “observe” plant behavior while varying operating conditions (less costly than physical system)
  - examine multiple technologies → focus resources on those with the most potential for return on investment

- **Model Attributes for Oxyfuel system**
  - The majority of system level components (are well understood and reliably modeled by industry standard software
  - Based on heat balances from real power plants
  - “New” Components (e.g boilers) must be verified against experimental data and CFD models

Systems Analysis - Results



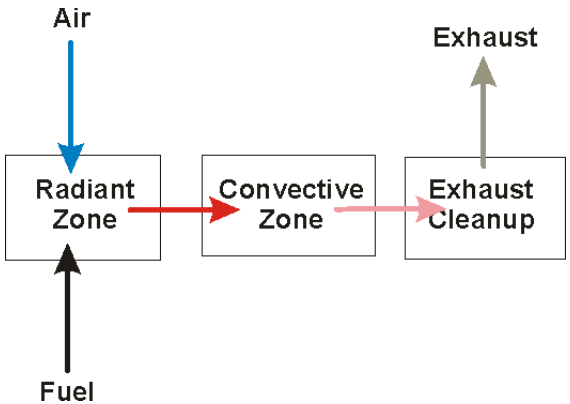
- **Analysis was performed of several plant designs**
- **Best case scenario of 3.1 % efficiency loss for oxyfuel**

Systems Analysis - Results

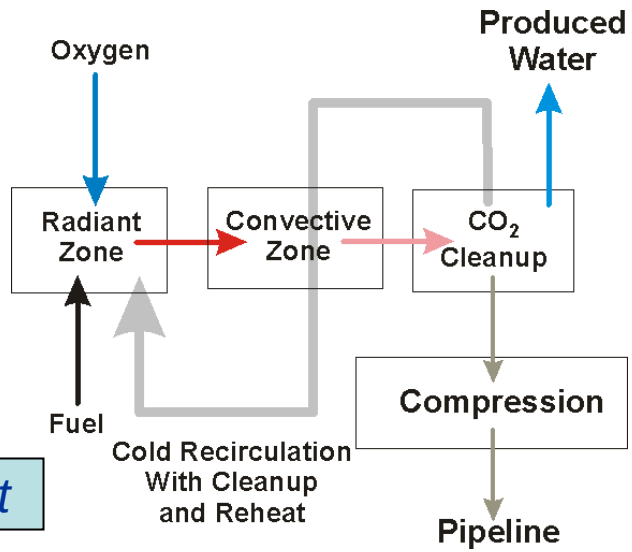
- **Oxyfuel vs. Air**
  - More ***shaft power*** is created with less coal
- **Heat Recovery or not**
  - Trade heat exchange surface area (capital cost) for heat rate (fuel operating cost) and power production (revenue)

Model	Thermal Efficiency (%)	Net Power (MW)	Coal (short ton/hr)	Gross Shaft Power (MW)
Base air	36.0	437	183	479
Base oxy-fuel	30.1	353	177	510
No heat recovery oxy-fuel	28.4	333	177	495

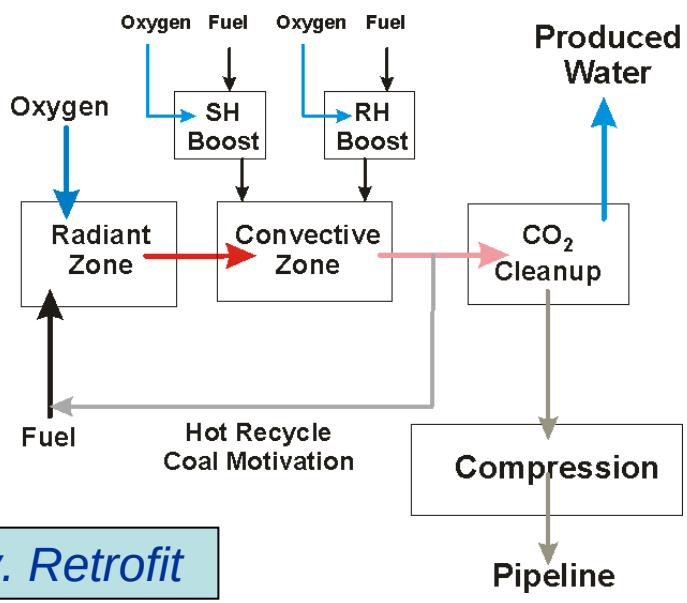
Systems Analysis – Plant Design



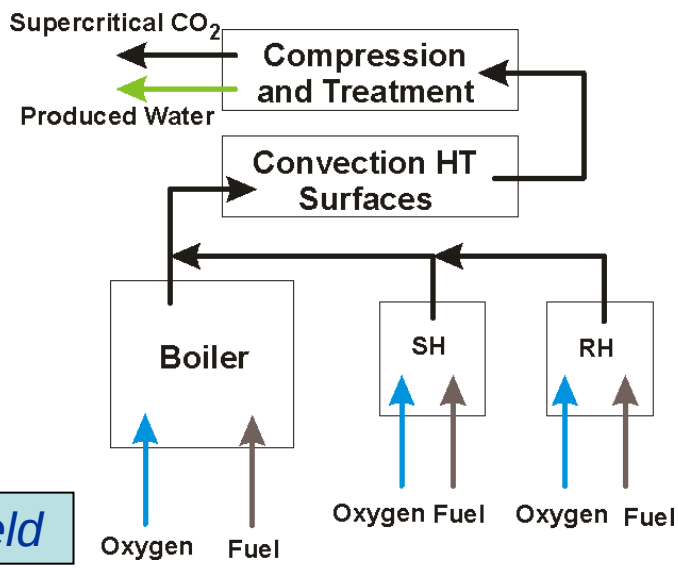
Air Fired



Retrofit

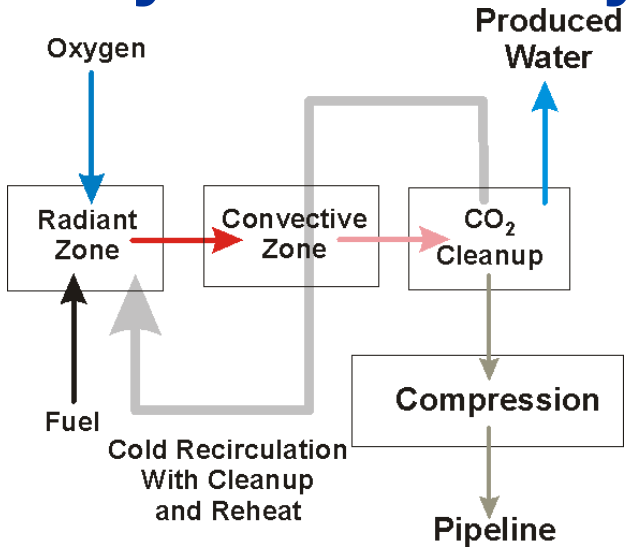


Adv. Retrofit

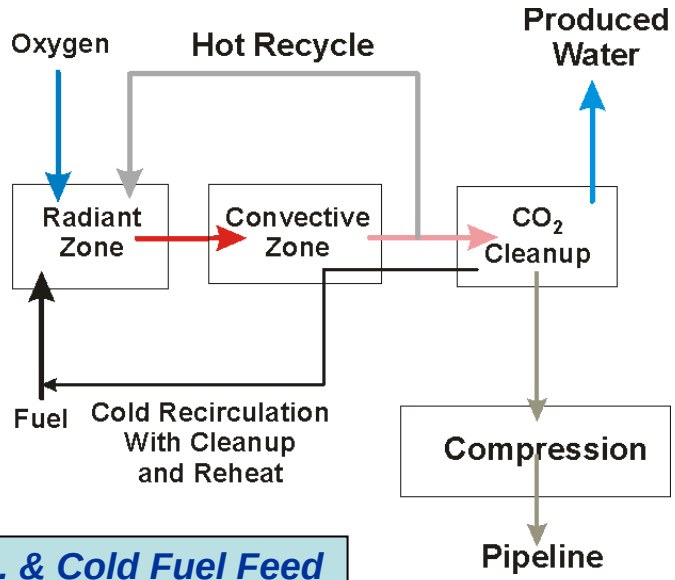


Greenfield

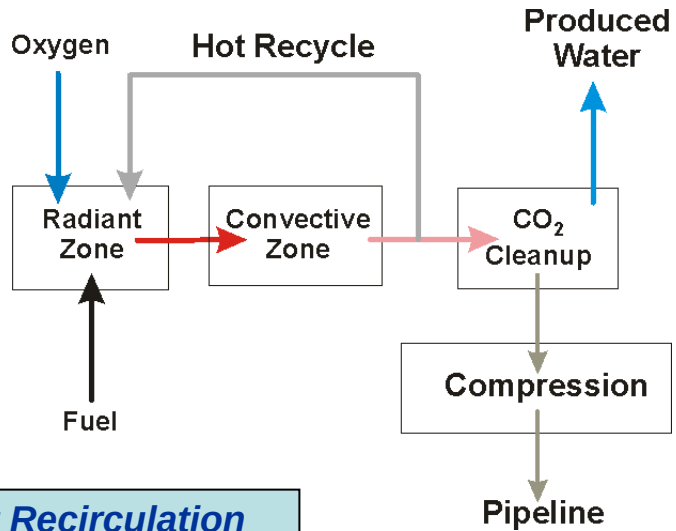
Systems Analysis - Recycle Schemes



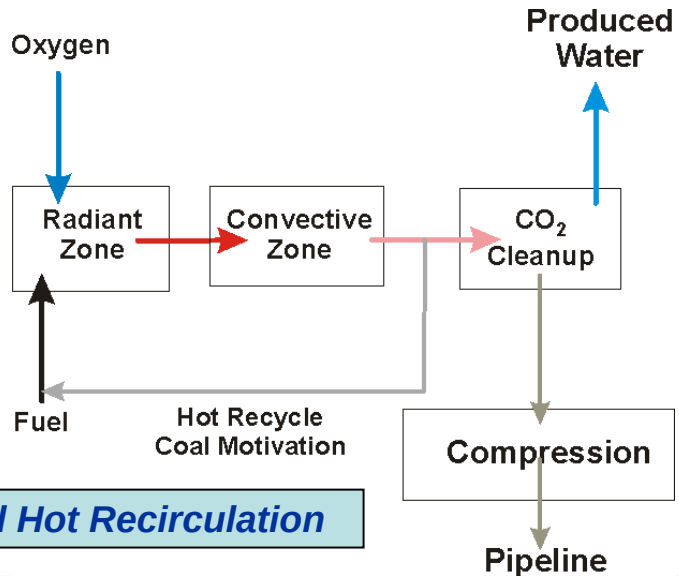
Clean and Cold Recycle



Hot Recirc. & Cold Fuel Feed

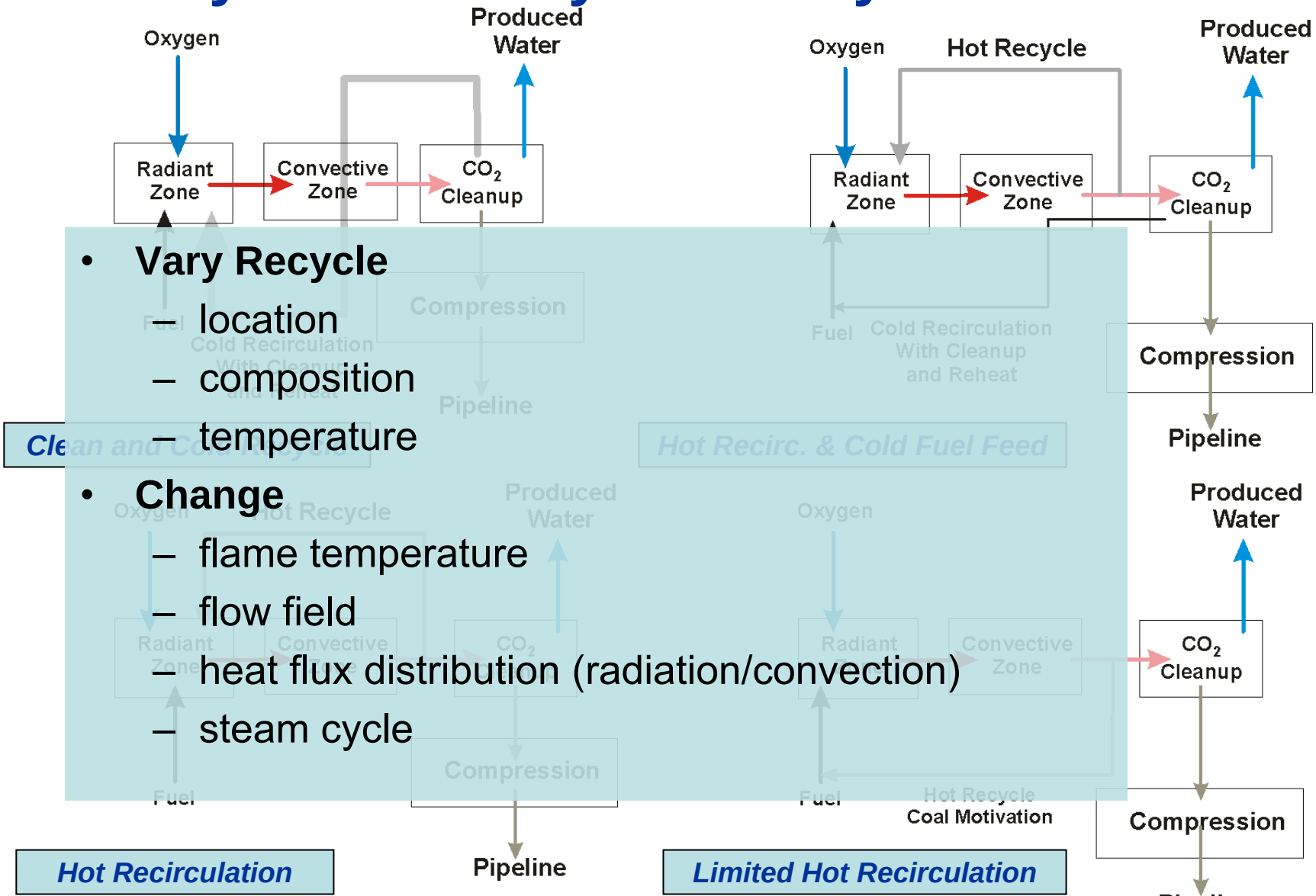


Hot Recirculation



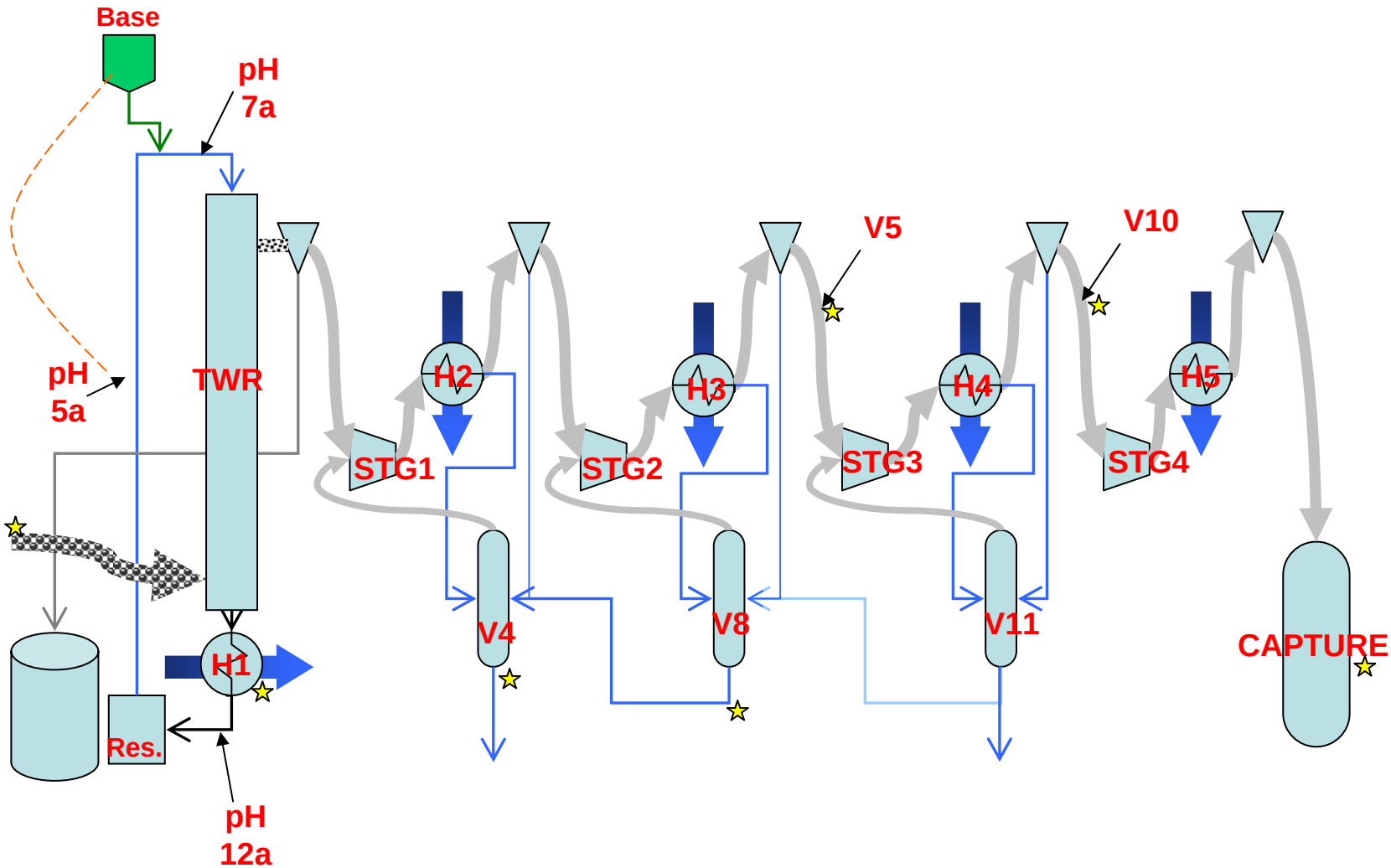
Limited Hot Recirculation

Systems Analysis - Recycle Schemes



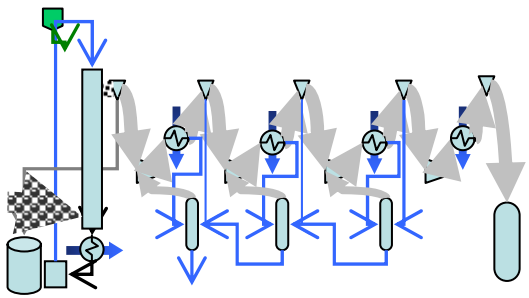
- **Vary Recycle**
  - location
  - composition
  - temperature
- **Change**
  - flame temperature
  - flow field
  - heat flux distribution (radiation/convection)
  - steam cycle

Integrated Pollutant Removal (IPR) System



IPR Discussion

- **Energy recovery/pollutant removal**
- **How does it work ?**
  - Capture, compress, clean on the way
    - Counter flow spray tower for latent heat plus dust and acid removal
      - Can be indirect heat exchanger
      - Coolant spray is recirculated and pH-balanced
    - Compression (ratio ~3X) to pipeline pressure ~2000psi
    - Intercooling
      - recovering latent and sensible heat
      - solubles captured and removed in intercooler condensate
- **Status at Jupiter**
  - Shakedown with oxy-coal
  - Initial chemistry
  - Demonstration of heat transfer



IPR - Exhaust Composition

- Sox drops out after 1st compression
- Most of the water removed in the first compression

	Conventional after economizer	Oxyfuel exhaust after splitter	After 1st compression	After 2nd compression	After 3rd compression
Gas Flow (kg/hr)	1,716,395	409,083	364,367	354,854	353,630
Vol flow (m^3/hr)	1,932,442	483,092	72,623	15,944	661
Inlet Pressure (psia)	14.62	15.51	62	264	1,500
Inlet Temperature (°F)	270	500	342	323	88.2
Density (kg/m^3)	0.8882	0.8468	5.017	22.26	534.6
H_2O	0.0832	0.3322	0.0695	0.00994	0.0004
Ar	0.0088	0.0115	0.0163	0.01730	0.0175
CO_2	0.1368	0.6131	0.8662	0.92161	*0.9305*
N_2	0.7342	0.0090	0.0128	0.01359	0.0137
O_2	0.0350	0.0250	0.0353	0.03755	0.0379
SO_2	0.0020	0.0091	0.0000	0.00000	0.0000

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Density (kg/m^3)	0.8882	***0.8468***	5.017	22.26	***534.6***
H_2O (fraction)	0.0852	0.3322	0.0695	0.00994	0.0004
Ar (fraction)	[illegible]	[illegible]	[illegible]	0.01730	0.0175
CO_2 (fraction)	[illegible]	0.6131	0.8662	0.92161	0.9305
N_2 (fraction)	0.7342	0.0090	0.0128	0.01359	0.0137
O_2 (fraction)	0.0350	0.0250	0.0353	0.03755	0.0379
SO_2 (fraction)	0.0020	0.0091	0.0000	0.00000	0.0000

- **mass flow slightly decreases (1.1:1)**
- **volume flow significantly decreases (731:1)**
- **pressure increase (1:100)**
- **Temperature decrease – intercooling for energy recovery**

Natural Gas Testing @ Jupiter Oxygen

<u>Tests</u>: Jupiter performed 4 screening tests at the 15 MWth test facility to collect data under each conditions. *NETL research staff provided additional instrumentation and data analysis for the tests*.

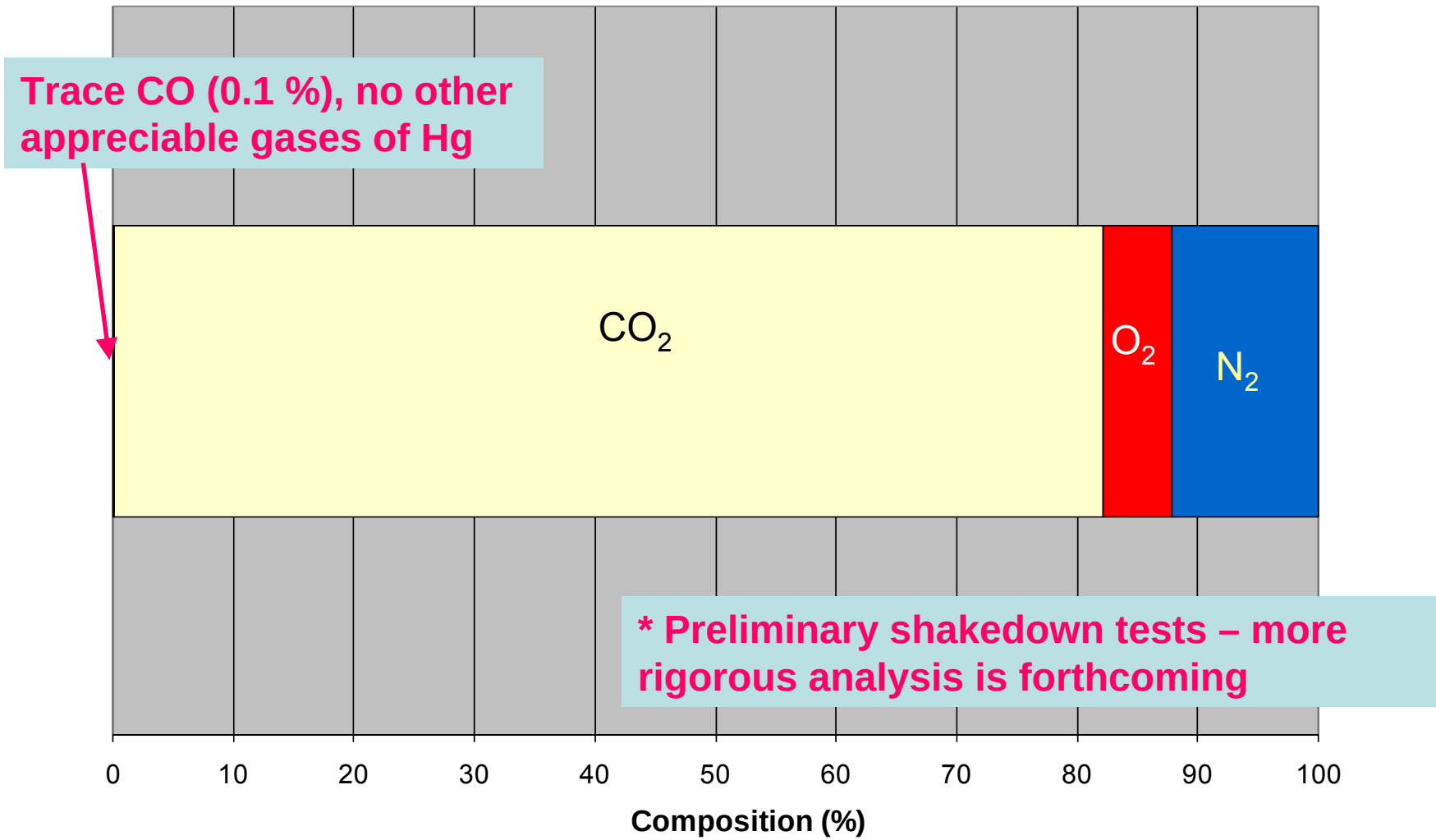
1	High Temp Oxy	***5345F (2952K)***	Only oxygen and natural gas at the burner
2	High Temp Oxy w/ recycle	***5300 F (2927K)***	Oxygen and natural gas at burner Recycle injected away from burner
3	Air	***3758 F (2070K)***	Excess Air
4	Low Temp Oxy	***3851 F (2121K)***	Oxygen and Recycle mixed upstream of the burner

Flame Temperatures Estimated From Radiation Measurements

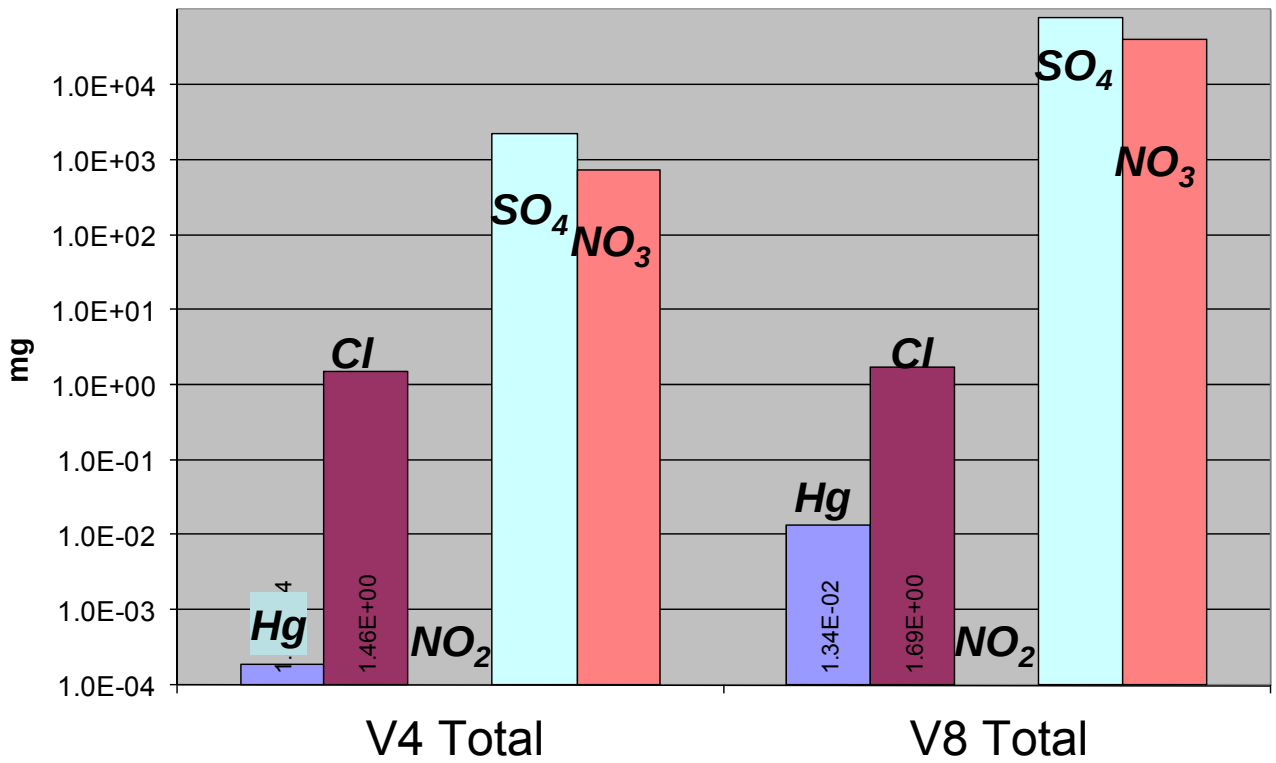
Natural Gas Testing @ Jupiter Instrumentation

- **Traversing thermocouples**
- **UV/VIS/NIR**
  - What instrument was used to measure ?
- **Mid IR**
- **Total radiometer measurements**
- **Chordals- 3 positions around boiler radiant section**
  - Heat flux
  - Tube-metal temperatures
- **Video / sonic readings**
  - accelerometers – 3 (2 on boiler shell, 1 on burner)
  - high speed camera in back port
- **Gardon gauges**
  - heat flux

Natural Gas Testing @ Jupiter
Captured Gas Mixture



Natural Gas Testing @ Jupiter
Aqueous Gas Species



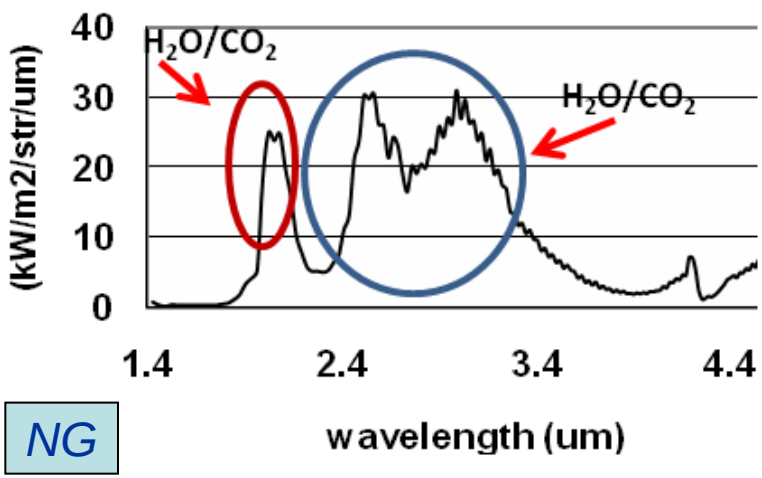
- **Accumulated of gas species in the liquid discharged of the IPR flash tanks**

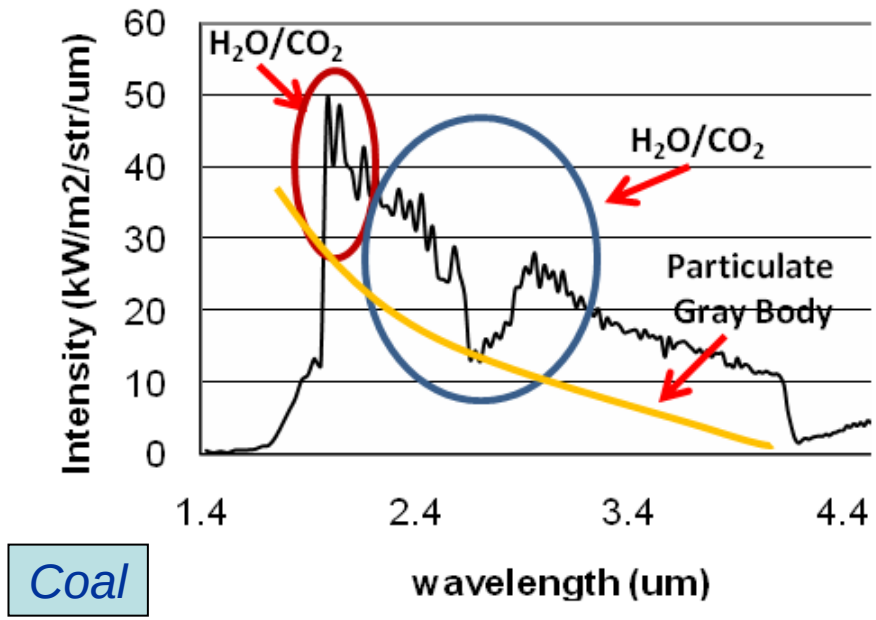
Coal Testing @ Jupiter Oxygen Hypotheses

1. Increased flame temperature shifts heat transfer distribution toward radiant zone.
2. Increased flame temperature does not damage boiler tubes.
3. Performance and geometry of flame
4. IPR (Integrated Pollutant Removal) can capture both sensible and latent heat from the exhaust gases.
5. IPR can recover sensible and latent heat during compression.
6. IPR can remove SOx during spray treatment.

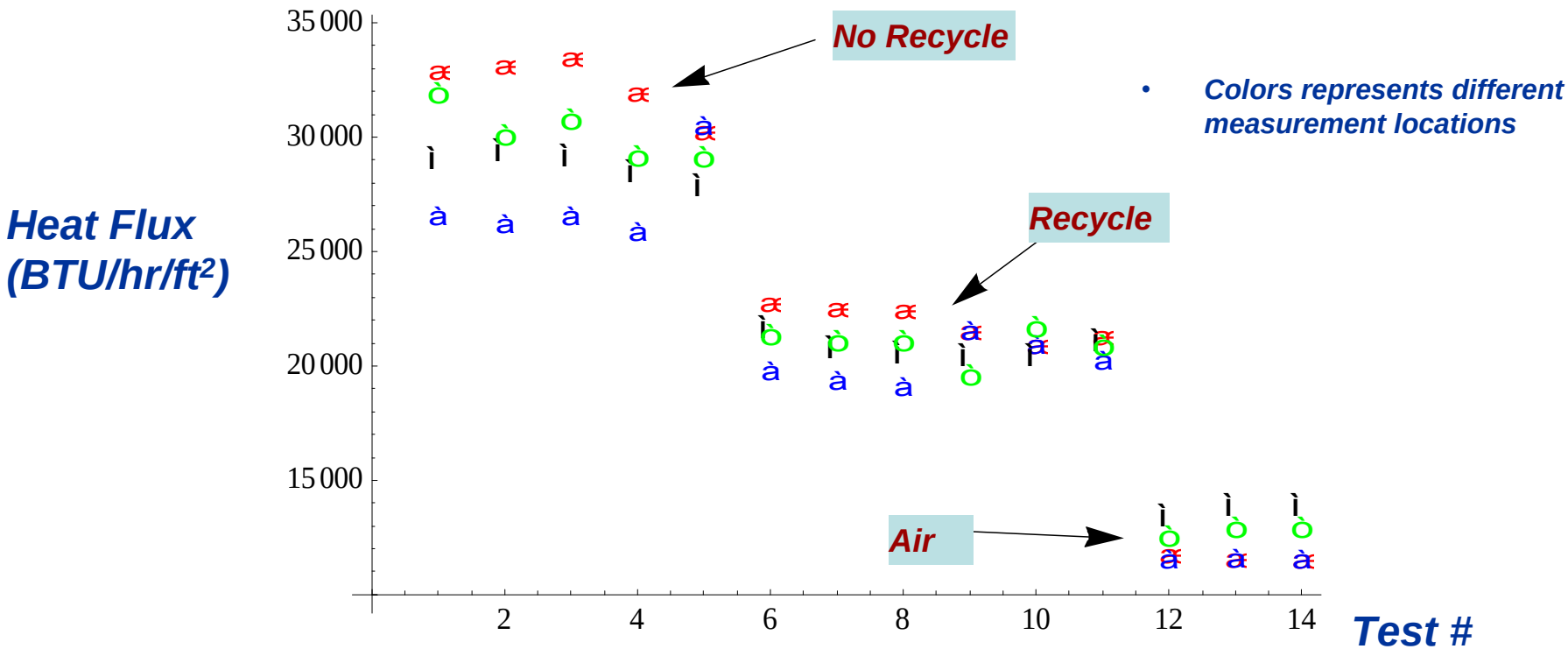
Coal Testing @ Jupiter Oxygen Radiation Measurements

- **Similar measured spectral intensity between NG and coal**
- **Presence of coal particles leads to increased intensity**





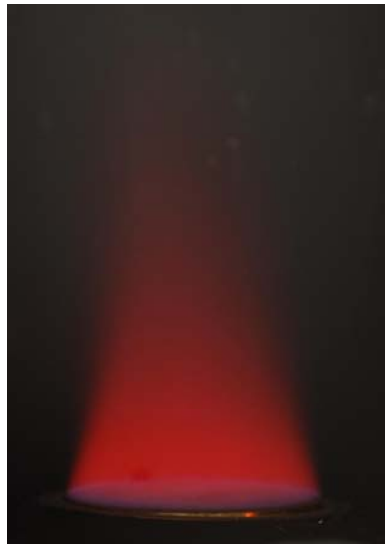
Coal Testing @ Jupiter
Heat Transfer Measurements

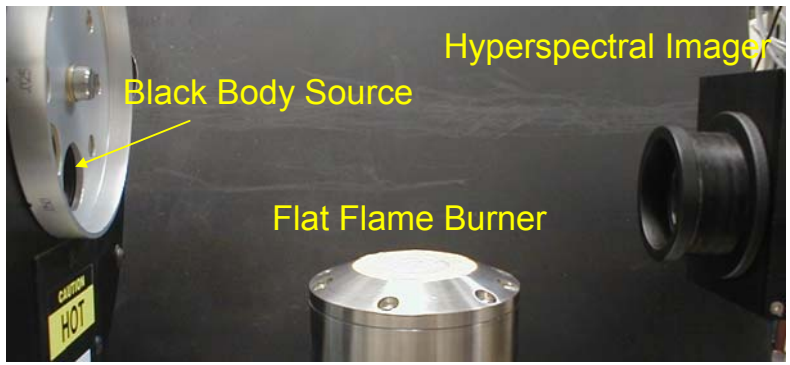


- **High temperature flame produces higher heat loads in the radiant section**

Laboratory Flame Experiments

- **Flat Flame Burner experiments – syngas/steam/oxygen**
- **Estimate the radiative absorption of flame gases**
  - Measure the intensity spectrum
  - Estimate the absorption from the difference between flame and no flame
- **Vary gas flows to access necessary operating conditions**





CFD Modeling – Intro

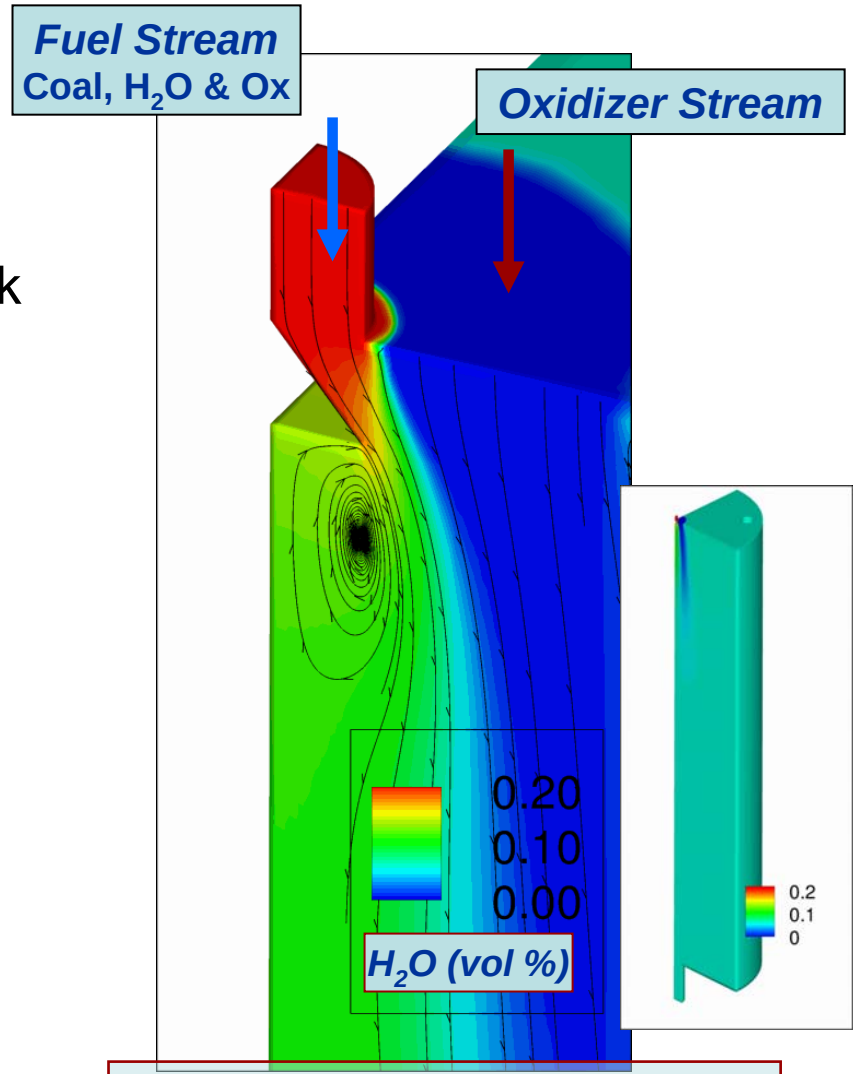
- **Goals**
  - Develop, validate, and apply computational fluid dynamics models for simulating oxy-fired PC combustion
  - Assess/improve tools for the design oxy-fuel systems

- **Two Thrusts**
  - Sub-model Validation/Development (Radiation, Chemistry, etc.)
  - General Validation

CFD Modeling – Accomplishments

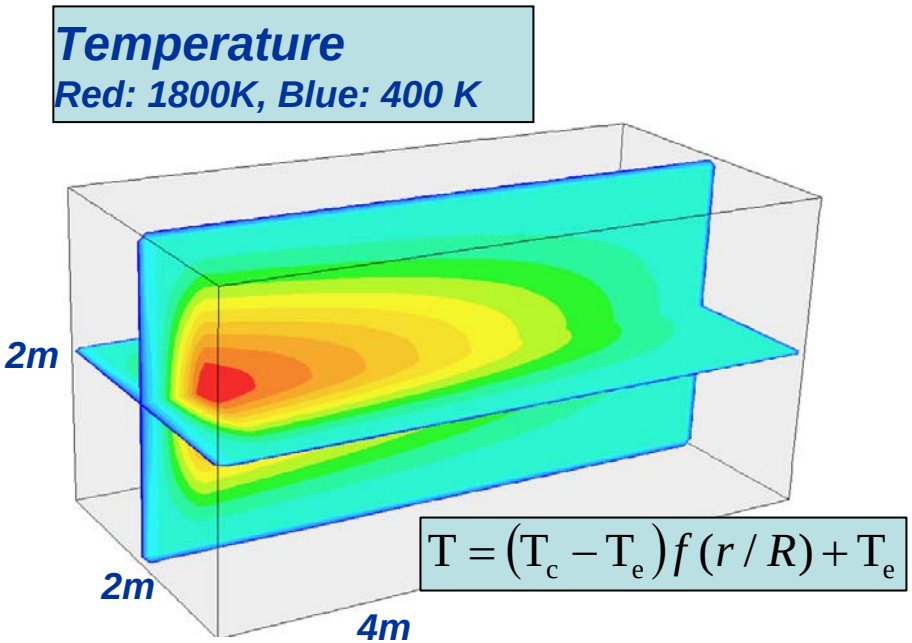
- **FY08 Activities**
  - Assessment of "gray-gas" radiation models for benchmark cases and at laboratory scale
  - Simulations of three laboratory PC-oxyfuel experiments (ANL, IHI, Chalmers)

- **FY09 Q1/Q2 Accomplishments**
  - Assessment of "gray-gas" radiation models at full scale



Fluent Simulations of a 100 kW Furnace (Chalmers)

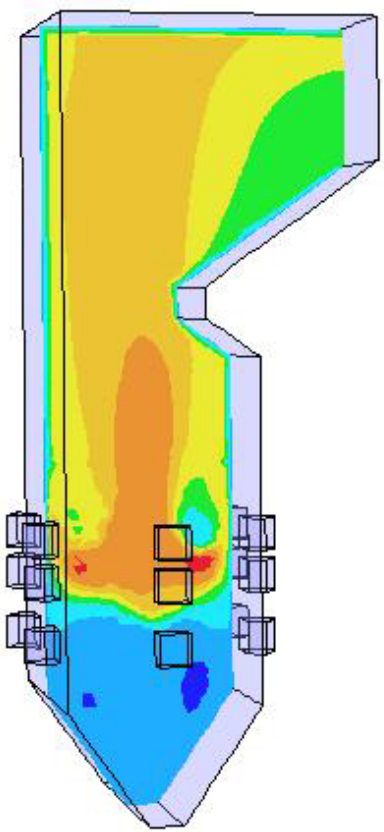
CFD Modeling - Box Furnace



- **Benchmark in simplified geometry**
- **Results of calculations using gray gas models are compared against narrow band models**
  - 1 & 2 literature data
  - 3 & 4 SLW model
- **EWB error < 20% for all gas mixtures**

	Mixture Composition (uniform)	%Error		
		WSGGM	Perry	EWBM
1	10 % CO_2, 20 % H_2O, 70% N_2	18	**10**	18
2	10 % CO_2, 10 % H_2O, 80 % N_2	20	**12**	19
3	65 % CO_2, 35 % H_2O	15	**8**	17
4	90 % CO_2, 10 % H_2O	28	28	**10**

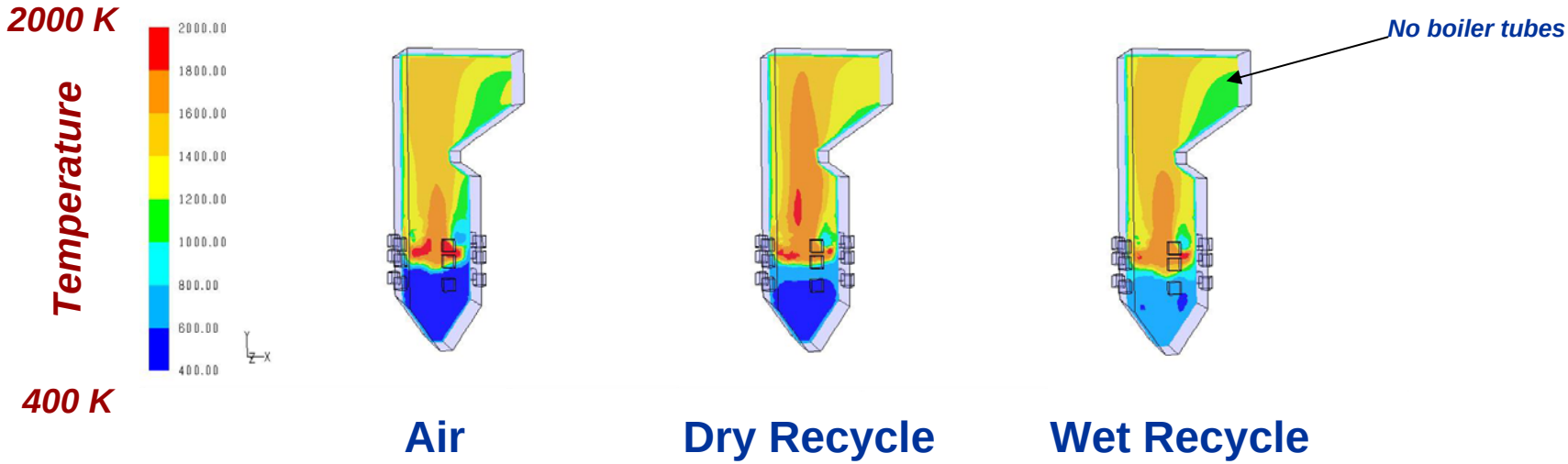
CFD Modeling – Boiler Simulation



	Air-Firing	Dry-Recycle	Wet-Recycle
Power	**120MWth**	**120MWth**	**120MWth**
Solids Flow (kg/s)	10	10	10
Solid Temp. (K)	300	300	300
Gas Inflow (kg/s)	126	126	126
Gas Temp. (K)	460	460	460
Pressure (atm)	1	1	1
mol% O_2	**21**	**29**	**24**
mol% CO_2	**0**	**71**	**50**
mol% H_2O	**0**	**0**	**26**

Change the composition of the gas feed to provide the same adiabatic flame temperature as air firing ("low temperature" flame)

CFD Modeling – Boiler Simulation



- **Different temperature distribution for Air, Oxy w/ dry-recycle, Oxy w/ wet-recycle**

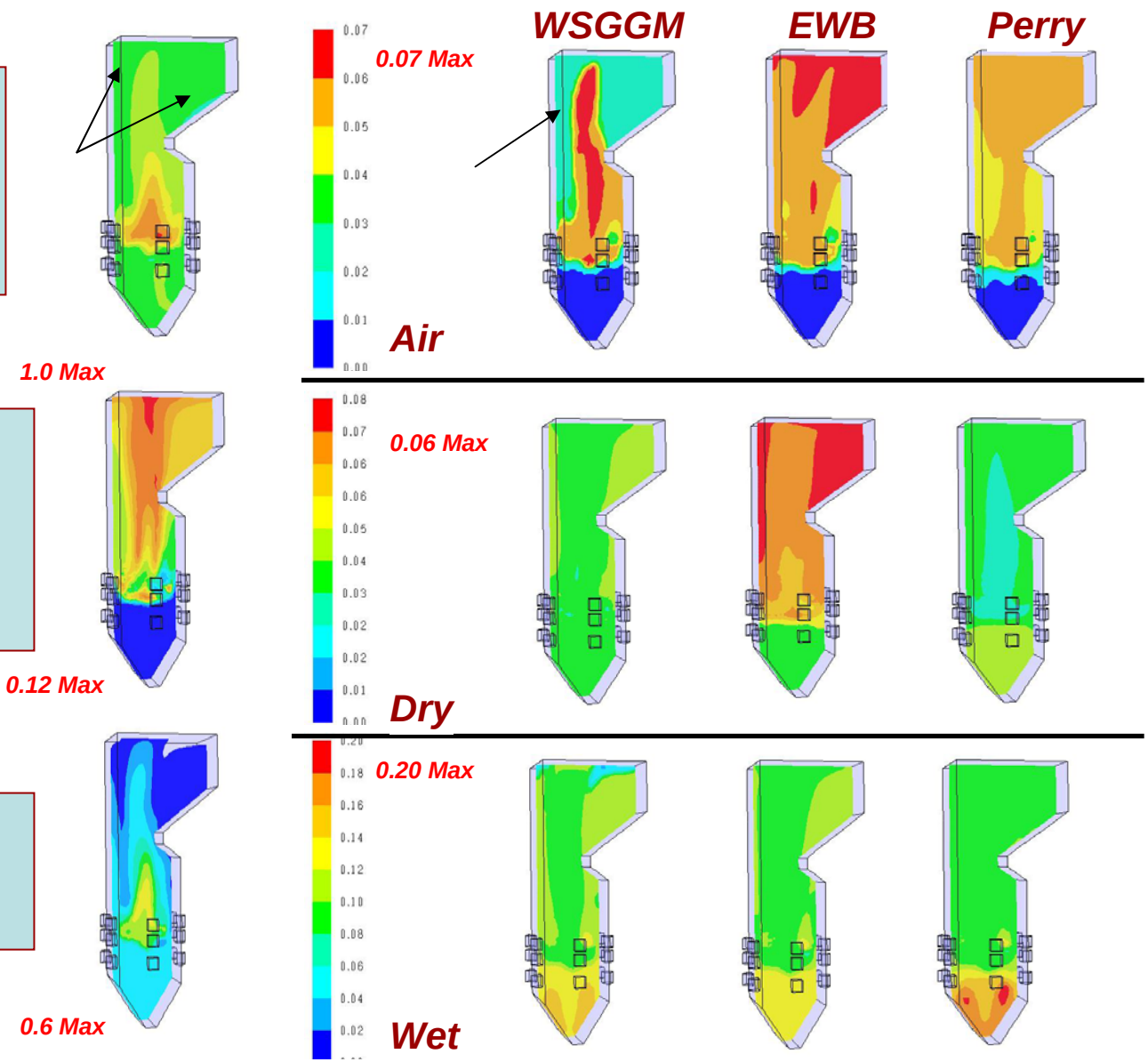
- **The primary purpose is to compare radiation models**

CFD Modeling - Boiler Simulation

$H_2O/CO_2 < 0.5$
WSGGM uses
CO2 coefficients

$H_2O/CO_2 < 0.12$,
both Perry and WSGG use
CO2 coefficients

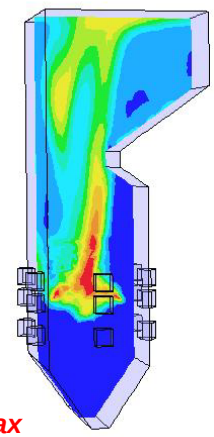
$0.5 < H_2O/CO_2 < 0.6$
within application range
of ***Perry and WSGG***



CFD – Boiler Simulation

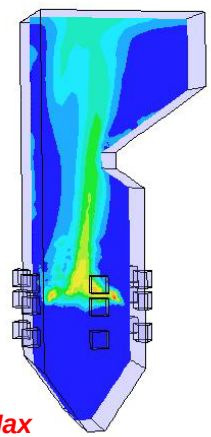
Particle/Gas Absorption Coeff. Ratio

Air



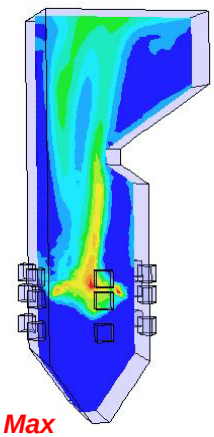
10.0 Max

Dry



20.0 Max

Wet



10.0 Max

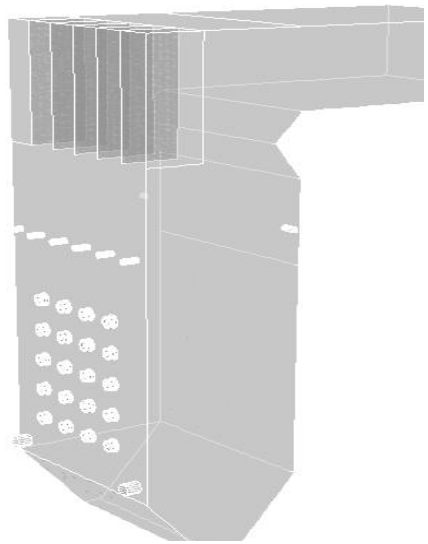
- ***Particle absorption tends to dominate in many regions***
  - *.. but not to the same extent in oxy-fired system*
  - *not necessarily over all wavelengths (this effect is not captured in a gray-gas model)*

CFD Simulation – Plans

- **Simulations of additional systems**

- **Validation Candidates**
  - Jupiter Oxygen (15 MWt)
  - CANMET (0.3 MWt)
  - Oslomej - RAFAKO (120 MWt - air)
  - Sines (300 MWt - air)
  - ENEL – Livorno (3 MWt)
  - Others ?

Jupiter Oxygen



CFD Modeling - Plans

- **What is the benefit and computational costs of additional model complexity ?**
  - How should resources be allocated ?
- **Radiation**
  - Non-gray gas models
  - Particle-scattering, absorption and emission
  - P_N vs. Discrete Ordinate
- **Turbulence-Radiation Interaction**
- **Coal Chemistry**
  - devolitization/oxidation kinetics
  - models for turbulence-chemistry interaction

Conclusions

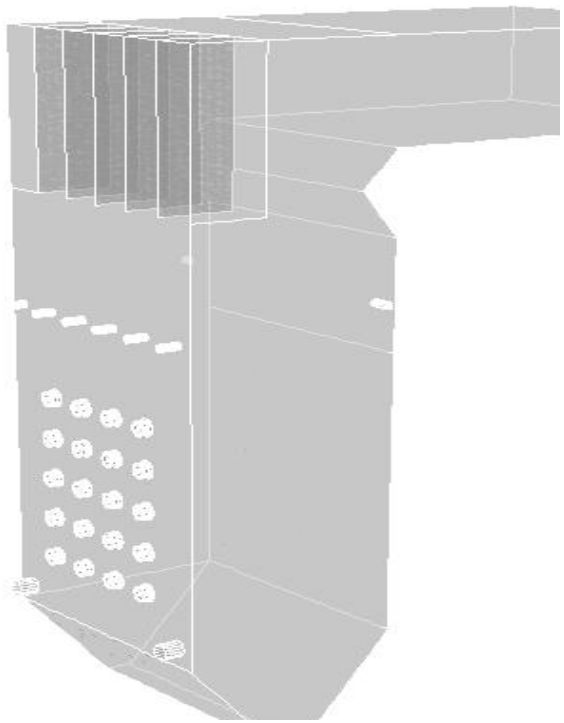
- **ORD has a several projects related to oxyfuel**
  - experiments at multiple scales
  - CFD and process simulations
  - process analysis and design
  - Materials and ash

- **POC:**
  - ***Materials*** – Gordon Holcomb
  - ***Systems Analysis*** etc. – Tom Ochs, Cathy Summers, Danylo Oryshchyn,Jared Ciferno
  - ***Lab. Experiments*** – Kent Casleton
  - ***CFD*** – David Huckaby

Extra Slides

CFD Modeling - Utility Boiler

- 300 MWe Utility Boiler
- Sines power plant
- Stoichiometry 0.85
- Gas Inlet temp = 377 C
- Coal inlet temp 75 C



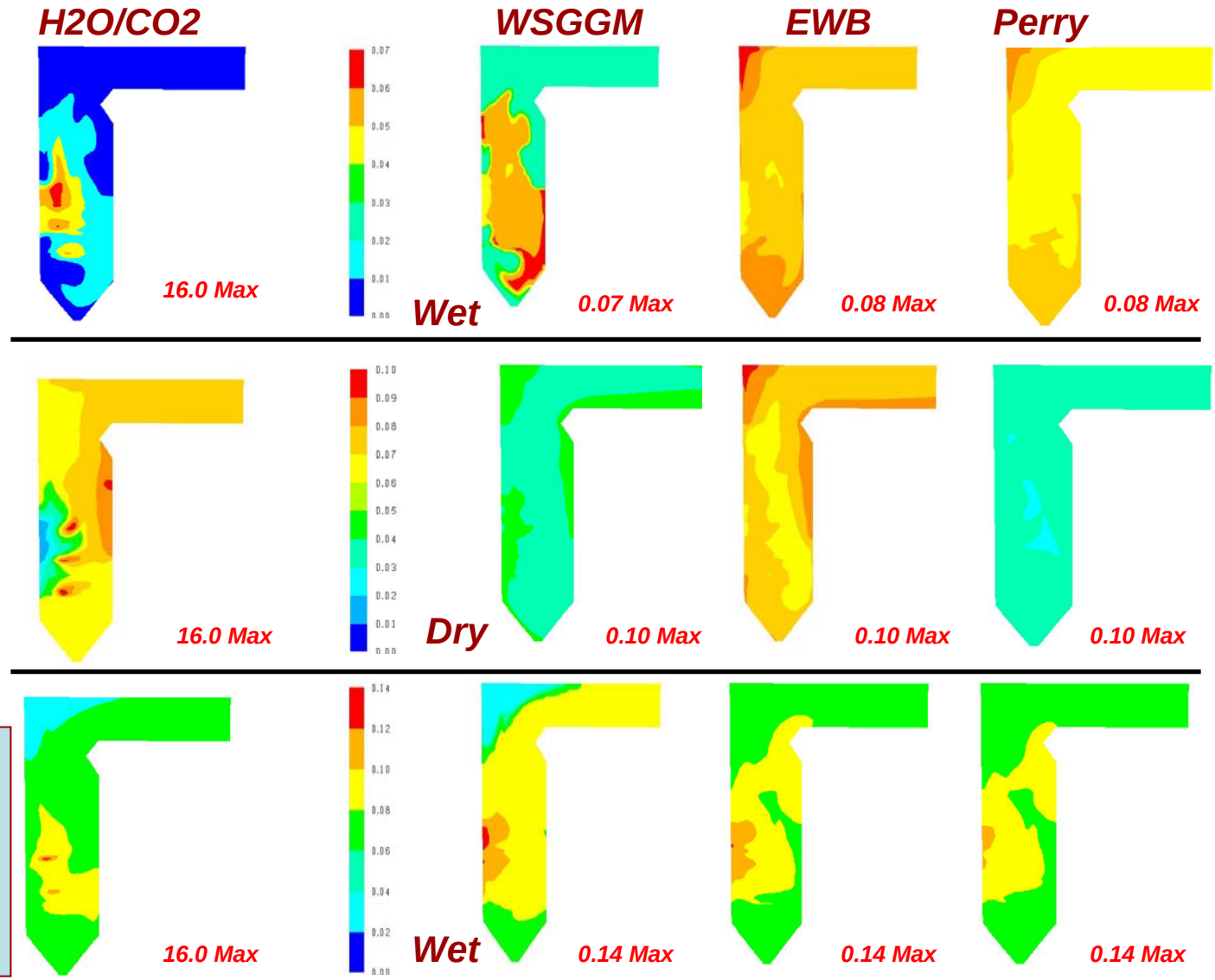
	Air	Dry-Rec.	Wet-Rec.
O_2	21	29	24
CO_2	0	71	50
H_2O	0	0	26

CFD Modeling – Utility Boiler

H2O/CO2 < 0.5
WSGGM uses CO2 coefficients

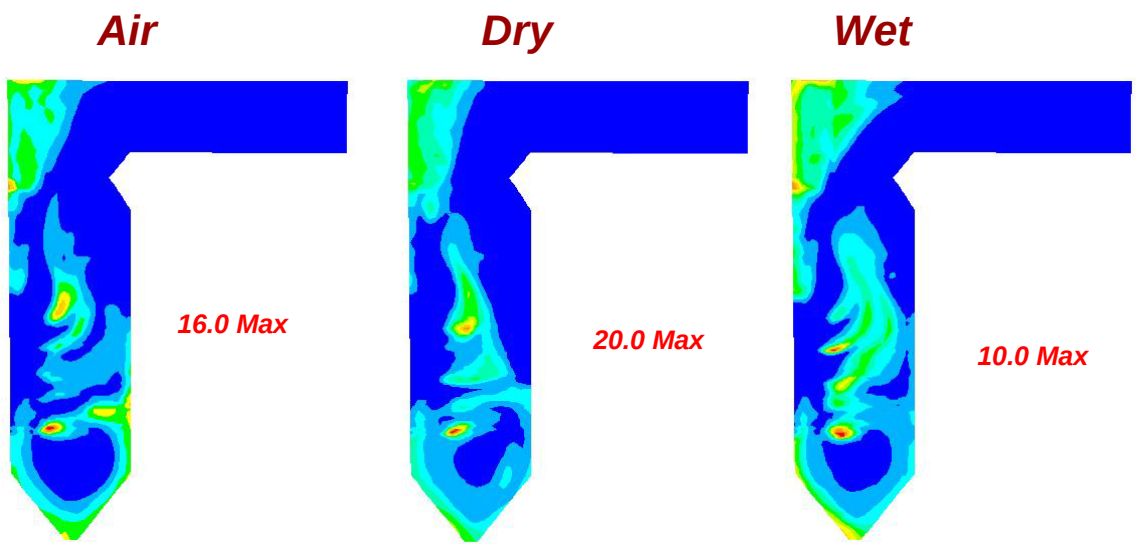
H2O/CO2 < 0.12,
both Perry and WSGG use CO2 coefficient

0.5 < H2O/CO2 < 0.6
within application range of ***Perry and WSGG***



CFD Modeling – Utility Boiler

Particle/Gas Absorption Coeff. Ratio



- **Significant Regions where Gas absorption exceeds particle absorption**