# Staged, High Pressure Oxy-Combustion Technology: Development and Scale-Up

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CONSORTIUM FOR CLEAN COAL UTILIZATION

# Project Overview

## Project Objectives: Phase II

Design and build a laboratory-scale facility and conduct laboratory-scale experiments and complimentary modeling that address the technical gaps and uncertainties addressed in Phase I.

Advance SPOC technology to TRL-5.

## Funding

Total project (Phases I & II): $5,243,789
- DOE share: $4,137,184
- Cost share: $1,106,614

## Project Performance Dates

10/01/2012 - 09/30/2016

## Project Participants

Washington University – Lead: SPOC development, experiments
EPRI – Technology evaluation, end-user insight, corrosion
ORNL – Corrosion study

# Technology Background

# Pressurized Oxy-Combustion

- The requirement of high pressure $CO_2$ for sequestration enables pressurized combustion as a tool to increase efficiency and reduce costs.

- Benefits of Pressurized Combustion
  - Recover latent heat in flue gas
  - Latent heat recovery can be combine with integrated pollution removal
  - Reduce gas volume
  - Avoid air-ingress
  - Higher partial pressure of $O_2$
  - Optically dense atmosphere

# Motivation for SPOC

Key Features:

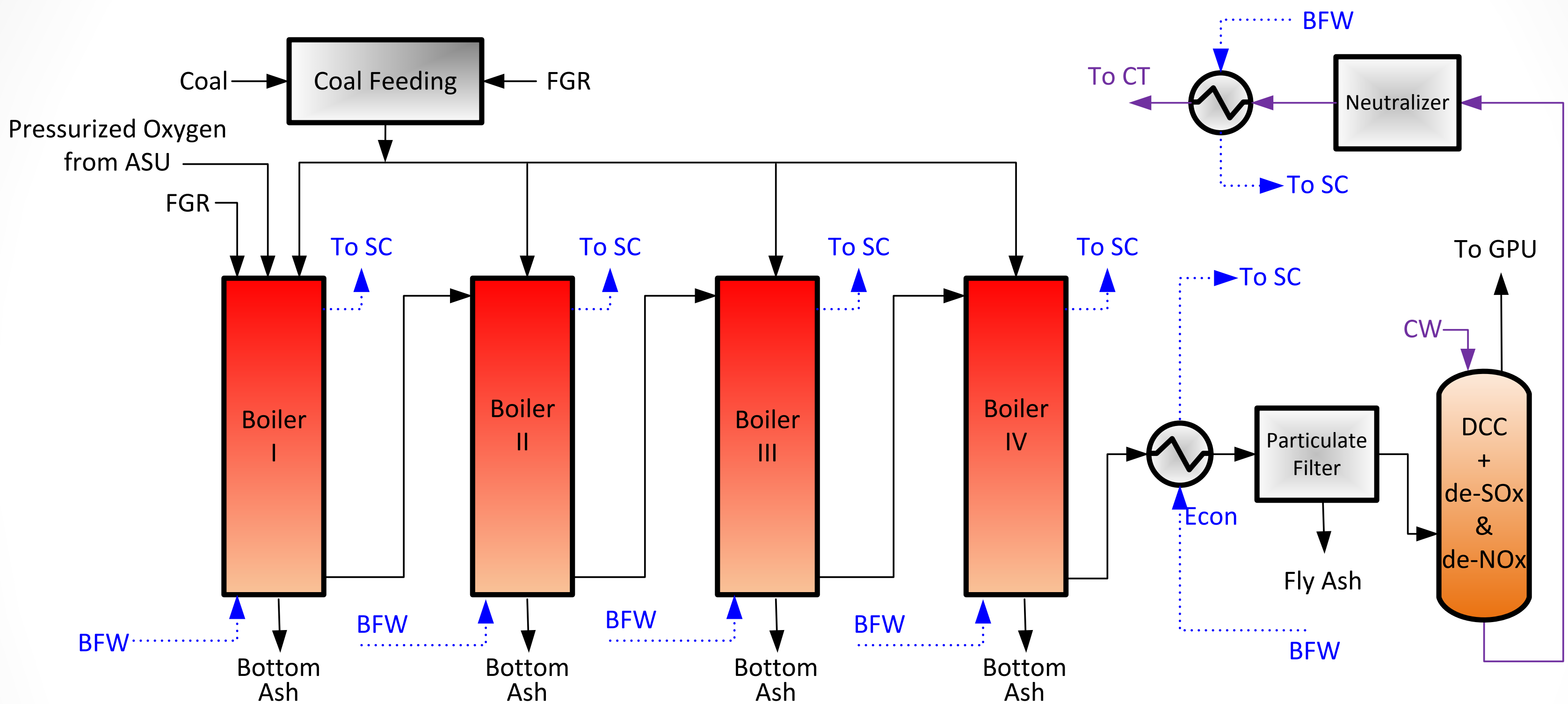
Improve capital costs by:

- Optimizing use of radiation to minimizing heat transfer surface area
- Minimizing recycled flue gas (RFG) and, thus, gas volume
- Minimizing equipment size
- Utilizing modular boiler construction

Improve operating costs by:

- Maximizing boiler efficiency
- Minimizing parasitic loads associated with RFG
- Utilizing "lead chamber" process for SOx & NOx removal
- Minimizing oxygen requirements
- Maximizing efficiency through dry feed
- Increasing performance of wet, low BTU fuels

# Schematic Process Diagram for SPOC




| LEGEND | | | | |
|---|---|---|---|---|
| **ASU: Air Separation Unit** | **BFW: Boiler Feed Water** | **GPU: Gas Processing Unit** | **CT: Cooling Tower** | **CW: Cooling Water** |
| **DCC: Direct Contact Cooler** | **Econ: Economizer** | **SC: Steam Cycle** | **FGR: Flue Gas Recirculation** | |

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# Plant Efficiencies

**a) supercritical steam conditions, net power output = 550 MW** (Phase I)

| | Air-fired | Atmos. P oxy-combustion | SPOC | |
|---|---|---|---|---|
| Coal type | Illinois #6 | Illinois #6 | Illinois #6 | PRB |
| Net generating efficiency, HHV (%) | 39.3 | 29.3 | 36.7 | 35.7 |

**b) independent study comparing two pressurized oxy-combustion processes**

| | Air-fired | Atmos. P oxy-combustion | | Pressurized oxy-combustion | |
|---|---|---|---|---|---|
| | | (conservative) | (optimized) | ISOTHERM | SPOC |
| Net generating efficiency, LHV (%) | 46.1 | 36.1 | 39.1 | 38.4 | 42.3 |

*6%-pts improvement in plant efficiency*


a. Gopan, A. et al. (2014) Applied Energy, 125, 179-188.

b. Hagi, H.,et al. (2014). Energy Procedia, 63, 431-439.

# Technical Approach/Project Scope

# Work Plan

**Tasks**

1. Project management
2. Design, fabrication and installation of high pressure combustion furnace
3. High pressure combustion experiments (heat flux, temp, ash, deposition)
4. Materials corrosion studies (high $O_2$ and $SO_2$ environments)
5. Modeling direct contact cooler
6. Re-evaluation of boiler design
7. Update process model and techno-economic analysis

# Projected Phase 2 Outcomes

- Proof of concept demo of coal combustion under SPOC conditions.

- Improved understanding of radiation heat transfer in pressurized oxy-combustion conditions

- Improved understanding of ash formation/deposition mechanism in pressurized oxy-combustion conditions

- Knowledge of performance of boiler tube materials under SPOC conditions

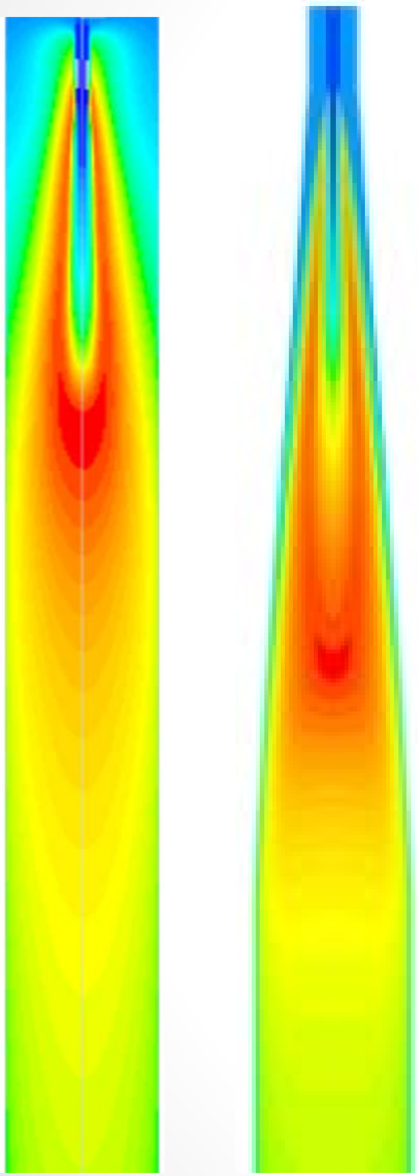
- Improved estimate of SOx, NOx removal efficiency in direct contact cooler

- Reduced uncertainty and contingencies → improved COE

# Progress and Current Status:

# Furnace Design

ANSYS FLUENT CFD



- Diameter is fixed – *heat transfer requirements.*
- Cylindrical vessel – *buoyancy effects significant*.
- Reducing inlet size of reactor – *increased axial velocity*.
- *Conical design – high initial velocity w/o compromising on overall heat transfer surface area.*

$$Ri_x = g\beta(T_{hot} - T_{surr})\frac{x}{v^2}$$

- At full scale – *Cone only forms a small part of the overall vessel.*

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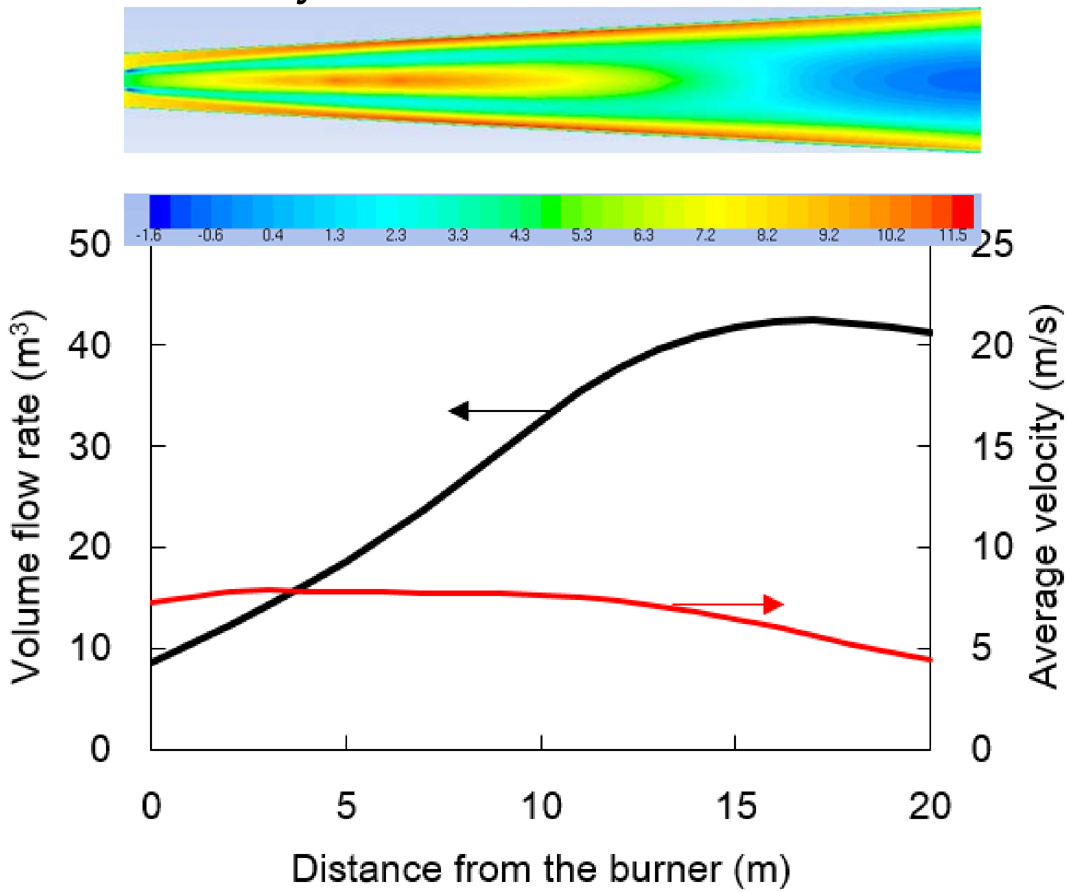
# Design of Conical Zone

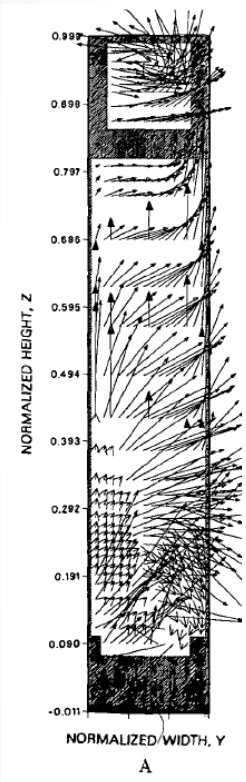
**Velocity contour**

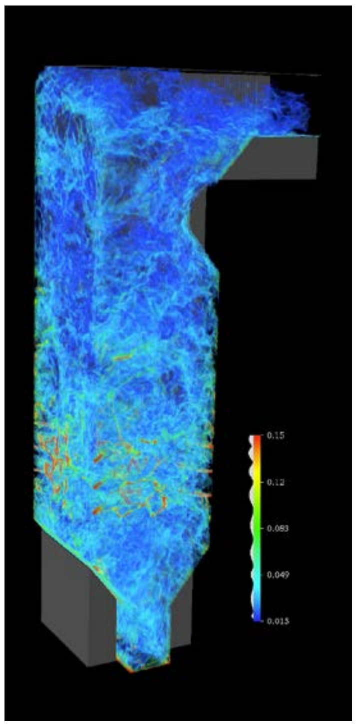



- $Q_{gas}$ increases due to 1) increase in $T$ and 2) gas generation via $C(s) \rightarrow CO_2\ (g)$
- The reactor is designed to achieve a nearly flat average gas velocity in the flame zone maintain a high Richardson Number.

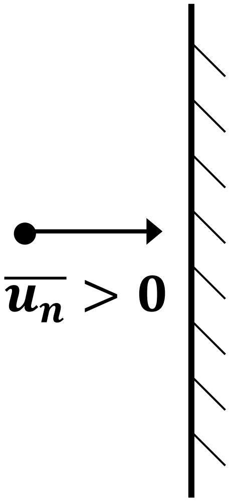
# Particle Deposition in Conventional and SPOC Boilers

Wall-fired T-fired



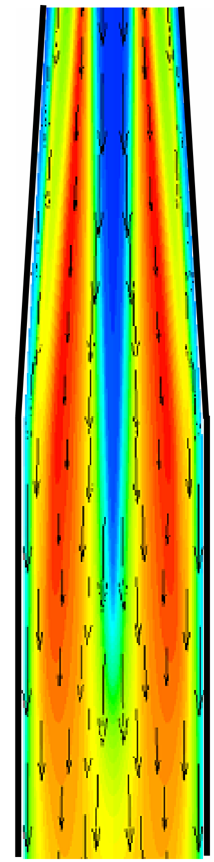
Courtesy of Phil Smith
U of Utah

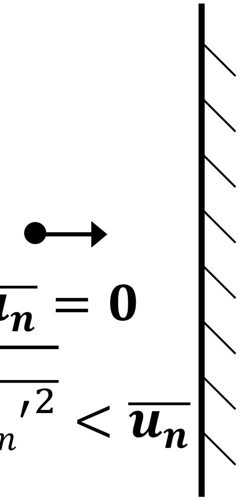


$\overline{u_n} > 0$

- **Ash particles deposit on wall due to inertial impaction**

SPOC





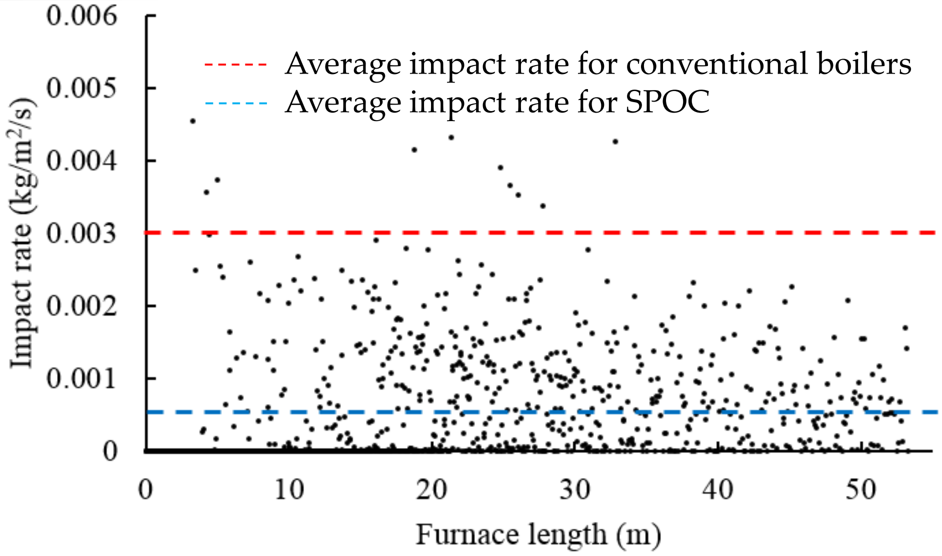
$\overline{u_n} = 0$

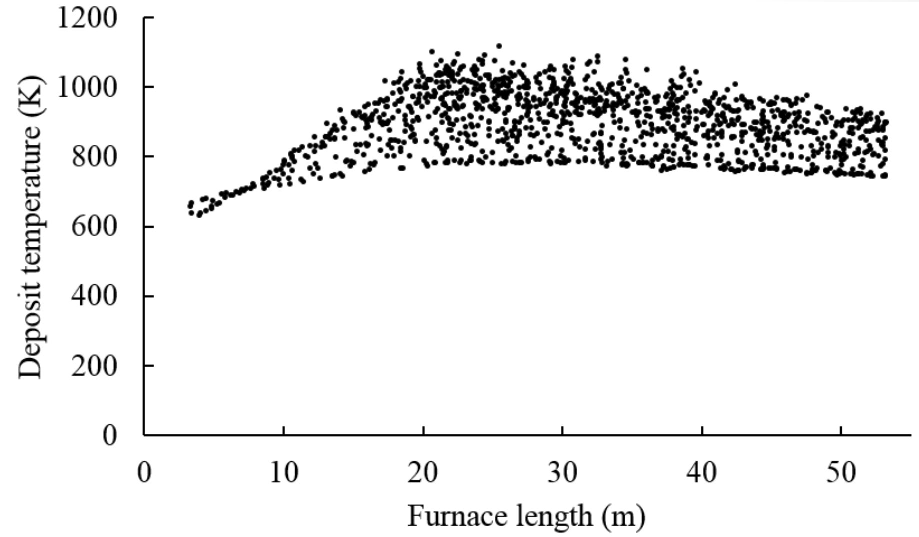
$\sqrt{\overline{{u_n}'^2}} < \overline{u_n}$

- **Ash particles deposit on wall due to eddy diffusion**
- **Lower ash deposition rate**
- **Particles have more time to cool before hitting the wall**

# SPOC particle deposition

- CFD simulation results



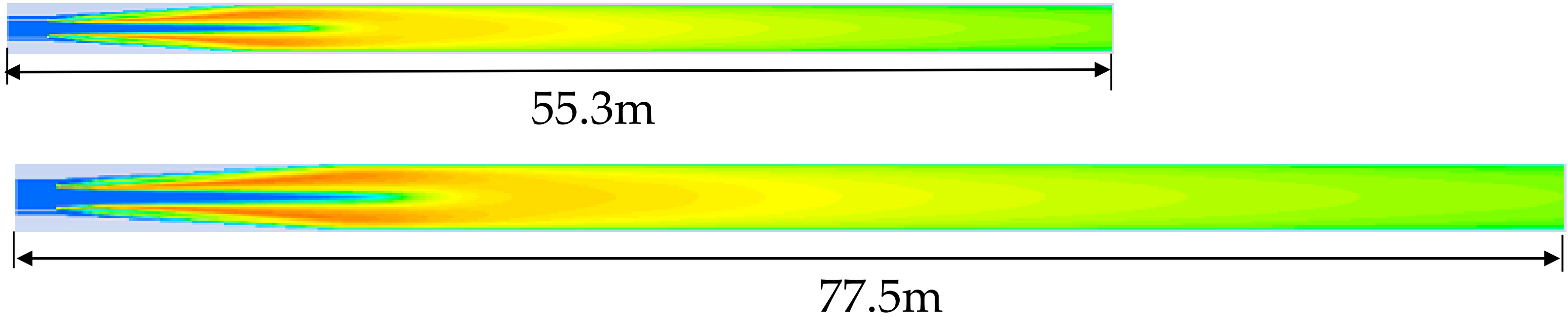



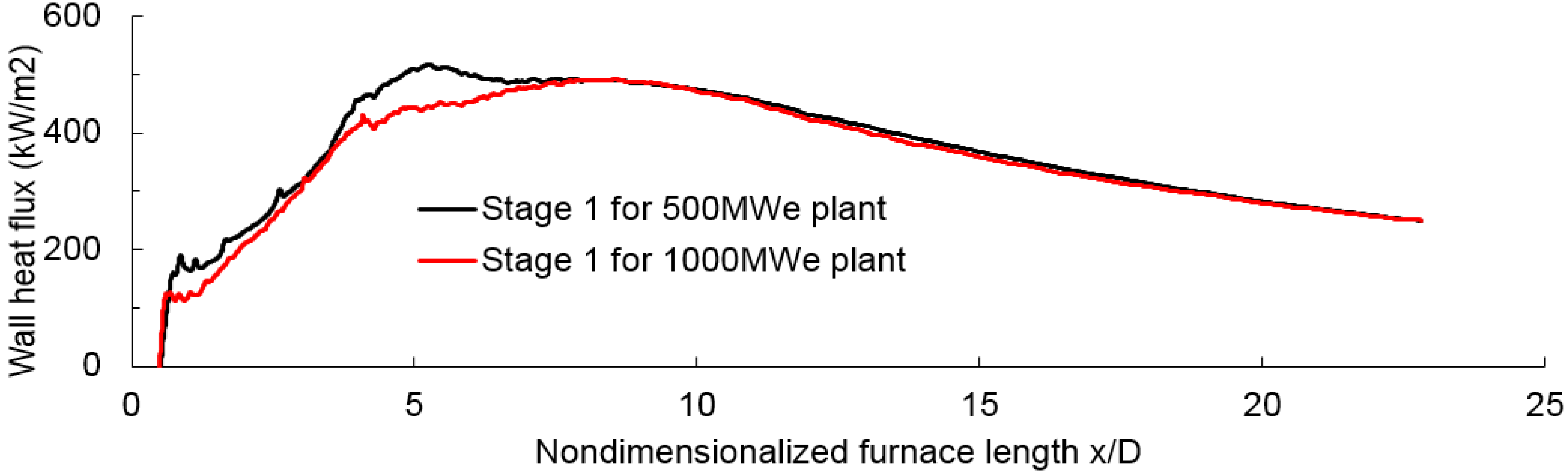

- The average particle impact rate in the SPOC boiler is an order of magnitude lower than that in conventional PC boilers[1]
- The temperatures of all ash deposits are lower than 850 $^{o}$C, which is much lower than the ash fusion temperature. Slagging is unlikely.

[1] Wang, H., & Harb, J. N. (1997) *Progress in Energy and Combustion Science, 23*(3), 267-282.

# Effect of Scale on Wall Heat Flux

- **Scale-up from 500 MWe to 1000 MWe**
- **Stage 1 results**

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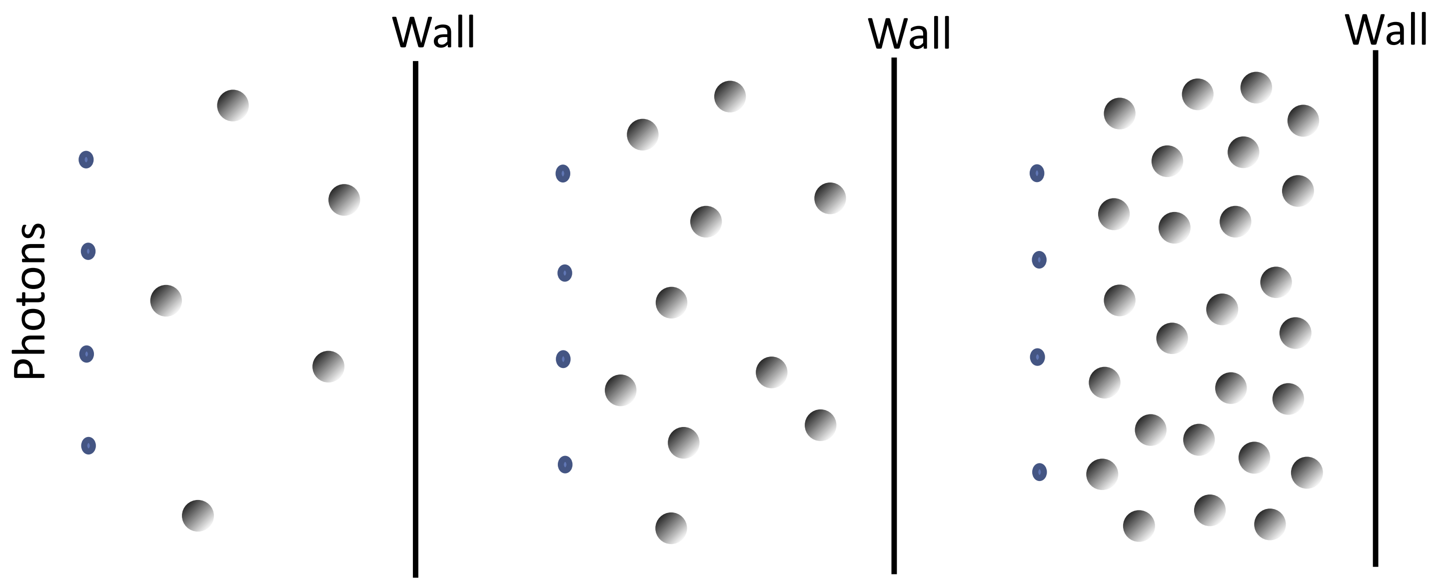
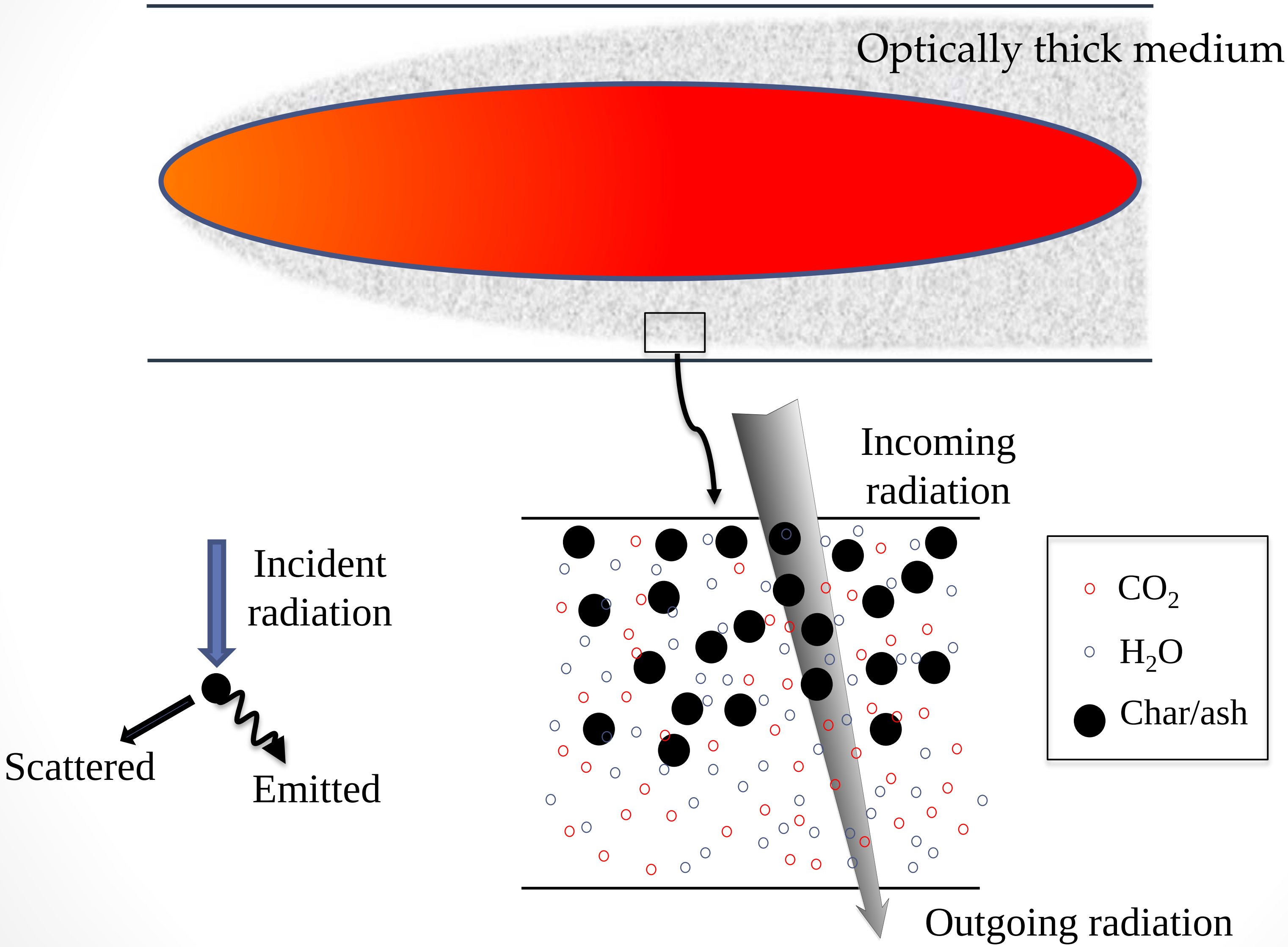
# Radiation and Particle Cloud Interactions

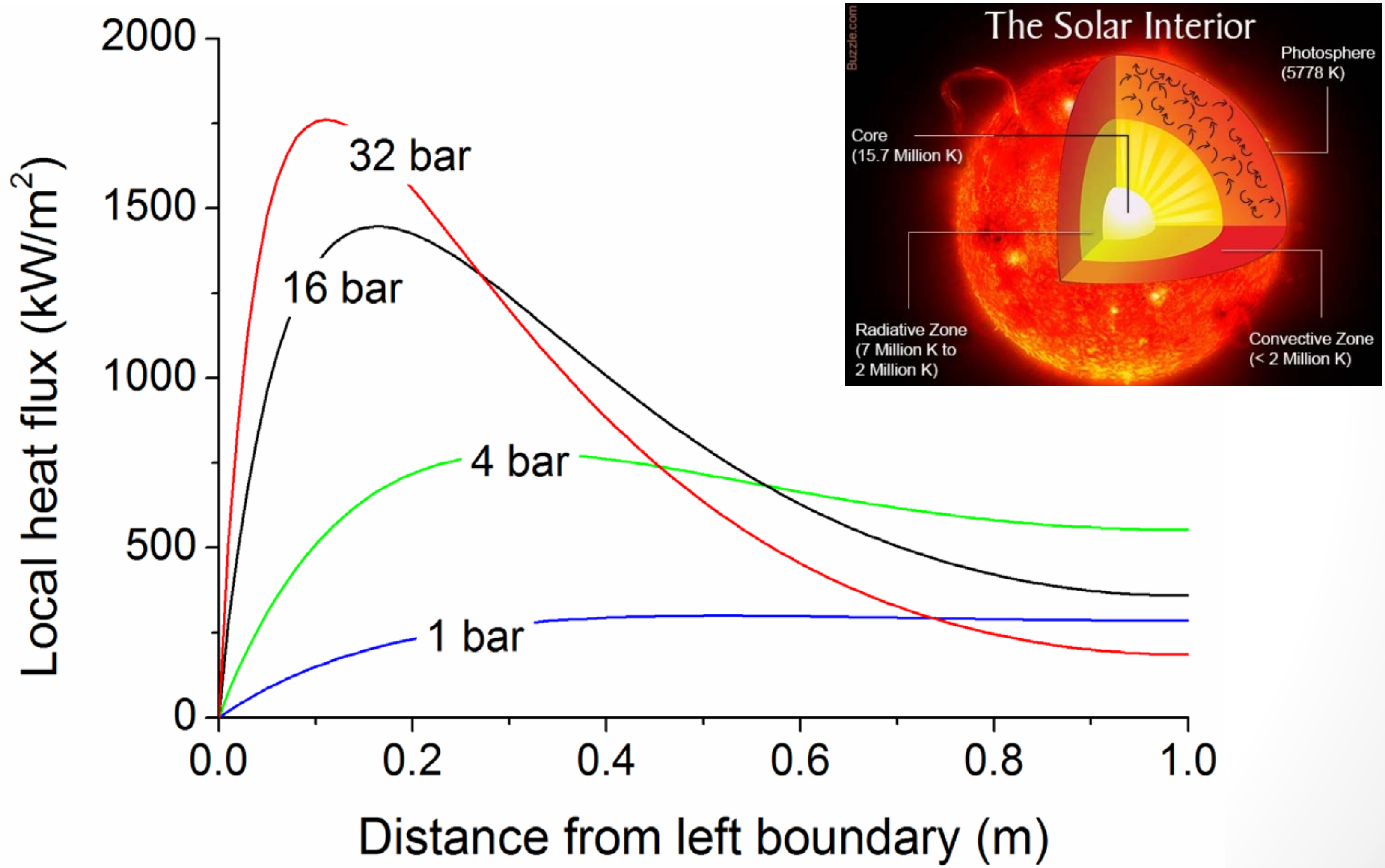



Optically thin medium Optically thick medium Optically dense medium

# Radiant Heat Transfer



# Fundamental study on radiation



# Test Facility Status

Year 1:

- Test facility engineering design
- Received & inspected the pressure vessel
- Start of lab renovation

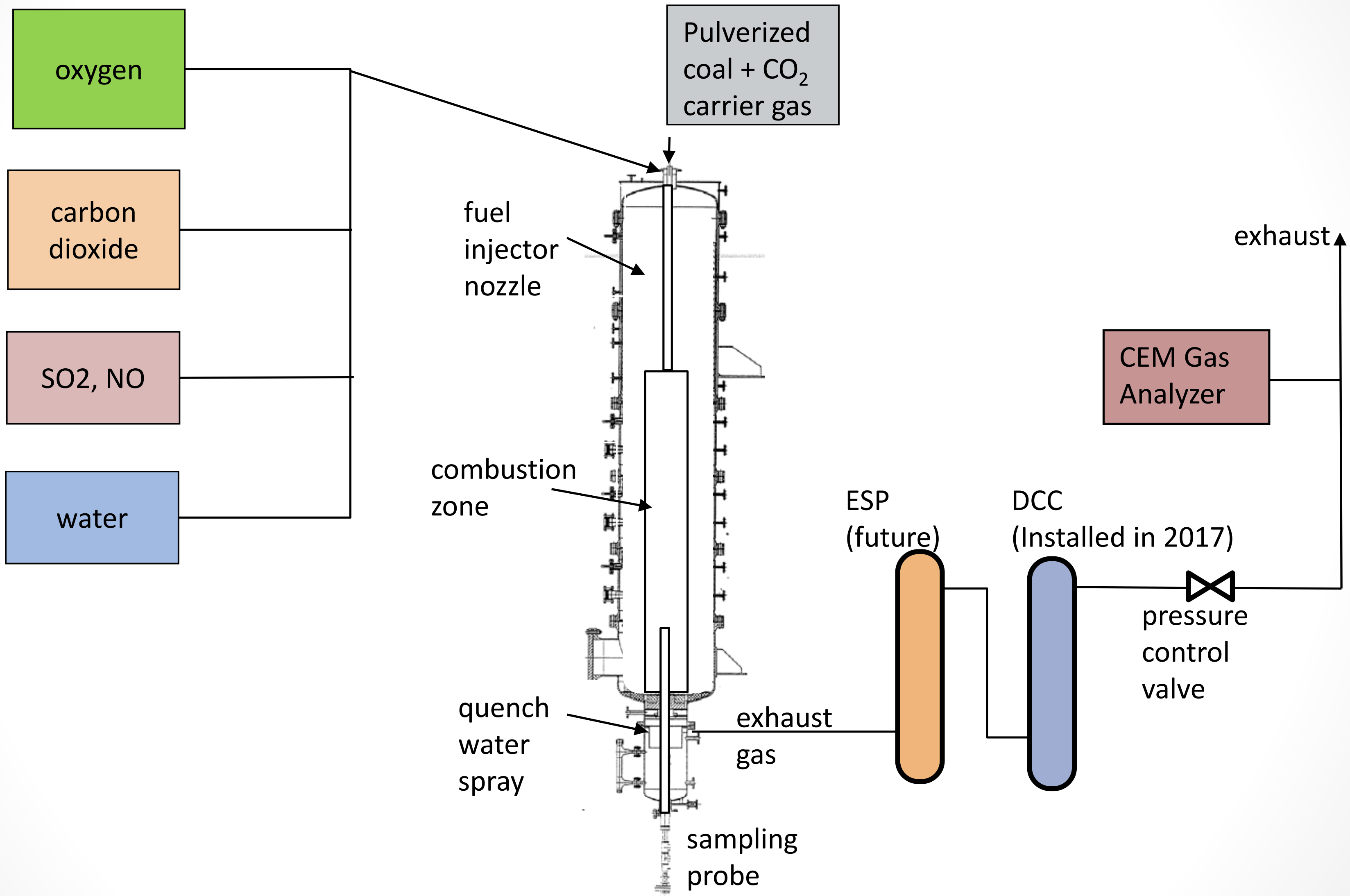
Year 2:

- Repaired, certified pressure vessel
- Vessel and supporting steel structure installed
- Piping, electrical for ancillary
- Design and fabrication of vessel interior parts

Year 3:

- $CO_2$ and $O_2$ bulk storage tanks
- Controls & data acquisition
- Coal feed system installation
- Commissioning

# Test Facility – Block Flow Diagram



# Pressurized Oxy-Combustion Facility

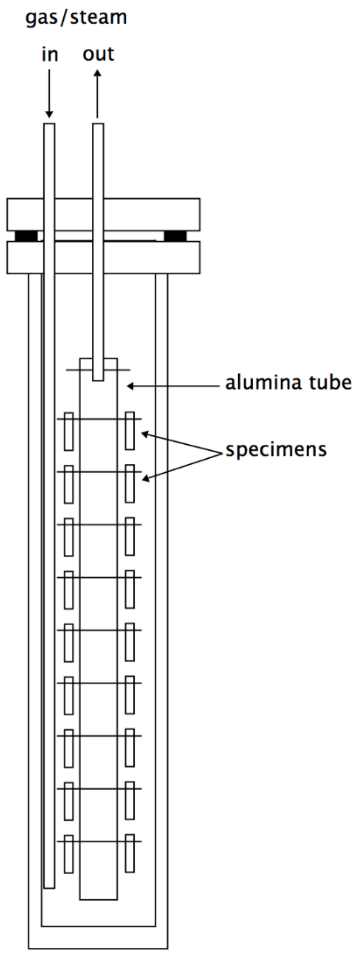
- ~100kW thermal input
- 1-15 bar
- Completing commissioning

# Progress and Current Status:
## Corrosion Tests

# Effect of Pressure on Fire-side Corrosion: Experiment Summary

- Gas only, 500-h screening experiments
  - o 600°C: Conventional supercritical, Fe-base alloys + overlays
  - o 800°C: A-USC, Ni-base alloys
    - 1 and 17 bar
    - 90%$O_2$-10%$H_2O$ with and without 0.1%$SO_2$
    - 4 sets of specimens at each temperature

- Effect of pressure on coal ash corrosion at 700°C
  - o 700°C selected as the typical temperature for peak fireside corrosion
  - o Specimens exposed bare and with synthetic ash reapplied after each cycle
  - o Oxy-fired gas 1: (63.4%$CO_2$-5%$N_2$-1.5%$O_2$-30%$H_2O$-0.1%$SO_2$)
    - Four 100-h cycles
  - o Oxy-fired gas 2: (63%$CO_2$-5%$N_2$-1.5%$O_2$-30%$H_2O$-0.5%$SO_2$)
    - 100-h, system plugged due to corrosion product (issue resolved)

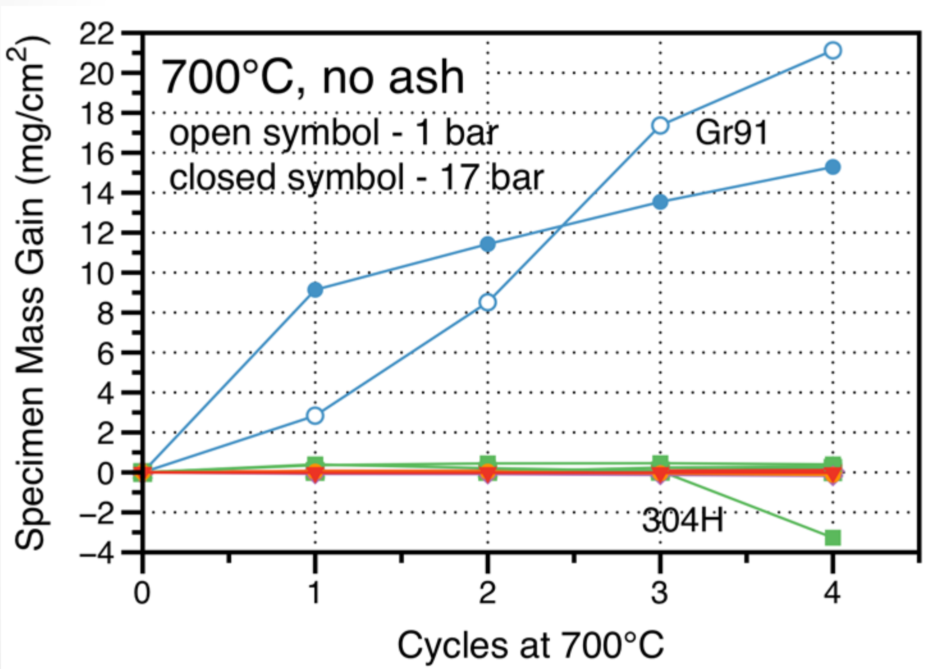


# Corrosion Tests with and without Ash

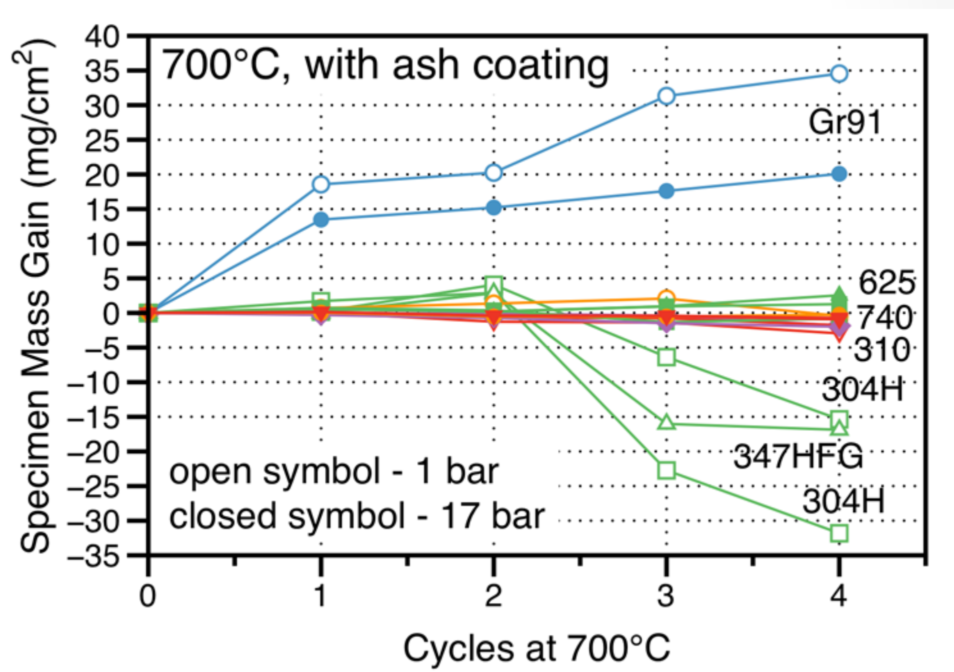
## 700°C: 63.4%$CO_2$-5%$N_2$-1.5%$O_2$-30%$H_2O$-0.1%$SO_2$

- Only minor effects of pressure observed

Bare specimens (gas only, no ash)




Synthetic ash recoated each cycle

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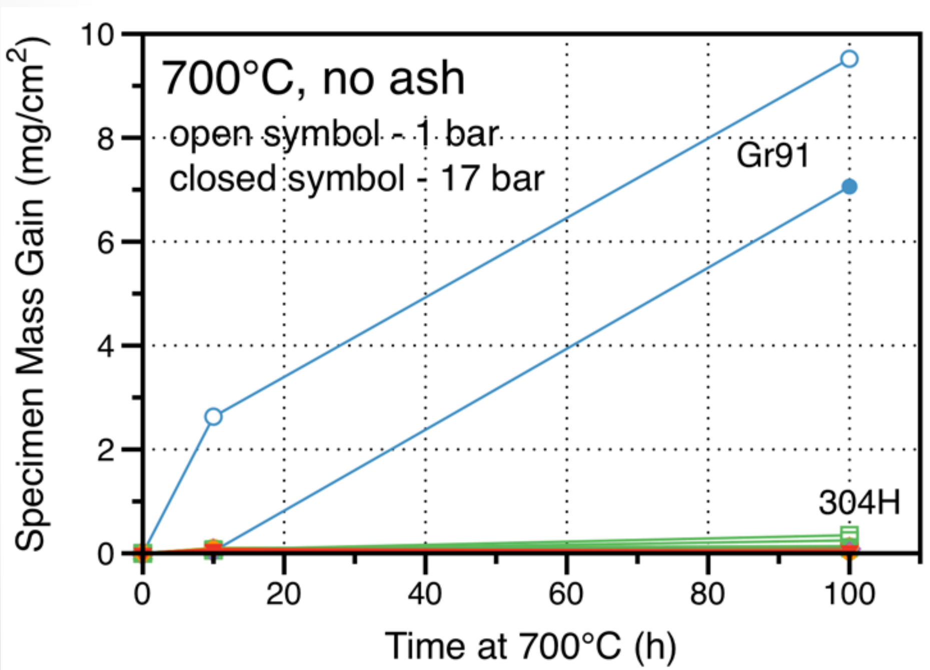
# Effect of Increased Sulfur

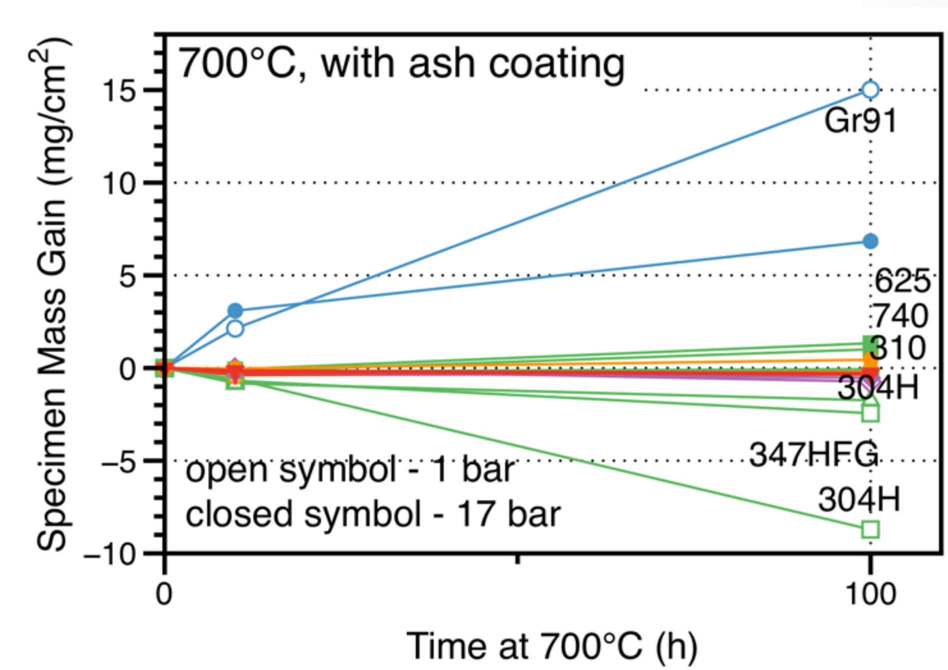
## 700°C 63.4%$CO_2$-5%$N_2$-1.5%$O_2$-30%$H_2O$-0.5%$SO_2$

- 100 h only
- Similar results to 0.1% $SO_2$
- No clear effect of pressure

Bare specimens (gas only, no ash)




Specimens with synthetic ash

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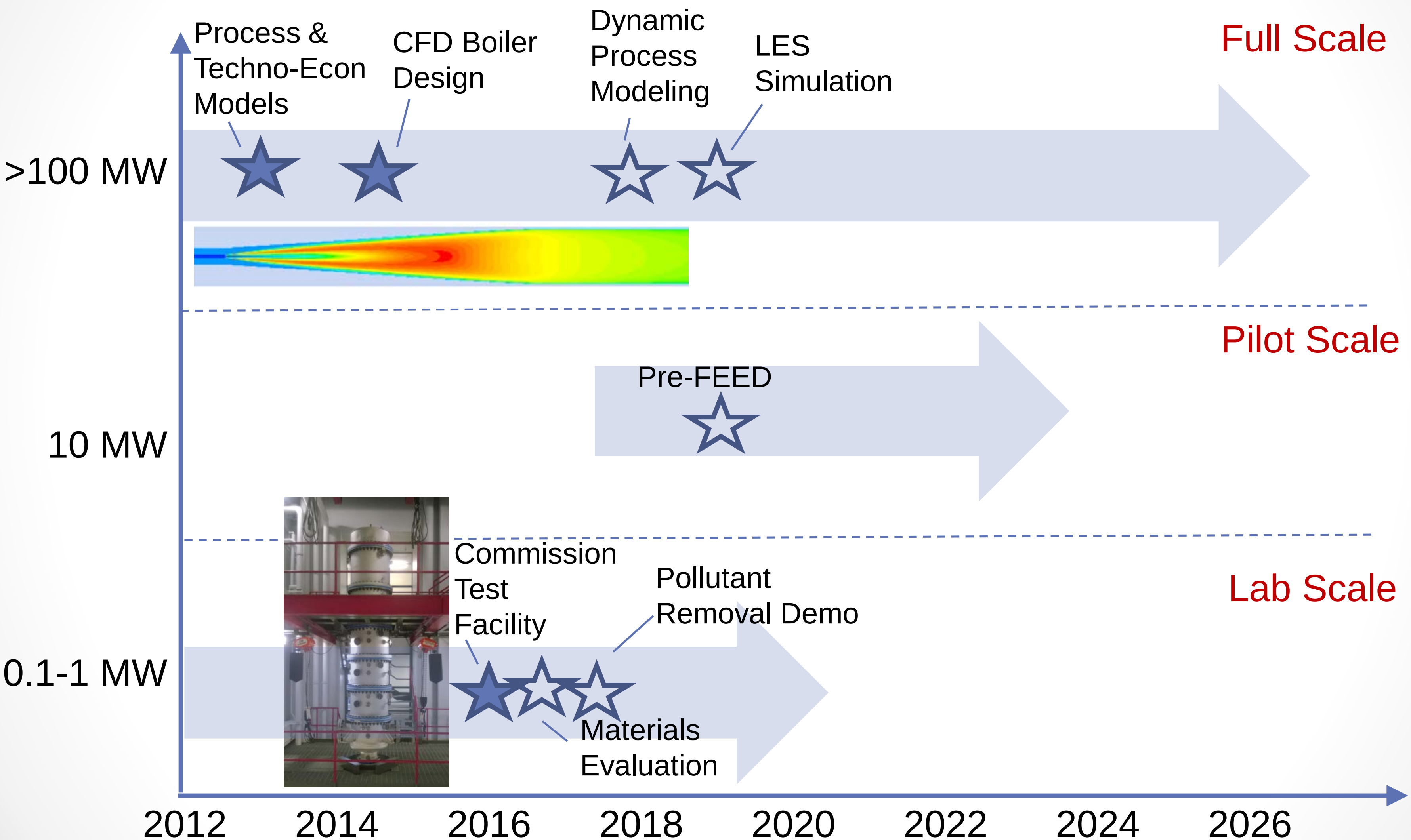
# Conclusions: Corrosion Tests

1) 90%$O_2$-10%$H_2O$ environment at 1 and 17 bar showed reaction rates similar to prior work in steam and air+$H_2O$ at 600° and 800°C
   - No detrimental effect of high $O_2$ environment was observed
2) Without ash, $SO_2$ addition was detrimental, especially at 17 bar
   - Higher $SO_2$ and $SO_3$ partial pressure at 17 bar
3) When synthetic coal ash was added at 700°C, no particular effect of pressure was observed.
   - With ash, mechanism is expected to change to coal ash corrosion, i.e. molten salt attack
   - Pressure has little effect on condensed salt phase on alloy surface
4) Higher alloyed steels (e.g. 310HCbN) and/or Ni-base alloys or overlay coatings on steels appear to be possible solutions for a high S coal SPOC environment.

# Project Status

- Year 3:
  - Pressurized combustion experiments
  - CFD model evaluation
  - Detailed boiler tube materials corrosion analysis
  - Process model and techno-economic analysis reevaluation
- After this project:
  - Advance technology to Pre-FEED for pilot scale facility.
  - U.S.-China Clean Energy Research Center (CERC-ACTC)
- Scale-up:
  - Results of our study will be used to attract potential industrial partners for pilot-scale demonstration

# Development Roadmap



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