Characterizing Impacts of High Temperature and Pressures in Oxy-Coal Combustion Systems

Reaction Engineering International
University of Utah
Jupiter Oxygen
Praxair

U.S. Department of Energy, Agreement DE-FE0025168

09-01-15 through 08-30-17

Project Partners

For Energy and Environmental Solutions

REACTION ENGINEERING INTERNATIONAL

THE UNIVERSITY OF UTAH

PRAXAIR

Jupiter Oxygen

Technical Approach

1. Design and construction of burners and injectors for 3 pilot-scale furnaces that will allow combustion with coal by a mixture of oxygen and minimum recycled flue gas
2. Detailed measurements of heat flux, flame and material temperatures and flame stability at high temperatures while firing at 100 kW and 1 MW and atmospheric pressures
3. Detailed measurements of heat flux and flame and material temperatures at elevated temperatures while firing at 300 kW and 17 bar
4. Detailed ash aerosol measurements at atmospheric and 17 bar pressure experimental conditions
5. Creation of mechanisms and correlations describing heat transfer and mineral matter transformations suitable for insertion into CFD simulation codes

Statement of Project Objective

Develop data and validate mechanisms describing heat transfer and ash deposition in high temperature oxy-coal combustion and elevated temperature pressurized oxy-coal combustion

Outcomes / Impacts

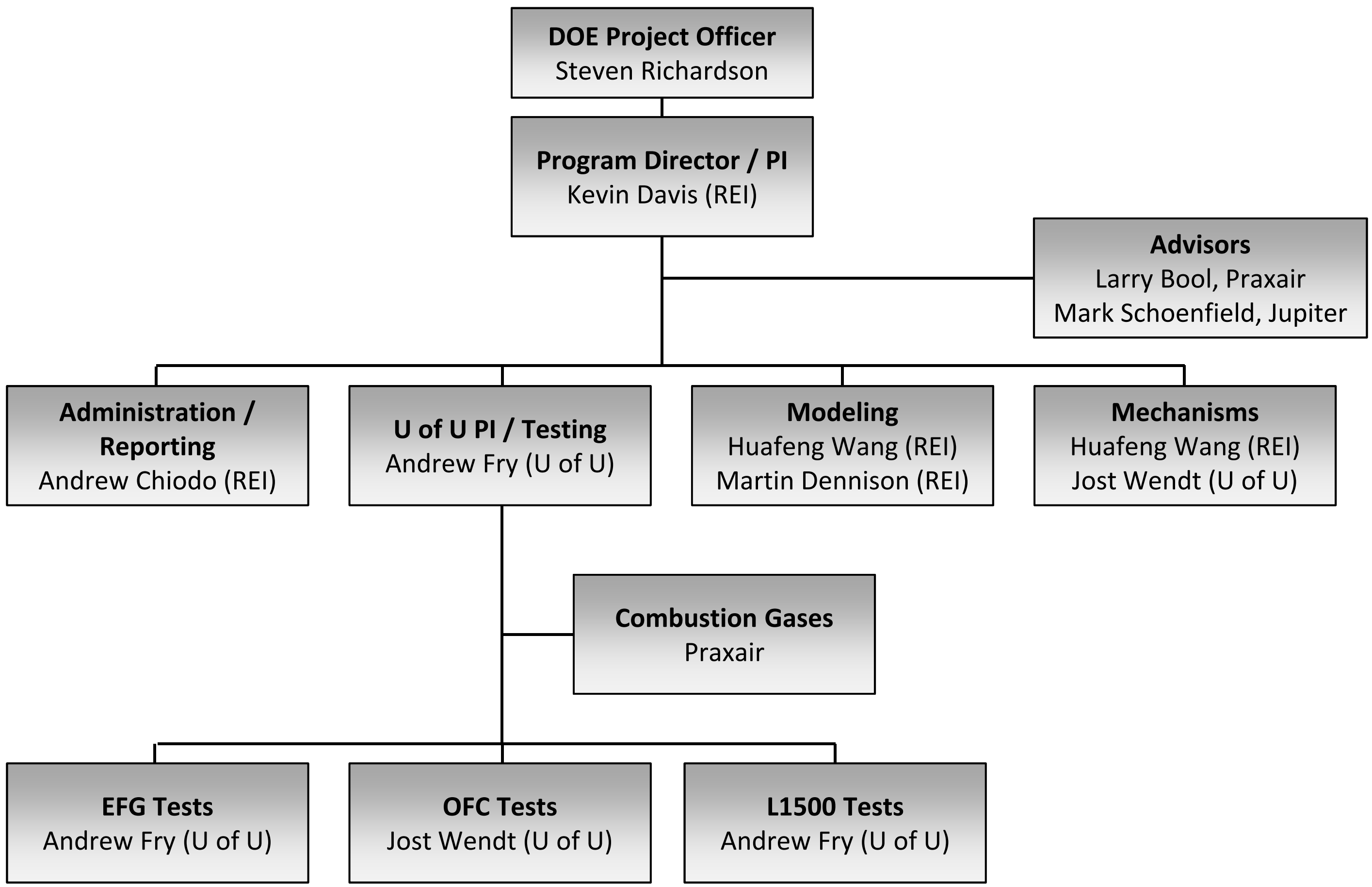
1) Multi-scale, high temperature and high pressure test data selected from a 100kW atmospheric laboratory combustor (OFC), a 1.5 MW atmospheric semi-industrial scale combustor (L1500), and a 300kW pressurized (17bar) combustor (EFG), all operating with the oxidant as 100% oxygen with minimal flue gas recirculation. The data will describe differences in flame characteristics, radiative heat flux profiles, fouling, and slagging for coal combustion under (directed) oxygen-firing conditions, including sensitivity to oxy-burner design and oxy-combustion pressure.

2) *Validated* mechanisms developed from multi-scale test data that describe fouling, slagging, and heat transfer, under high temperature atmospheric and elevated temperature high pressure coal oxy-combustion conditions. The mechanisms will be in a form suitable for inclusion in CFD models or process models.

3) Principles to guide design of high temperature, high pressure, pilot-scale and full-scale coal oxy-firing systems, such that boiler operational impacts from pressurized oxy-combustion retrofits are minimized.

4) Assessment of high temperature oxy-combustion and pressurized oxy-combustion impacts on key parameters relevant to oxy-coal fired utility boilers, using computational fluid dynamics (CFD) modeling of multi-scale atmospheric and pressurized oxygen-fired operation, together with the information generated in this research.

Project Organization



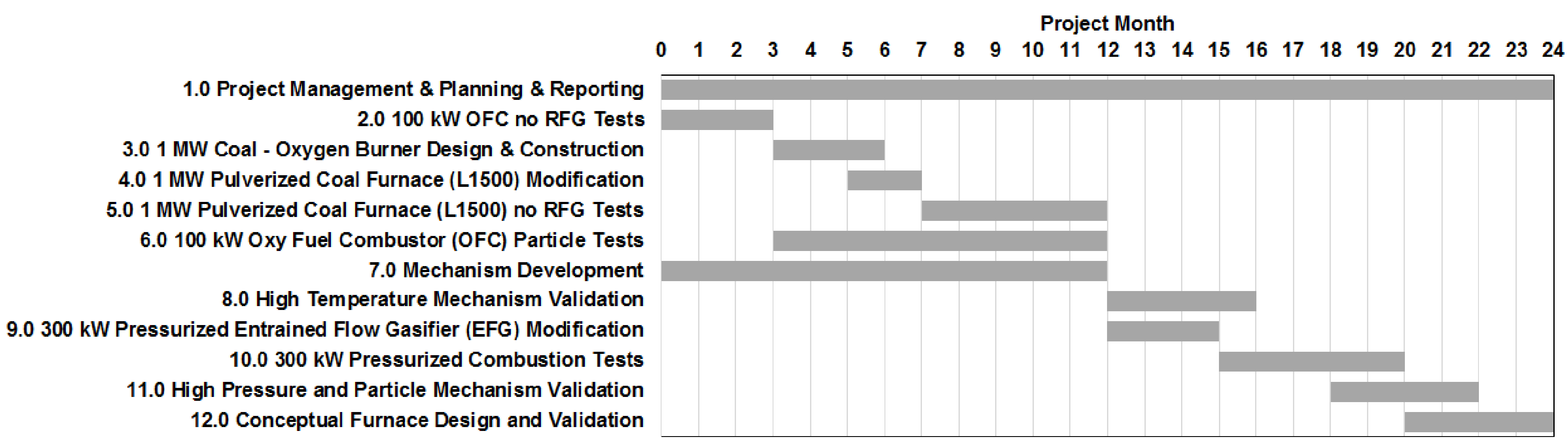
Project Management Plan

REI Shall:

- Manage and direct the project in accordance with a Project Management Plan (PMP) to meet all technical, schedule and budget objectives and requirements
- Maintain the project management plan and update as necessary
- Coordinate activities in order to effectively accomplish the work
- Ensure that project plans, results, and decisions are appropriately documented and project reporting and briefing requirements are satisfied
- Manage risk in accordance with the risk management approach specified in the project management plan and as discussed in subsequent slides

Project Timeline

09-01-15 through 08-30-17



Task 1.0 Project Management & Planning

REACTION ENGINEERING INTERNATIONAL

THE UNIVERSITY OF UTAH

Subtask 1.1 – Update Project Management Plan.

Subtask 1.2 – Submission and approval of required NEPA documentation.

Subtask 1.3 – Set up contracts with DOE and all project subcontractors.

Subtask 1.4 – Hold Project Kickoff Meeting.

Subtask 1.5 – Process contractor and sub-contractor invoices and payments.

Subtask 1.6 – Hold regular project team review meetings to assess progress and identify concerns.

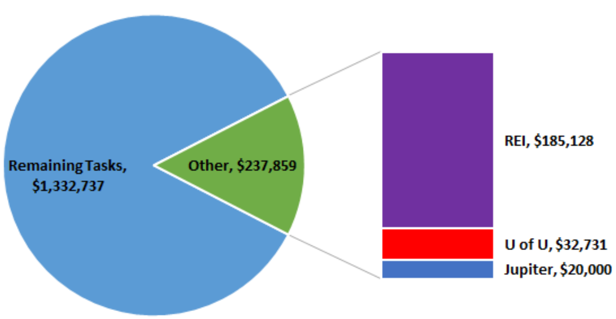
Subtask 1.7 – Provide quarterly Progress Reports to DOE, including updates on Milestone Status and Project Timeline.

Subtask 1.8 – Prepare annual Topical Report for DOE.

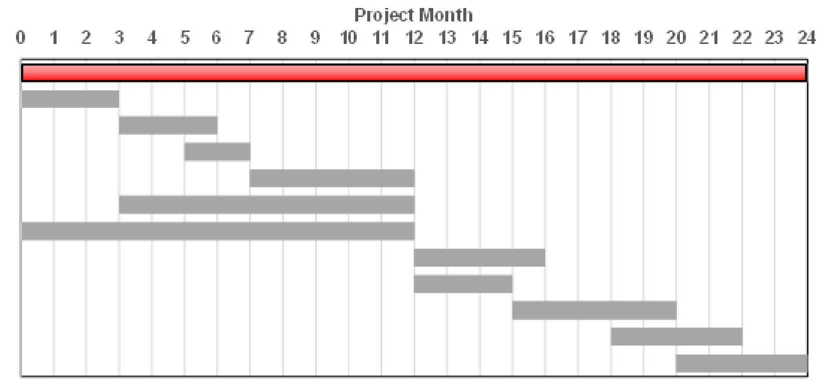
Subtask 1.9 – Provide annual technical briefing to DOE Project Officer.

Subtask 1.10 – Present project results at DOE/NETL Annual Contractor's Review Meeting.

Subtask 1.11 – Provide project Final Report to DOE.



09-01-15 through 08-30-17



Milestones

Phase I (Year 1) Milestones	
Phase I Milestone	**Scheduled Completion**
1. Updated Project Management Plan (Task 1)	11/30/15
2. Kickoff Meeting (Task 1)	12/31/15
3. OFC high-oxygen firing tests completed (Task 2)	2/28/16
4. L1500 oxy-coal burner constructed (Task 4)	4/30/16
5. L1500 high-oxygen firing tests completed (Task 5)	11/30/16
6. OFC ash particle tests completed (Task 6)	11/30/16
7. Annual topical report completed (Task 1)	10/31/16

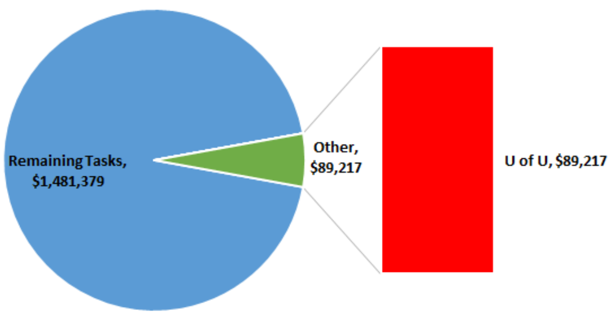
Phase 2 (Year 2) Milestones	
Phase II Milestone	**Scheduled Completion**
1. 300 kW pressurized EFG modifications completed (Task 9)	12/31/16
2. 300 kW pressurized EFG oxy-firing tests completed (Task 10)	6/30/17
3. Final presentation at DOE (Task 1)	12/31/17
4. Final technical report completed (Task 1)	11/30/17

Task 2.0 100 kW OFC no RFG Tests

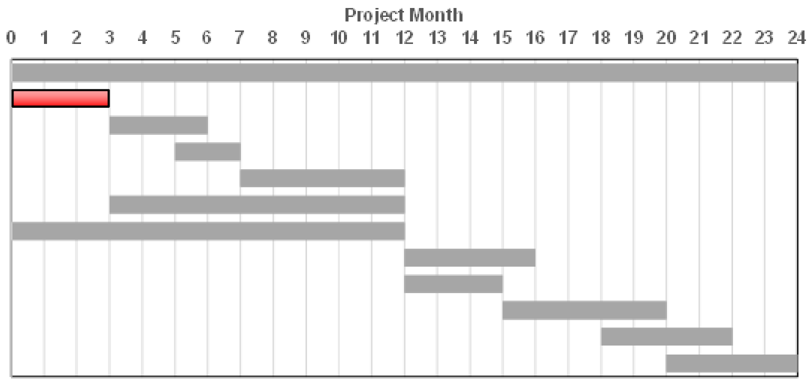
THE UNIVERSITY OF UTAH

Subtask 2.1 – Design and build minimum recycle OFC burners

Subtask 2.2 – OFC no RFG testing

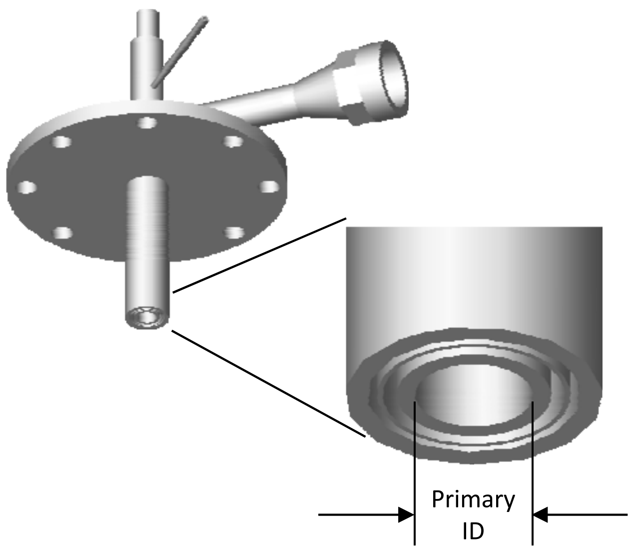


09-01-15 through 10-01-15



Task 2.0 100 kW OFC no RFG Tests

Subtask 2.1 – Design and build minimum recycle OFC burners



- Current axial burner
  - Primary pipe ID is too large
  - O_2 concentration is limited to 60% in the O_2 / CO_2 Mixture
- Build one burner with:
  - Smaller primary ID
  - Only one annular register
- Build second burner with:
  - Smaller primary ID
  - Only one annular register
  - O2 jets for mixing

- Oxygen jets will induce mixing and allow transition from axial jet to well mixed
- Investigate multiple velocities at the burner tip

Task 2.0 100 kW OFC no RFG Tests

Subtask 2.2 – OFC no RFG testing

THE UNIVERSITY OF UTAH

We will test for 4 weeks using one coal. There will also be limited testing with petroleum coke. Limited testing of slurry firing.

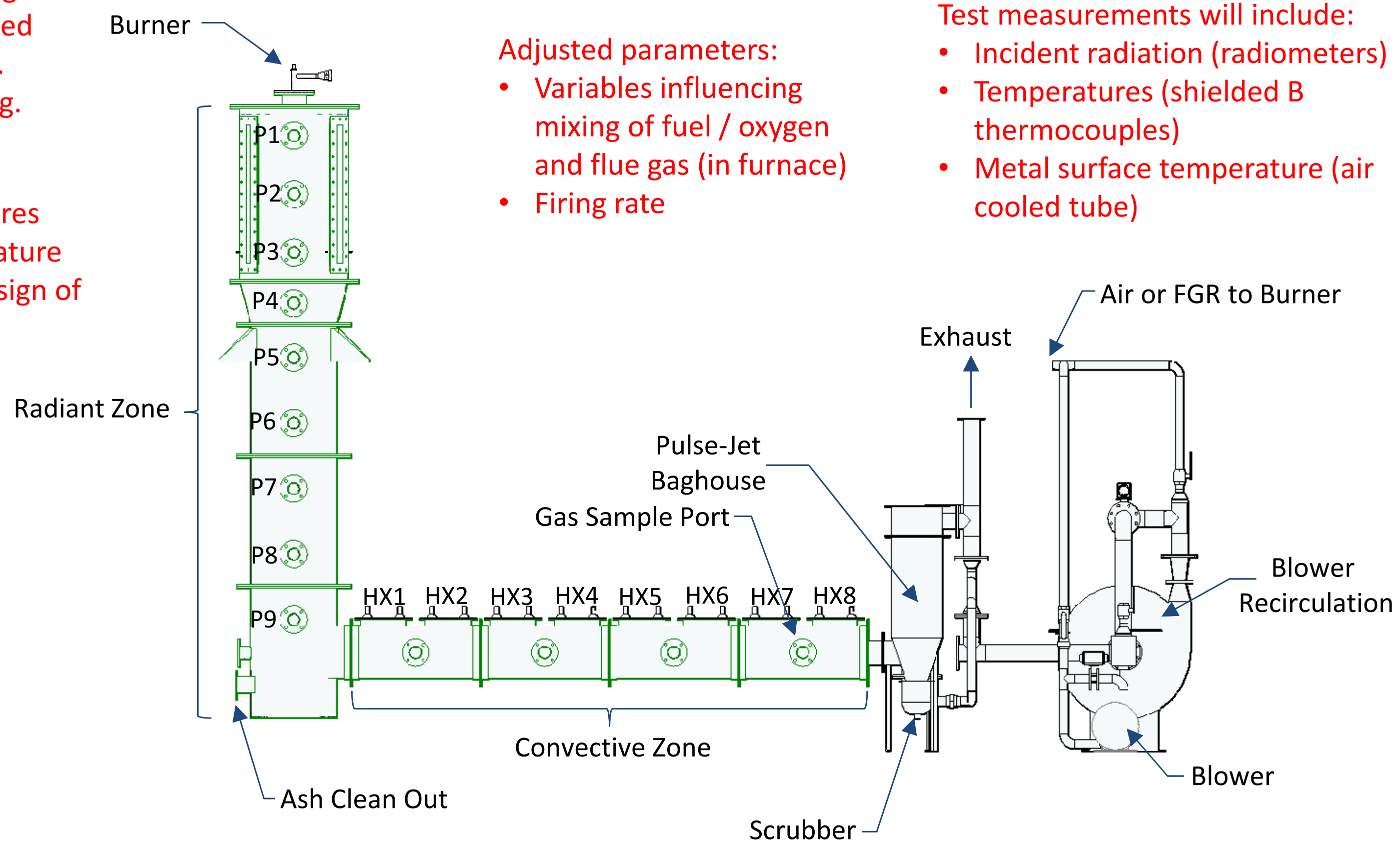
Determination of temperatures that satisfy material temperature limits. Used to help with design of L1500 firing system

Adjusted parameters:

- Variables influencing mixing of fuel / oxygen and flue gas (in furnace)
- Firing rate

Test measurements will include:

- Incident radiation (radiometers)
- Temperatures (shielded B thermocouples)
- Metal surface temperature (air cooled tube)

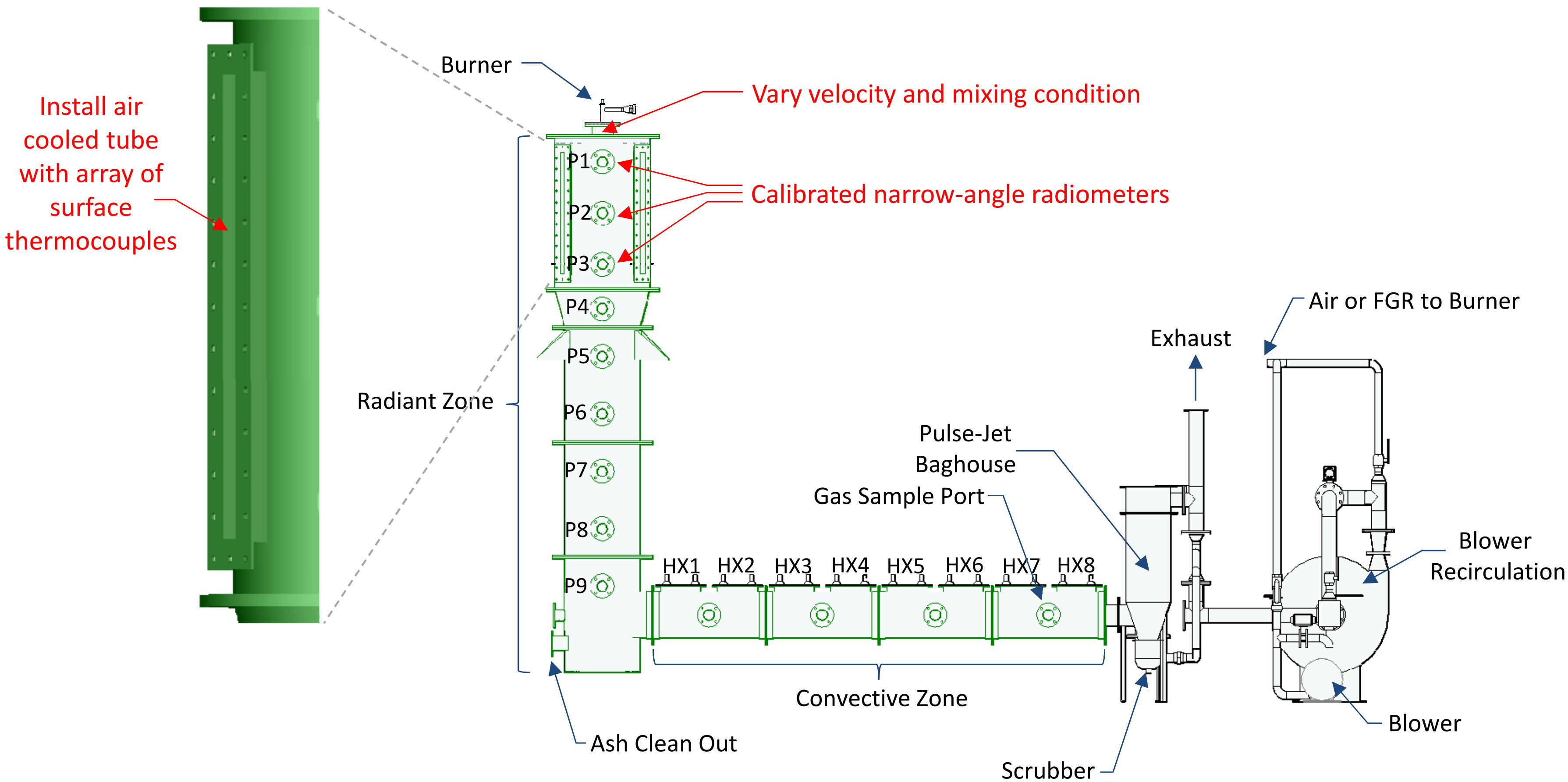


THE INSTITUTE FOR CLEAN AND SECURE ENERGY
AT THE UNIVERSITY OF UTAH

Task 2.0 100 kW OFC no RFG Tests

Subtask 2.2 – OFC no RFG testing

THE UNIVERSITY OF UTAH

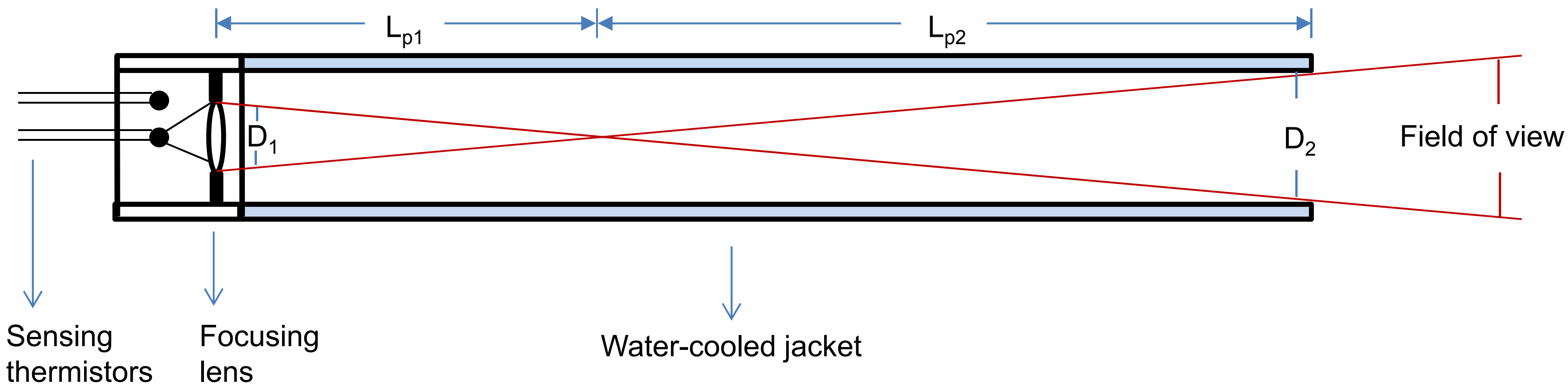


Task 2.0 100 kW OFC no RFG Tests

Subtask 2.2 – OFC no RFG testing

THE UNIVERSITY OF UTAH

Radiometer Configuration



$$\alpha_{\text{field of view}} = 2 * \text{Tan}^{-1}((D_2/2)/L_{p2}) = 2.74$$

Three radiometers will be installed opposite the cooling plates. Angle of view Includes only the cooling plate surface

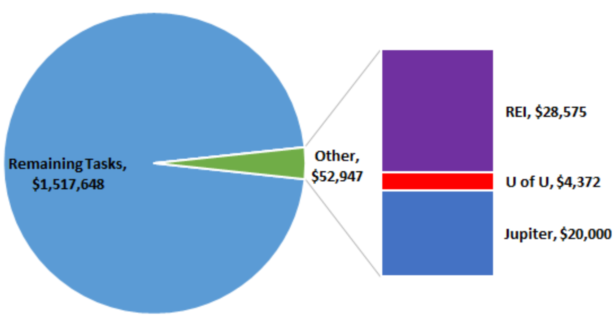
Black body radiator will be used to calibrate these devices

Task 3.0 1 MW Coal-Oxygen Burner Design

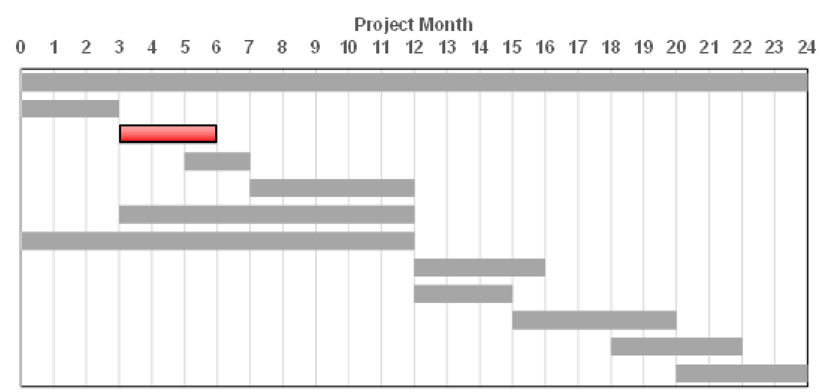
REACTION ENGINEERING INTERNATIONAL

THE UNIVERSITY OF UTAH

- Leverage existing model of OFC to interpret data of Task 2
  - Verify models ability to represent high temperature combustion
- Leverage existing model of L1500 and simulations for Jupiter Oxygen to determine staring point of design
- Constrained to minimum recycle (FGR only in the Primary)
- Three additional independently metered O2 streams
- Transition from axial jet to mixed combustion conditions



12-01-15 through 02-29-16



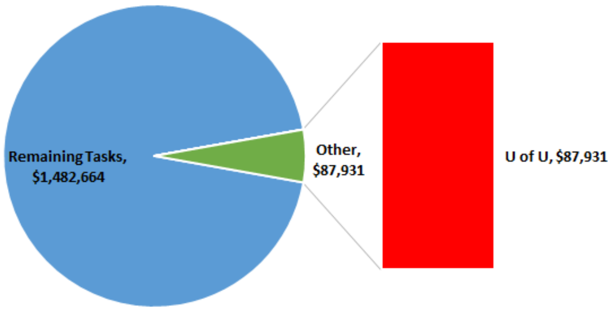
Task 4.0 1 MW Pulverized Coal Furnace (L1500) Modification

THE UNIVERSITY OF UTAH

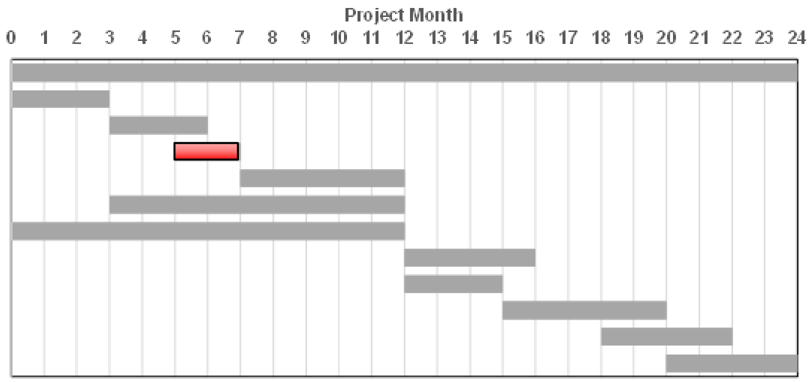
Subtask 4.1 – Burner Construction

Subtask 4.2 – Burner Installation and Integration

Subtask 4.3 – Installation of Metering Devices



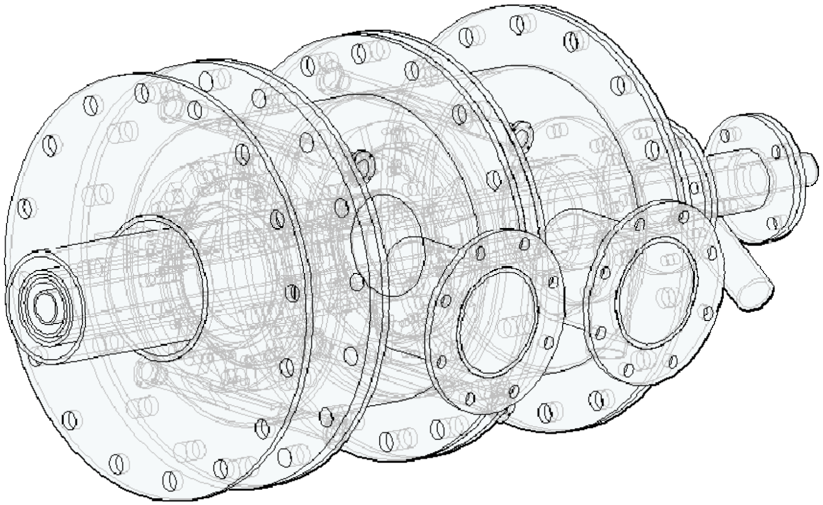
02-01-16 through 03-31-16



Task 4.0 1 MW Pulverized Coal Furnace (L1500) Modification

Subtask 4.1 – Burner Construction

- University possesses the necessary resources to manufacture a near zero recycle burner
  - Skilled personnel
  - Equipment (welding and cutting)
  - Facilities (machining)
- The existing dual-register low-NOx burner was fabricated in-house
- Praxair will provide input for safety concerning materials and preparation for the handling of pure and nearly pure O_2 streams

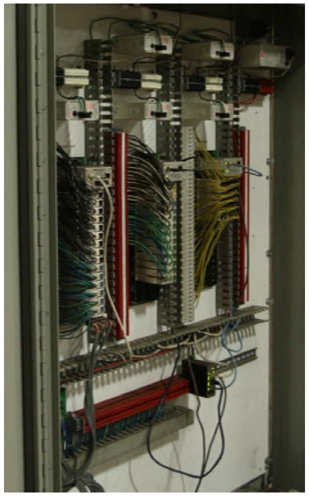


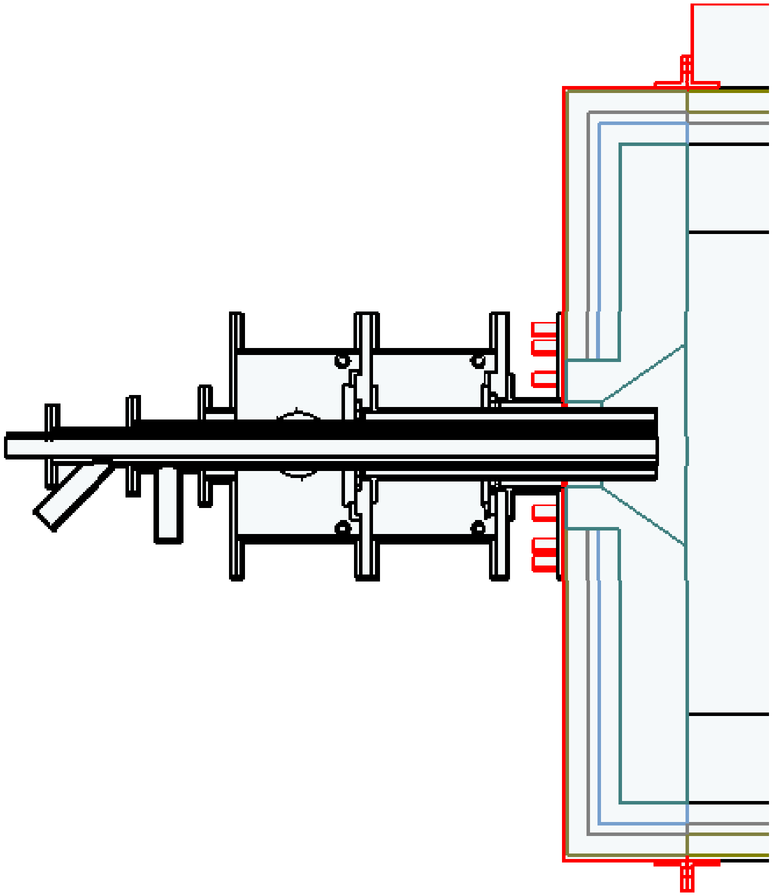
Task 4.0 1 MW Pulverized Coal Furnace (L1500) Modification

Subtask 4.2 – Burner Installation and Integration

THE UNIVERSITY OF UTAH

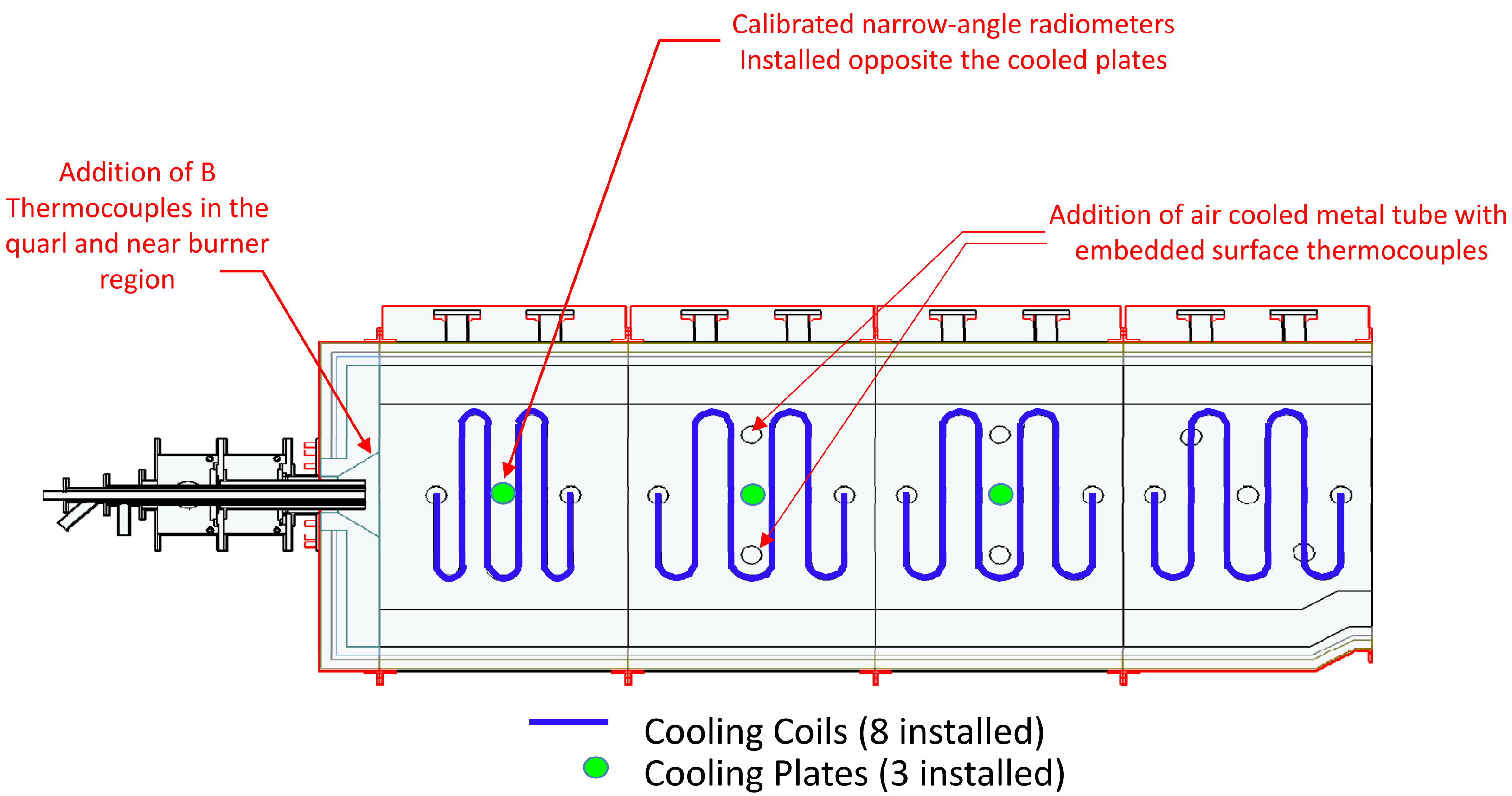
- Existing burner will be removed and replaced by newly fabricated burner
- Connection will be made to:
  - 4 independently controlled O_2 streams
  - 1 Natural Gas stream
  - 3 independently controlled Air / FGR streams (1 containing coal)
- Calibration of stream flows will be performed
- Integration into existing OPTO 22 control system and safety strategy





Task 4.0 1 MW Pulverized Coal Furnace (L1500) Modification

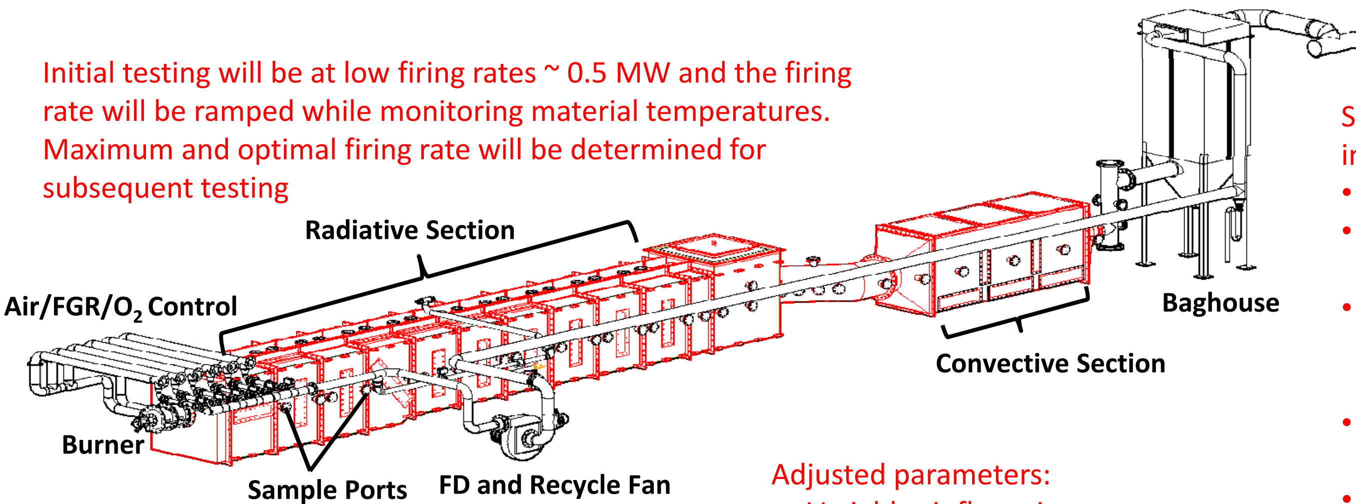
Subtask 4.3 – Installation of Metering Devices



Task 5.0 1 MW Pulverized Coal Furnace (L1500) No RFG Tests

We will test for 3 non-consecutive weeks using one coal. There will also be limited testing with petroleum coke.

Initial testing will be at low firing rates ~ 0.5 MW and the firing rate will be ramped while monitoring material temperatures. Maximum and optimal firing rate will be determined for subsequent testing

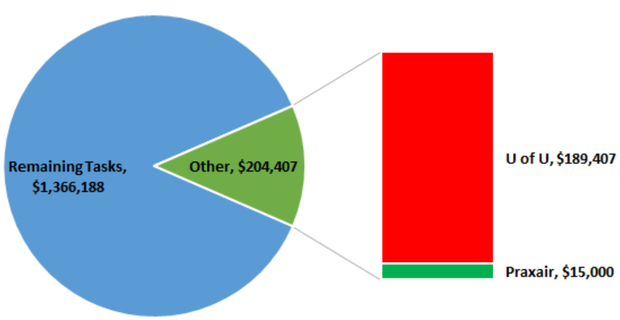


Subsequent test measurements will include:

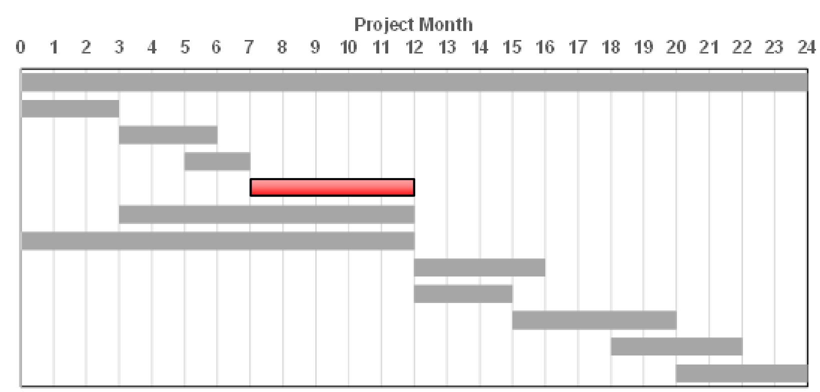
- Incident radiation (radiometers)
- Temperatures (shielded B thermocouples)
- Heat flux & metal surface temperature (deposition Probe & air cooled tube)
- Gas & particle temperatures (high speed IR video)
- Deposition (deposition probe)

Adjusted parameters:

- Variables influencing mixing of fuel / oxygen and flue gas (in furnace)
- Firing rate



04-01-16 through 08-31-16



6.0 100 kW Oxy Fuel Combustor (OFC) Particle Tests

THE UNIVERSITY OF UTAH

We will test for 8 weeks using one coal. There will also be limited testing with petroleum coke. Limited testing of slurry firing.

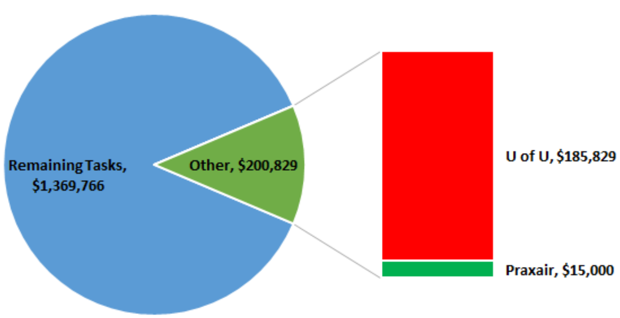
Operate at minimum recycle conditions and firing rate determined in Task 2.2 using both the axial jet burner and the mixing burner.

Adjusted parameters:

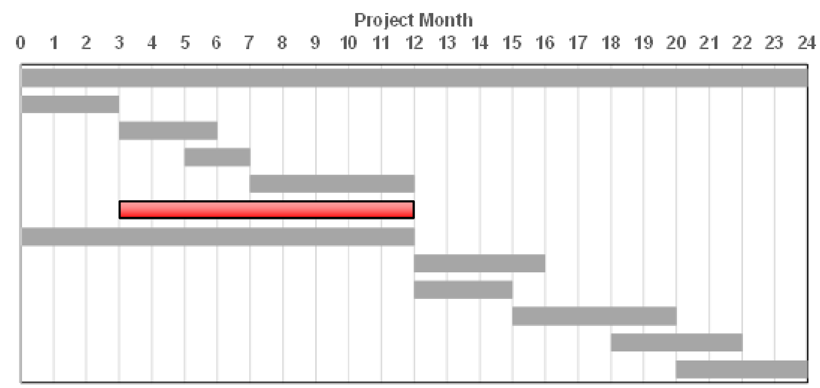
- Variables influencing mixing of fuel / oxygen and flue gas (in furnace)
- Firing rate

Test measurements will include:

- Entrained particle PSD and composition (SMPS, APS & BLPI)
- Deposition (Deposition probe)

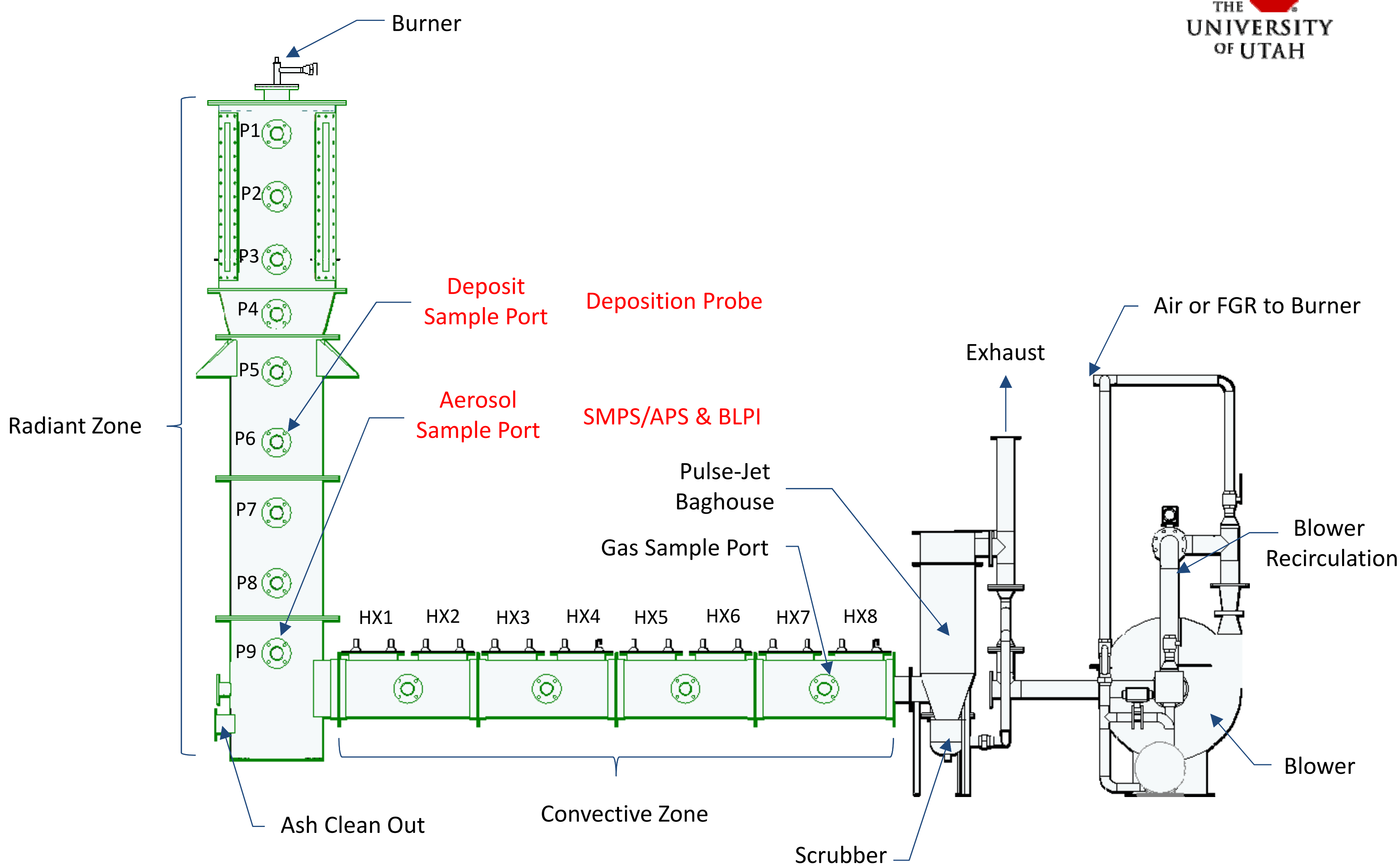


12-01-15 through 08-31-16



6.0 100 kW Oxy Fuel Combustor (OFC) Particle Tests

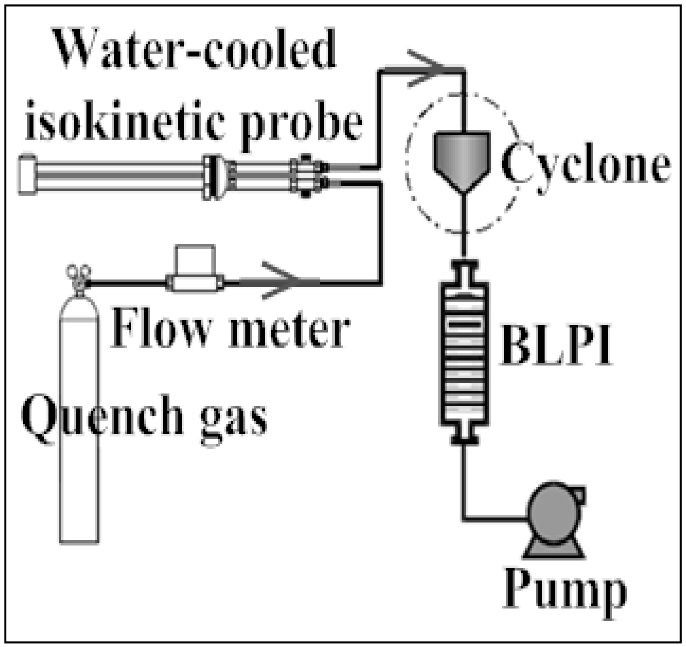
THE UNIVERSITY OF UTAH



6.0 100 kW Oxy Fuel Combustor (OFC) Particle Tests

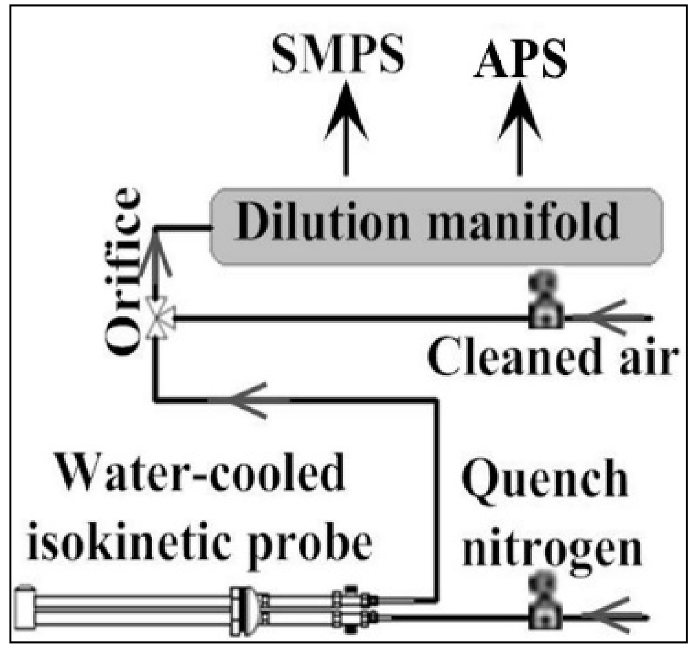
THE UNIVERSITY OF UTAH

Berner Low-pressure Impactor (BLPI)



BLPI: 0.0324 – 15.7 µm
11 cutoff diameters
Collects size-segregated entrained ash samples for later gravimetric and chemical analysis

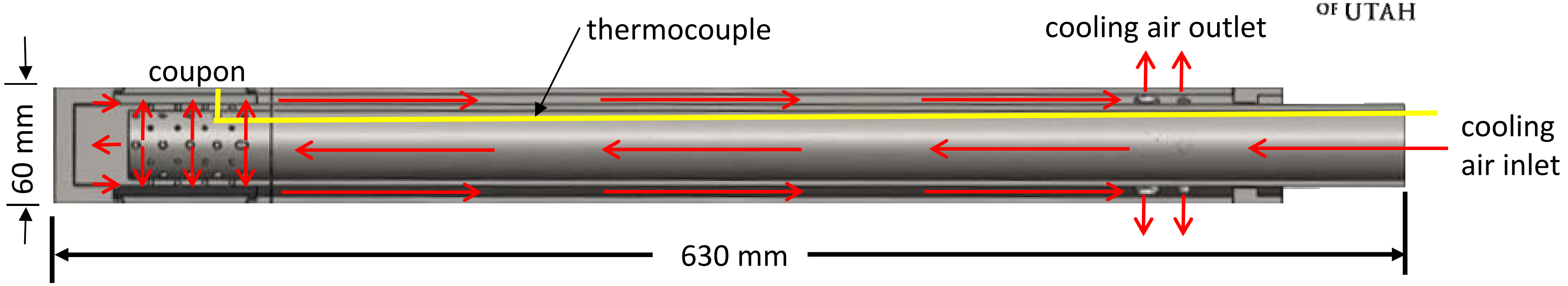
Scanning Mobility Particle Sizer (SMPS)
Aerodynamic Particle Sizer (APS)

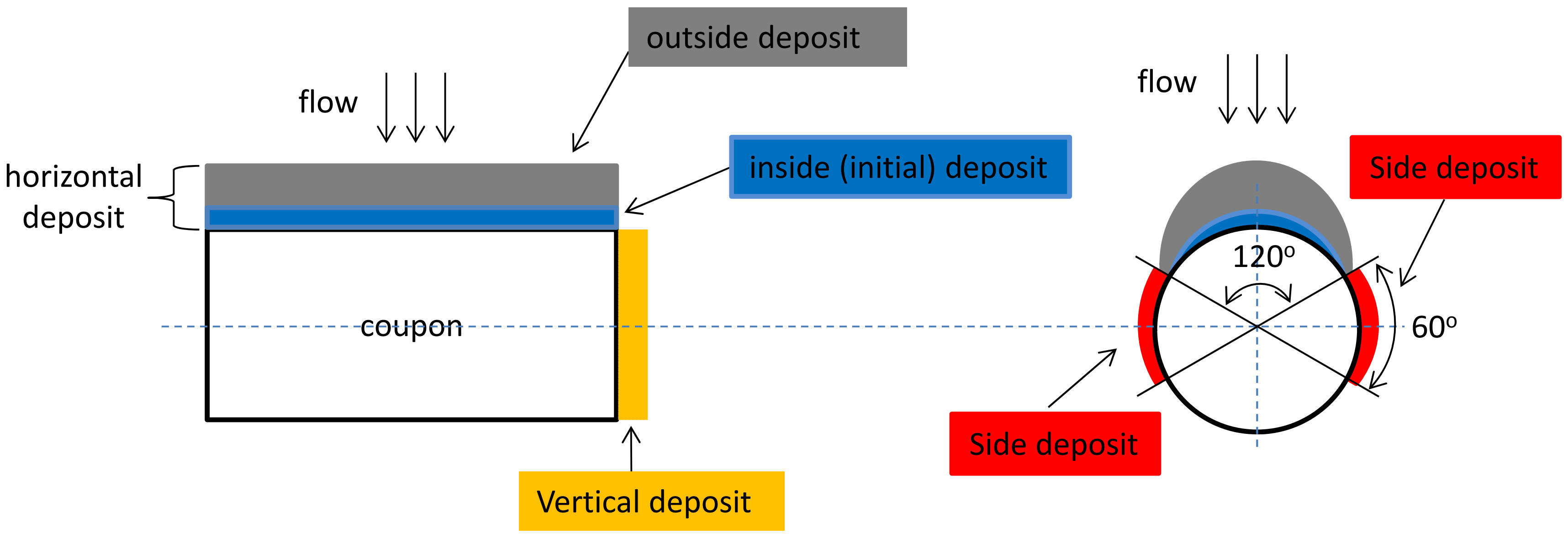


SMPS: 0.0143 – 0.6732 µm
APS: 0.532 – 20 µm

Collects real-time entrained particle size distribution data

6.0 100 kW Oxy Fuel Combustor (OFC) Particle Tests





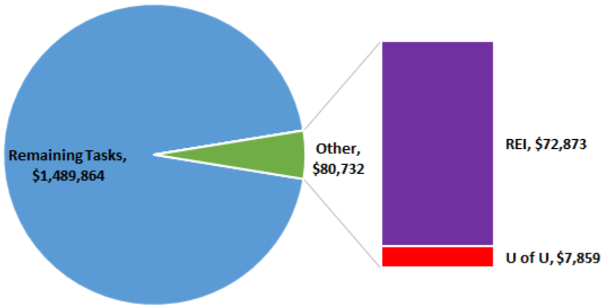
Task 7.0 Mechanism Development

REACTION ENGINEERING INTERNATIONAL

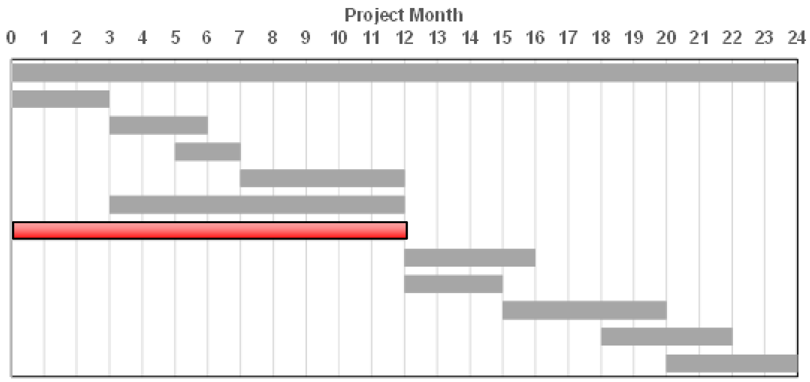
THE UNIVERSITY OF UTAH

Subtask 7.1 – Literature review

Subtask 7.2 – Mechanism Modification



09-01-15 through 08-31-16



Task 7.0 Mechanism Development

Subtask 7.1 – Literature review

REACTION ENGINEERING INTERNATIONAL

THE UNIVERSITY OF UTAH

- REI has attained extensive experience modeling oxy-coal combustion during the previously-completed DOE-funded program (DE-NT0005288), as well as in commercial projects
- The literature review will focus on identifying effects of high temperature and pressure regimes on:
- Radiative heat transfer
  - Gas property models and limitations of existing models
  - Particulate property models
- Convective heat transfer
  - Gas transport properties
- Char Oxidation
  - Limitations of extended single film model implemented and verified during the previous DOE-funded oxy-coal program
  - Roles of gasification reactions under high temperature and pressure
- Deposition
  - Mineral matter transformation mechanisms
  - Chemical and physical properties of ash aerosols
  - Formation mechanisms of ash deposits and properties of deposited ash

Task 7.0 Mechanism Development

Subtask 7.2 – Mechanism Modification

REACTION ENGINEERING INTERNATIONAL

THE UNIVERSITY OF UTAH

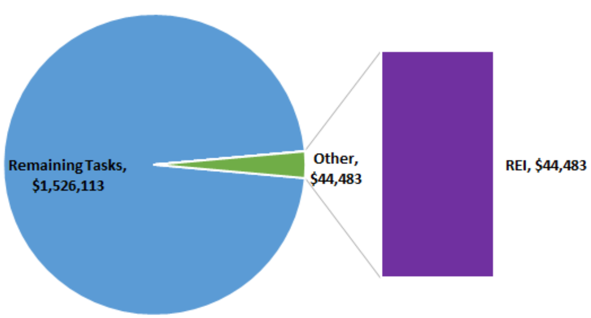
With the existing mechanisms as the starting point, REI will assess high temperature and pressure effects on radiative and convective heat transfer, char oxidation, and deposition

- Decisions to modify existing mechanisms will be based on review of the literature
- Predictions from modified mechanisms will be verified against literature data and data gathered during this program's experiments

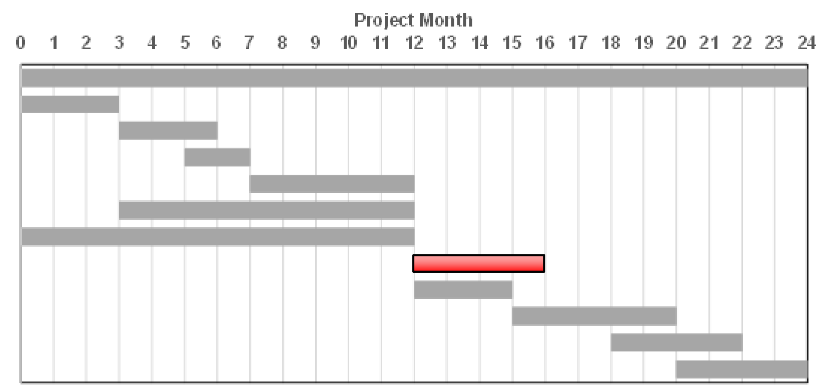
Task 8.0 High Temperature Mechanism Validation

REACTION ENGINEERING INTERNATIONAL

- Modeling of L1500 test data from task 5 for mechanism validation and adjustment
- Focus will be on:
  - Temperatures
  - Heat flux
  - Radiation
    - Predictions of radiant heat transfer from modified gas property models
    - Radiative absorption and scattering efficiencies
    - Soot behavior at high temperature
  - Char Oxidation
    - Roles of gasification reactions a high temperatures



09-01-16 through 12-31-16



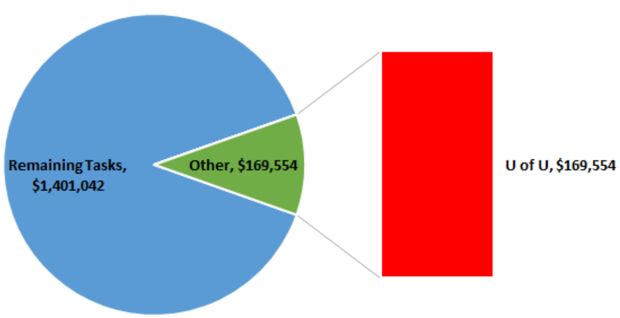
Task 9.0 300 kW Pressurized Entrained Flow Gasifier (EFG) Modification

THE UNIVERSITY OF UTAH

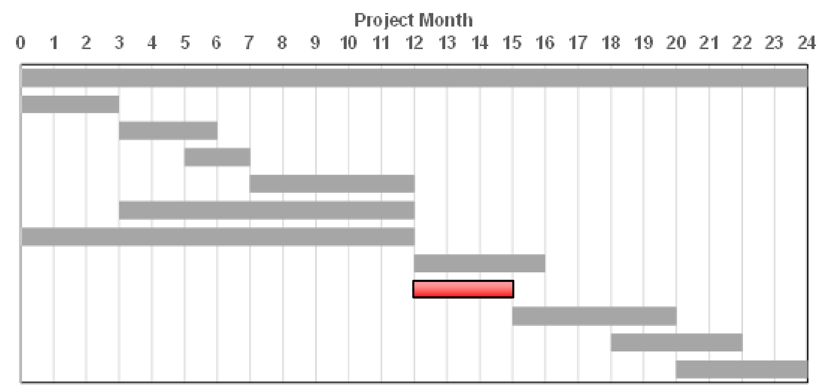
Subtask 9.1 – Refractory Re-Pour

Subtask 9.2 – Injector Design and Construction

Subtask 9.3 –Radiometer, Cooling Tube and Particle Probe Construction and Installation



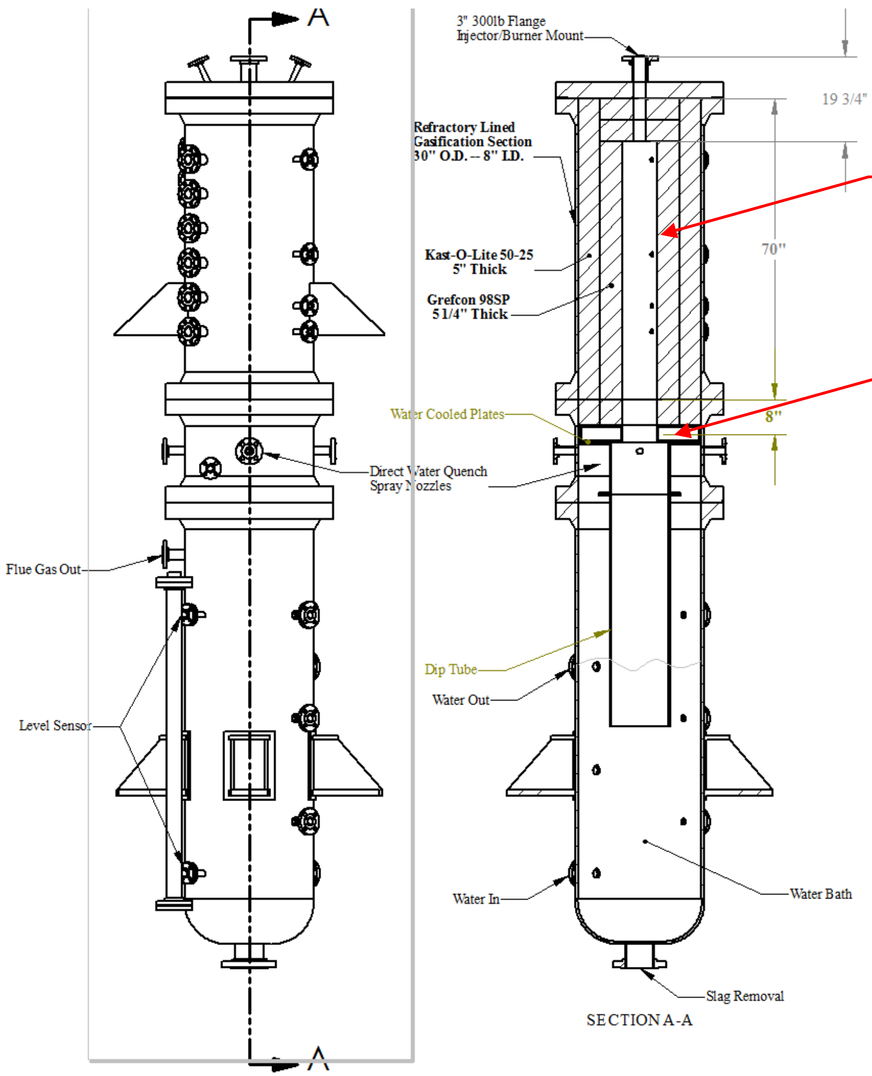
09-01-16 through 11-30-16



Task 9.0 300 kW Pressurized Entrained Flow Gasifier (EFG) Modification

Subtask 9.1 – Refractory Re-Pour

THE UNIVERSITY OF UTAH

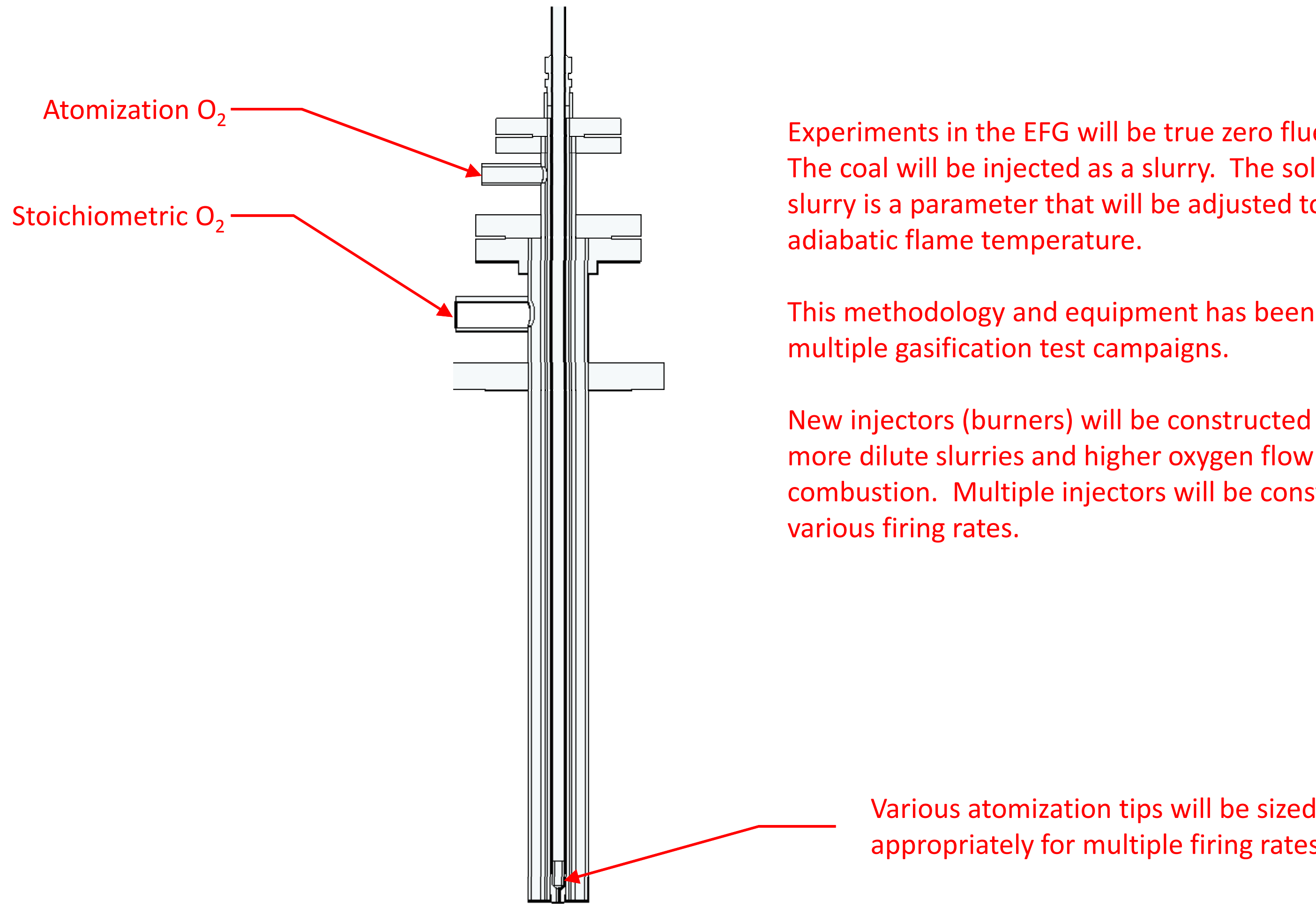


Current refractory is suitable for reducing conditions and is significantly eroded. It will be replaced with refractory suitable for both oxidizing and reducing conditions.

A modification to the water cooled plates will be considered to reduce slag freezing at the reactor outlet

Task 9.0 300 kW Pressurized Entrained Flow Gasifier (EFG) Modification

Subtask 9.2 – Injector Design and Construction



Experiments in the EFG will be true zero flue gas recycle. The coal will be injected as a slurry. The solid content of the slurry is a parameter that will be adjusted to manipulate the adiabatic flame temperature.

This methodology and equipment has been proven in multiple gasification test campaigns.

New injectors (burners) will be constructed that will handle more dilute slurries and higher oxygen flow rates for combustion. Multiple injectors will be constructed to handle various firing rates.

Task 9.0 300 kW Pressurized Entrained Flow Gasifier (EFG) Modification

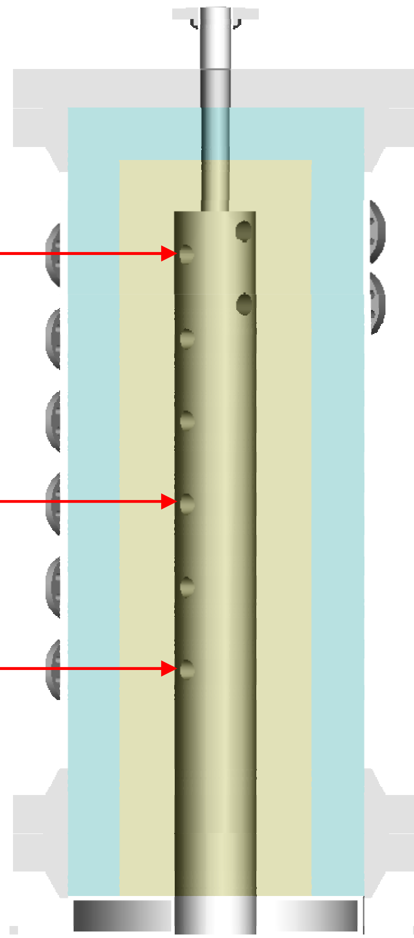
Subtask 9.3 –Radiometer, Cooling Tube and Particle Probe Construction and Installation

THE UNIVERSITY OF UTAH

New narrow angle radiometers will be constructed that are appropriate for pressure and for the smaller ID access ports

New deposition probe will be fabricated for pressure conditions (no removable coupon) with safety interlocks on the cooling air in and out. Metering will be included to determine surface temperature and heat flux

Gas sample port will be installed for extractive particle measurements



Safety will be of highest consideration for high pressure tests at high temperature. Safety interlocks including a high temperature and pressure valve will be installed on each furnace penetration, which will close in the case of compromised hardware.

This approach has been proven effective on other research programs on the EFG at higher pressures.

Task 10.0 300 kW Pressurized Combustion Tests

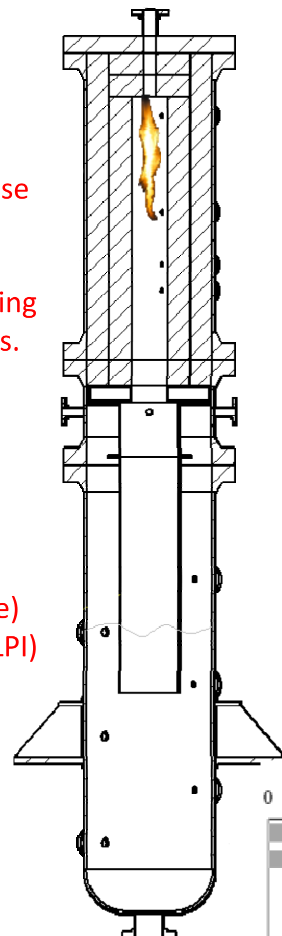
THE UNIVERSITY OF UTAH

We will test for 6 weeks using one coal. There will also be limited testing with petroleum coke. The furnace will be operated at 250 psi. There will be no flue gas recycle in these experiments

Initial testing will be at low firing rates ~ 100 kW and the firing rate will be ramped while monitoring material temperatures. Maximum and optimal firing rate will be determined for subsequent testing

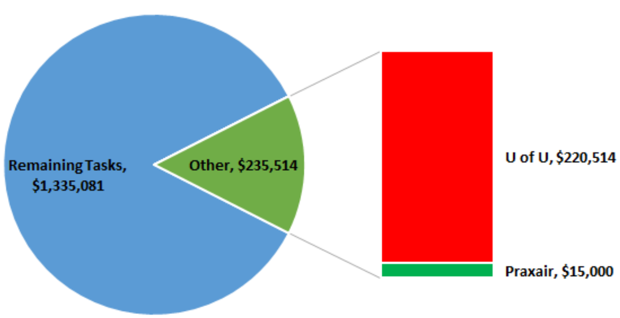
Subsequent test measurements will include:

- Incident radiation (radiometers)
- Temperatures (shielded B Thermocouples)
- Heat flux & metal surface temperature (Deposition Probe)
- Entrained particle PSD and composition (SMPS, APS & BLPI)
- Deposition (Deposition probe)

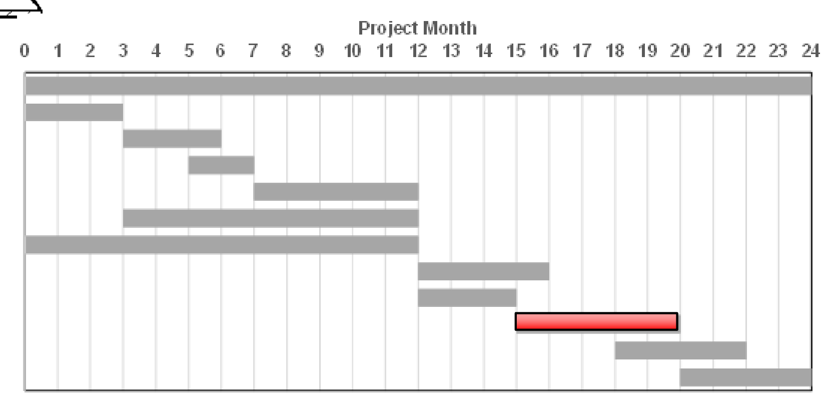


Adjusted parameters:

- Firing rate
- Slurry water content
- Overall SR



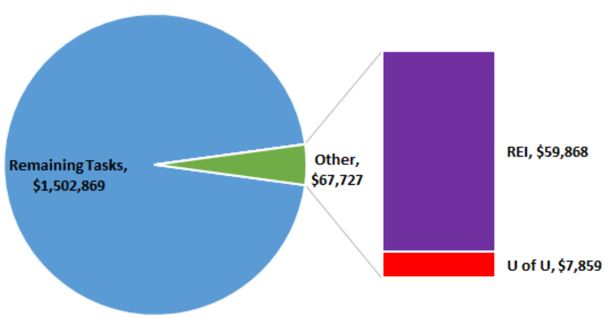
12-01-16 through 04-30-17



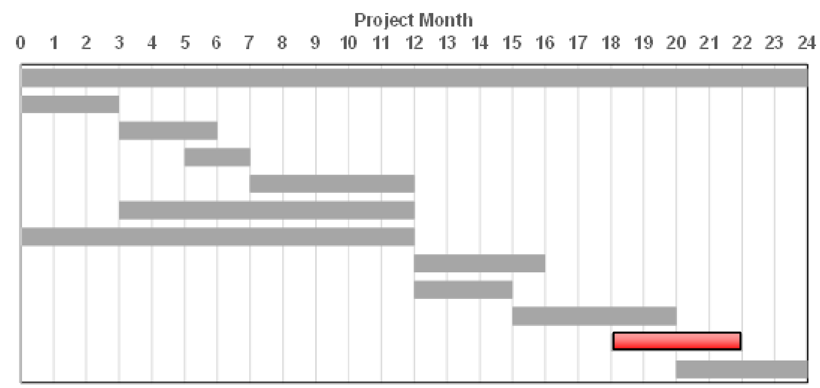
Task 11.0 High Pressure and Particle Mechanism Validation

REACTION ENGINEERING INTERNATIONAL

- Modeling of EFG test data from task 10 for mechanism validation and adjustment
- Focus will be on:
  - Temperatures
  - Heat flux
  - Radiation
    - Predictions of radiant heat transfer from modified gas property models
    - Radiative absorption and scattering efficiencies
    - Soot behavior at high temperature and pressure
  - Char Oxidation
    - Roles of gasification reactions at high temperatures and pressures



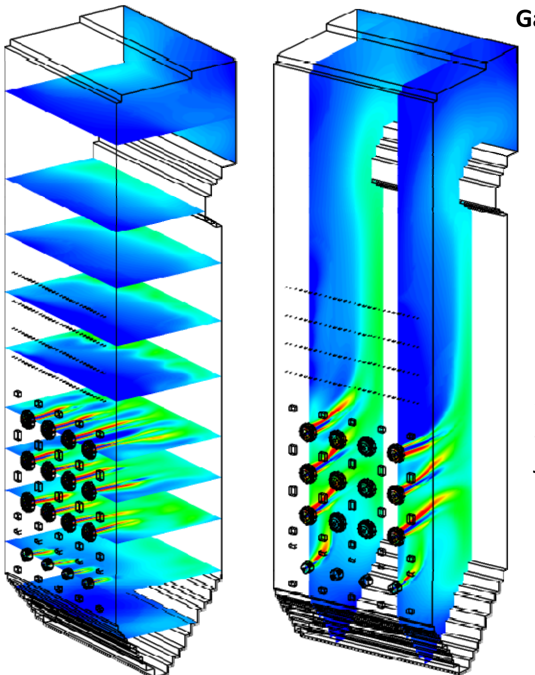
03-01-17 through 06-30-17



12.0 Conceptual Furnace Design and Validation

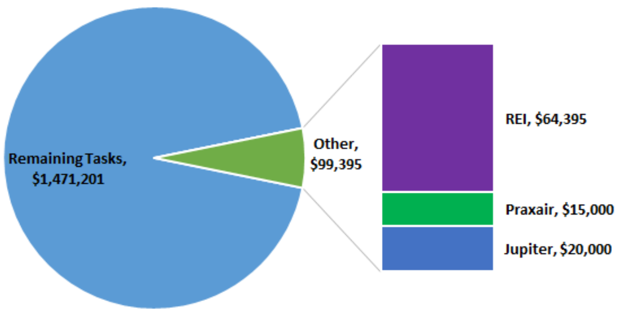
REACTION ENGINEERING INTERNATIONAL

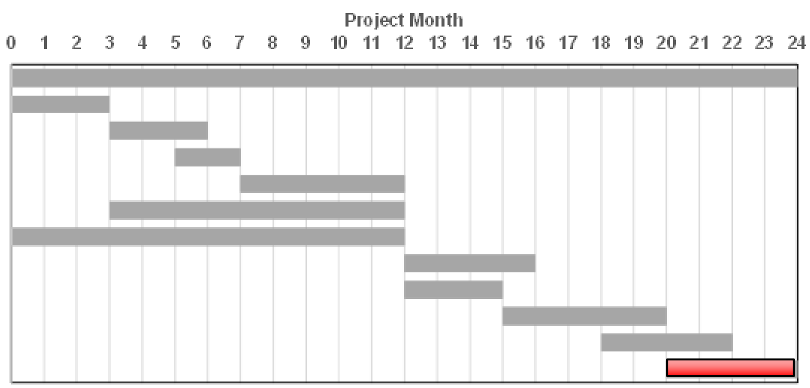
- Modeling of conceptual combustion systems at scales larger than test furnaces
- Start with scaled versions of L1500 and EFG (Test Boxes)
- 10 MW, 100 MW & 1000 MW



From REI assessment of oxy-fuel combustion for Jupiter Oxygen Corp.

05-01-17 through 08-29-17

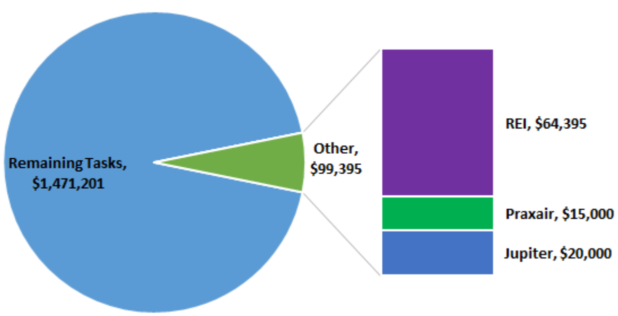




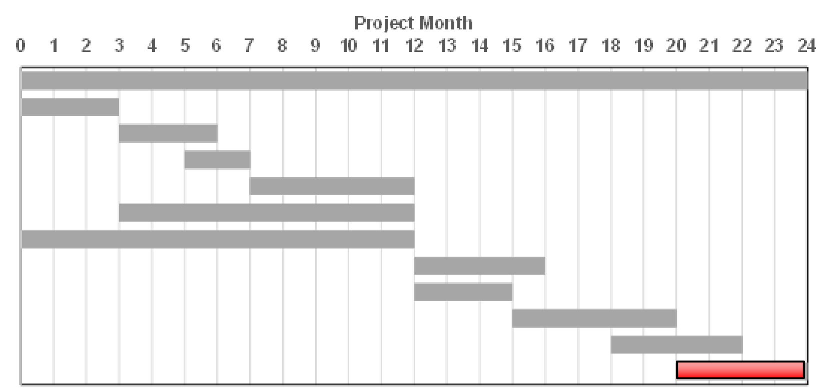
12.0 Conceptual Furnace Design and Validation (Continued)

REACTION ENGINEERING INTERNATIONAL

- L1500
  - High temperature and atmospheric
  - Some variation of firing system configuration
- EFG
  - Elevated temperature and high pressure
- Focus on flame geometry, temperatures and heat distribution
- Not optimized for specific performance parameters or furnace configurations



05-01-17 through 08-29-17



Deliverables

1. **Subtask 1.7 – Quarterly Progress Reports**

   Due: 01-29-16, 04-29-16, 07-29-16, 10-31-16, 01-31-17, 04-28-17, 07-31-17, 08-31-17

2. **Subtask 1.8 – Topical Report for Budget Period 1**

   Due: 10-31-16

3. **Subtask 1.9 – Annual technical briefings to DOE Project Officer.**

   Due: TBD

4. **Subtask 1.10 – Technical presentation at DOE/NETL Annual Contractor's Review Meeting.**

   Due: TBD

5. **Subtask 1.11 – Final Project Report to DOE.**

   Due: 08-31-17

Decision Points

1. **Subtask 4.3 –** After modification of the L1500 for high temperature, minimum RFG testing a go/no-go decision will be made to advance the project into Task 5.

2. **Task 9.0 –** After executing high temperature atmospheric tests in the L1500 and modifying the EFG for elevated temperature and high pressure tests, a go/no-go decision will be made to advance the project into Task 10.

Target criteria developed based on the required performance of the technology will be evaluated. The evaluations and recommended decision will be submitted to DOE in a Decision Point report for concurrence. The DOE will make the determination of approval/disapproval based on the attainment of performance targets and success criteria. If these targets are not met the project may be redirected to address them.

Risk Management

Three major risks to project success are:

1) Furnace malfunction or failure in the combustors that would prevent completion of scheduled tests

- The 100 kW Oxy-Fuel Combustor (OFC)

  If unavailable, difficulties arise in characterizing the ash vaporization behavior under the range of oxygen firing conditions desired.

  - *Used over the past six years to conduct tests similar to that proposed here.*
  - *Limited number of ash characterization tests could be performed on the L1500 pilot-scale facility in the event the OFC becomes unavailable.*

- 1 MW pilot-scale furnace at the University of Utah (the L1500)

  If unavailable, oxy-coal burner optimization and flame temperature measurements could not be completed.

  - *An established furnace regularly used for a wide range of applications.*
  - *Previous successful use for oxy-combustion testing.*

- The 300 kW pressurized entrained flow gasifier (EFG)

  If unavailable, high pressure tests could not be completed

  - *Used successfully on several coal combustion/gasification programs and is currently operational.*

- If repairs needed on any of the above, test schedules with the other two furnaces could be rearranged allowing progress on the program to continue

Risk Management (Continued)

2) Loss of required cost-share funds due to withdrawal of one or both of the primary funding organizations, Praxair and Jupiter Oxygen Corporation (JOC)
   - REI has received commitment letters from all team members who have committed to provide cost-share for this program.

   Incentives for participation
   - Praxair's interests in research supporting future Praxair projects.
   - Praxair's established relationship with the University of Utah
   - JOC's further attainment of knowledge and experience with oxy-firing design principles.
   - JOC's established relationship with REI and utilization of REI's modeling services
3) Loss of key technical investigators from REI or University of Utah
   - Significant technical depth within each of the participating organizations.
   - REI management experience and technical expertise to oversee and evaluate all aspects of the proposed work.
   - REI will lead frequent review meetings with team members to track technical progress
   - REI's close proximity to University of Utah testing facilities allows for quick response to problems that may arise.

Questions