Recovery Act: Oxy-combustion: Oxygen Transport Membrane Development

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Presentation Outline

- Oxygen Transport Membrane Introduction
- Progress towards CCS with the Praxair Advanced Power Cycle
- OTM for Industrial Applications (Recovery Act)
- Progress towards OTM Syngas applications

OTM: Reactively Driven Oxygen

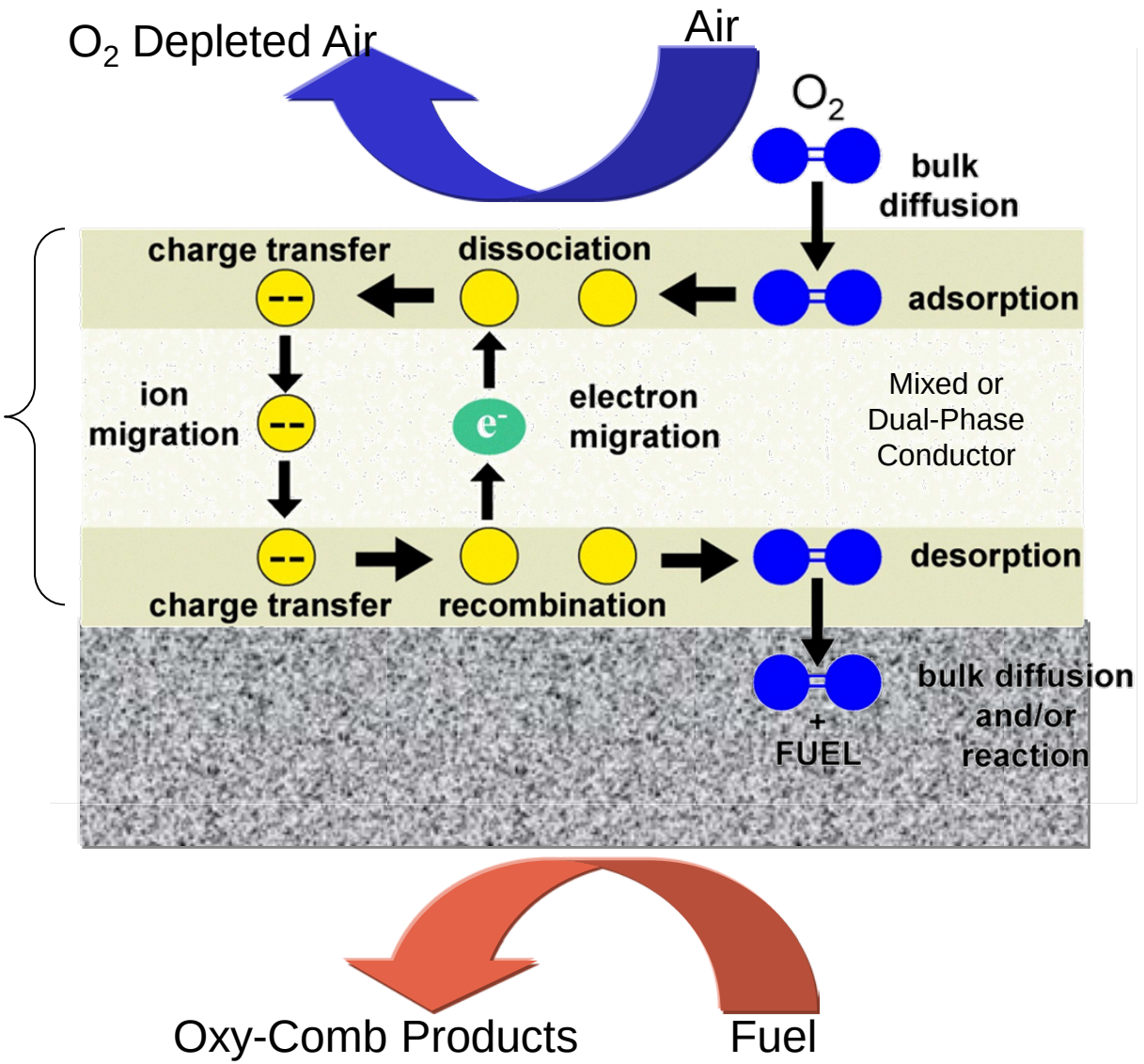
Active Layers

-Porous Cathode

-Dense Gas Separation Layer

-Porous Anode

Porous Support



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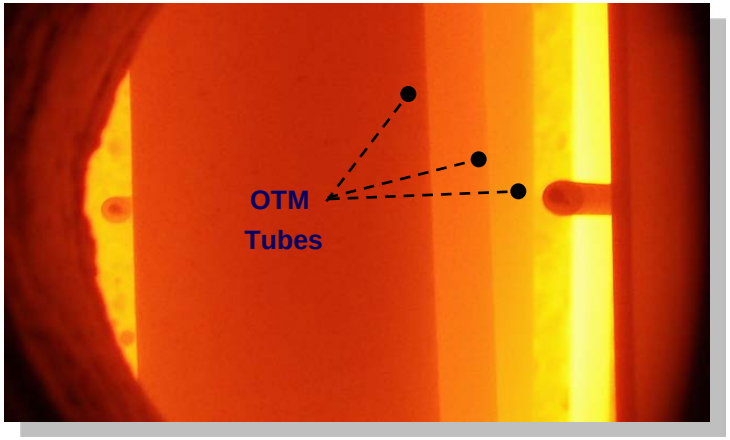
OTM Integrated Oxygen Supply

- Membrane built into combustion zone
  - Oxygen is consumed at membrane surface
- Step-change in efficiency
  - >70% reduction in ASU power
  - Oxygen flows from high-to-low <u>partial pressure.</u> Low pressure air is source of oxidant
- Enables zero emissions coal fired power plant - Advanced Power Cycle
  - 97% CO_2 capture
  - Potential to achieve DOE goals



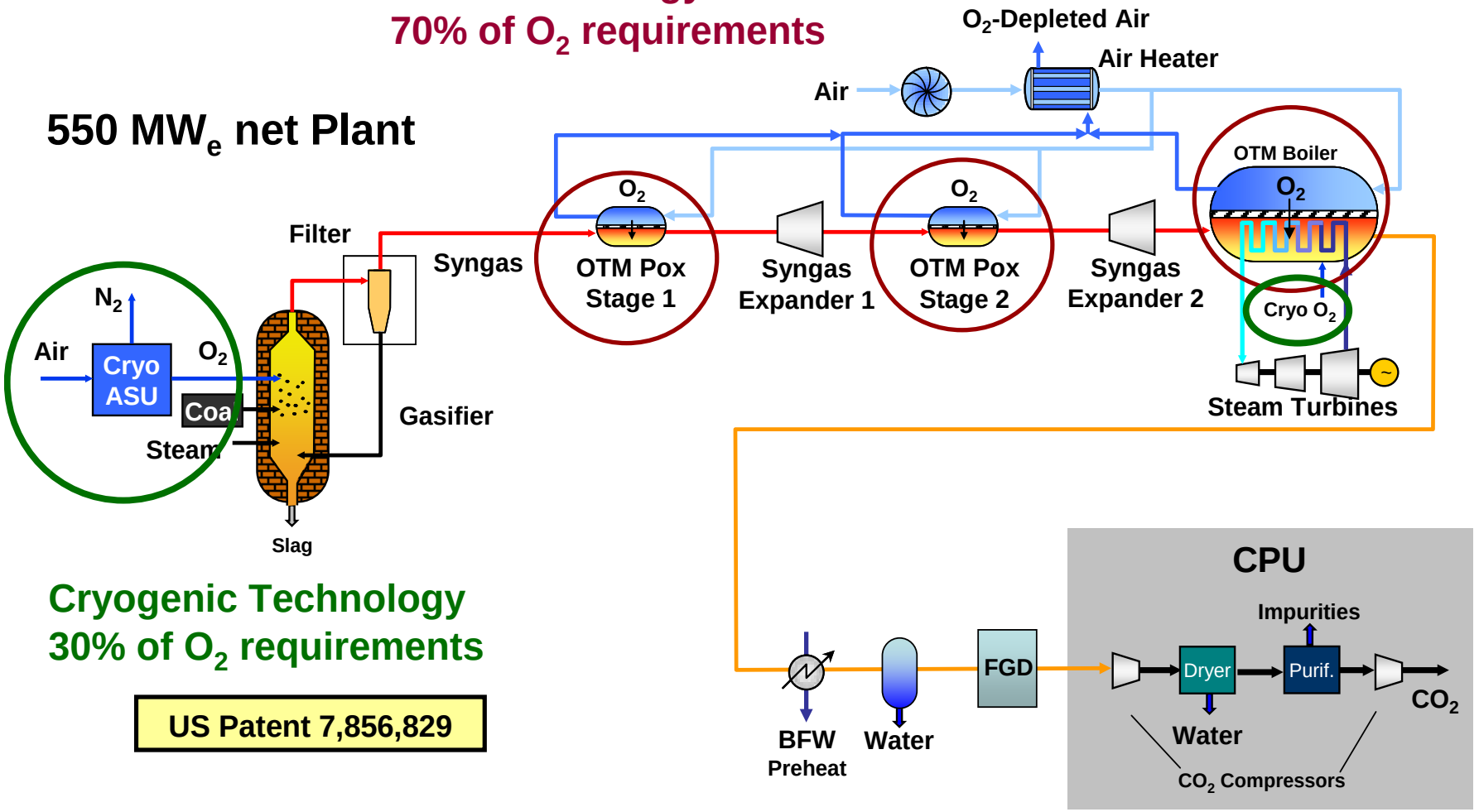
Oxy-Combustion on OTM Surface

Looking through reactor port

OTM Advanced Power Cycle

OTM Technology
70% of O_2 requirements

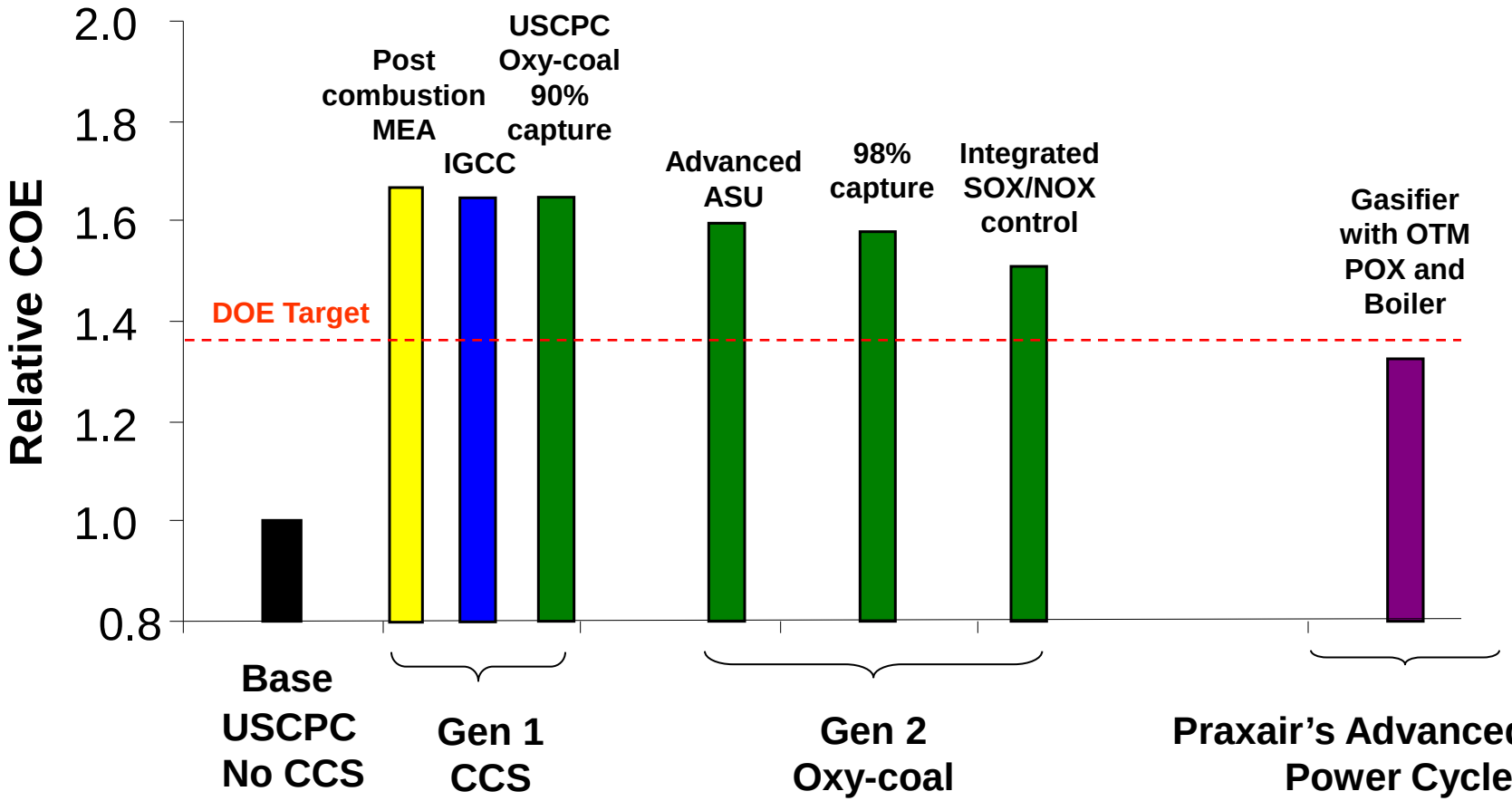
550 MW_e net Plant



Cryogenic Technology
30% of O_2 requirements

US Patent 7,856,829

Advancing Oxyfuel Technology: Relative COE



Commercial now	Demo/scale up Ready full scale in 2015	Developmental Commercialize 2015-2020	Commercial after 2020

Progress Towards CCS

- **Tested >100 lab-scale single tubes**
  - **No failures due to thermal or chemical transients**
  - **Achieved target oxygen flux (>3X increase)**
  - **Demonstrated stability in 1%H_2S**
  - **Initiated coal gas tests at U-Utah**
  - **Started long-duration testing of membrane performance**
- **Evaluated several membrane manufacturing processes (pressing, extrusion and casting)**
- **Subcontract with Shaw Energy and Chemical for Boiler and POx design**

		OTM FGD Process Cases			Air-PC CASE
	Case	1 SC	2 USC	3 AdvUSC	Praxair/DOE SC No CCS_1
Net Efficiency (HHV)		36.3%	37.2%	39.7%	39.7%
Plant Cost ($/kW)		$2,894	$2,887	$2,997	$1,908
	Coal Price ($/MMBtu)				
Increase in COE	1.8	39.4%	38.4%	39.7%	---
	3.0	34.9%	33.8%	33.8%	---
	4.0	32.1%	30.8%	30.0%	---
Removal Cost ($/ton)$_2$	1.8	$ 34.04	$ 34.07	$ 37.44	---
	3.0	$ 35.22	$ 35.06	$ 37.44	---
	4.0	$ 36.29	$ 35.82	$ 37.44	---
Avoided Cost($/ton)$_3$	1.8	$ 37.51	$ 36.66	$ 37.64	---
	3.0	$ 38.80	$ 37.72	$ 37.64	---
	4.0	$ 39.98	$ 38.54	$ 37.64	---

1 Reference DOE/NETL-2007/1291 scaled to 2008 capital using data from SteamPro™ and Peace™ software.

2 $$\text{Removal Cost} = \frac{COE_{with\ CCS} - COE_{w/o\ CCS}}{CO_2 Total_{with\ CCS} - Emissions_{with\ CCS}}$$

3 $$\text{Avoided Cost} = \frac{COE_{with\ CCS} - COE_{w/o\ CCS}}{Emissions_{w/o\ CCS} - Emissions_{with\ CCS}}$$

Praxair and Shaw Energy & Chemical:

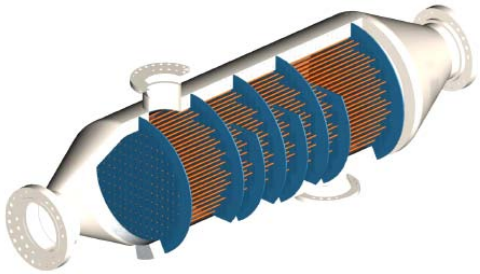
Pilot Scale:

Basic engineering design and cost estimate with scaling factors:

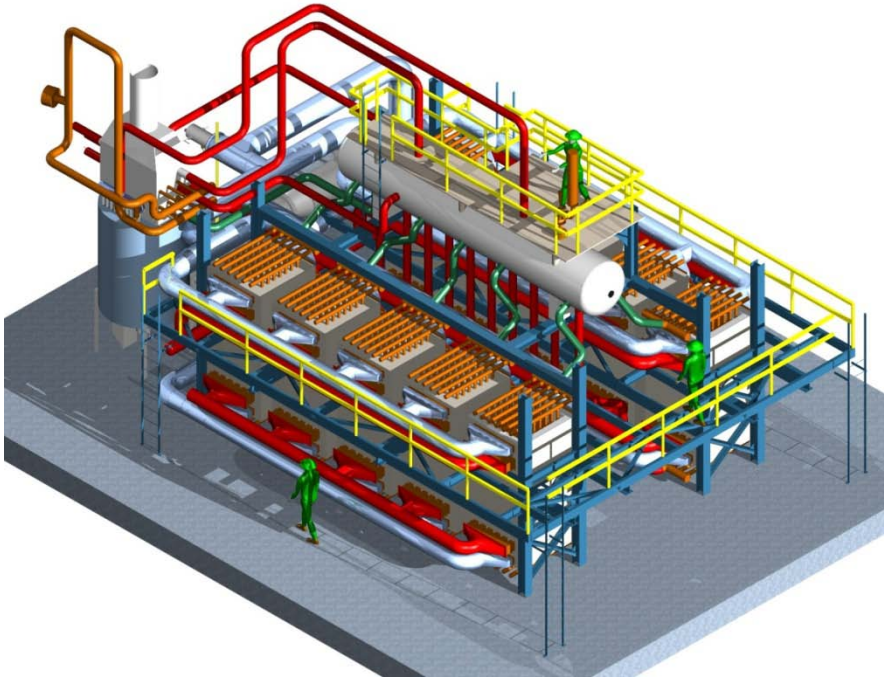
- 7.5 MW_{th} boiler producing saturated steam
- 5 tpd O2 skidded POx development unit

- Concept selection completed Q2 2011
- Target completion Q4 2011

OTM POx



OTM Boiler



University of Utah: OTM Coal Gas Testing

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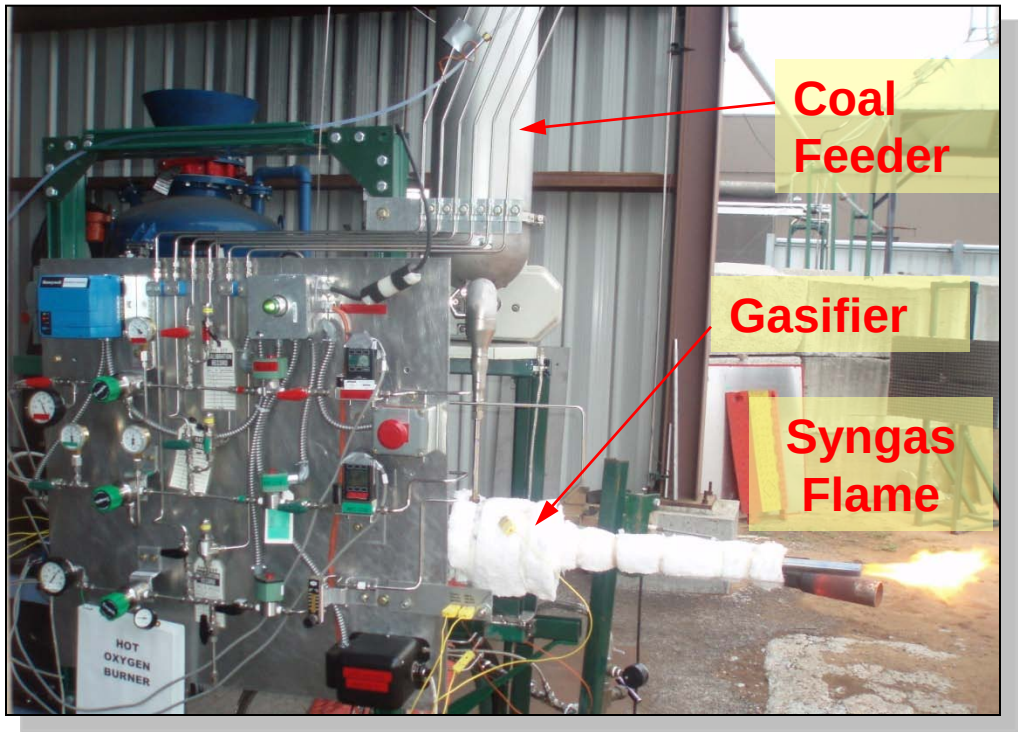
UC3 UTAH CLEAN COAL CENTER

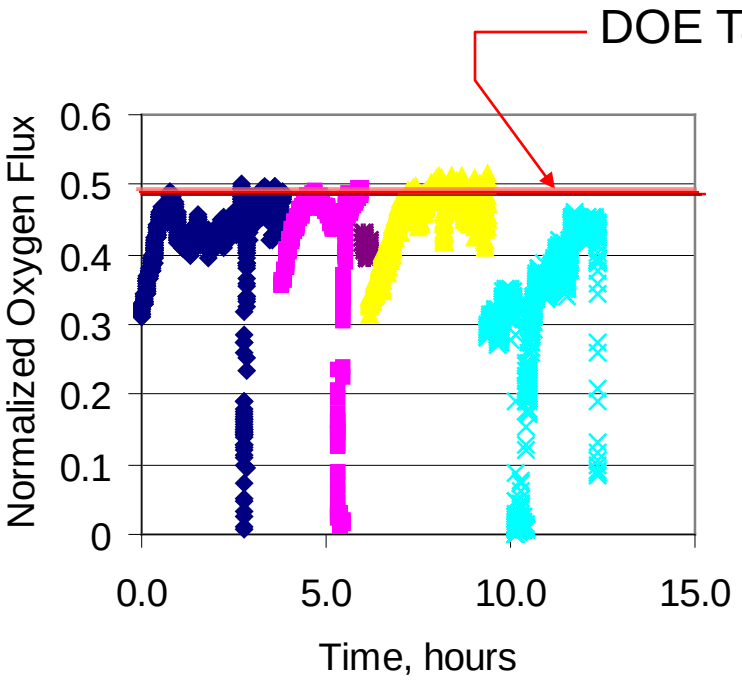
Praxair HOB Coal Gasifier

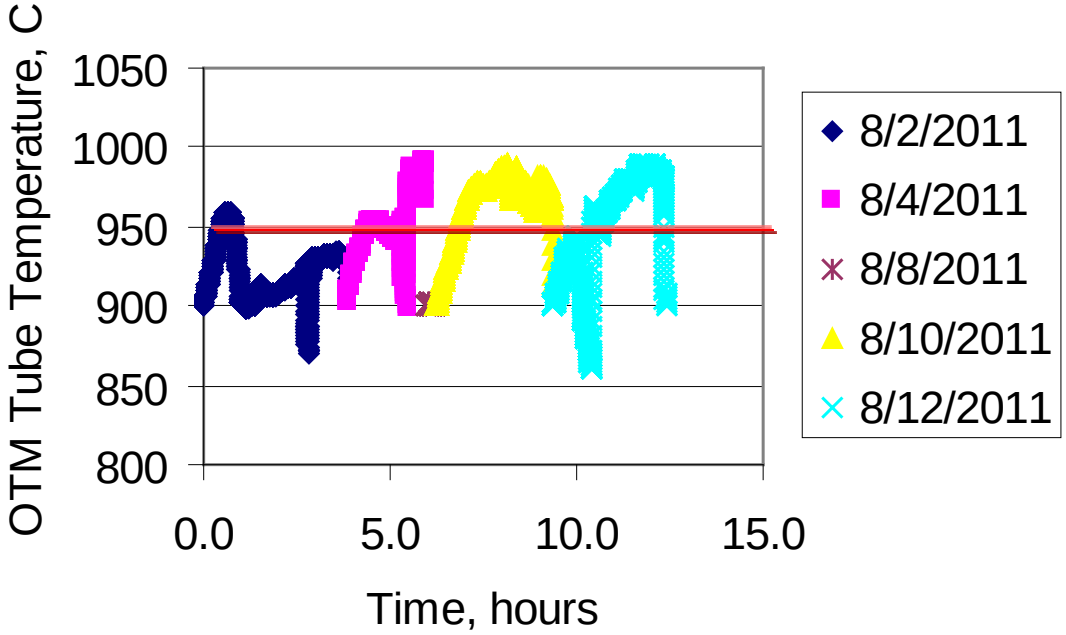


OTM multi-tube coal syngas reactor (University of Utah)

- Praxair HOB technology developed for control of jet momentum in large scale combustion applications
- Lab-scale (coal feed rate < 30 g/hr.) HOB constructed and tested at Praxair

Membrane Performance on Gasified Coal





- **Coal Gas testing initiated Q4/2010**
- **Current Coal Type: Low Sulfur Utah/PRB Blend**
- **Oxygen flux target (driven by DOE goals <35% increase in COE with respect to Air Fired PC)**
- **Target based on coal price $3/MMBTU and prelim. estimate of OTM Cost Allocation ($/ft2)**

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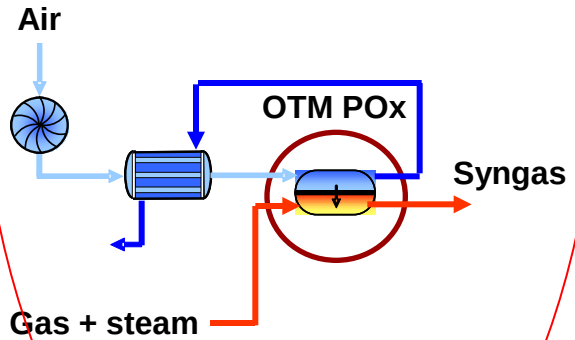
Recovery Act: OTM for Industrial Applications

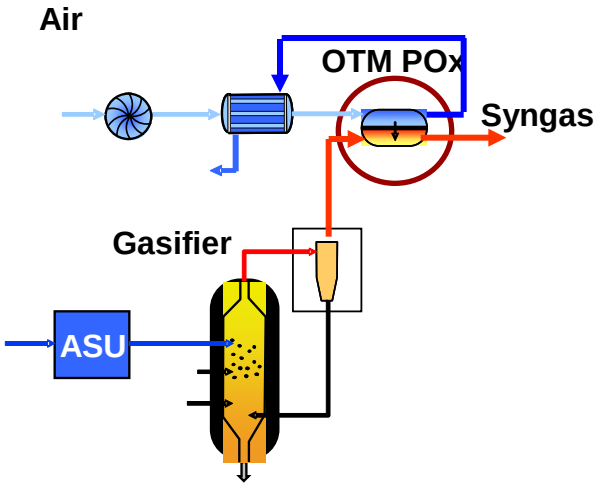
OTM Autothermal Reformer

- Syngas for chemicals
- Low H_2O/C ratio
- Syngas: H_2/CO = 1.8-2.3
- High pressure syngas
- Near term applications



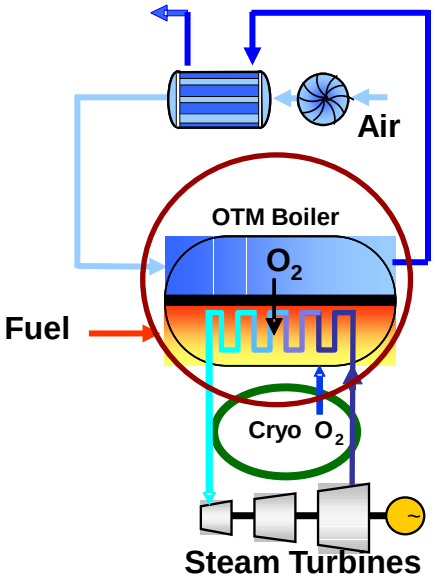
OTM POx

- Low cost syngas from gasifier
- Near/intermediate term applications



OTM Boiler

- Process heating, steam/power with CCS
- Long term applications



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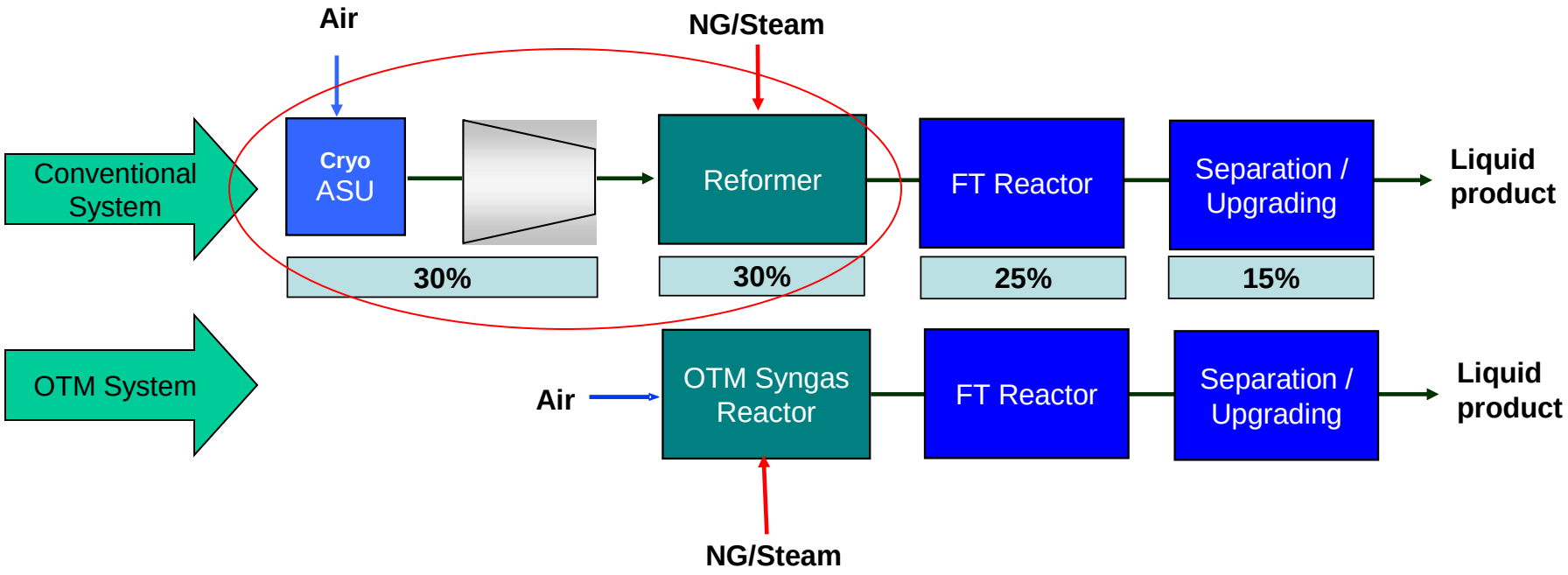
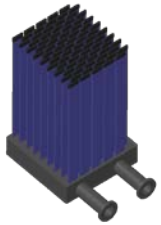
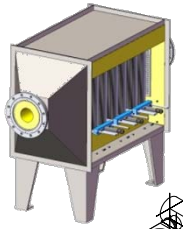
Industrial Applications: Syngas: Impact of OTM Membrane Process

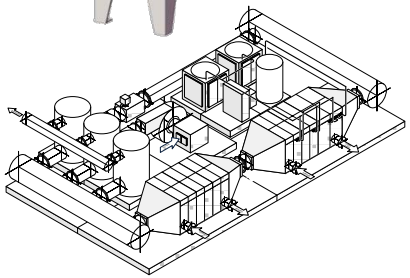


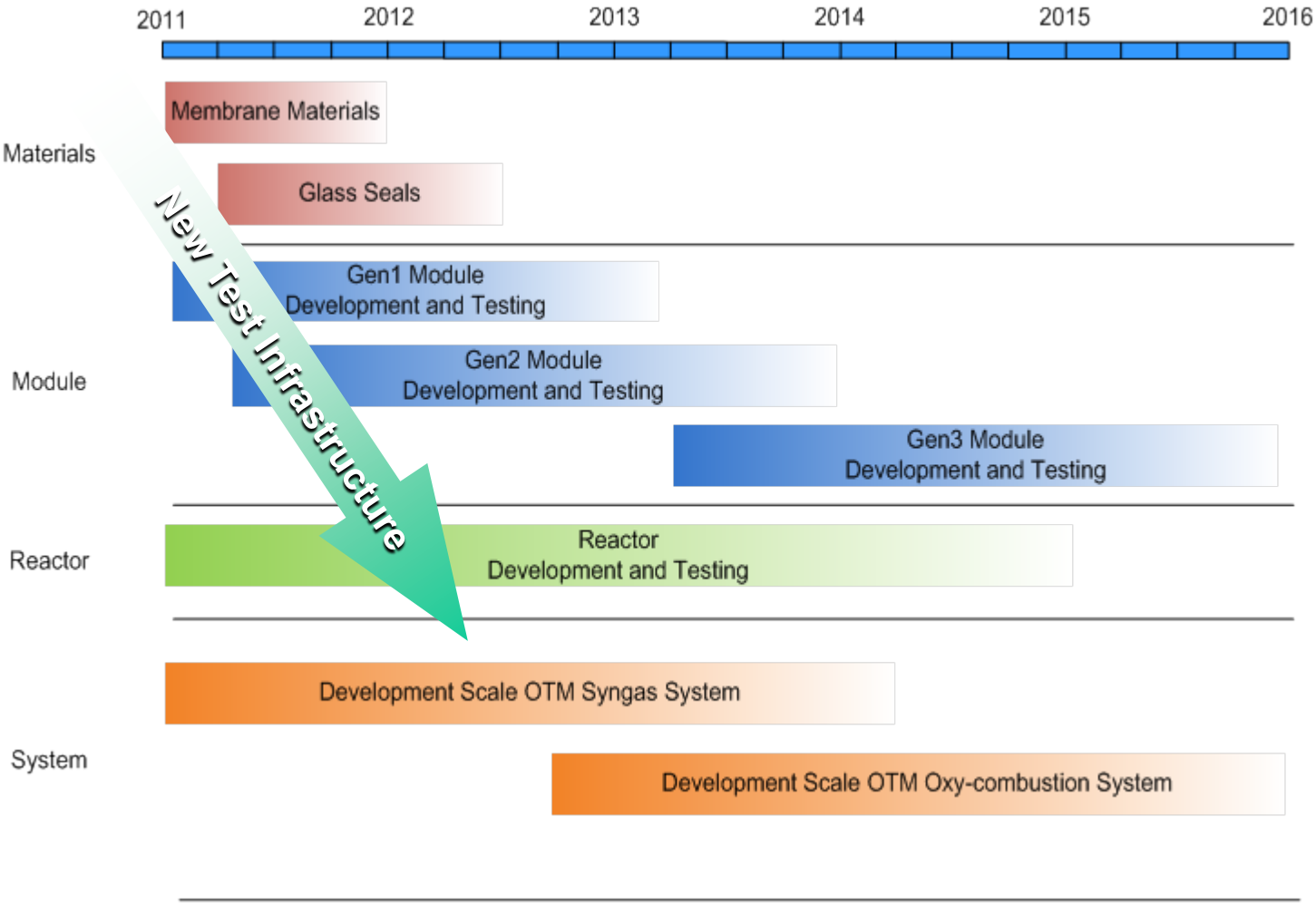
- **OTM Syngas reactor permits 20 to 40% CAPEX reduction**

Phase 3 Scope of Work:
OTM Development Roadmap





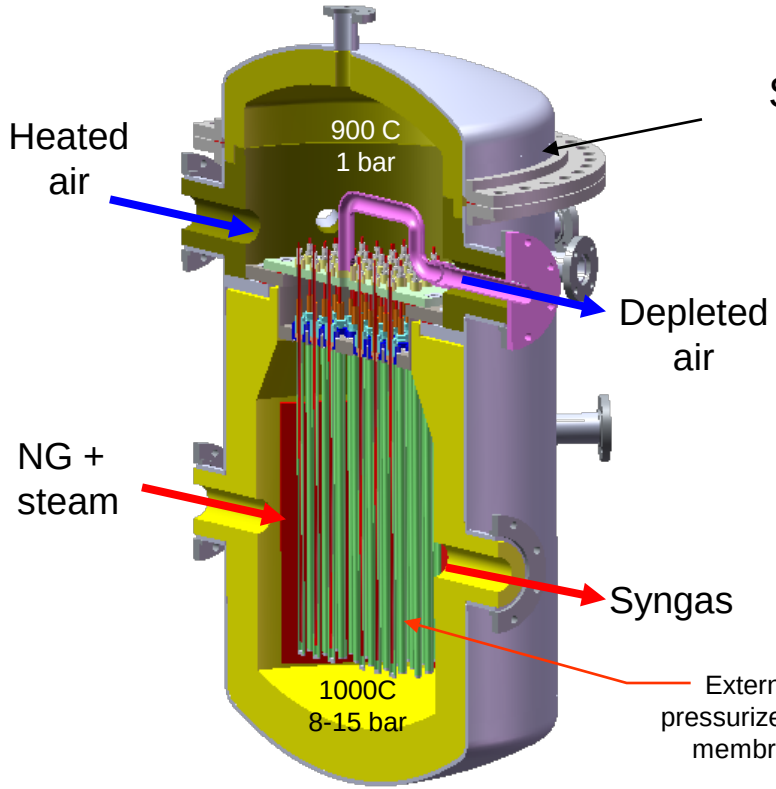




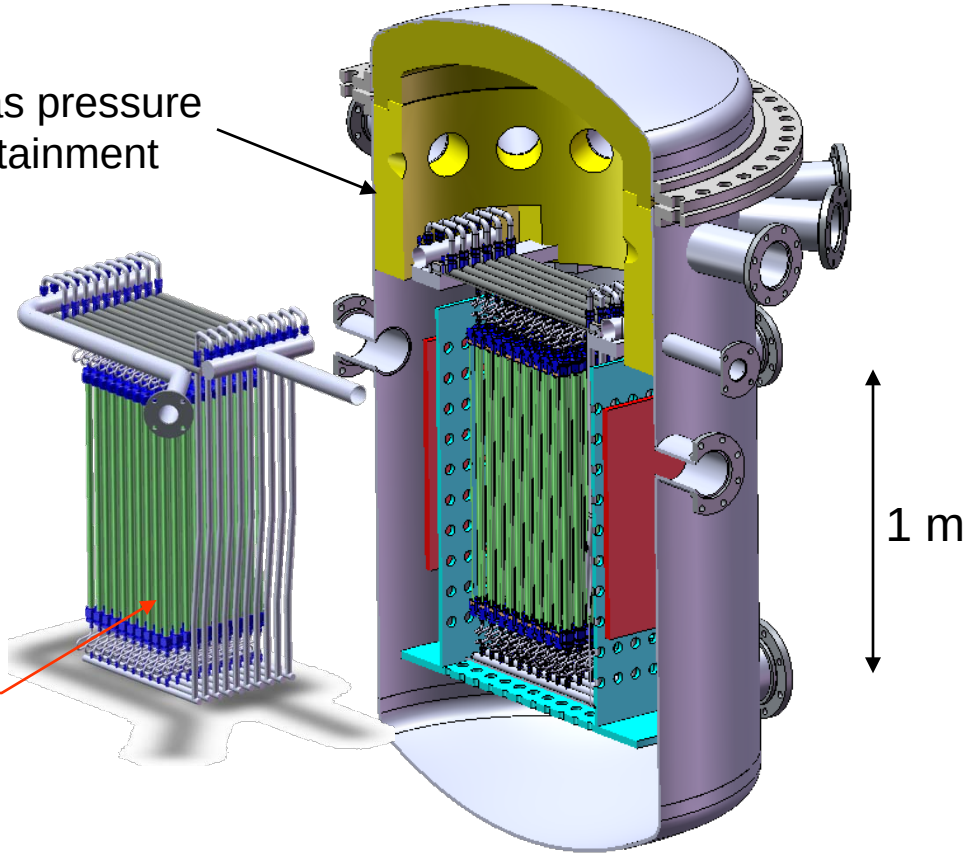
Focus on understanding cost, performance, reliability and degradation

Initial OTM Syngas Reactor Concepts

Tubesheet Concept



Tube-manifold Concept



Challenges:

- High usage of high temperature metal alloys
- Inefficient packaging of membrane→ large pressure vessels
- Pressure vessel pass-throughs require both pressure and temperature isolation

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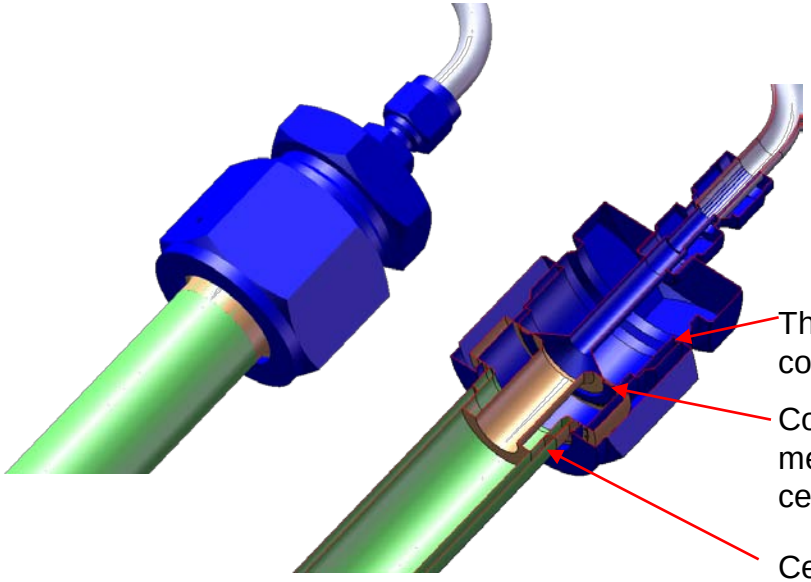
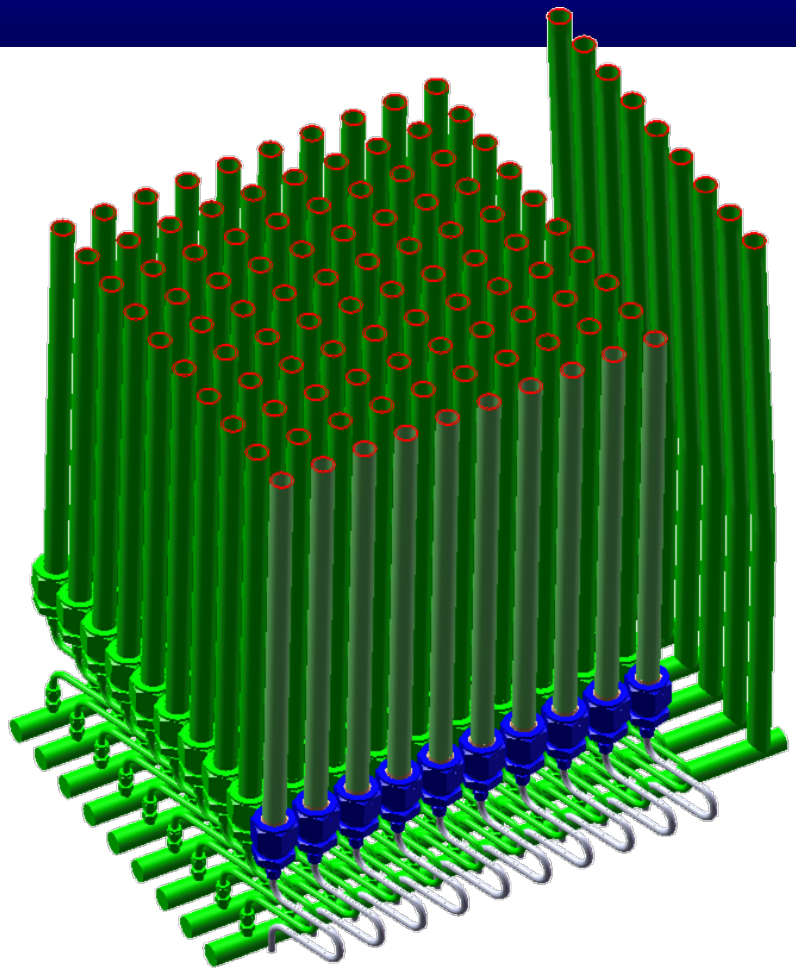
Initial OTM Membrane Seal Concepts





Challenges:

- Reduce number high-temperature metal-to-ceramic tube seals
- Develop low-cost and reliable ceramic-to-ceramic seals and efficient manifold concepts (Integrated OTM Modules)

Praxair and Saint-Gobain: Ceramic Module Development:

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SAINT-GOBAIN

Performance

- Meets flux target
- Long term degradation

Reliability

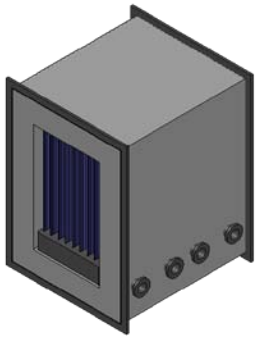
- Long term module reliability
- Seal/manifold technology unproven

Cost

- Module cost
- System integration cost

Praxair Membrane

Praxair Module Concept



Siemens SOFC Module

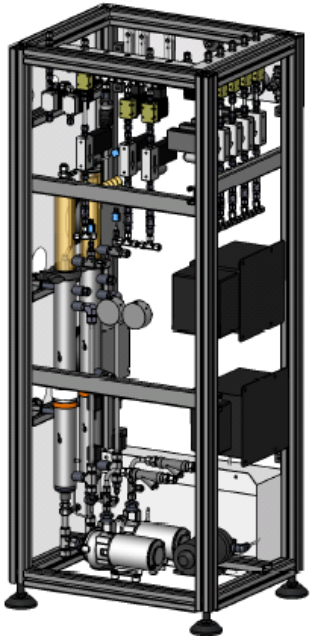
Fuel Cell Energy SOFC Module

Engage ceramics partner to accelerate module development and mitigate risk

Module Development: New Single Tube Testing Infrastructure

- Low pressure OTM test reactors
  - Additional in-house system online October
  - 2x turnkey systems from Greenlight Innovation
    - Enable long term, unattended operation
    - October delivery / installation

- High pressure OTM test reactors
  - Additional high pressure reactor online September
  - Looking to add additional capability

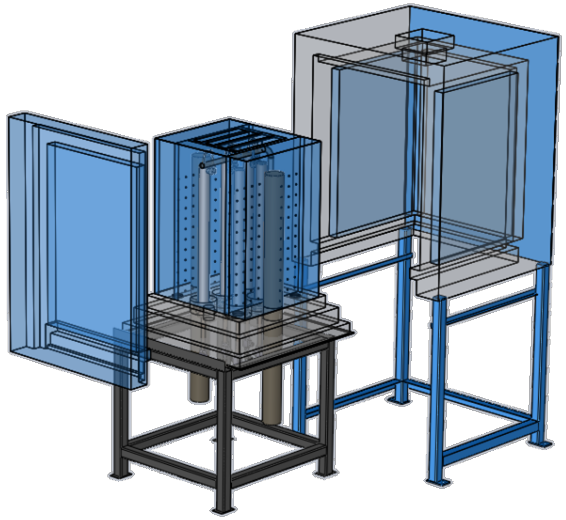


Membrane Development: New OTM Module Testing Infrastructure

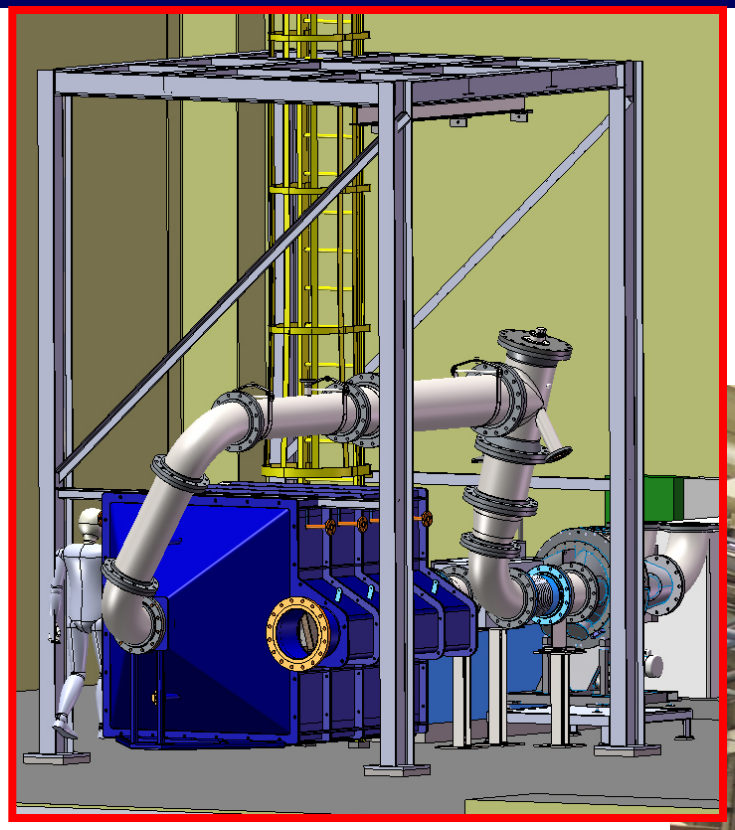
PRAXAIR

Prototype module testing lab:

- New lab build at Praxair (PTC)
- Features
  - Supports testing of OTM modules with natural gas and syngas
  - Supports long-term testing of multiple OTM modules
- Current activity
  - Upgrading flammable gas storage and supply systems
  - Upgrading electrical supply
  - Installing equipment and analytical systems
- Expected completion in Q4



System Development:
New System/Reactor Testing Infrastructure



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