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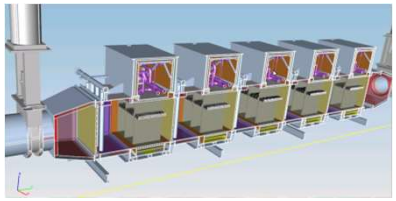


OTM Combined Reformer for IGCC Power Systems

DOE/NETL Cooperative Agreement DE-FE0023543

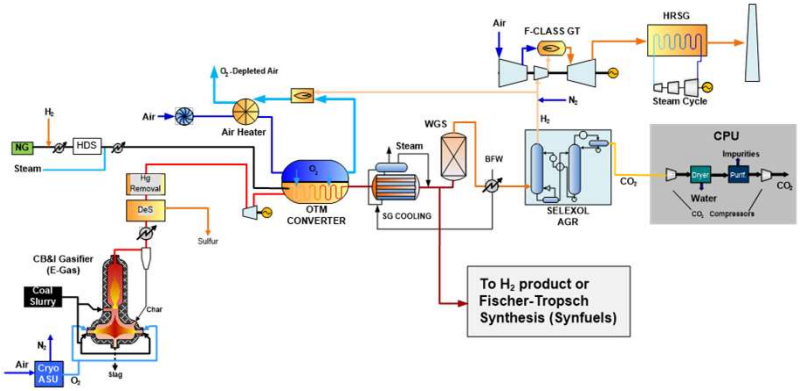
Juan Li

DOE/NETL Gasification Systems and Coal & Coal-Biomass to Liquids Project Review Meeting

Pittsburgh, PA ● April 10, 2018

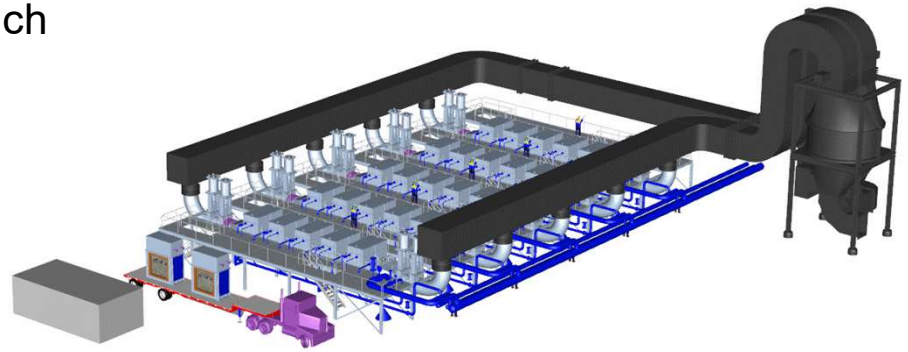
Project Overview

- **OTM-Enhanced Coal Syngas for Carbon Capture Power Systems and Fuel Synthesis Applications**
  $10MM, 50% DOE share
  Oct. 1 2014 – June 30, 2018

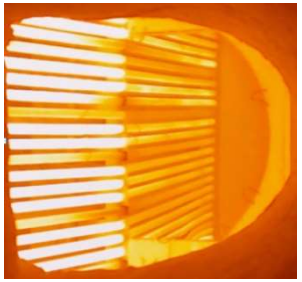


- **Project Goal**

  Develop and demonstrate OTM converter which can enhance IGCC power cycle and improve syngas quality for liquids synthesis



- **Project Objectives**
  - Complete TEA of OTM IG-NGCC process with CO_2 capture
  - Develop stable catalyst for coal syngas
  - Target high pressure operation
  - Develop OTM modules and demonstrate in small pilot scale test with coal syngas



Project Tasks

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- **Task 1 – Project Management**
- **Task 2 – Process Development and Techno-economic Analysis**
  - OTM-Enhanced IGCC w/capture
  - OTM-Enhanced IG-NGCC w/capture
  - Advanced Coal + NG to liquids plant
- **Task 3 – Catalyst Integration and High Pressure Ceramics**
  - Catalyst development and integration
  - High pressure ceramics development
- **Task 4 – Medium Pressure Module Integration**
  - Panel array module level with NG and simulated coal syngas
  - Performance of OTM, catalyst, and module seals
- **Task 5 – Small-Pilot Scale Test of OTM Converter and TDA CO_2 Separation Technology**
  - Modification of OTM development system for larger capacity
  - Integration with TDA's WGS/CO_2 capture system

Reactively-Driven Oxygen Transport Membranes

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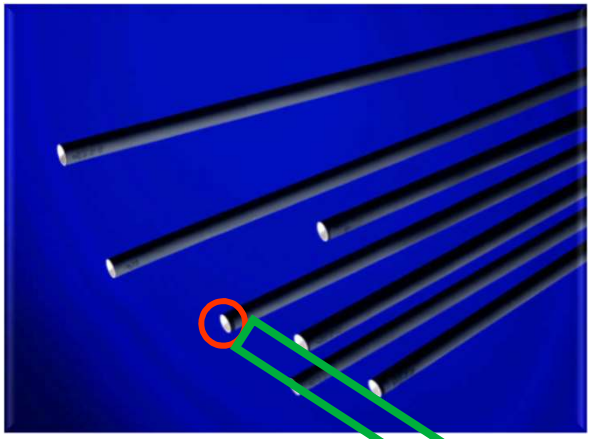
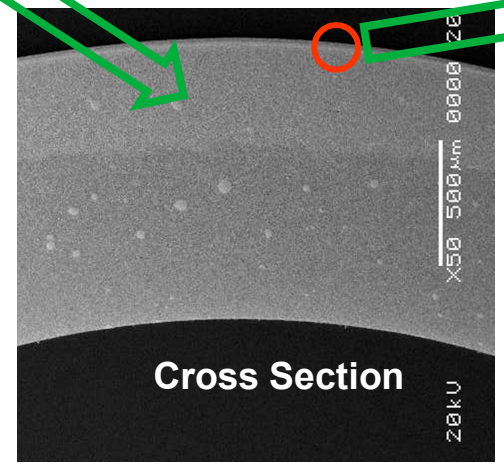


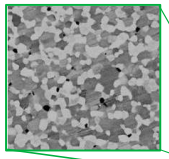


Microstructure

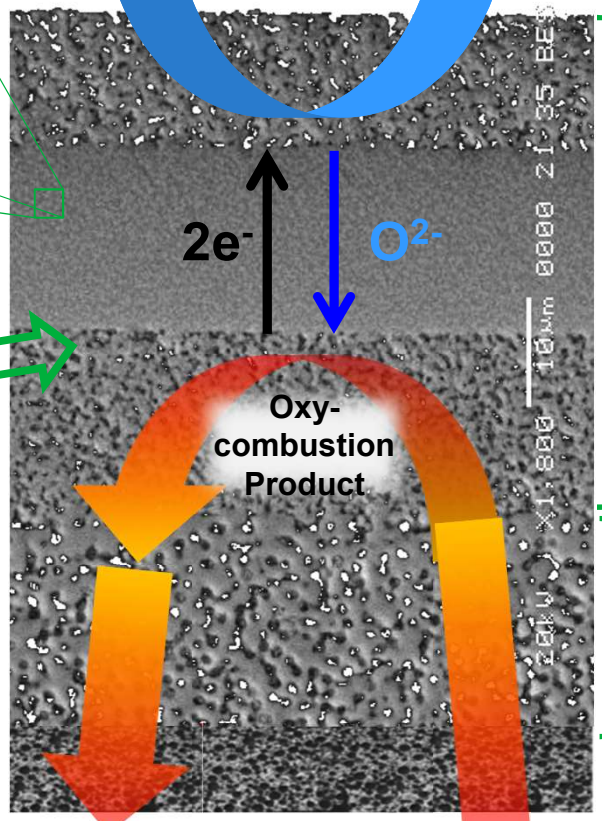
Low Pressure Air

900-1000°C

Depleted Air



Dual phase dense layer



Combustion-Driven Air Separation at High Pressure without ASU and Air Compression

Praxair OTM Syngas Technology

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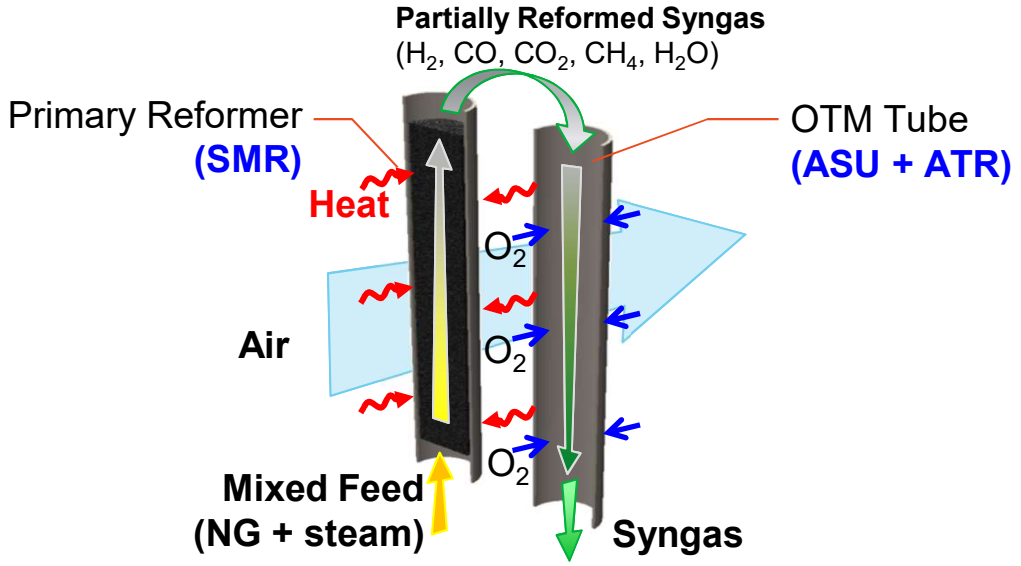
Multi-process combined reforming

Primary Steam Methane Reformer (SMR)

Secondary Auto Thermal Reformer (ATR)

Air Separation Unit (ASU)

Solid state combined reforming with OTM



Combined Reforming in a Single Integrated Efficient Package

OTM-Enhanced IG-NGCC Concept (Coal + NG)

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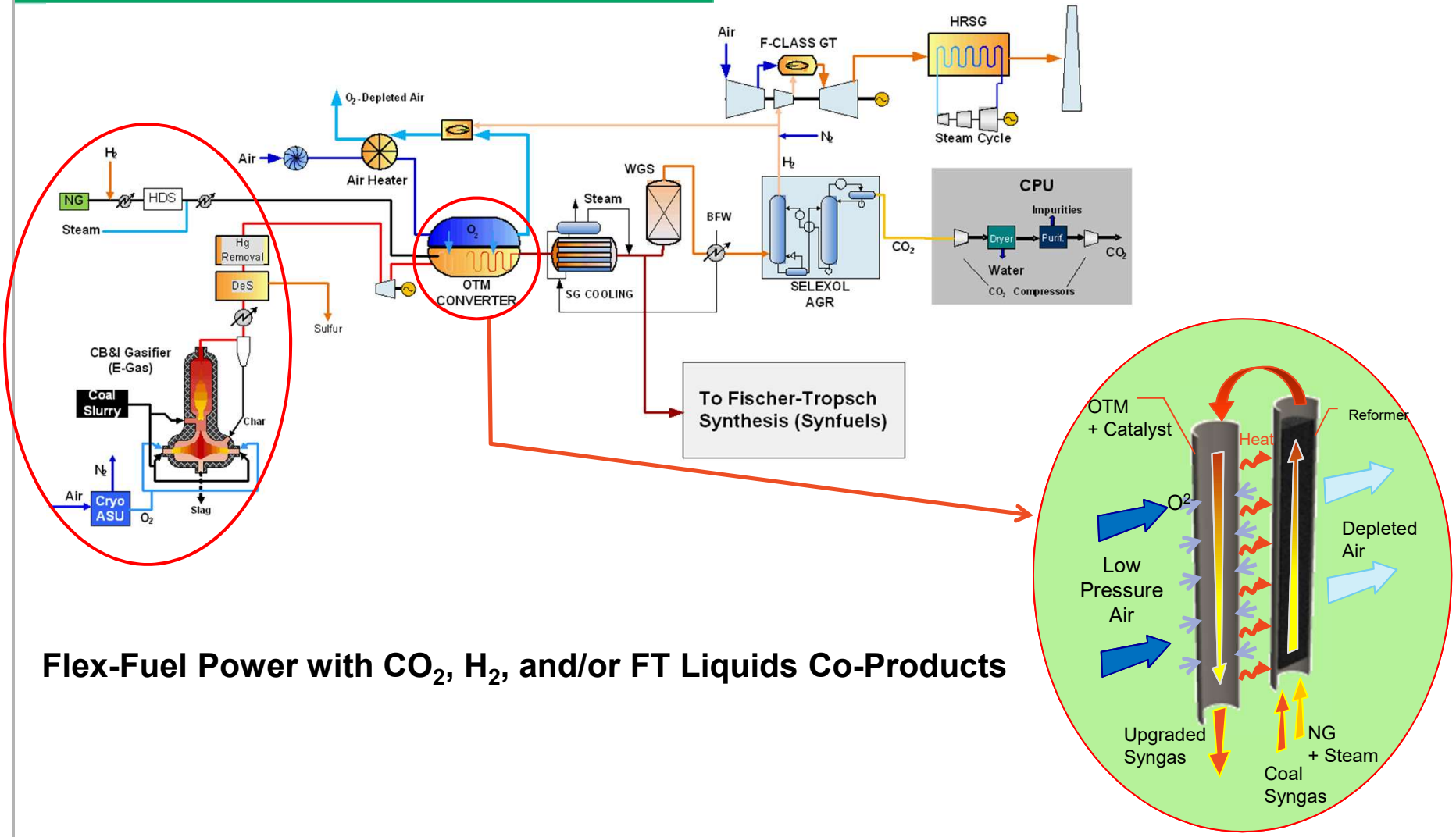

Flex-Fuel Power with CO_2, H_2, and/or FT Liquids Co-Products

Integration of OTM Syngas into Coal + NG Power Cycle with CCS

Task 2 – IGCC Plants Performance and Cost

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Power Plants	IGCC Power Plants (550 MWe)				
	TRIG Gasifier		E-Gas Gasifier		
	PRB Coal		Illinois #6 Coal		
	DOE Case S2B**	OTM IGCC	DOE Case 4*	OTM IGCC	OTM IG-NGCC
Fuel Feed	100% Coal	100% Coal	100% Coal	100% Coal	10% NG (HHV) + Coal
OTM O_2 / Cryo O_2	0%	12%	0%	11%	17%
Carbon Capture Rate	83.2%	92.1%	90.4%	90.9%	90.9%
Net Plant Efficiency (HHV)	31.8%	34.9%	31.0%	34.4%	35.4%
COE, $/MWh	$122.7	$107.8	$139.1	$127.7	$124.2
CO_2 Captured Cost, $/tonne	$46.1	$28.3	$55.7	$46.3	$44.2

- Enabling TRIG gasifier IGCC to achieve 90%+ carbon capture rate
- 10% – 14% increase of plant net efficiency
- 8% – 12% reduction of cost of electricity
- 17% – 39% reduction of carbon capture cost

* NETL Cost and Performance Baseline for Fossil Energy Plants, Vol 1, Rev 2a, 2013.
** NETL Cost and Performance Baseline for Fossil Energy Plants, Vol 3a, 2011.

Task 2 – CTL Plants Performance and Cost

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CTL Plants	DOE CTL Baseline w CO_2 Vent*	OTM CTL w CO_2 Vent	
Total Production of FT Liquids, bpd	50,000	50,000	
Fuel Feed	100% Coal	23% NG (HHV) + Coal	
Plant Thermal Efficiency (HHV)	54.0%	55.8%	
% Carbon Conversion to FT Liquids	41%	45%	
NG Price ($/MMBtu)	No impact on COP	$3.0	$6.13
COP FT Diesel, $/$bbl_{FTD}$**	$123.1	$109.9	$117.6

- 3% increase of plant thermal efficiency
- 9% increase of carbon-to-liquids conversion
- 5% – 11% reduction of cost of production

* NETL, Cost and Performance Baseline for Fossil Energy Plants, Vol 4, 2014.
** COP values are for financial structure with loan guarantees.

Integrated OTM Combined Reformer Panel

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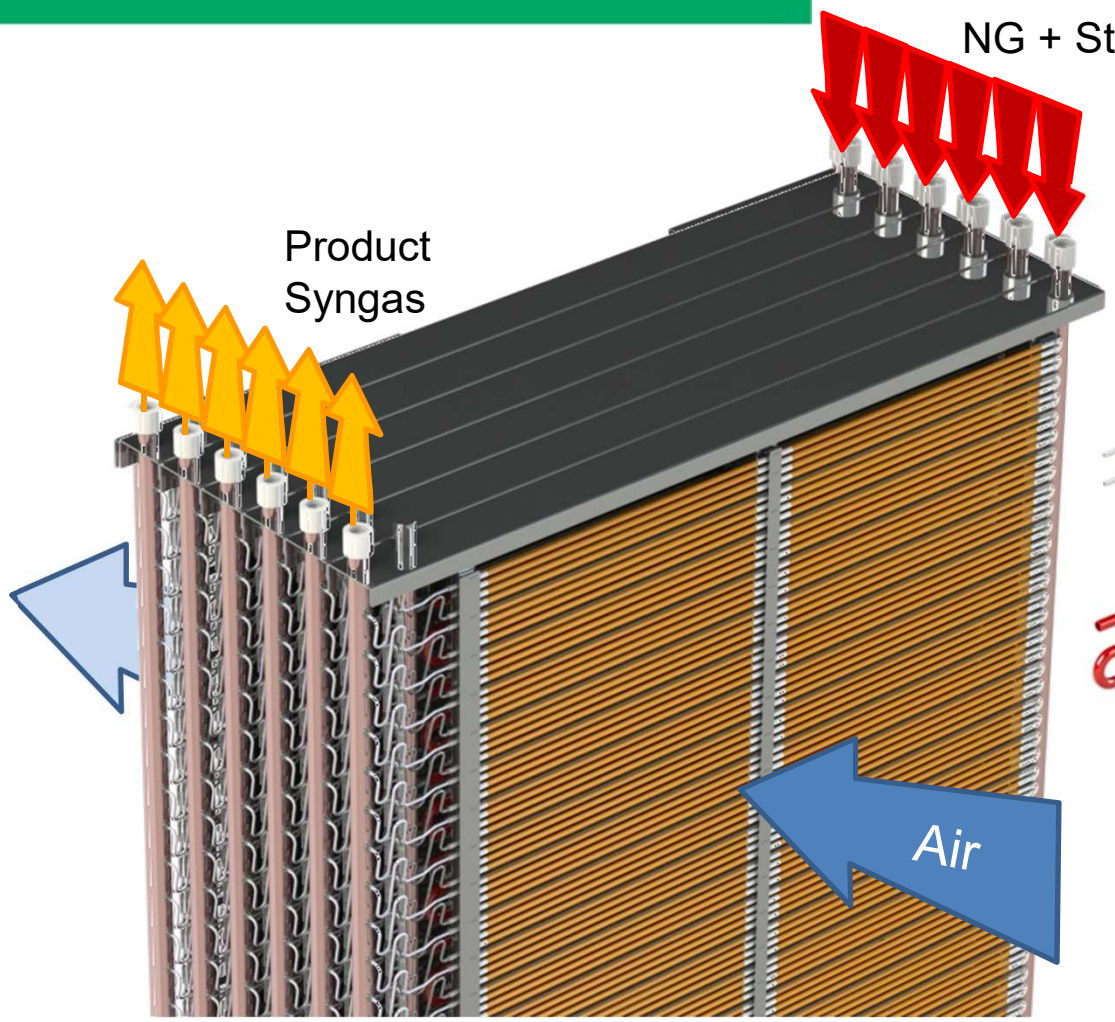

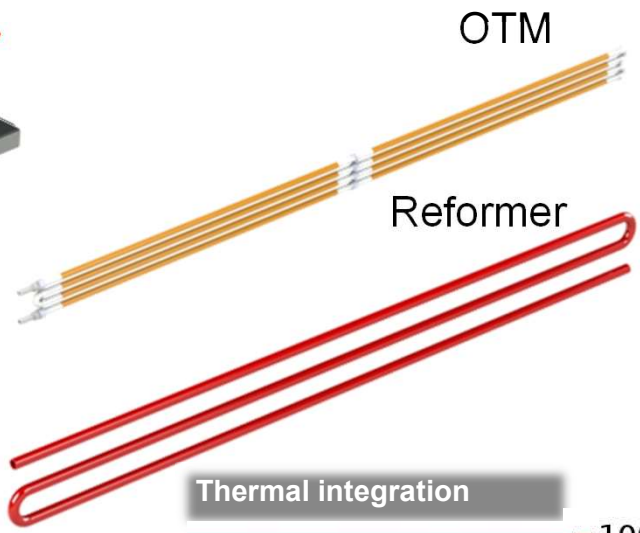

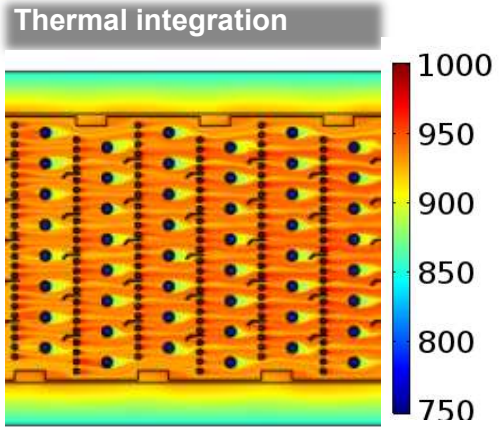

Scalable Module Design of OTM Combined Reformer

Task 3 – Development of Reformer Catalyst

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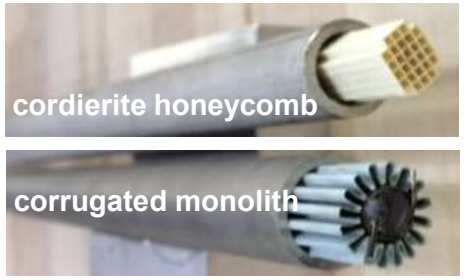
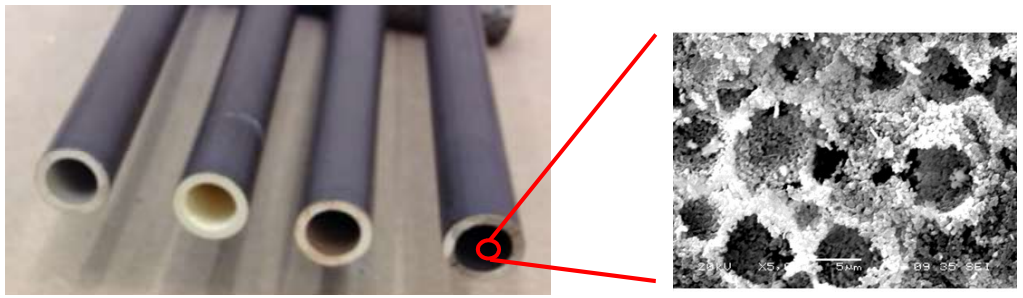
- **Primary reformer: Structured catalyst substrate with high heat transfer**



conventional catalyst substrate

PX spiral monolith

- **Secondary reformer: Cost-effective integration with OTM**



highly porous structure

- **Down-selected suitable catalyst materials**
  - High methane conversion
  - Long-term stability
  - Coking resistance
  - Contaminant tolerance

Task 3 – Impact of Coal Syngas Impurities

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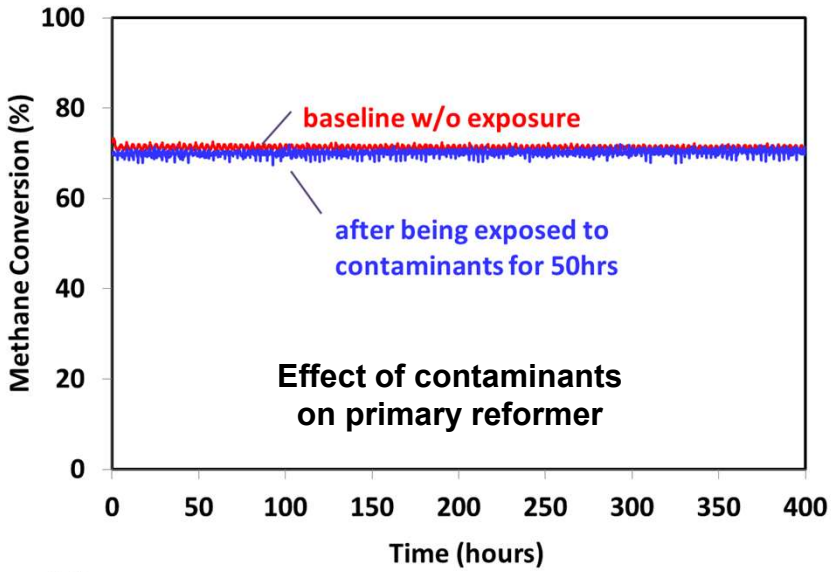
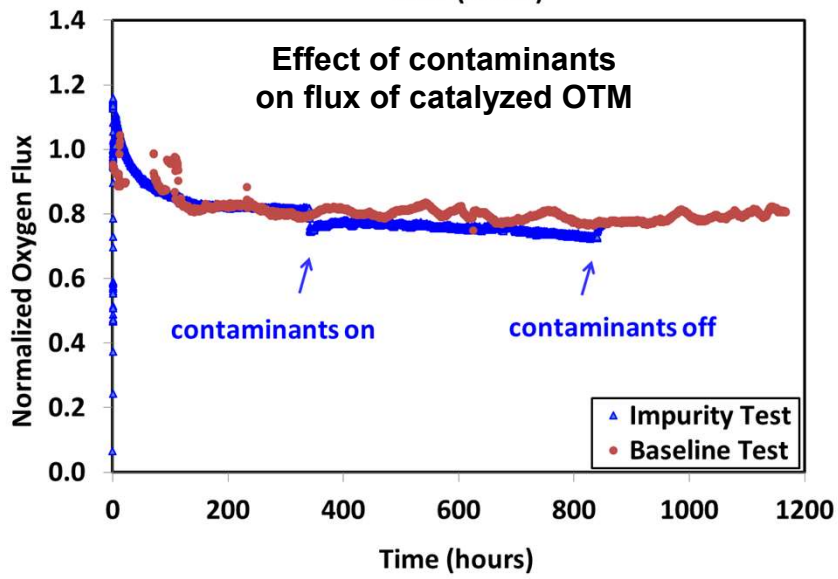
Coal syngas impurity test

(fueled with H_2/N_2/contaminants)

Contaminant	Level (ppm)
Arsine, AsH_3	1
Phosphine, PH_3	1
Hydrogen selenide, H_2Se	1
Hydrogen sulfide, H_2S	2





Low Impact of Coal Syngas Contaminants on Performance

Task 3 – Mechanical Properties for High Pressure Operation

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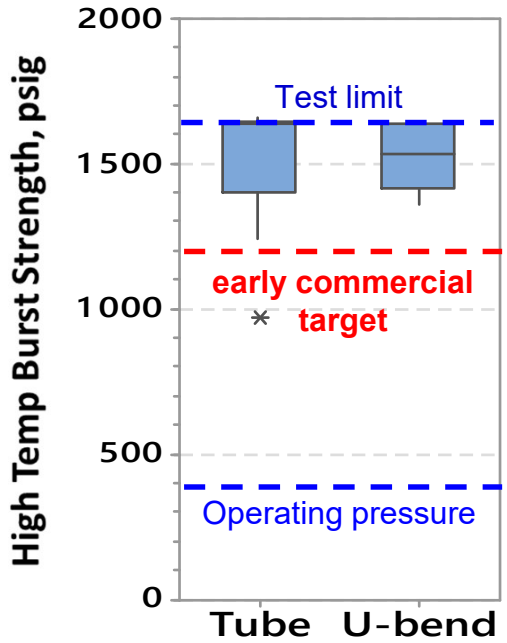
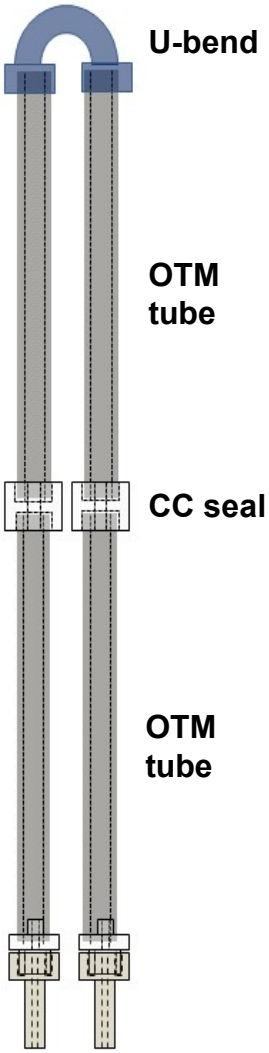
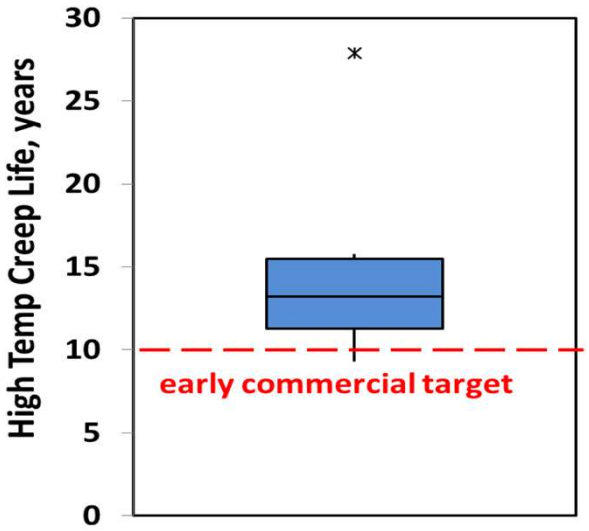
Burst Strength (1000°C)





OTM Tube Creep Life (1000°C, 400 psi)



CC Seal Reliability

Temp.	Run time Months	Failures
950	48	0/30
975	45	0/30
1000	43	0/30

100 psi, >20 thermal cycles

Creep Life and Tube Strength Meet Early Commercial Targets

Task 4 – OTM Single Panel Test

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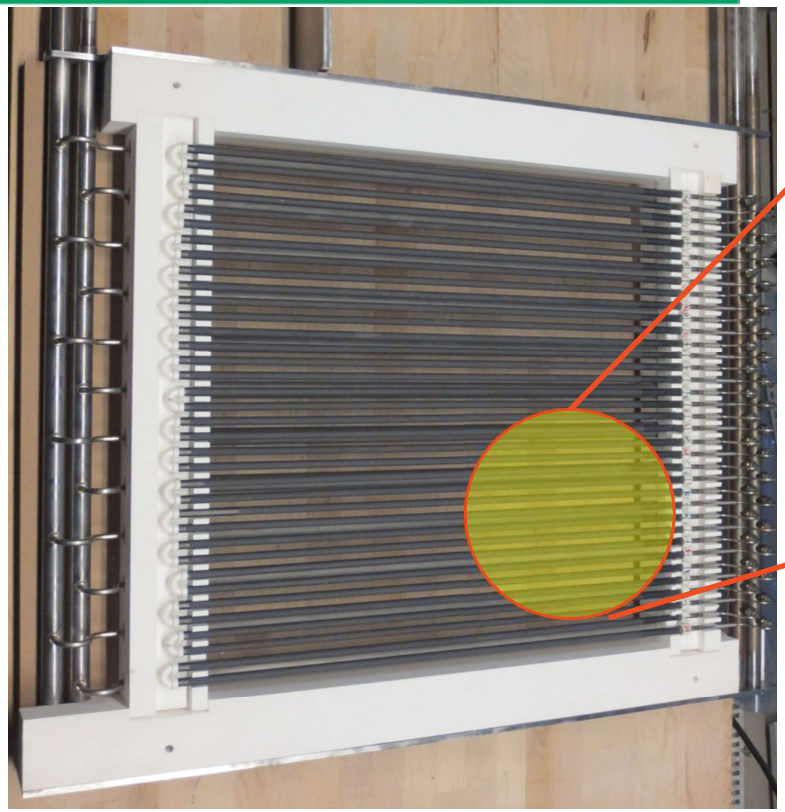
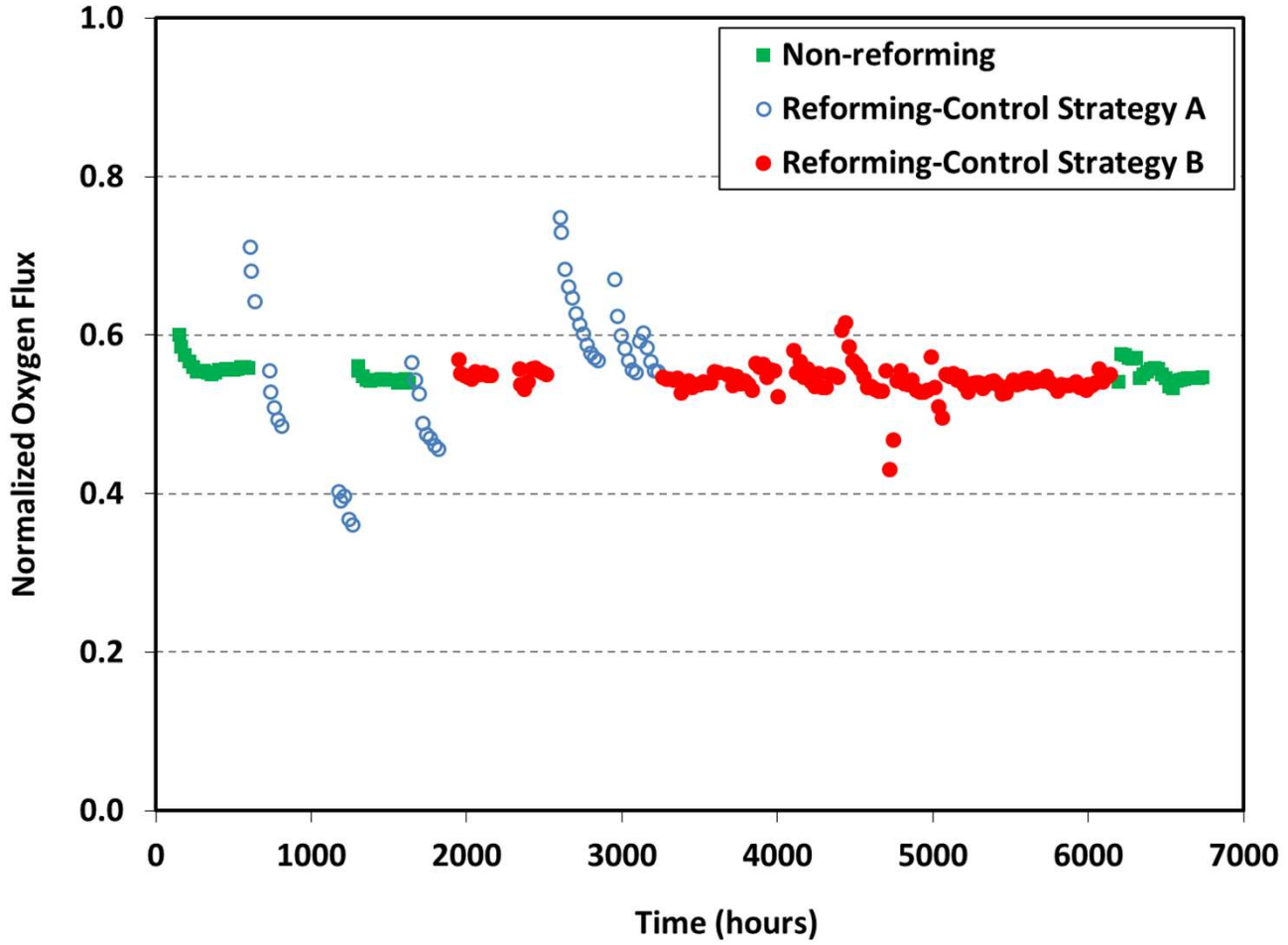


- 20+ OTM single panels tested with NG and simulated coal syngas.
- Latest panel running for 14 months at 150 psi w/o failure.
- Demonstrated > 99% CH_4 conversion.

OTM Dry Syngas Product Components	NG Feed	Simulated Coal Syngas/NG Feed
H_2	69.9%	41.6%
CH_4	0.12%	0.02%
CO	20.7%	34.1%
CO_2	8.6%	19.4%
Product H_2/CO Ratio	3.4	1.2

Stable Operation and High CH_4 Conversion

Task 4 – OTM Oxygen Flux Degradation



Negligible Performance Degradation of OTM Panel Control Strategy Optimization

Task 5 – OTM Panel Array Scale Up

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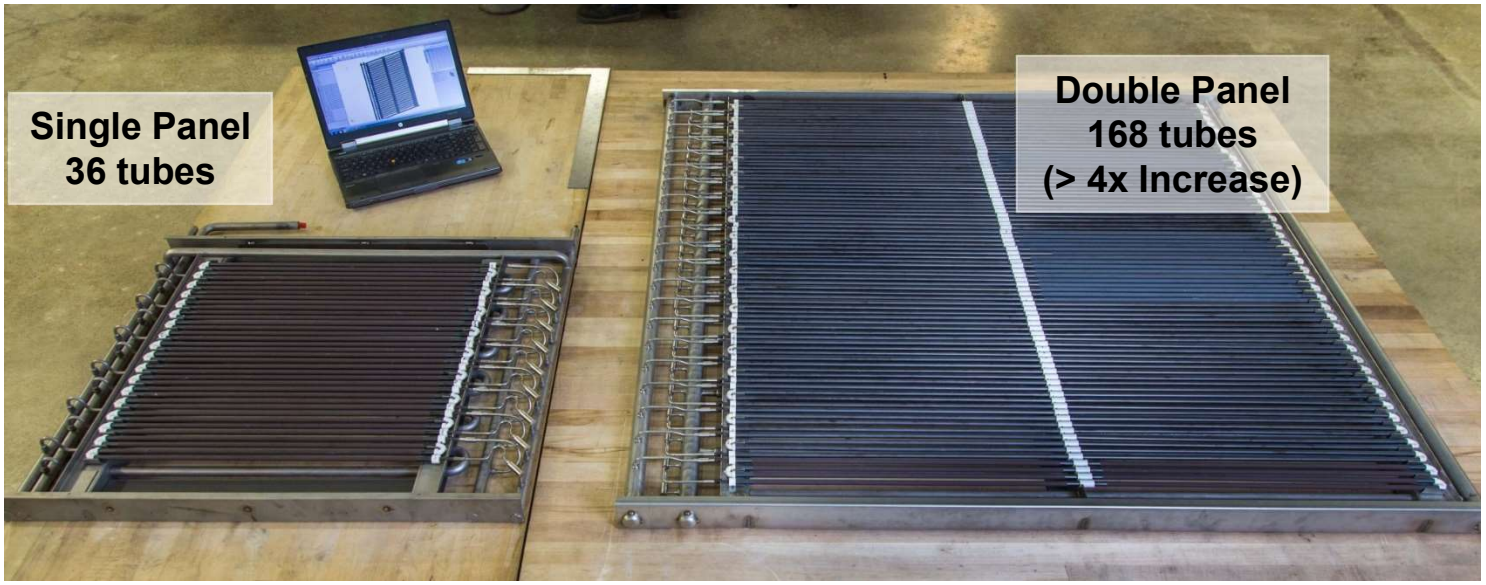

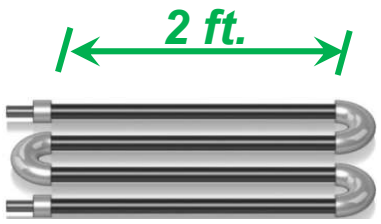

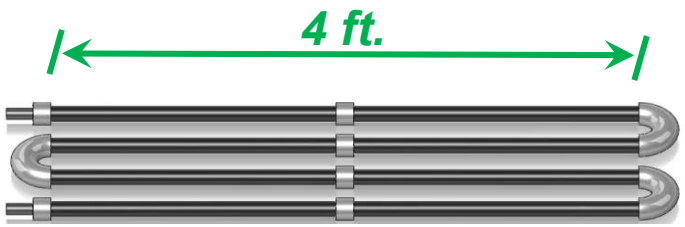

Replication of Ceramic Elements Facilitate Mass Manufacturing

Task 5 – OTM Pilot Scale System

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New Reactor and Infrastructure for Commercial Scale Panel Operation

Task 5 – Fuel Test of OTM Pilot System

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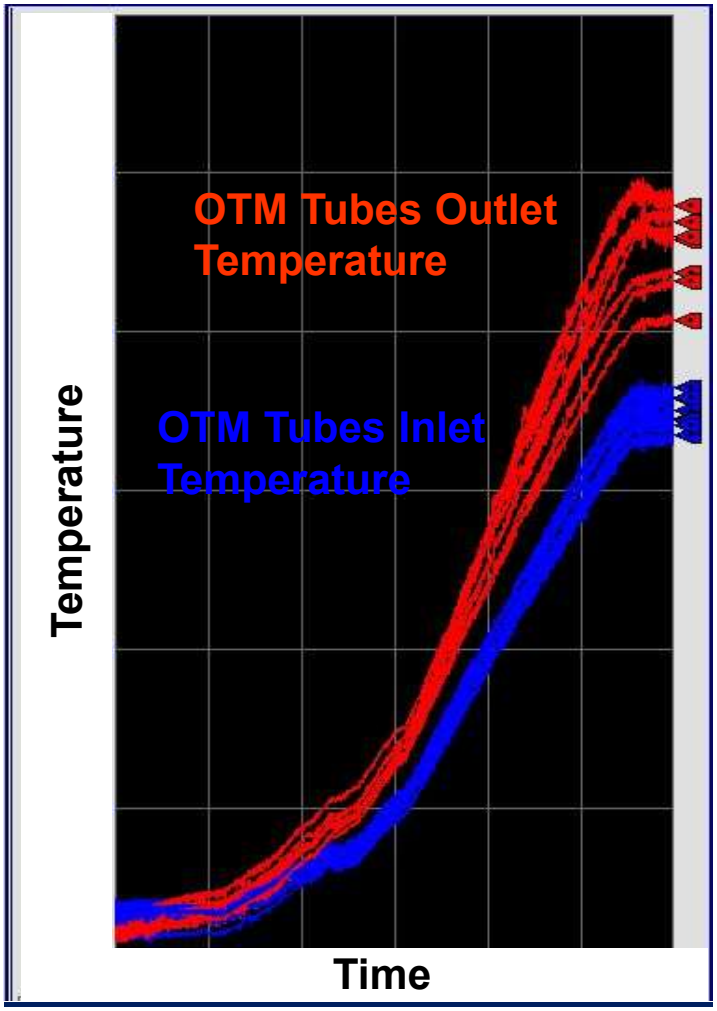

	Commercial Target	Pilot System
Normalized Feed Consumption [BTU / SCF of SG]	1	0.9
Normalized Oxygen Transported [O_2 / OTM tube]	1	1.0
Normalized Syngas Production [SG / OTM tube]	1	1.0
Syngas H_2/CO	3.0	3.0

Reliable Startup and Operation of OTM Commercial Scale Panels

Task 5 – Small Pilot Scale Integration

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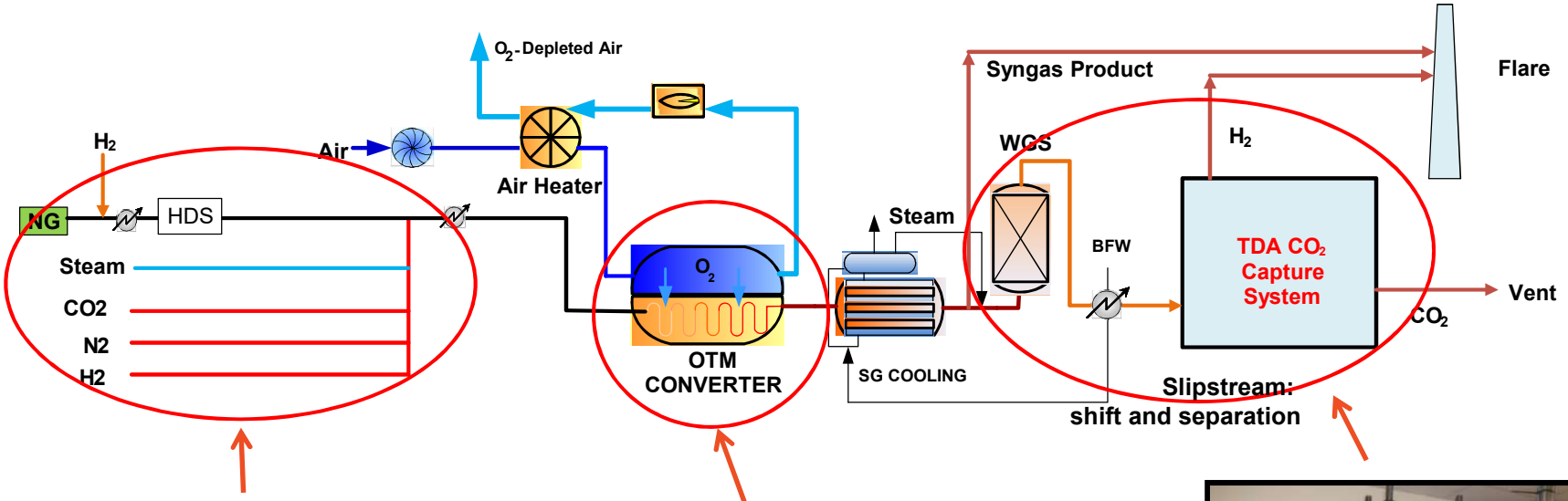

Simulated Coal Syngas

OTM Pilot System

TDA WGS/Capture Skid

Task 5 – Small Pilot Scale Integration

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Summary

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- **OTM Combined Reformer Addition to IGCC Plant**
  - Improves net efficiency and carbon capture rate
  - Reduces cost of electricity and CO_2 capture cost
- **OTM Combined Reformer Addition to CTL Plant**
  - Improves thermal efficiency and carbon conversion rate
  - Reduces cost of production
- **OTM Component Development**
  - Reformer catalysts: demonstrated stable performance and impurity tolerance
  - OTM and seals: demonstrated target burst pressure and creep life
  - OTM panels: demonstrated >99% CH_4 conversion and stable performance under coal syngas/NG
- **OTM Pilot Scale System**
  - Upgraded existing OTM reactor
  - Demonstrated reliable startup and control strategies for OTM double panels
  - Will test OTM panels with TDA CO_2 capture unit in 2018 Q2

Development and Performance Targets are Met and/or Exceeded

Acknowledgements

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Backup Slides

Ceramic Membrane– Mass Produce 1,000's for a System

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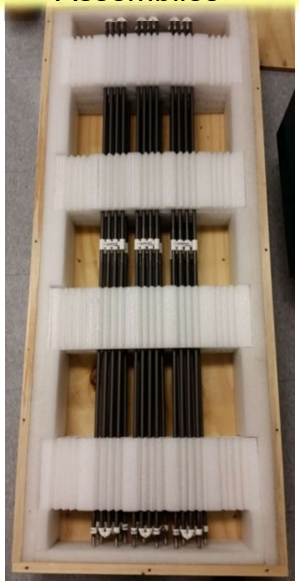
Substrate extrusion

Coating

High temperature firing

Seal assembly

Finished Multi-tube Assemblies



Isolation Valve Performance During a Test

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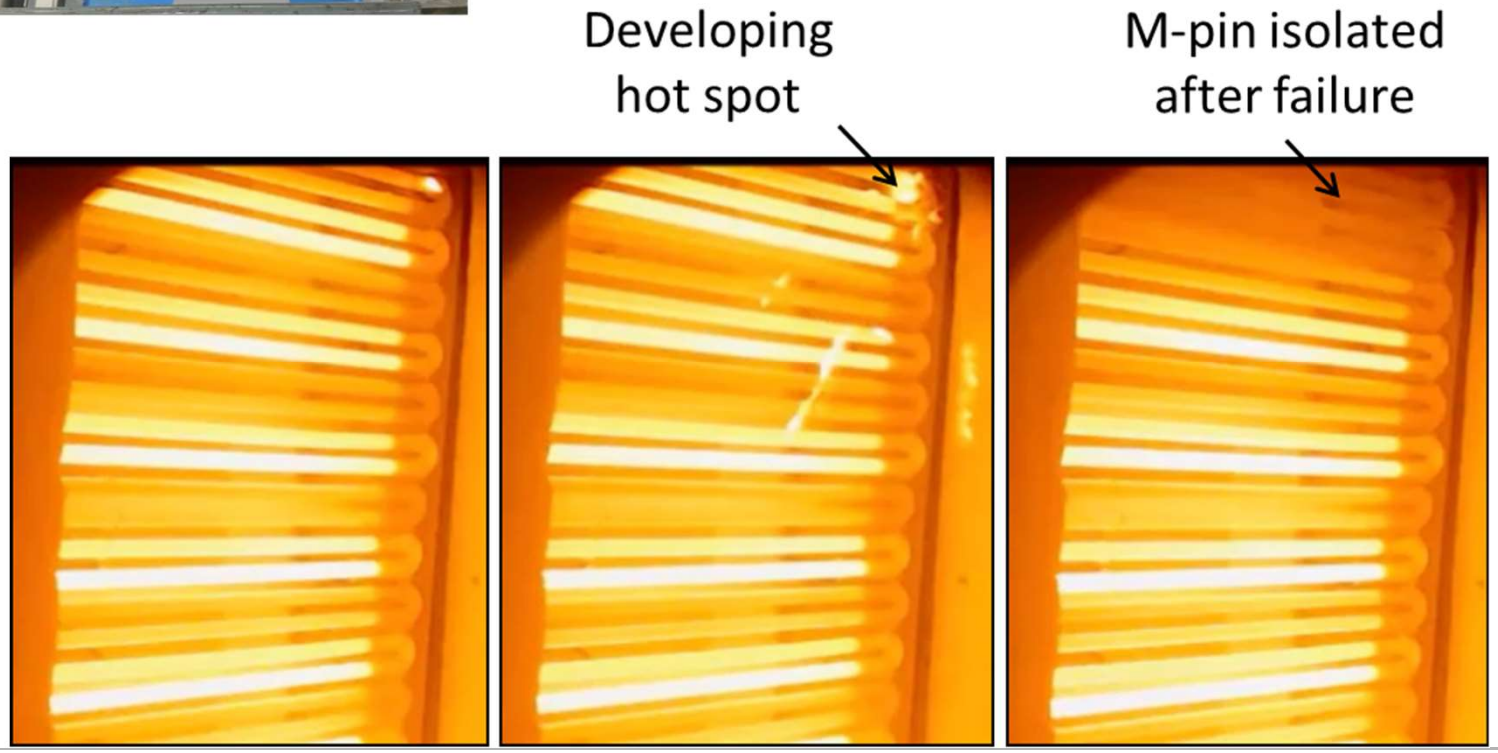

Project Milestones

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Milestone #	Milestone Title / Description	Estimated Completion Date	Actual Completion Date
1	Determine target operating conditions for OTM	12/31/2014	completed
2	Concept select OTM IG-NGCC flow sheet	11/30/2015	completed
3	Complete heat and material analysis for OTM IGCC case	01/31/2016	completed
4	Complete heat and material analysis for OTM IG-NGCC case	05/31/2016	completed
5	Complete analysis for IG-NG Coal-to-liquids plant	12/31/2016	completed
6	Evaluate performance of membrane at high pressure at target fuel conversion on simulated coal syngas	05/31/2016	completed
7	Commence creep/endurance tests at high pressure	12/31/2015	completed
8	Evaluate performance of module at intermediate pressure on test skid	05/31/2016	completed
9	Capital cost estimates and economics analysis complete	03/31/2017	completed
10	Start to integrate OTM converter with TDA CO_2 separation system	09/30/2017	completed
11	evaluate performance of OTM converter with TDA CO_2 separation system	06/30/2018	In progress