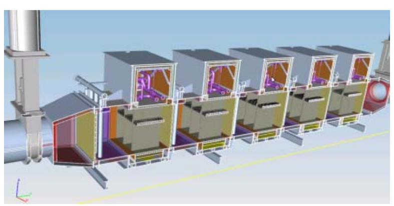
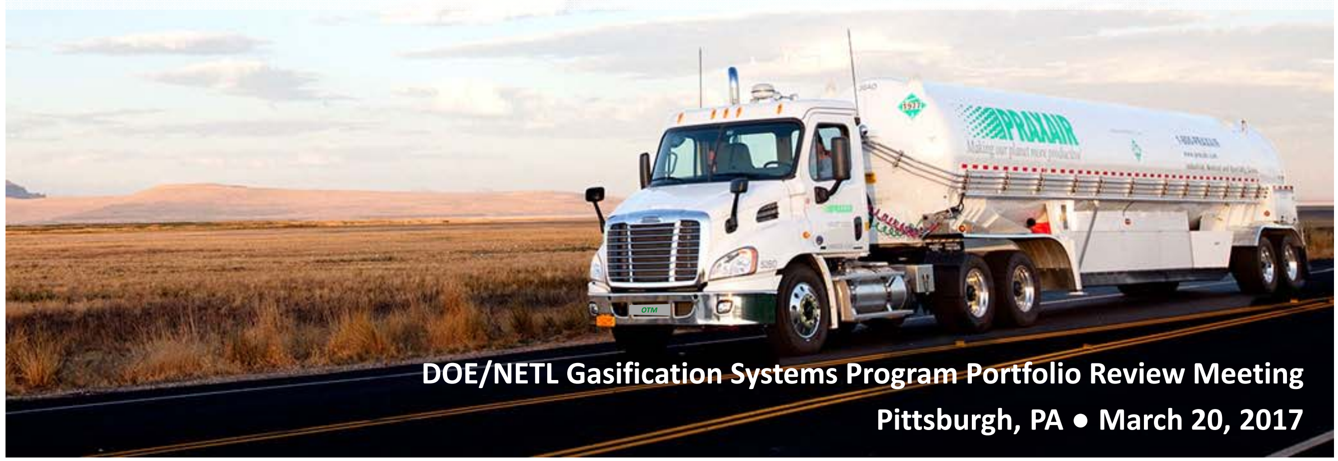


OTM-Enhanced Coal Syngas for Carbon Capture Power Systems and Fuel Synthesis Applications

DOE/NETL Cooperative Agreement DE-FE0023543

Juan Li



DOE/NETL Gasification Systems Program Portfolio Review Meeting

Pittsburgh, PA ● March 20, 2017

Project Overview

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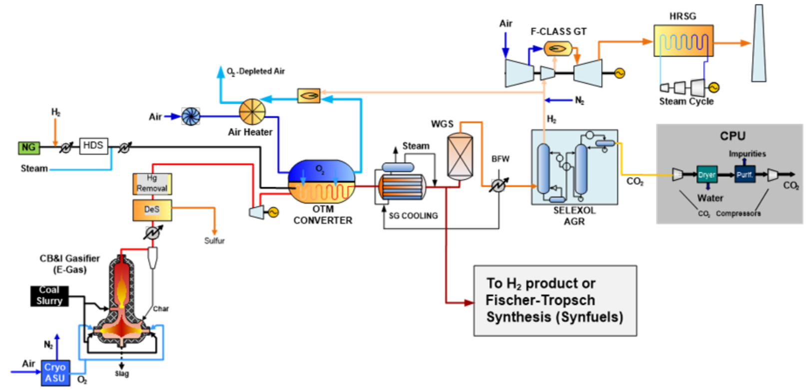
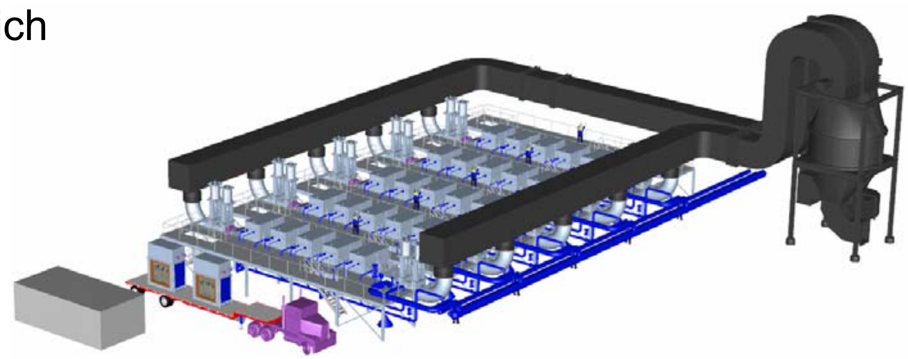
- **OTM-Enhanced Coal Syngas for Carbon Capture Power Systems and Fuel Synthesis Applications**
  $10MM, 50% DOE share
  Oct. 1 2014 - Dec. 31, 2017

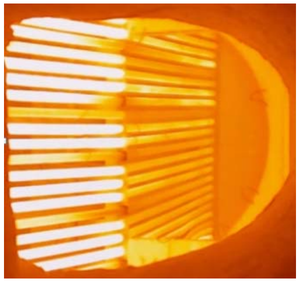


- **Project Goal**

  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

- **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 (100-500 OTMs)
  - Integration with TDA's WGS/CO_2 capture system

Reactively-Driven Oxygen Transport Membranes

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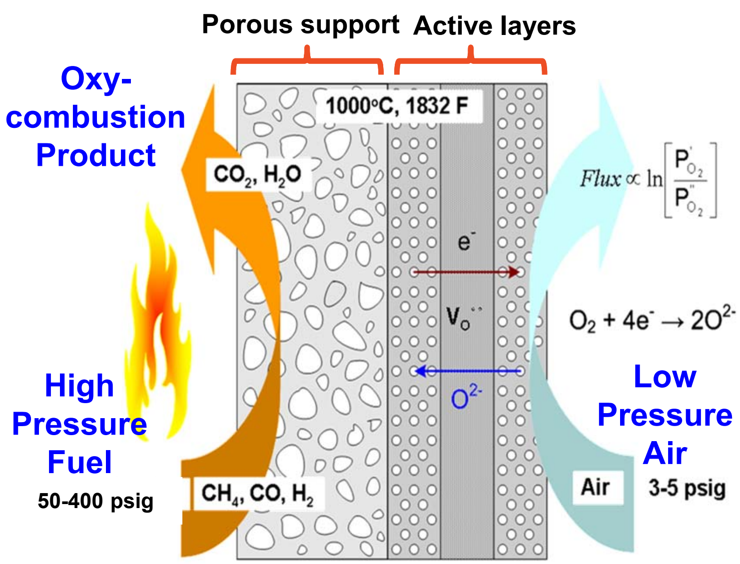
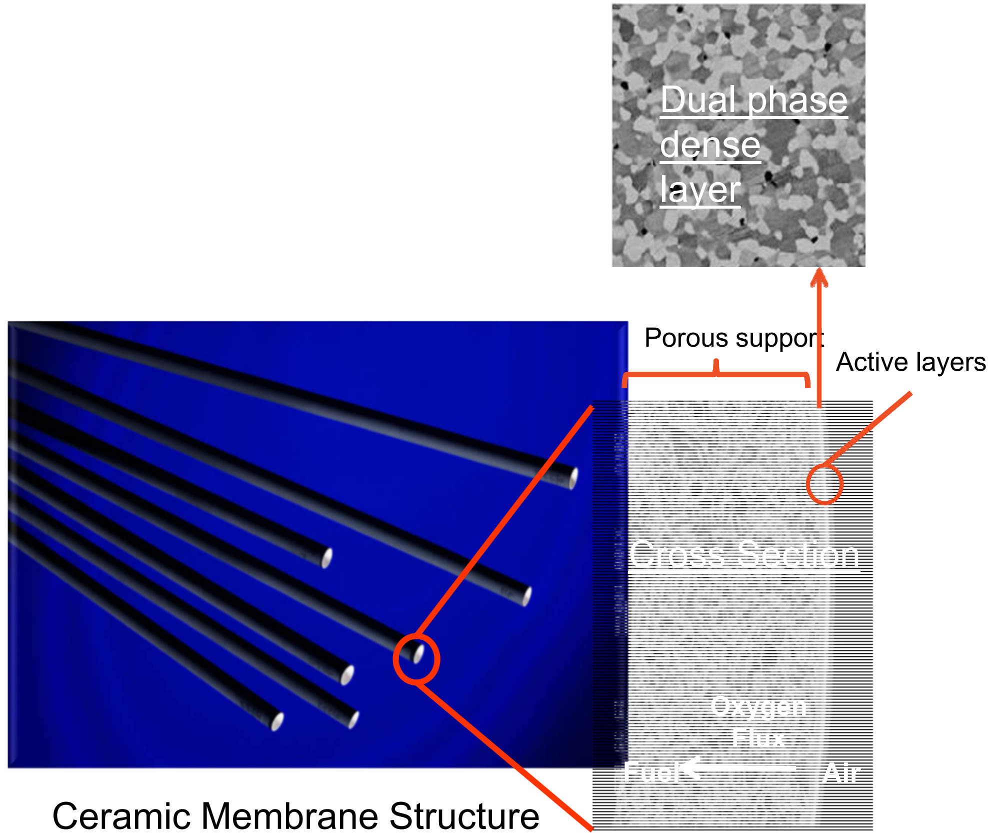


Ceramic Membrane Function



Ceramic Membrane Structure

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

Praxair OTM Syngas Technology

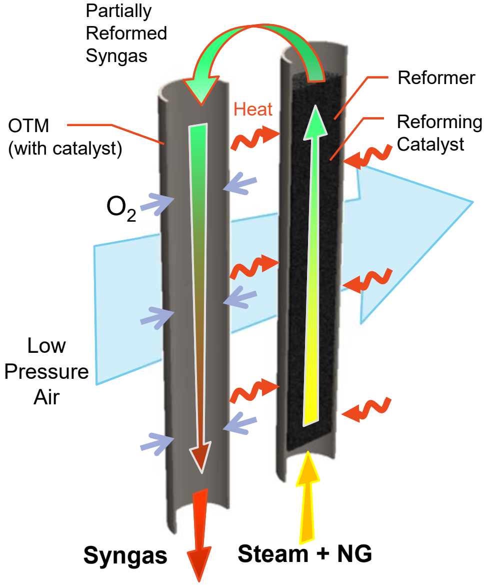
Multi-Process Combined Reforming

Primary Steam Methane Reformer

Secondary AutoThermal Reformer

Air Separation Unit

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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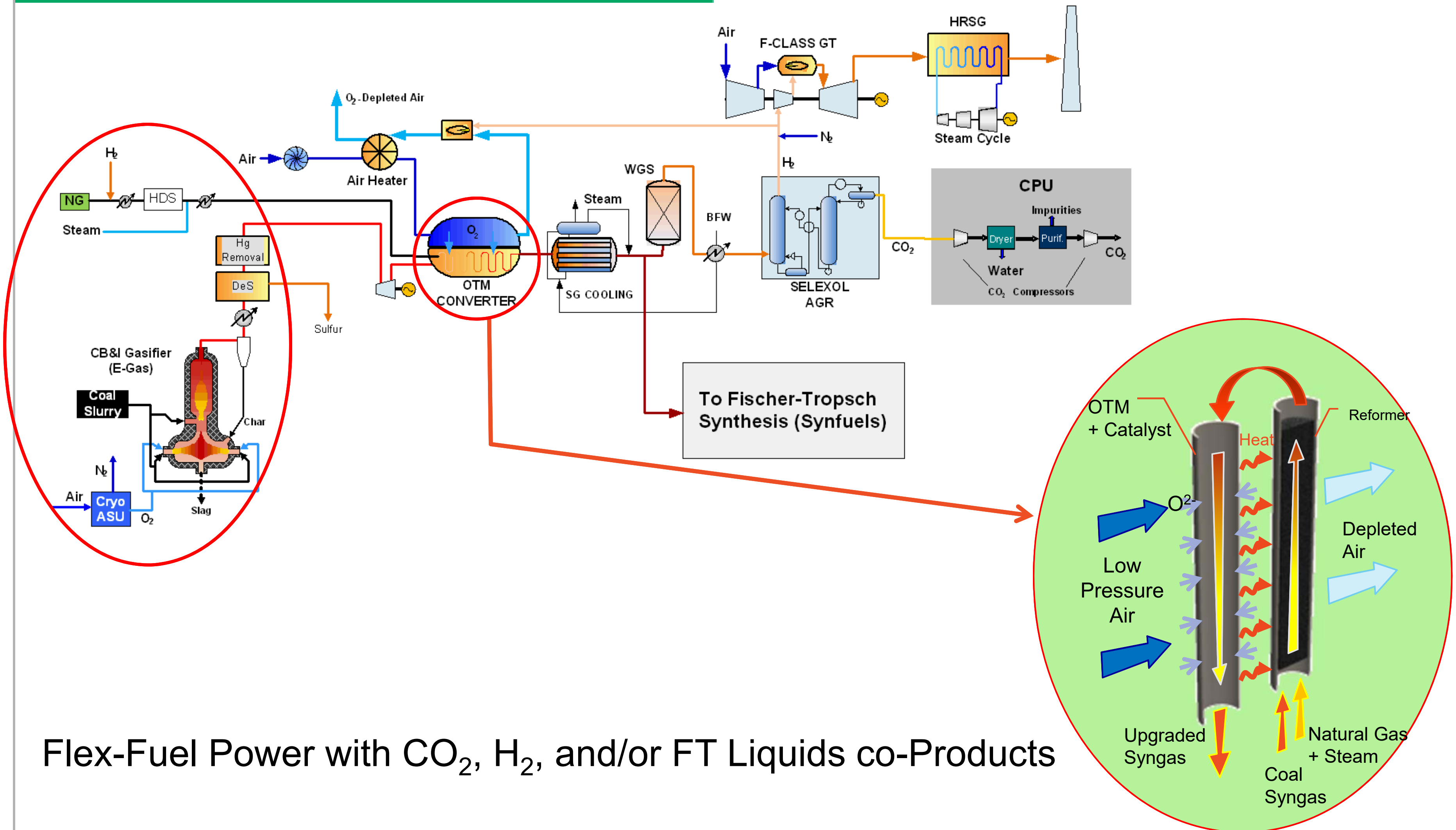

Flex-Fuel Power with CO_2, H_2, and/or FT Liquids co-Products

Integration of OTM Syngas into Coal + NG Power Cycle w/ CCS

Task 2 – BFD of OTM-Enhanced IG-NGCC Plants

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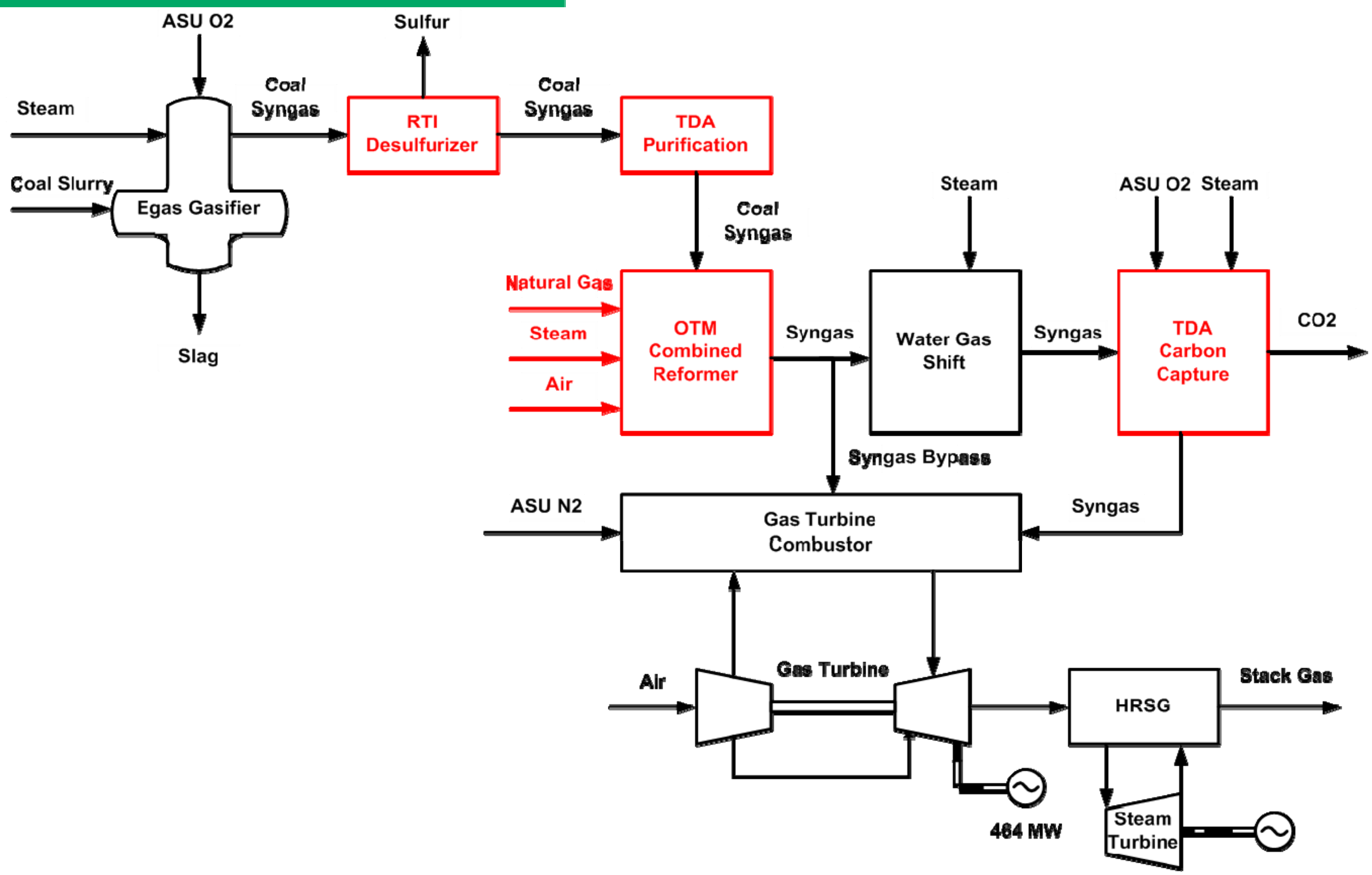

- Similar flow diagram as DOE IGCC baseline
- Addition of OTM combined reformer for CH_4 slip conversion
- Utilization of warm-gas cleanup (RTI, TDA) and CO_2 capture (TDA) technologies

Task 2 – IGCC Plants Performance and Cost

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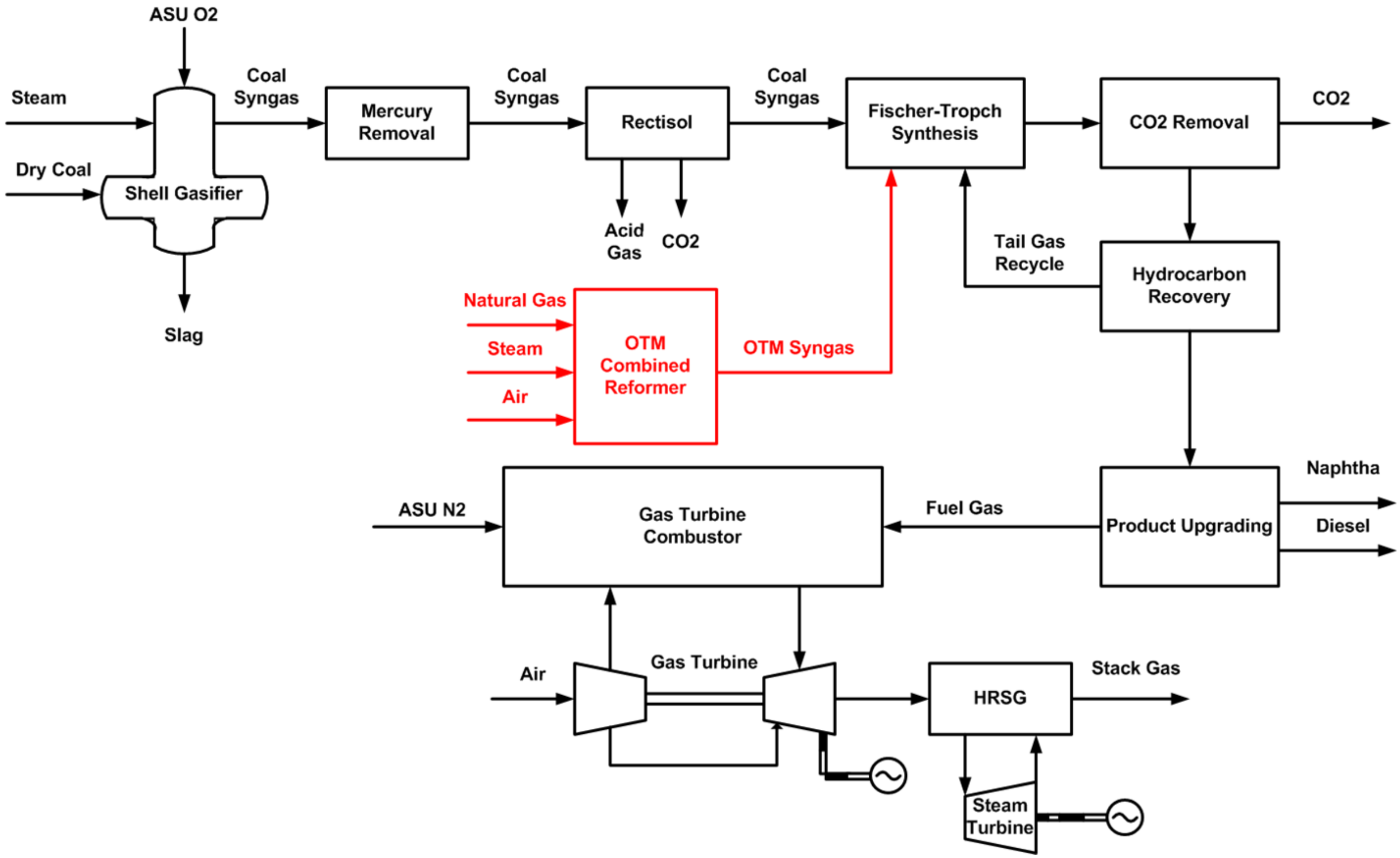
Power Plants	IGCC Power Plants				
	TRIG Gasifier		E-Gas Gasifier		
	PRB Coal		Illinois #6 Coal		
	DOE Case S2B**	OTM IGCC	DOE Case 4*	OTM IGCC	OTM IG-NGCC
Carbon Capture Rate	83.2%	92.1%	90.4%	90.9%	90.9%
Total Power, kWe	621,300	702,603	703,700	711,805	713,070
Total Auxiliaries, kWe	160,450	130,312	190,090	130,391	119,886
Net Power, kWe	460,850	572,291	513,610	581,414	593,184
Net Plant Efficiency (HHV)	31.8%	34.9%	31.0%	34.4%	35.4%
OTM O_2 / Cryo O_2	0%	12%	0%	11%	17%
% NG by HHV	0%	0%	0%	0%	10%
TOC, $/kW	$4,484	$3,840	$4,252	$3,914	$3,669
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
CO_2 Avoided Cost, $/tonne	$60.8	$32.7	$73.4	$54.1	$47.9

- **Enabling TRIG gasifier IGCC to achieve 90%+ carbon capture rate**
- **10 – 14% increase of IGCC 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 — BFD of OTM-Based CTL Case



- Similar flow diagram as DOE CTL baseline
- Addition of OTM combined reformer to improve carbon conversion and syngas quality

Task 2 — CTL Plants Performance and Cost

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CTL Plants	DOE Large CTL w CO_2 Vent*	DOE Small CTL Concept 2**	OTM-based CTL w CO_2 Vent
Total Production of F-T Liquids, bpd	49,992	9,609	9,998
Naphtha, bpd	14,762	4,262	2,952
Diesel, bpd	35,230	5,347	7,046
Total Power, kWe	472,800	113,126	99,173
Total Auxiliaries, kWe	375,718	73,598	60,952
Net Power, kWe	97,082	39,528	38,221
Coal Feed Flow (lb/hr)	1,750,518	354,488	266,079
% NG by HHV	0.0%	0.0%	7.7%
Plant Thermal Efficiency (HHV)	54%	50%	68%
% Carbon in Naphtha and Diesel	41%	< 42%	52%
COP F-T Diesel, $\$/bbl_{FTD}$	$123.1	$172.0	$145.2
Equivalent Crude Oil Price, $\$/bbl_{ECO}$	$106.9	$149.3	$126.0

- 27% increase of carbon conversion to F-T liquids
- 25 - 36% increase of plant thermal efficiency
- 16% reduction of COP for small-scale CTL plant

*NETL, Cost and Performance Baseline for Fossil Energy Plants Vol 4: 2014.
**NETL, Technical and Economic Assessment of Small-Scale Fischer-Tropsch Liquids Facilities, 2007

Task 3 — Development of Primary Reformer Catalyst

- **Developed new-structured catalyst substrate with higher heat transfer**

Conventional catalyst substrate

PX spiral monolith

- **Down-selected suitable catalyst materials**
  - ✓ High methane conversion – PX
  - ✓ Long-term stability – RIT, PX
  - ✓ Coking resistance – PX
  - ✓ Contaminant tolerant – PNNL, PX

Task 3 – Accelerated Stress Test of Primary Reformer Catalyst

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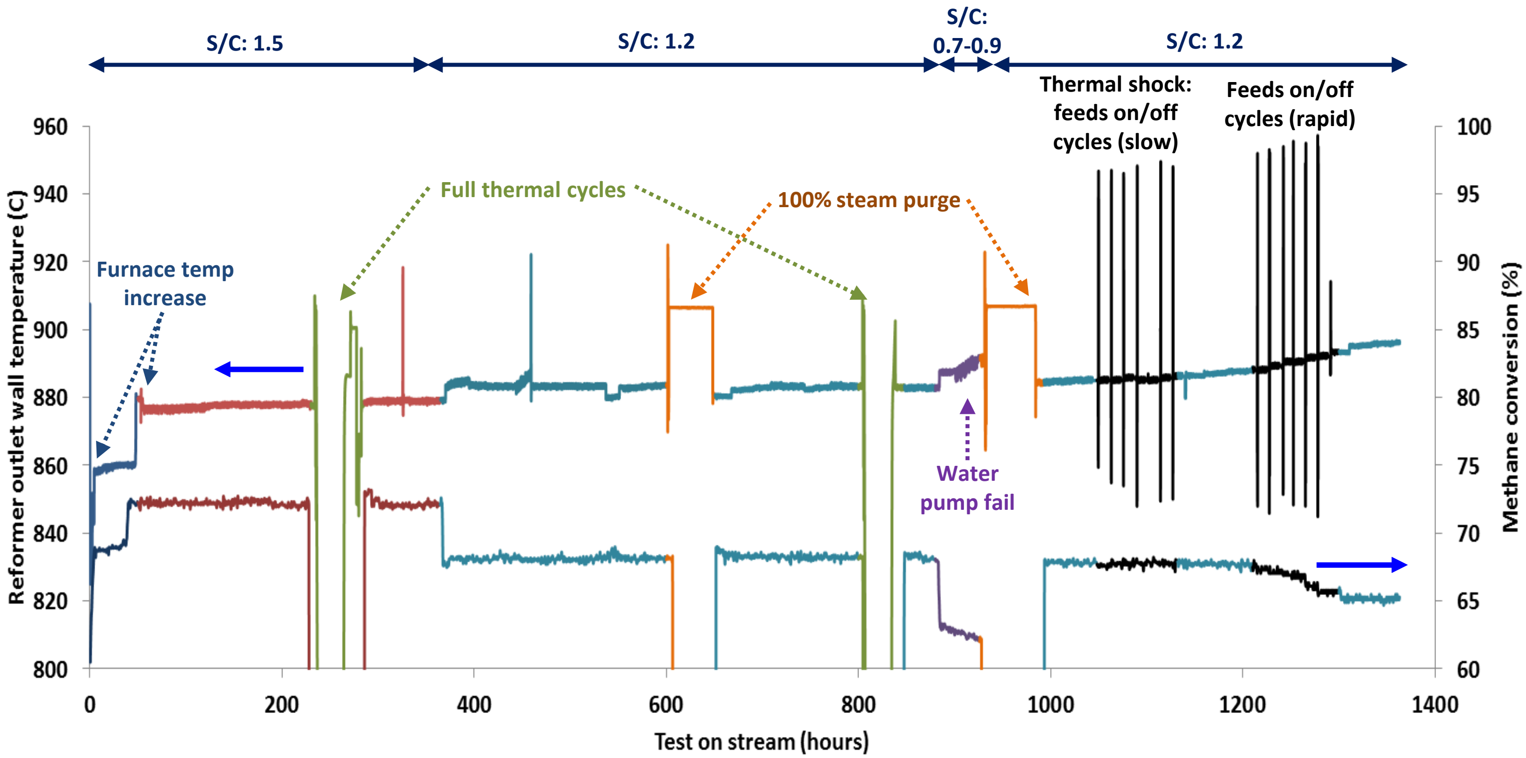

maintain good catalyst coating adhesion

Stable Catalytic Performance of Selected Primary Reformer

Task 3 – Development of OTM Secondary Reformer Catalyst

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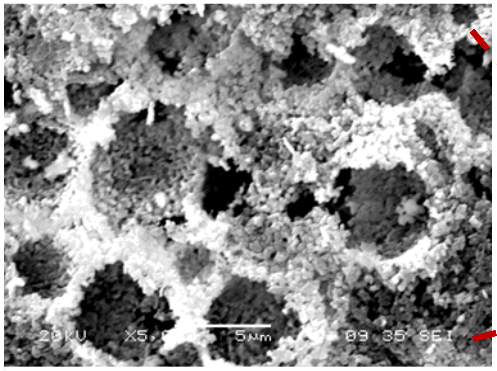
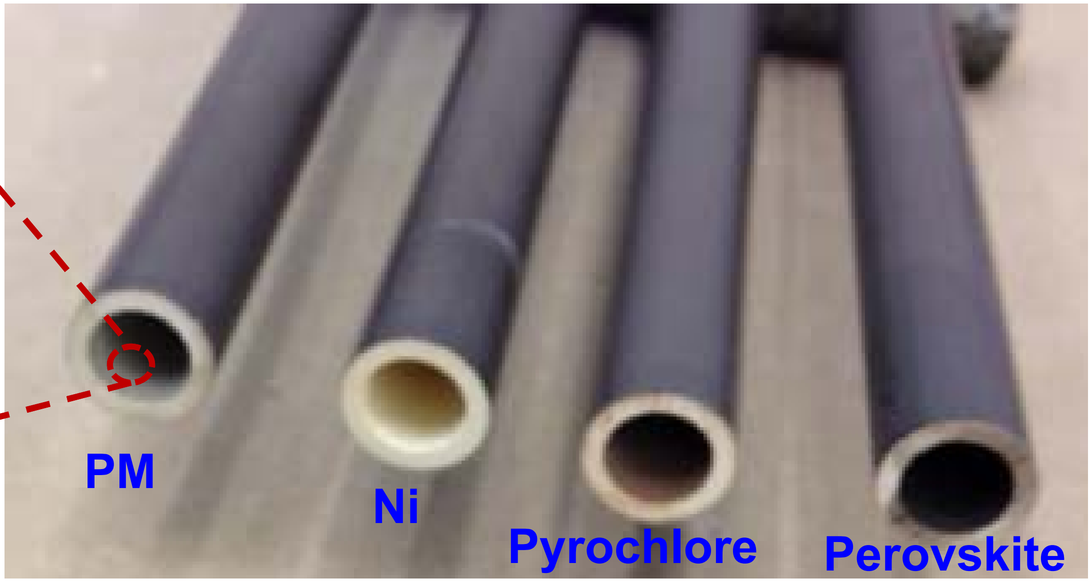
- Developed cost-effective techniques for OTM catalyst integration

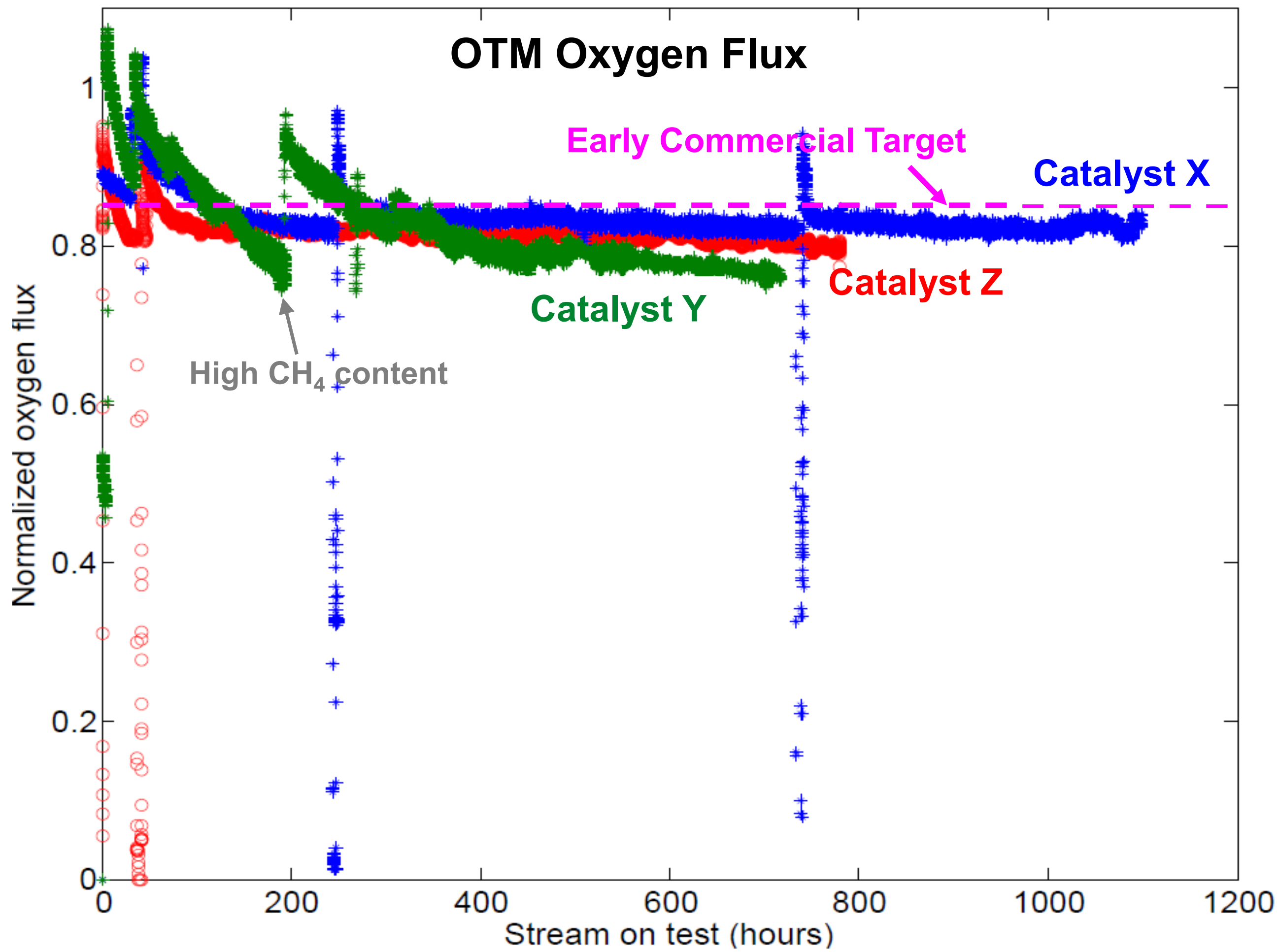


Highly porous structure



- Down-selected suitable catalyst materials
  - ✓ High methane conversion – PX
  - ✓ Long-term stability – PX
  - ✓ Contaminant tolerant – PNNL, PX

Task 3 — Performance of Catalyzed OTM Tube



Stable O_2 Flux and Close Equilibrium CH_4 Conversion with Selected Catalyst

Task 3 – Impact of Coal Syngas Impurities on OTM Reformer

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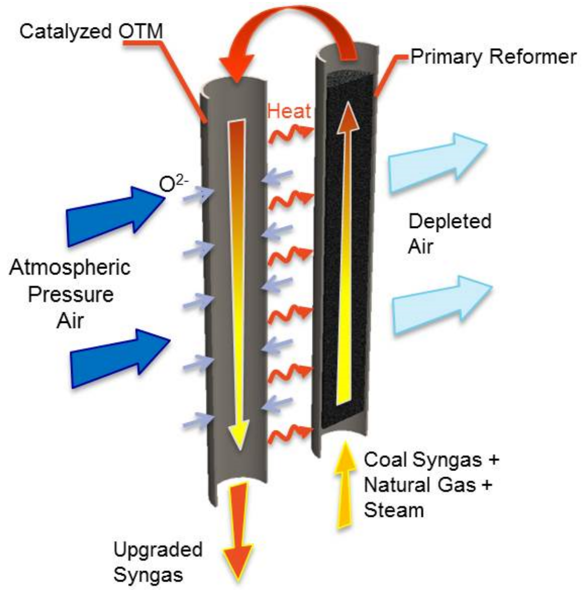
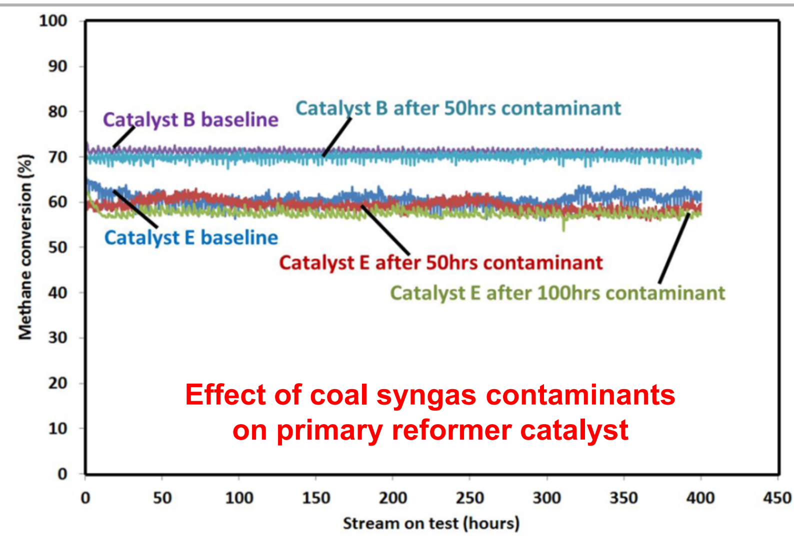
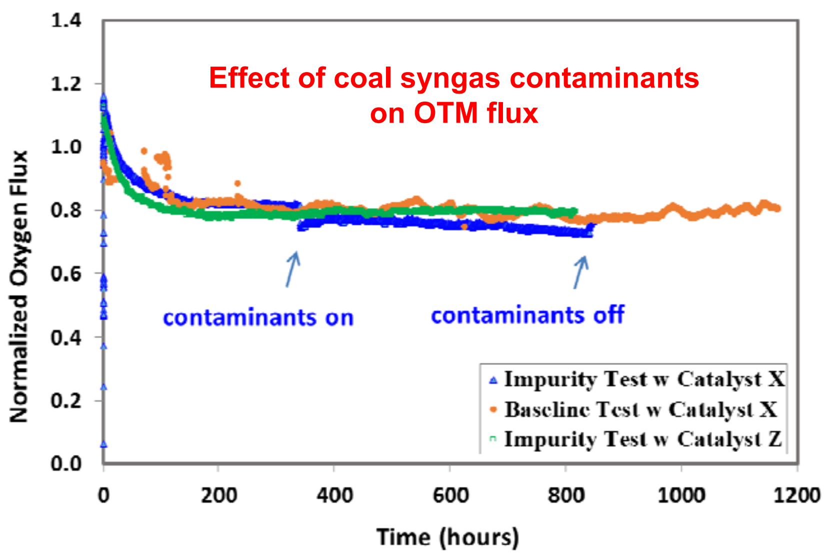




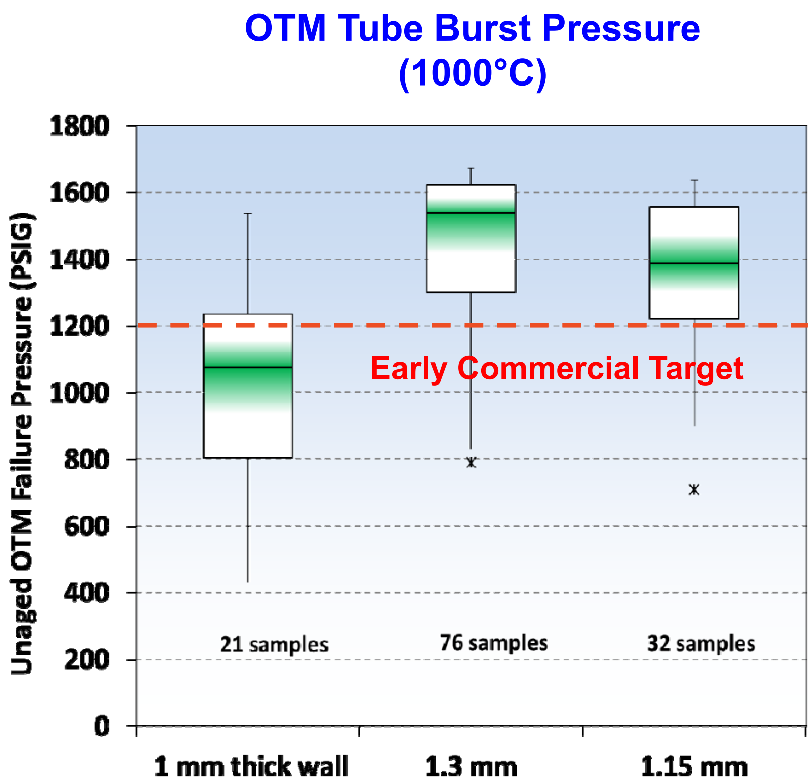
Coal syngas impurity test
(fueled with H_2/N_2/contaminants)

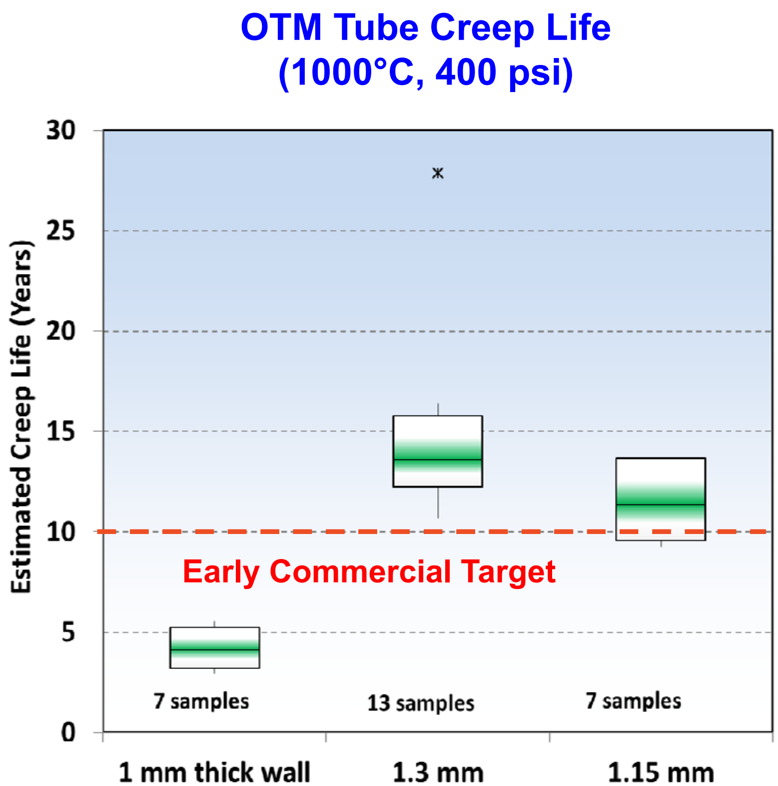
Contaminant	Level (ppm)
Arsine, AsH_3	1
Phosphine, PH_3	1
Hydrogen selenide, H_2Se	1
Hydrogen sulfide, H_2S	2



Low Impact of Coal Syngas Contaminants on Performance

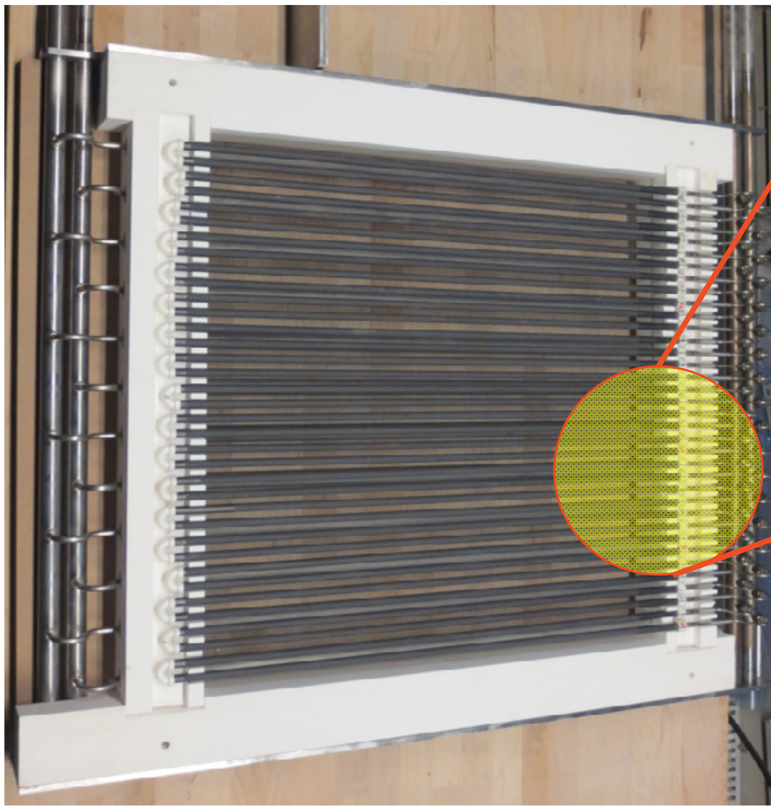
Task 3 – Mechanical Properties for High Pressure Operation

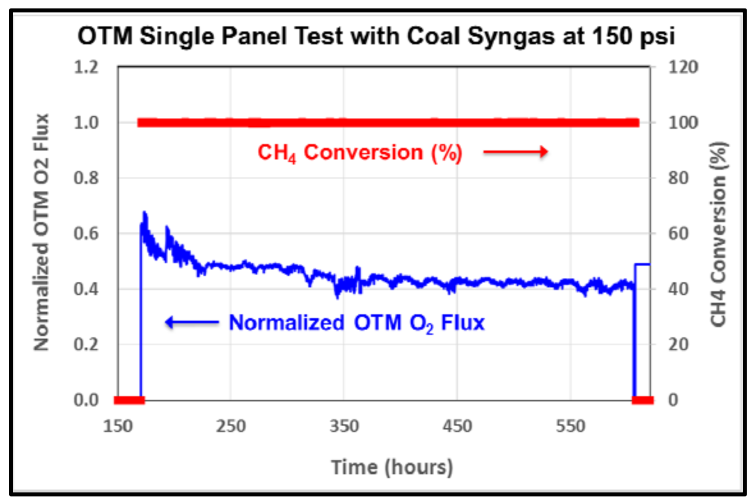




Creep Life and Tube Strength Meet Commercial Targets

Task 4 – OTM Single Panel Test with Coal Syngas





Smooth Operation and High CH_4 Conversion with Coal Syngas

Task 5 – Small Pilot Scale Integration

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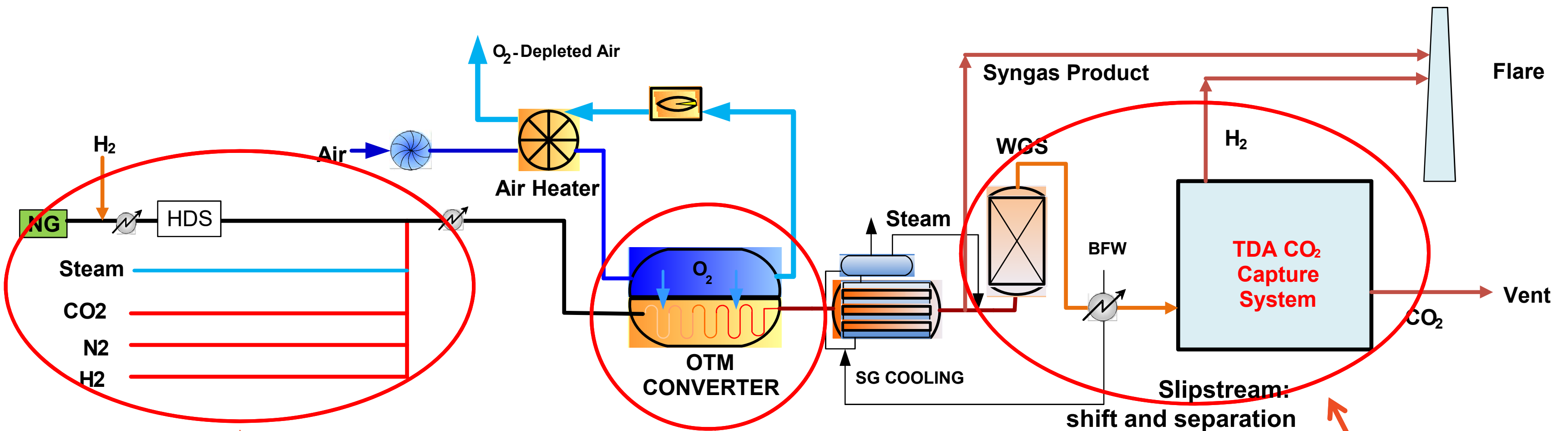

Simulated Coal Syngas

OTM Small Pilot Reactor

TDA Shift/Capture Skid

Task 5 – OTM Small Pilot Reactor

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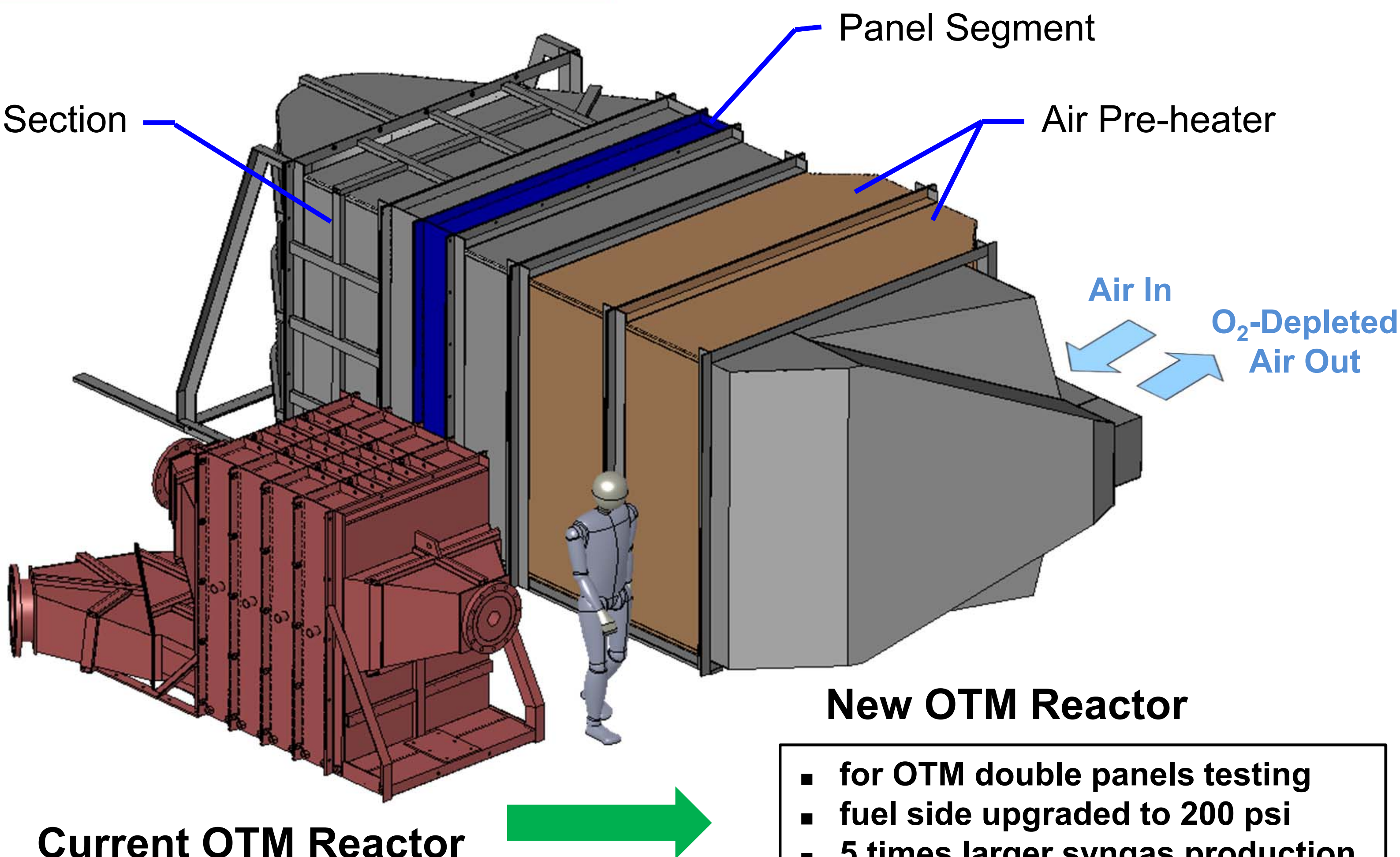

- for OTM double panels testing
- fuel side upgraded to 200 psi
- 5 times larger syngas production
- 10 times higher process air flow

Larger Operation Capacity to Support OTM Double Panel Test

Task 5 – OTM Small Pilot Scale System

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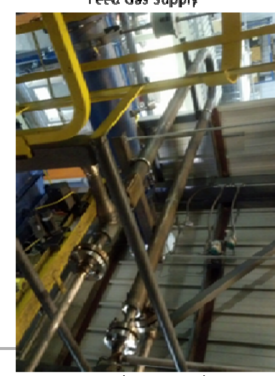
Air Blower

Fuel Side Upgrade

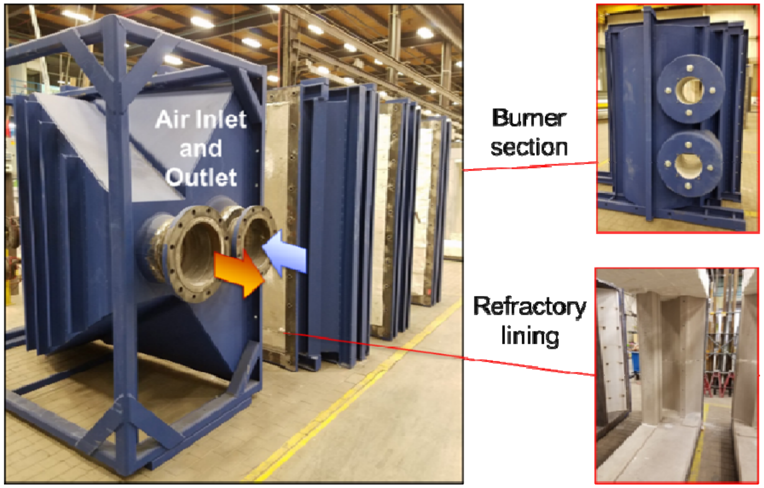
Feed Gas Supply

Process Gas Preheaters and Prereformer



Syngas Cooler Heat Exchanger

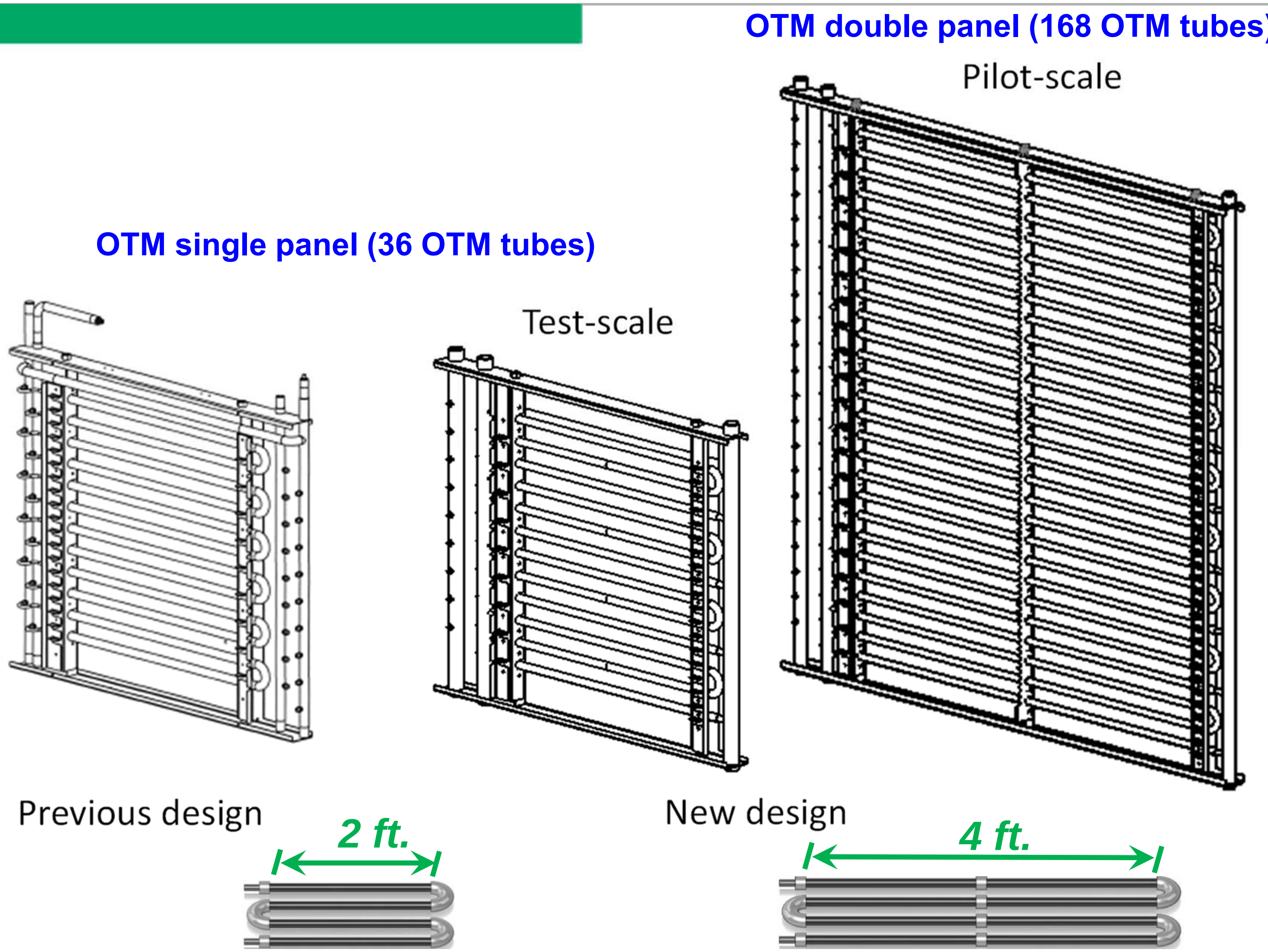
High Pressure Gas-Fired Boiler



New OTM Reactor

Air Burner Skid

Task 5 – OTM Panel Development



Larger Panels through Longer Ceramic Units / More Units

Summary

- OTM Converter Addition to IGCC Plant
  - Improves plant net efficiency and carbon capture rate
  - Reduces cost of electricity and carbon capture cost
- Reformer Catalysts
  - Demonstrated stable performance
  - Demonstrated coal syngas impurity tolerance
- OTM Materials and Seal
  - Demonstrated target flux, burst pressure and creep life
- OTM Panel
  - Demonstrated operation with coal syngas
  - Demonstrated high CH_4 conversion (>99%)
- OTM Small Pilot System
  - Completed design
  - Upgrading existing reactor
  - Will test OTM double panels with TDA CO_2 capture unit in 2017 Q2

Acknowledgements

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Thank you!

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TDA Research

Pacific Northwest NATIONAL LABORATORY

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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

Isolation Valves

Developing hot spot

M-pin isolated after failure

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	06/30/2017	In progress
11	evaluate performance of OTM converter with TDA CO_2 separation system	12/31/2017	In progress