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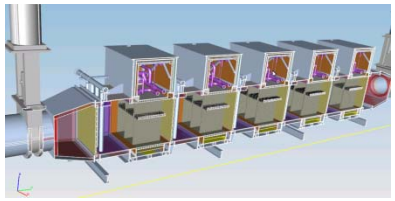

# Praxair's Oxygen Transport Membrane Technology for Syngas and Power Applications

**Juan Li**

**DOE/NETL Gasification and C&CBTL Workshop**

**Morgantown, WV • August 10, 2015**

# Project Overview – OTM for Industrial Applications

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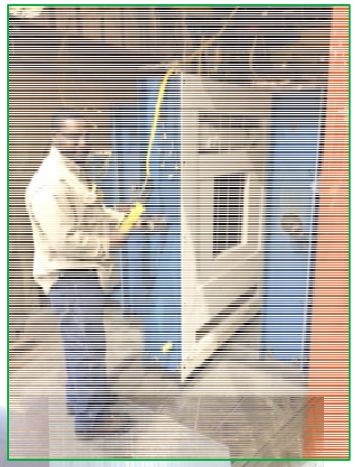
- **OTM for Industrial Applications (ARRA)**

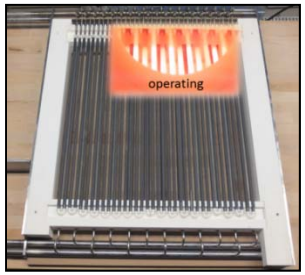
  5 year (2010-2015)

  $55MM, 63% DOE share

— **Project Objectives**

- Develop robust, cost effective membranes
- Develop multi-tube OTM modules
- Demonstrate conversion of NG to syngas with OTM modules
- TEA of NG-fired oxycombustion power cycle with CCS



# Project Overview – OTM-Enhanced Gasification

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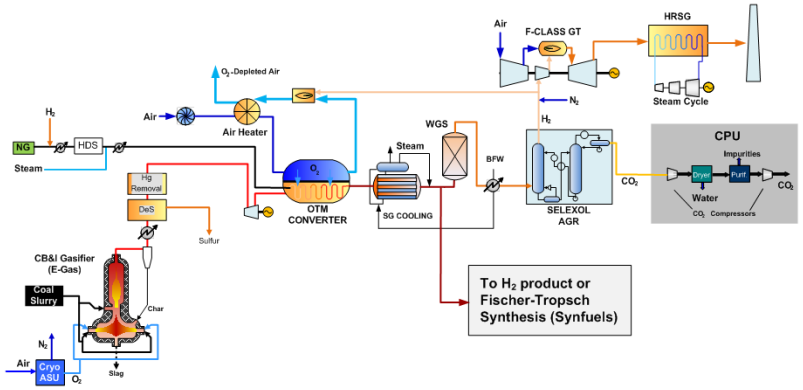
## OTM-Enhanced Coal Syngas for Carbon Capture Power Systems and Fuel Synthesis Applications

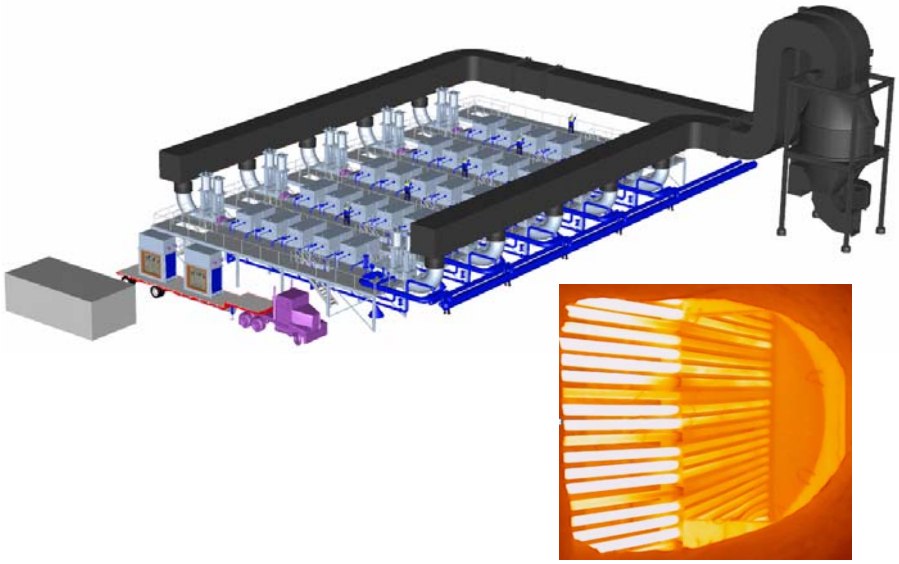
$10MM, 50% DOE share

2 year, Oct. 1 2014 - Sept. 30 2016

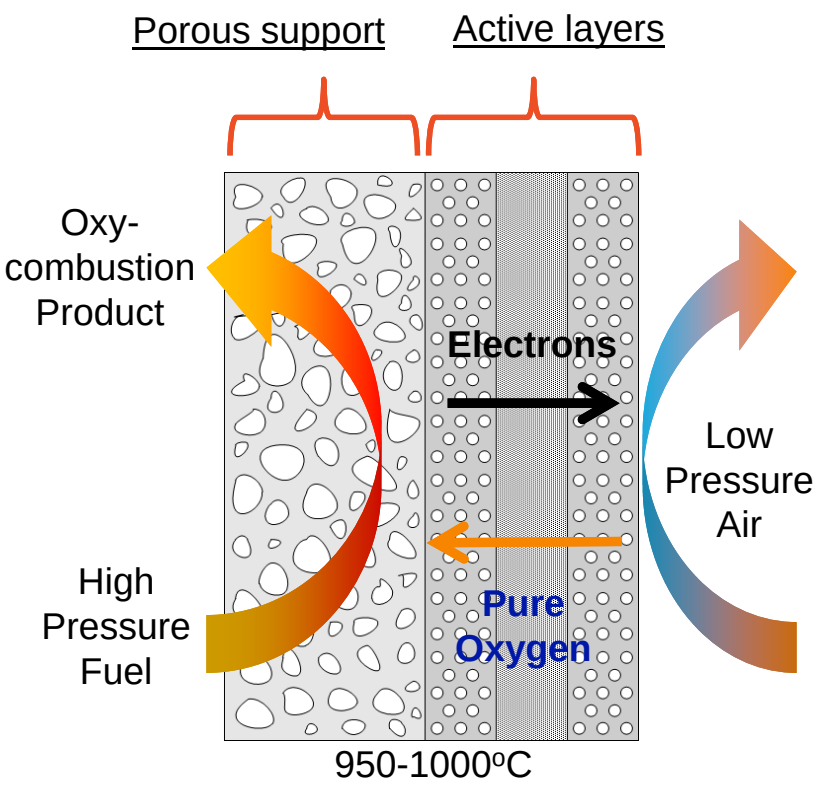
### — Project Objectives

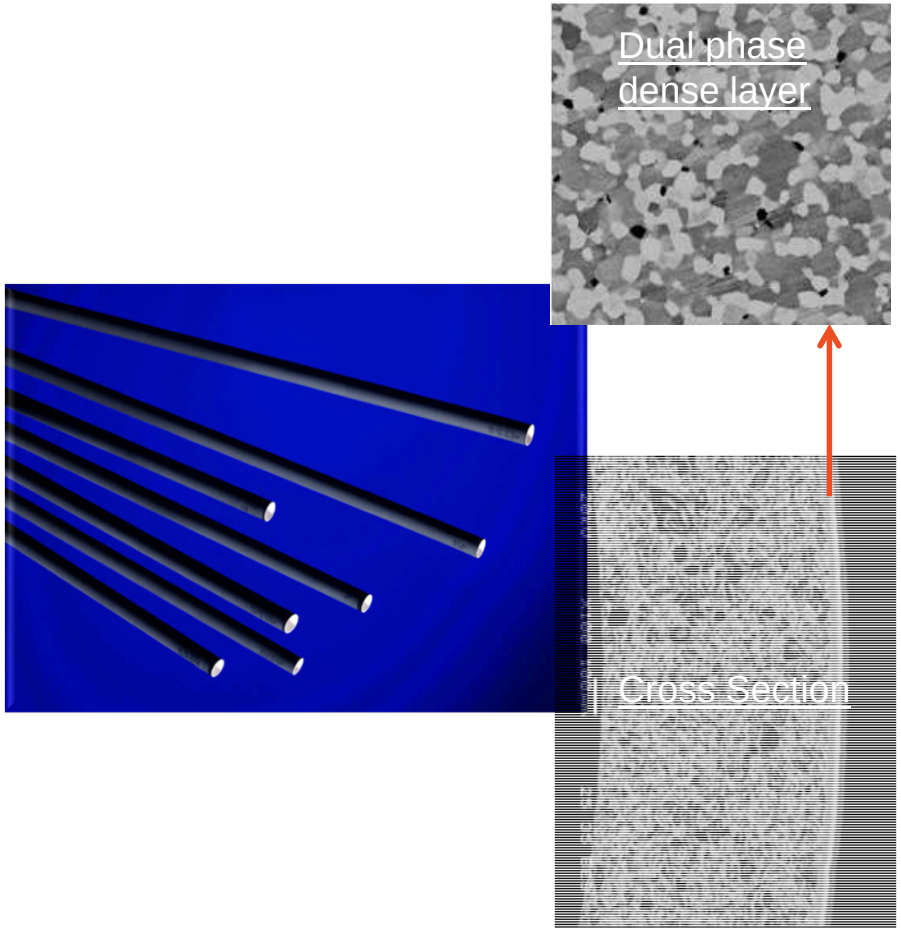
- TEA of OTM-enhanced IG-NGCC process w/$CO_2$ capture
- Develop OTM with integrated catalyst
- Develop OTM supporting layer and ceramic seal for high pressure application
- Develop OTM modules and demonstrate in small-pilot scale test with simulated coal syngas



# Praxair OTM – How it works:




**Combustion-driven air separation at high pressure without ASU and air compression**

# Praxair OTM Syngas Technology

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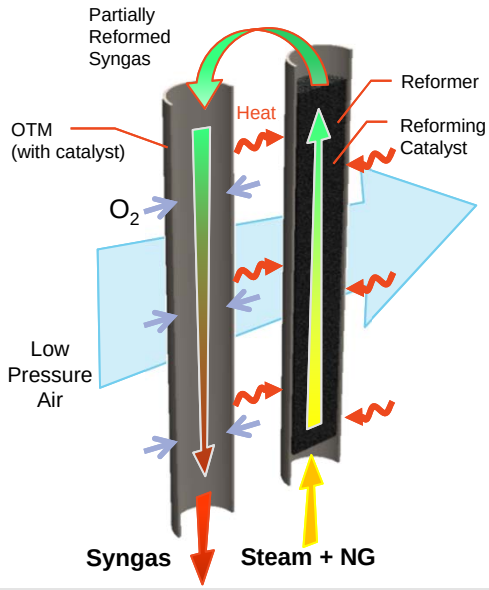
Multi-Process Combined Reforming

**Primary Steam Methane Reformer**

**Secondary AutoThermal Reformer**

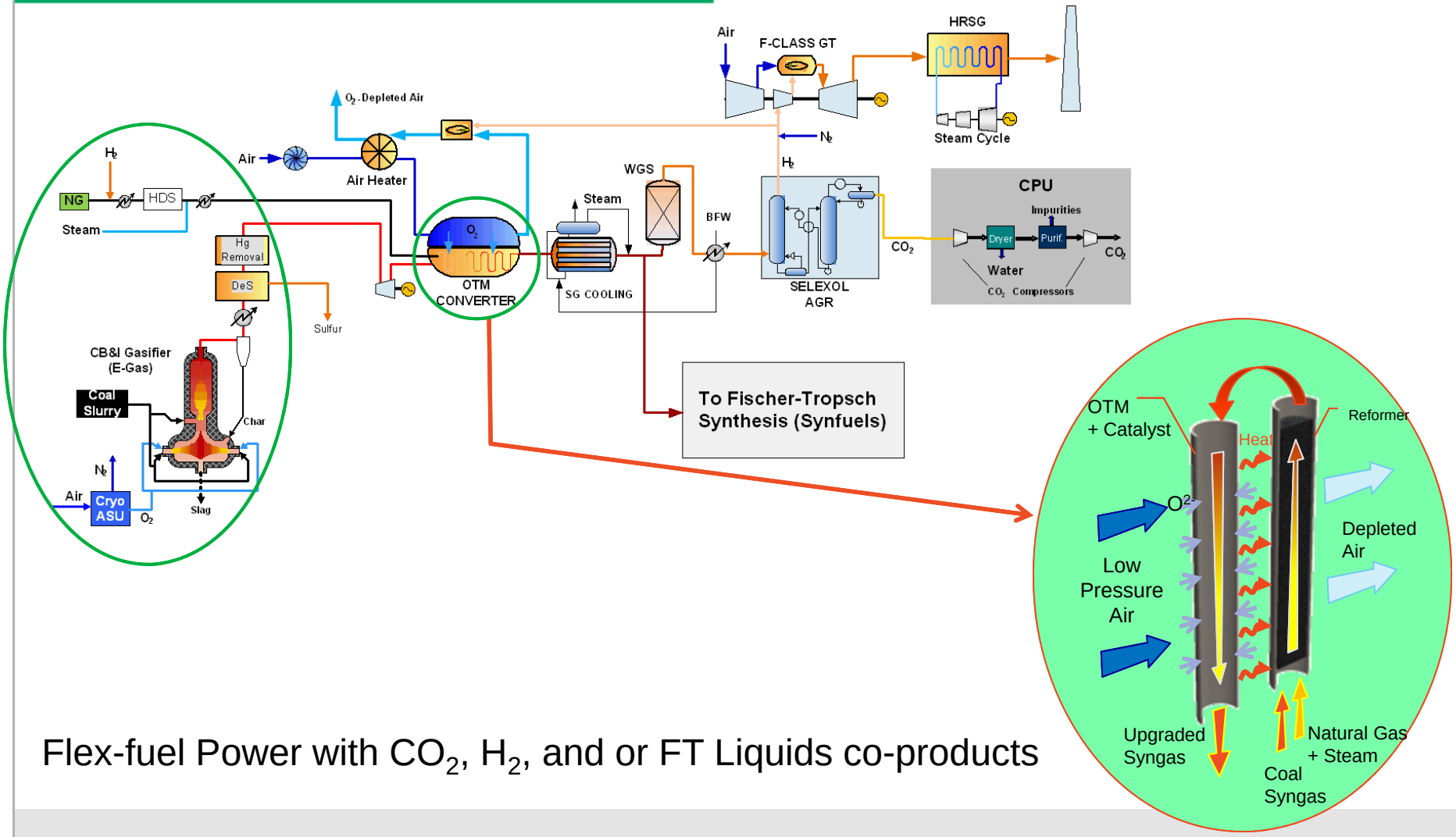
**Air Separation Unit**

Solid state combined reforming with OTM




**Combined reforming in a single integrated efficient package**

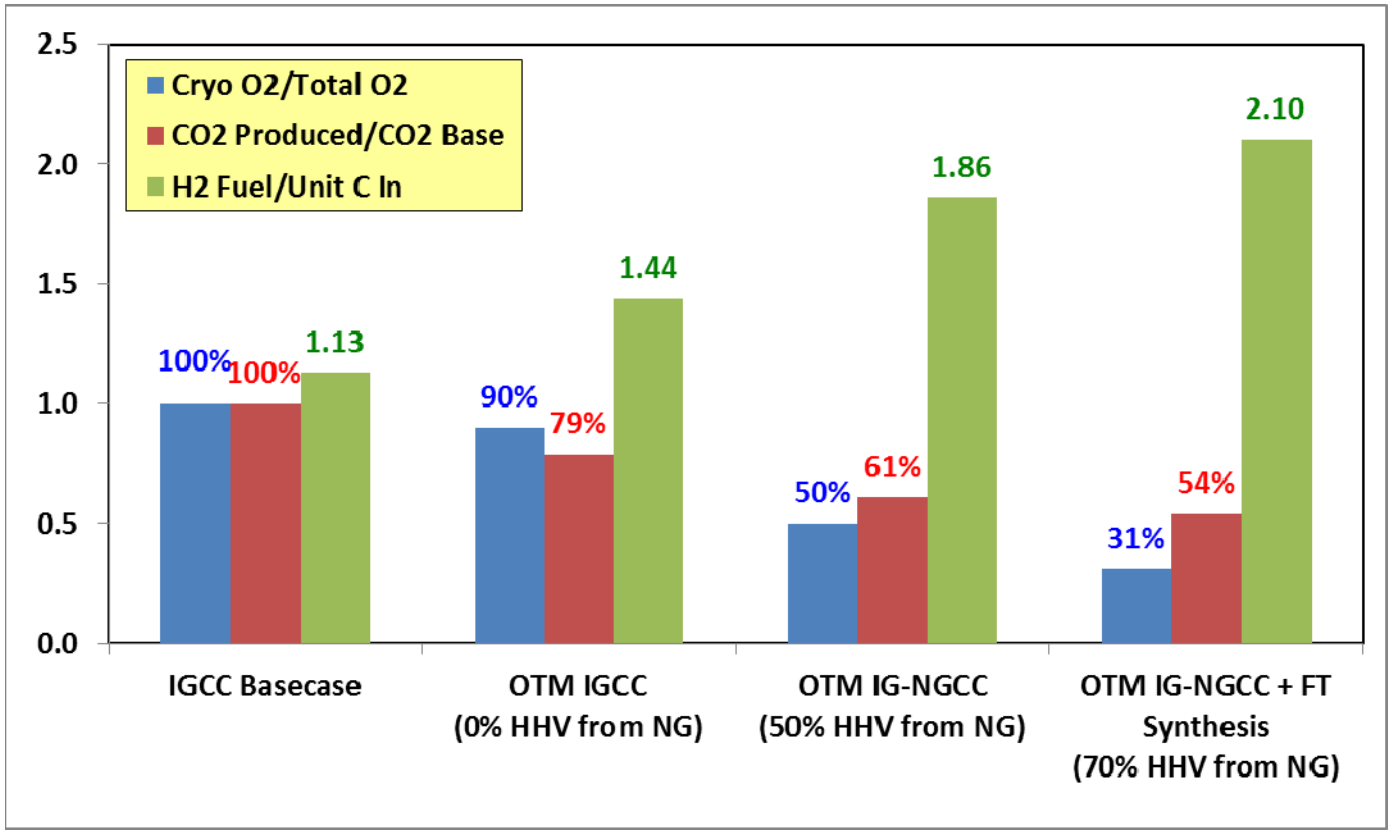
# OTM-Enhanced IG-NGCC Concept (NG+Coal)




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**

# Gasifier Integration Vision




**Benefits of OTM-Enhanced IG-NGCC vs IGCC**

- Smaller cryo ASU
- Reduced carbon footprint
- Improved syngas quality for FT liquids
- Dual plant feedstock
- Increased plant operation flexibility to meet power requirement change

**Synergies in GTCC + Fossil Fuel to Liquids**

# An ARRA Success Story…

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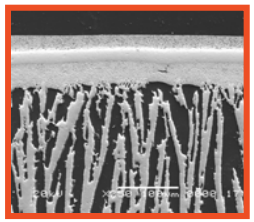
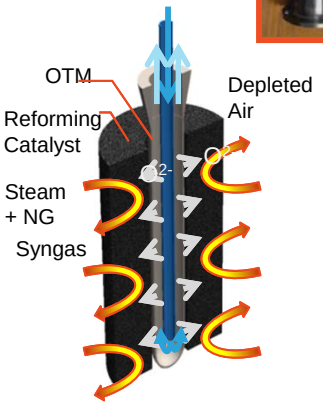
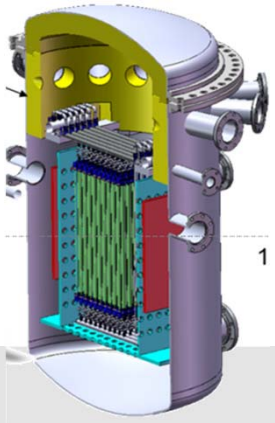
## Early OTM

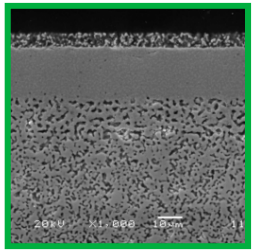




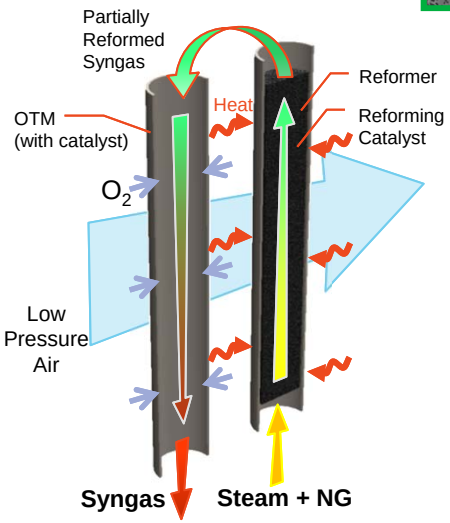

### Membrane

- 2X increase in $O_2$ flux
- 4X increase in creep life
- 10X reduction in degradation



### Process

- Optimal $H_2$/CO ratio
- Higher NG conversion
- Lower $CO_2$ footprint




### System

- Low pressure shell
- Scalable architecture
- Modular construction
- Demonstrated complete syngas island
- Robust operability and control

**Breakthrough innovations on all fronts**

# Test Systems Developed in ARRA Project

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Single Tube Testing → Module Testing → System Testing



### Membranes can deliver requirements of the process

- Flux and fuel conversion demonstrated
- >42,000 hrs over 67 tubes
- Focus on Gen 2 membrane characterization at high pressure

### Modules have shown excellent operational flexibility

- 17 Modules tested (>370 OTM tubes)
- More than 8,000 hrs of flux testing
- >40 module thermal cycles
- Ceramics robust to thermal and chemical cycling

### Successful multi-module syngas production

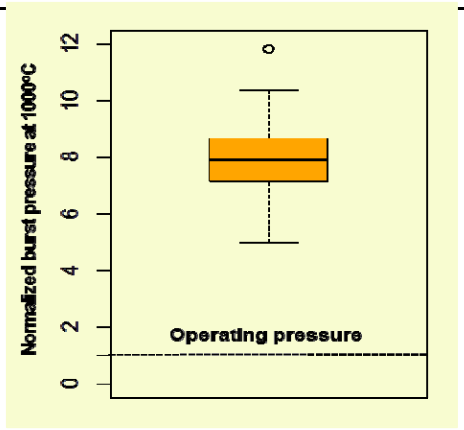
- Operating with 6 panel modules (216 OTM tubes)
- Representative commercial process elements
- Multiple successful heating / cooling cycles
- Capacity up to 190 $Nm^3$/hr syngas

**Successful integration of membranes into systems**

# Technology Development – Seal and Membrane

High temp burst test

Pressure integrity:
> 4X safety factor

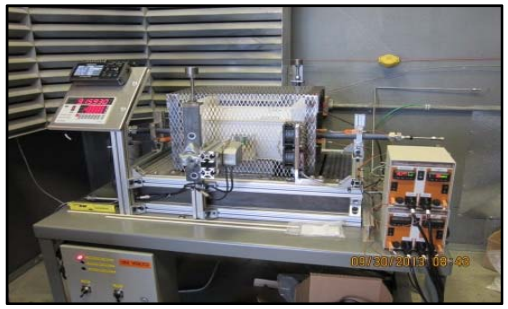




Baseline Aging Test (BAT)

Accelerated life and
reliability testing of tubes &
seals in progress

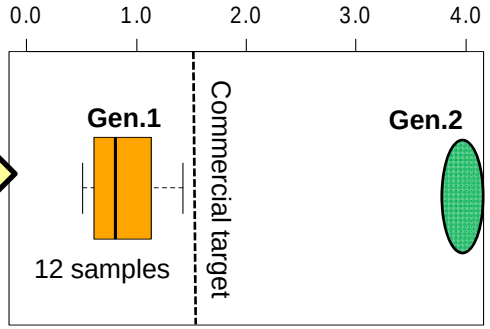
| | Run time, hrs | Thermal cycles | Failures |
|---|---|---|---|
| BAT # 01 | 16350 | 10 | 0 |
| BAT # 02 | 14400 | 7 | 0 |
| BAT # 03 | 13390 | 8 | 0 |



On-line laser creep test

Creep/reliability test

~4X increase in
OTM creep life



# Integrated Combined Reformer Panel Array

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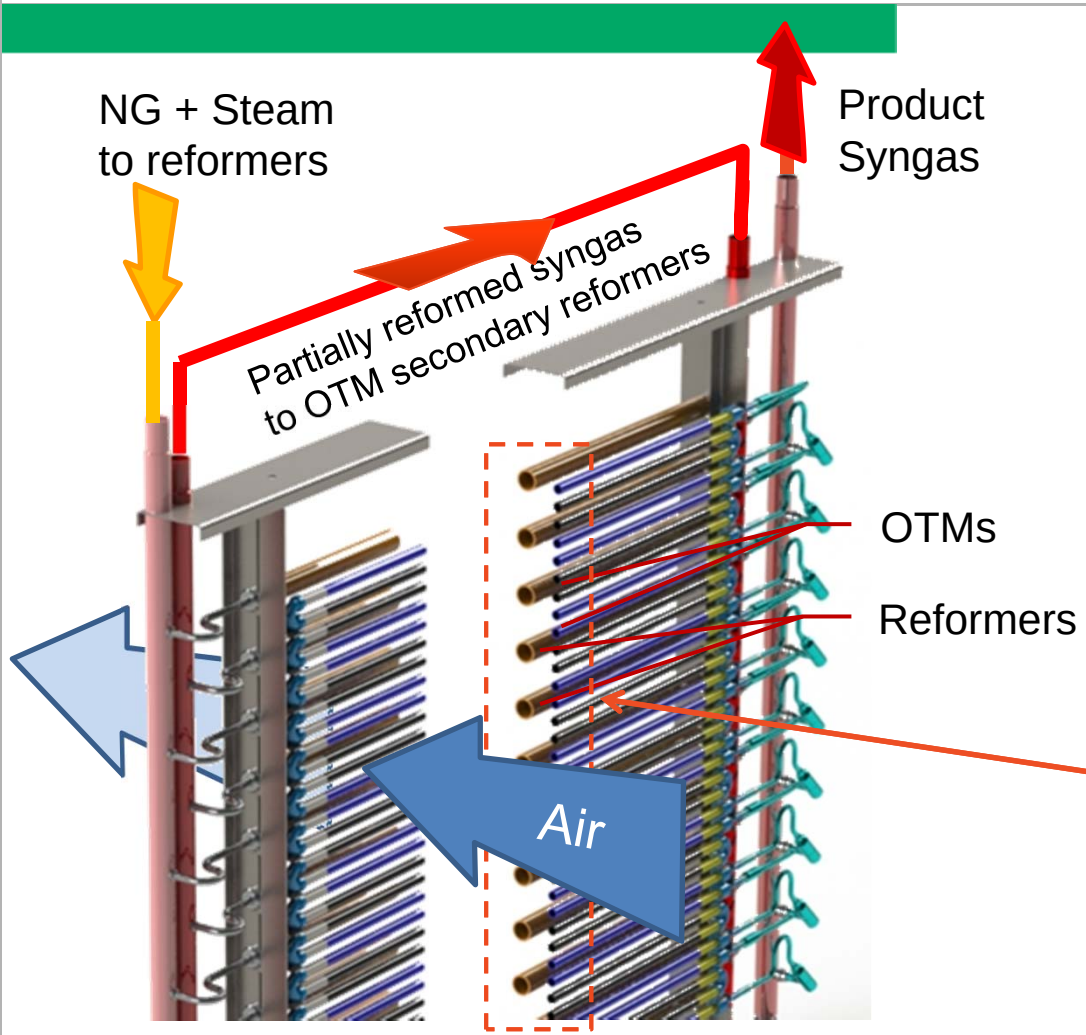
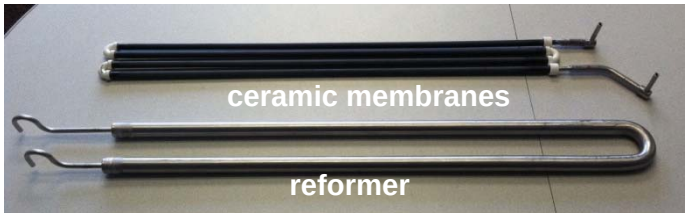
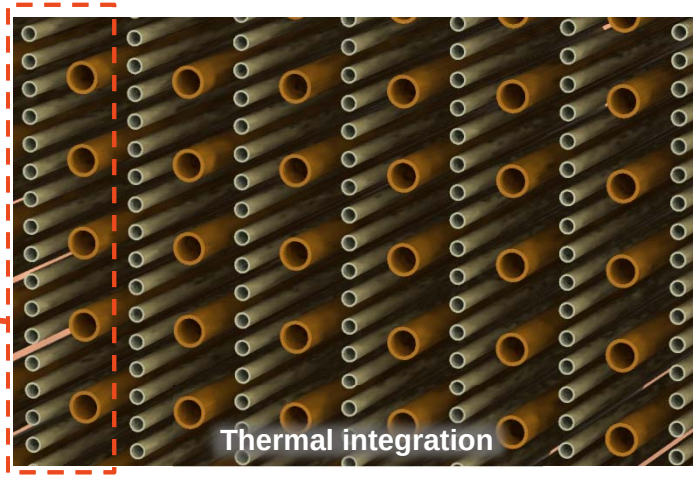


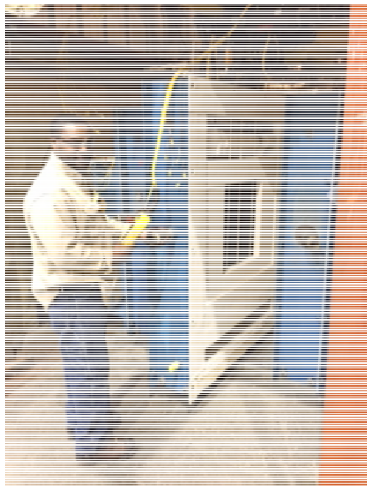



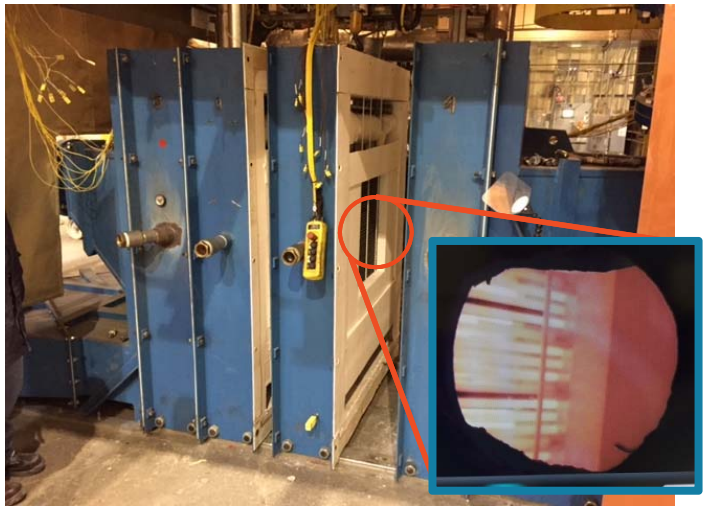




**Combined reforming in a single pass**

# Reliable Operation of Development System

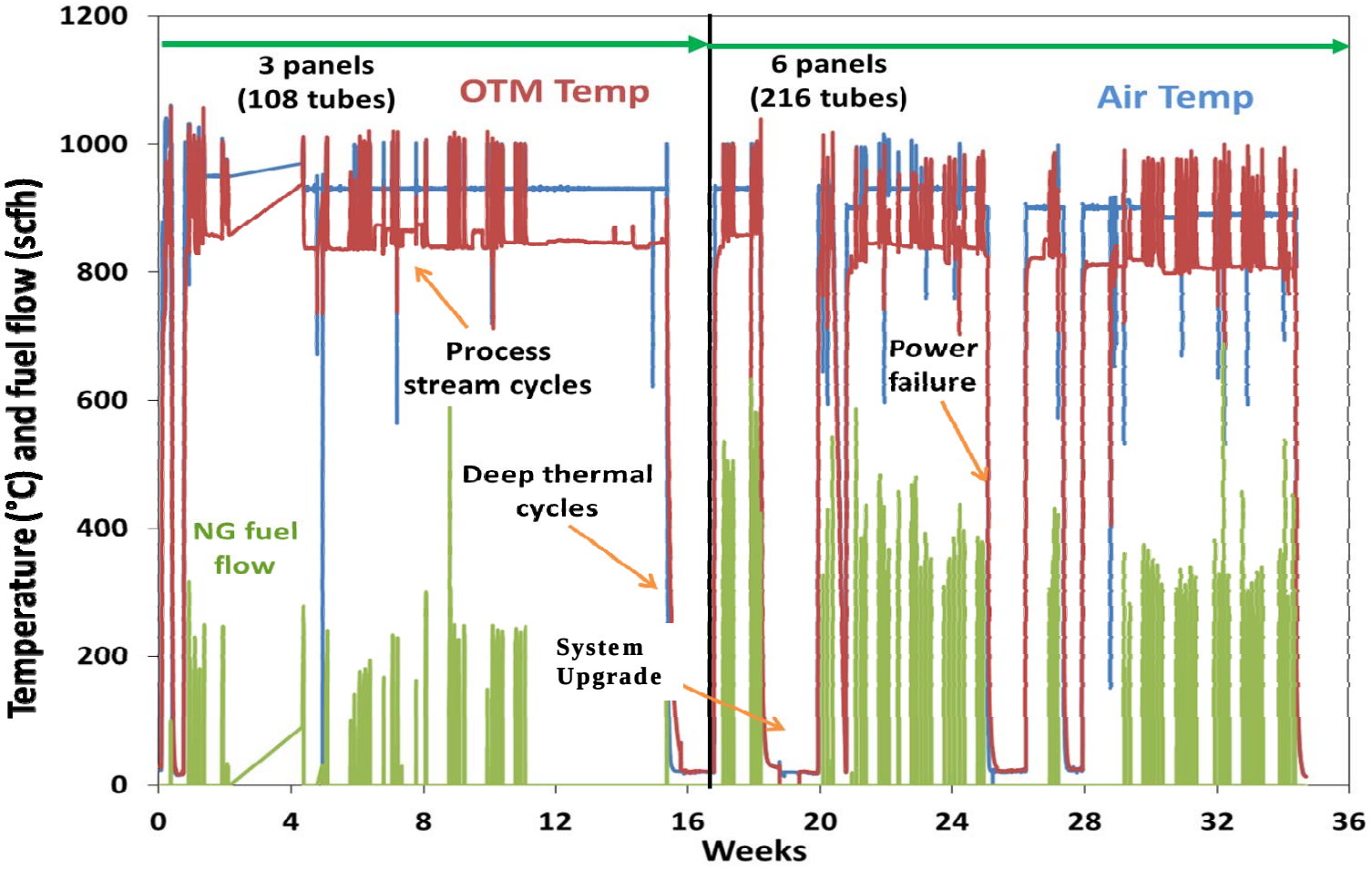
- 6 panel arrays (216 OTM tubes)
- Daily operation since October 2014
- 7 full thermal cycles
- >100 start-up / shut-down cycles





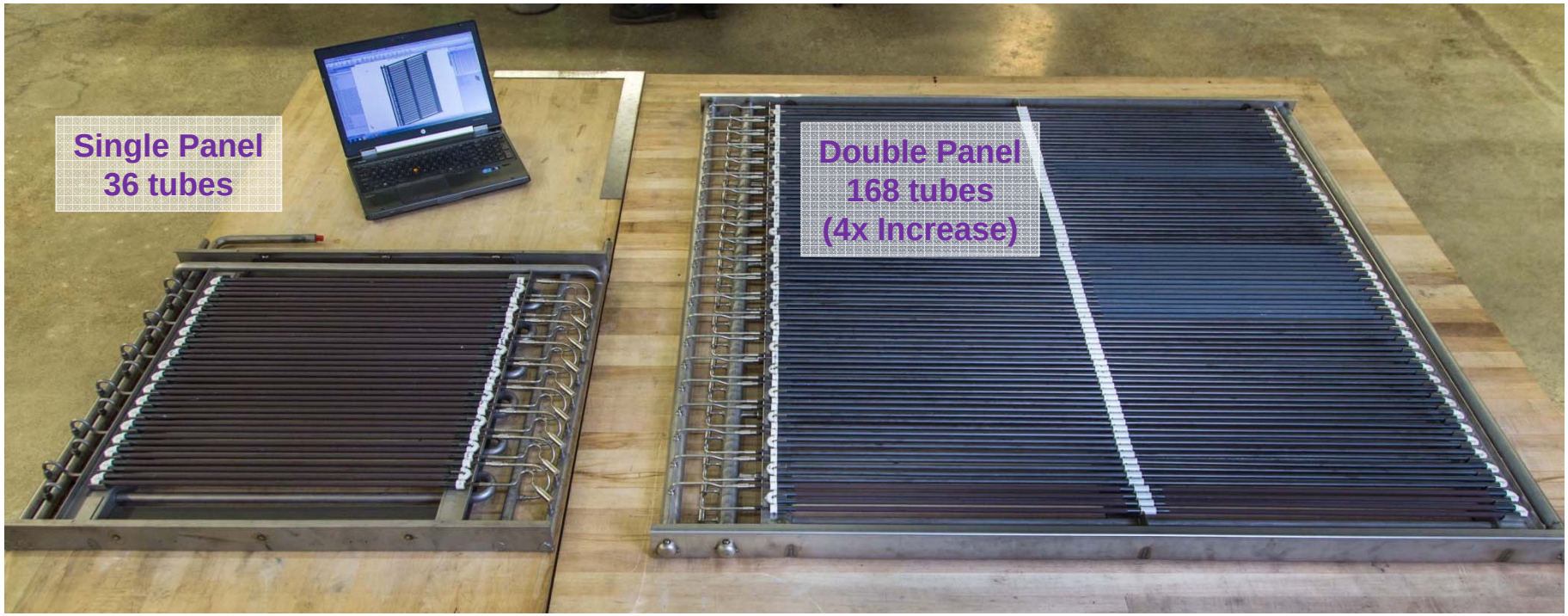
**Technology ready for larger scale demonstration**

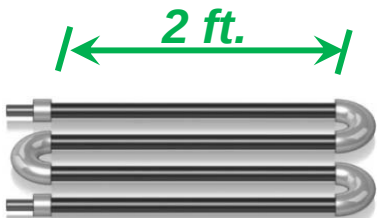
# OTM Development System

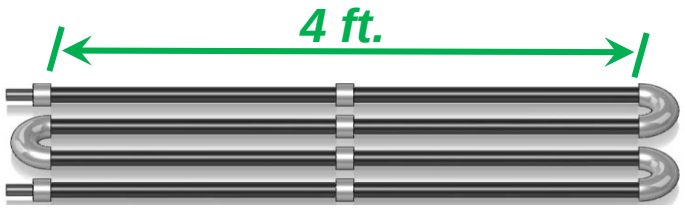



**Panels have operated through multiple thermal, pressure, fuel cycles and shocks**

# Panel Array Scale-up

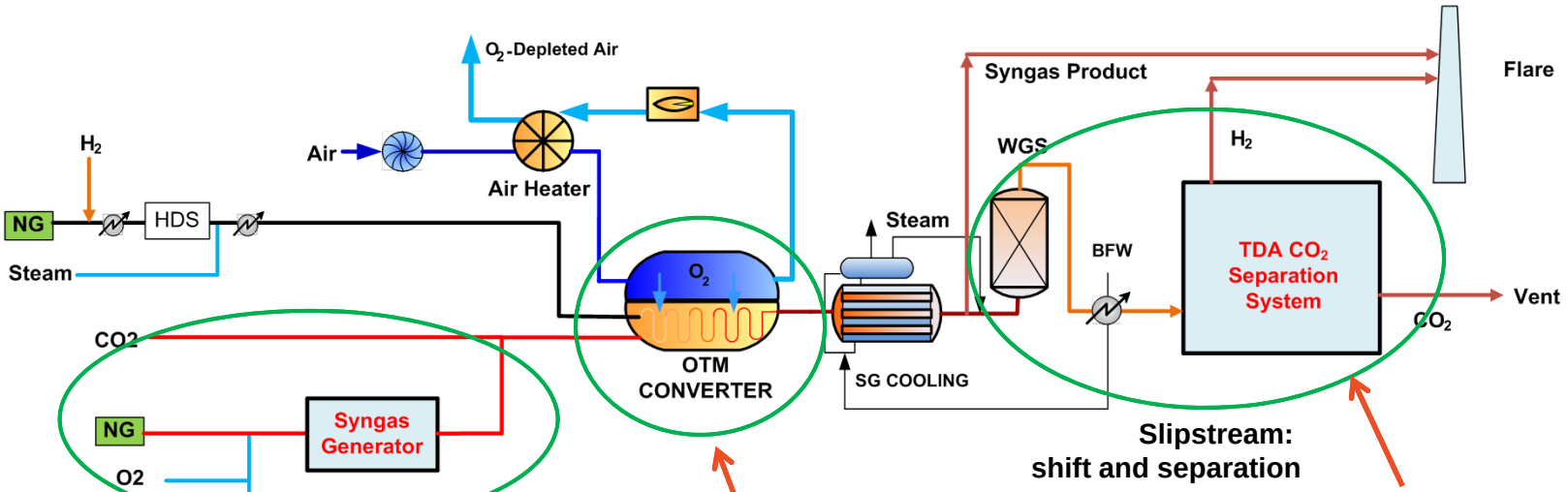



**Larger panels through longer ceramic units / more units**

# Small-Pilot Scale Integration





PX Syngas Generators (simulate coal syngas)

OTM Syngas Reactor

TDA Shift/Separation Skid

# Summary and Plan

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## Key Result

- Step change in membrane materials and mfg. process
- OTM and seals robust to pressure and thermal cycles
- Demonstrated process to make syngas with ceramic membranes
- Module design to achieve thermal integration and facilitate scale-up
- Compelling economics for chemicals synthesis and power w/CCS applications

## Next Step

- Process simulation and TEA of OTM-enhanced IG-NGCC process
- Development of OTM with integrated catalyst for coal syngas and high pressure operation
- Small-pilot scale test of OTM converter with TDA's WGS/$CO_2$ separation equipment

# Acknowledgements

This material is based upon work supported by the Department of Energy under Award Number DE-FE26-07NT43088 and DE-FE0023543. Neither the United States Government nor any agency thereof, nor any of their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof. The views and options of authors expressed herein do not necessarily state or reflect those of the United States government or any Agency thereof.

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**Thank you!**