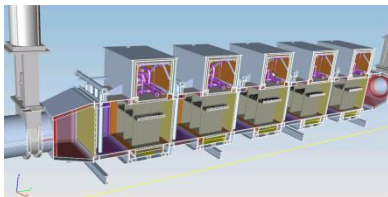


Praxair's Oxygen Transport Membrane Technology for Syngas and Power Applications

Juan Li



DOE/NETL Carbon Capture Meeting
Pittsburgh, PA • June 26, 2015

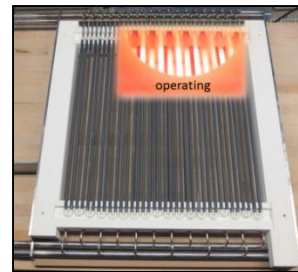
❑ OTM for Industrial Applications (ARRA)

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



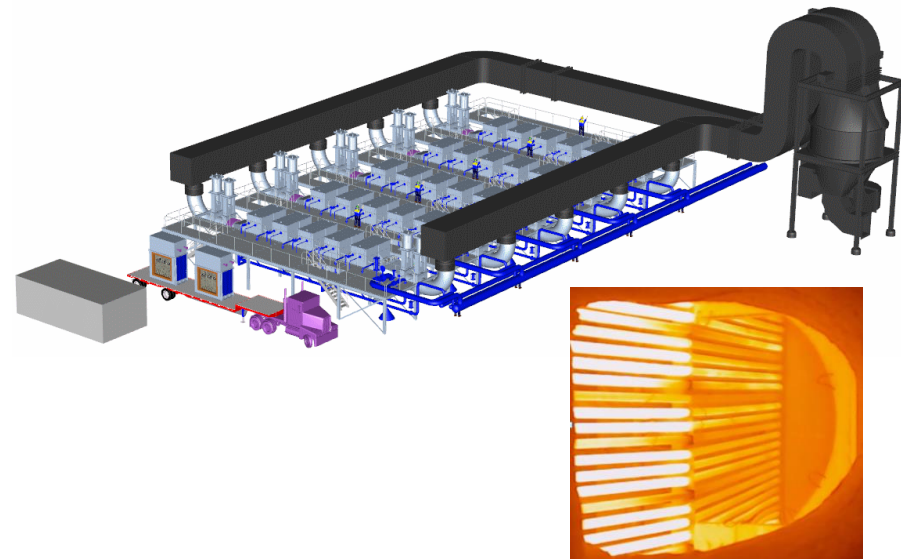
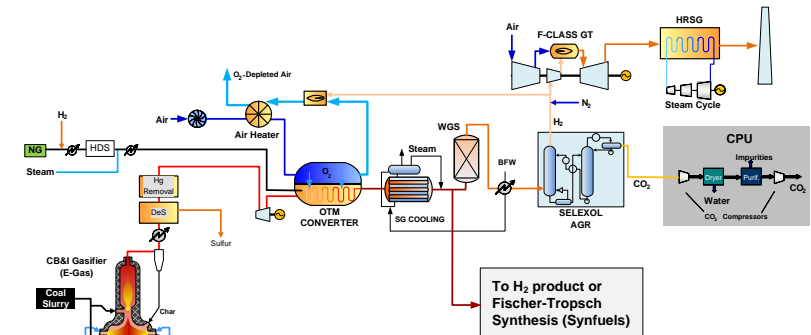
OTM-Enhanced Coal Syngas for Carbon Capture Power Systems and Fuel Synthesis Applications

\$10MM, 50% DOE share

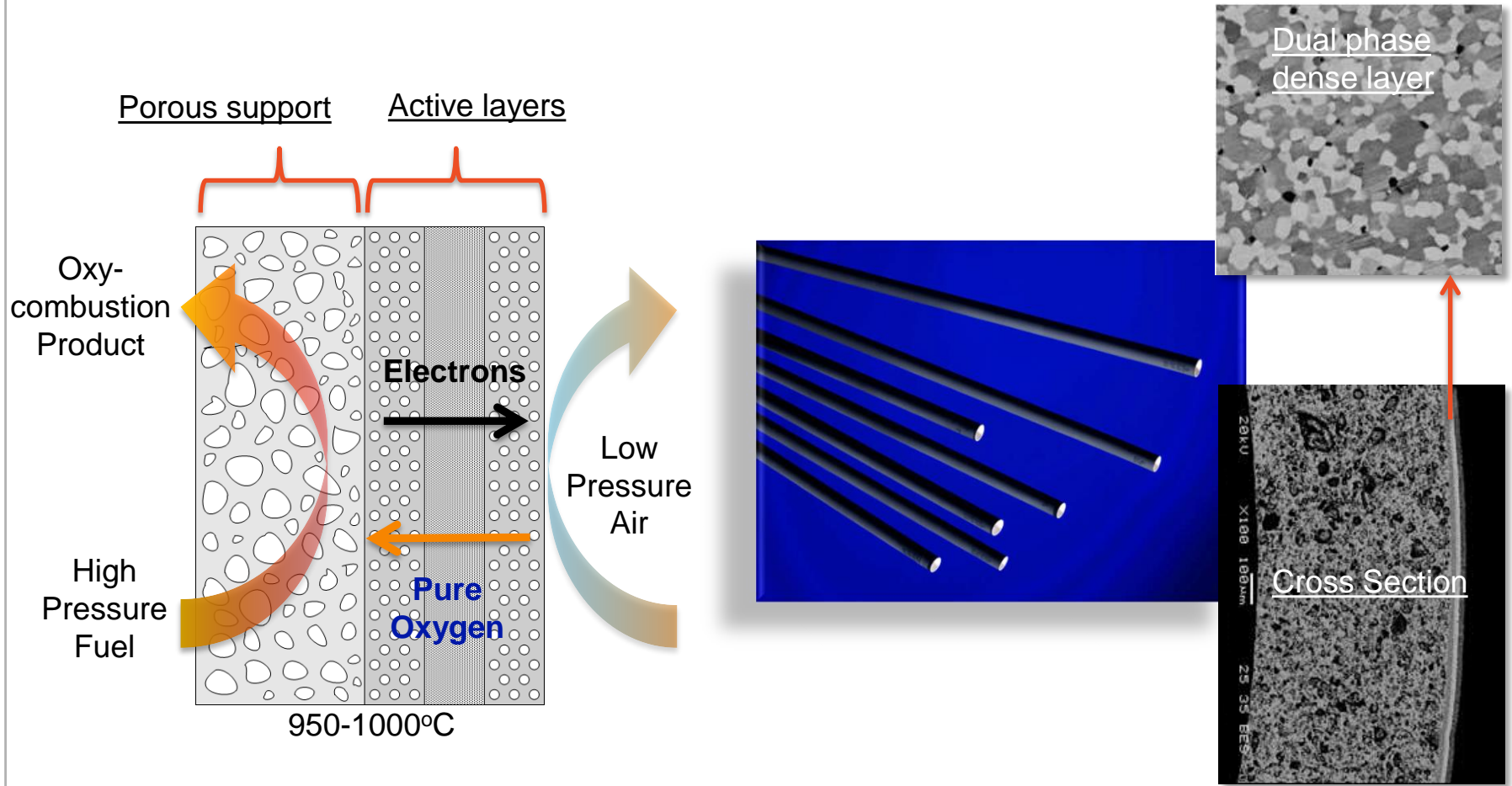
2 year, Oct. 1 2014 - Sept. 30 2016

— Project Objectives

- TEA of OTM-enhanced IG-NGCC process w/CO₂ 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

Multi-Process
Combined
Reforming



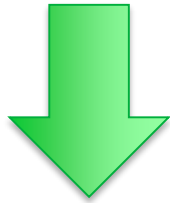
**Primary Steam
Methane Reformer**



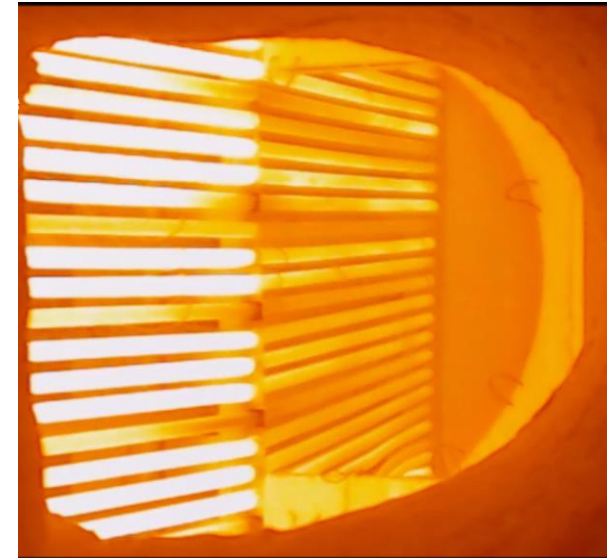
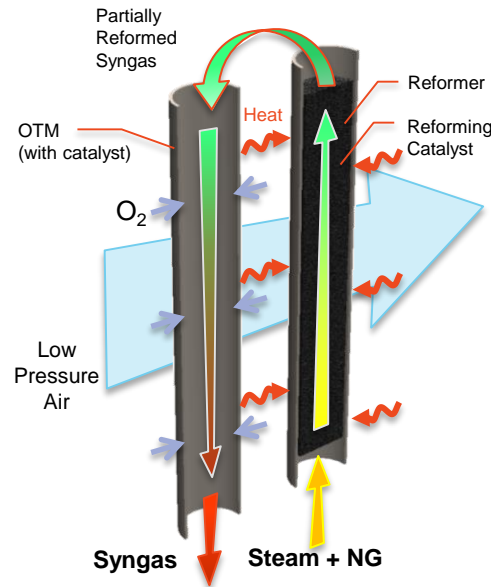
**Secondary AutoThermal
Reformer**



**Air Separation
Unit**

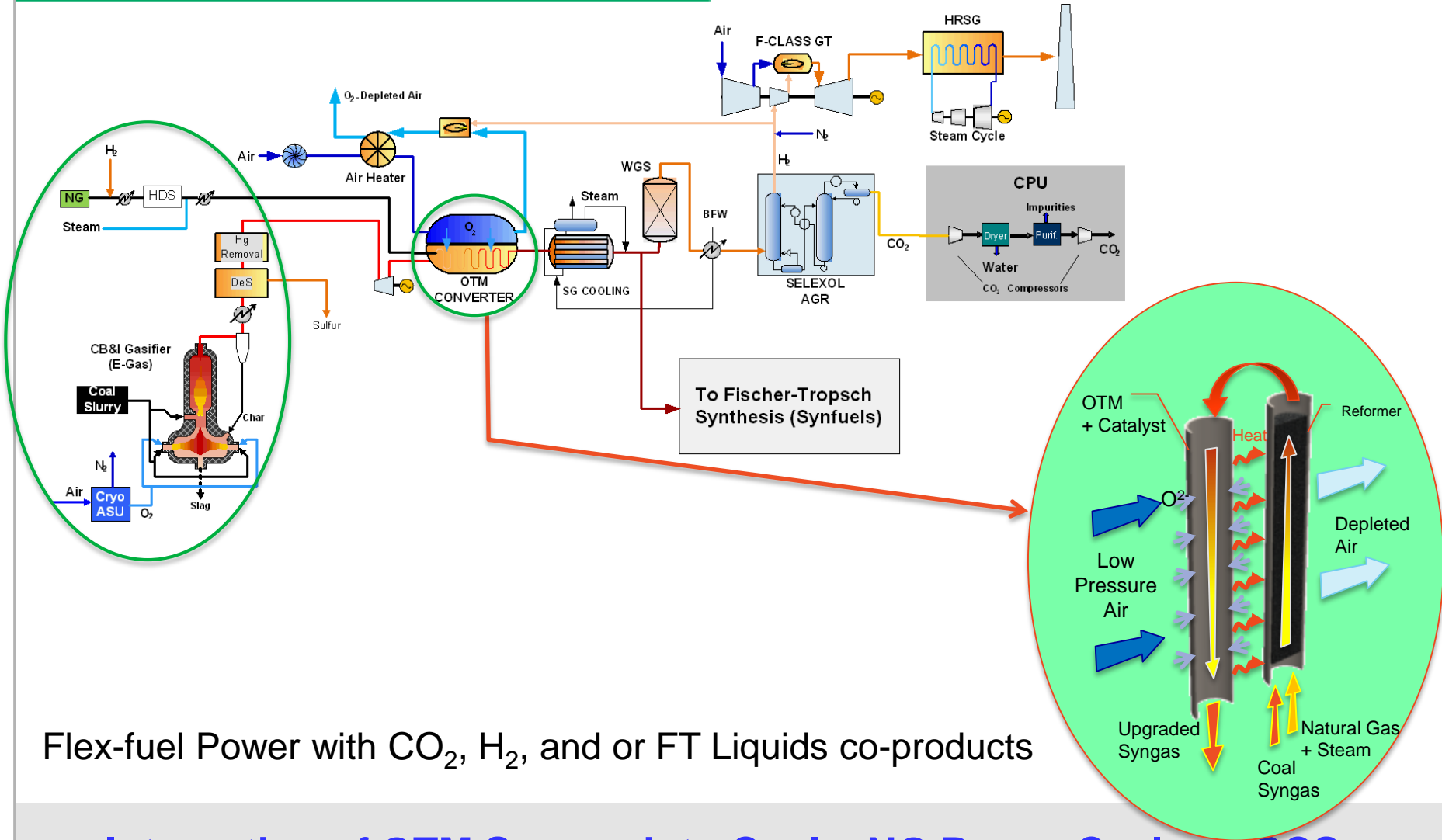


Solid state
combined
reforming with
OTM



Combined reforming in a single integrated efficient package

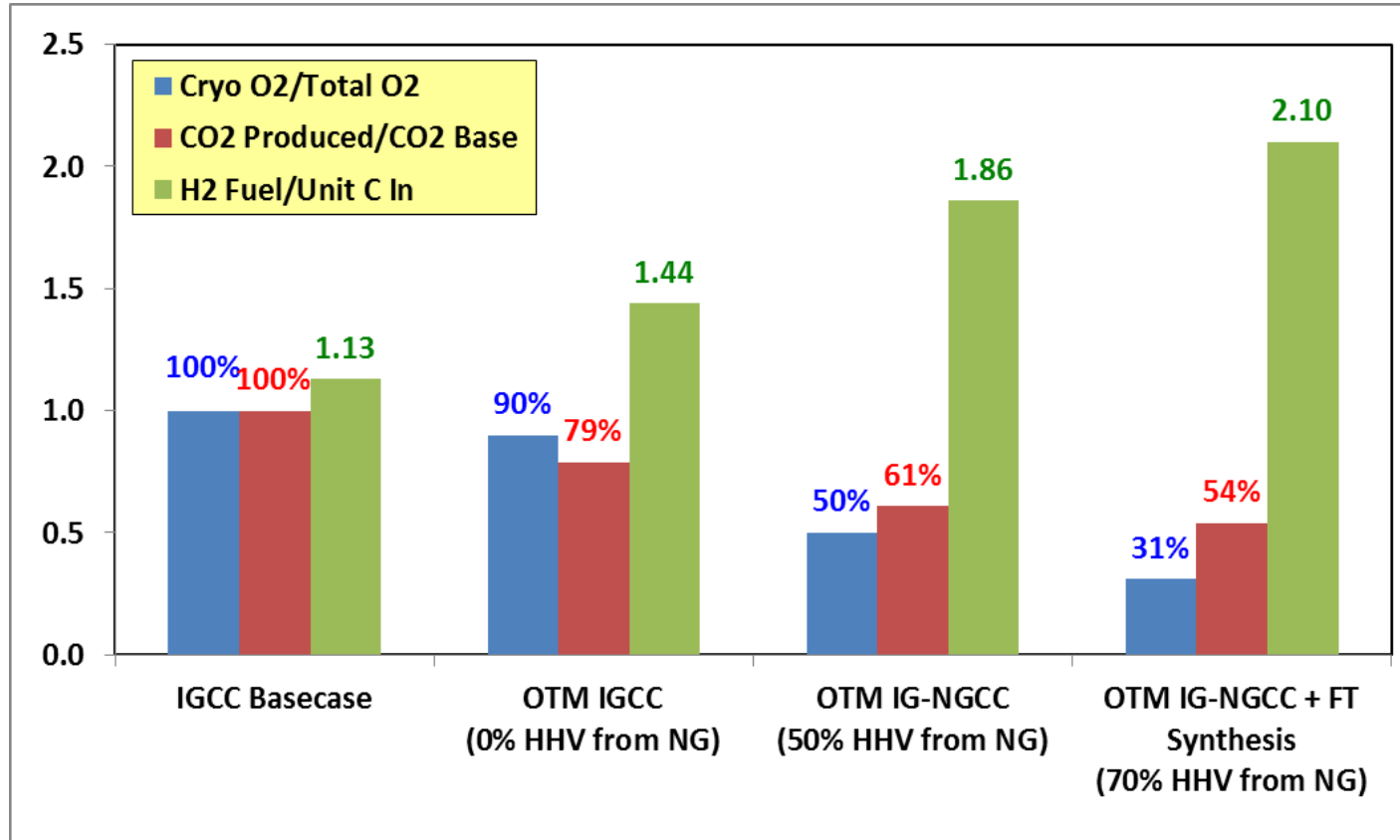
OTM-Enhanced IG-NGCC Concept (NG+Coal)



Flex-fuel Power with CO₂, H₂, and or FT Liquids co-products

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

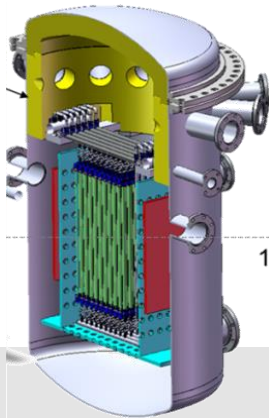
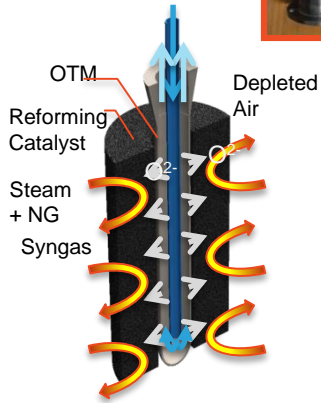
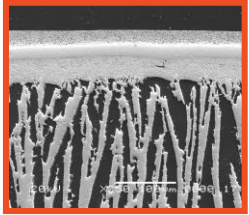
Gasifier Integration Vision



Synergies in GTCC + Fossil Fuel to Liquids

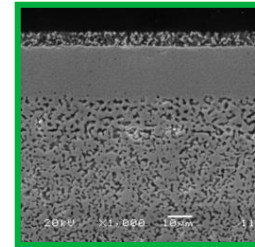
An ARRA Success Story...

Early OTM



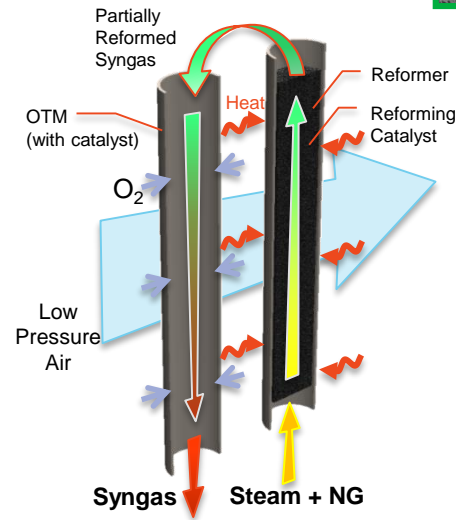
Membrane

- 2X increase in O₂ flux
- 4X increase in creep life
- 10X reduction in degradation



Process

- Optimal H₂/CO ratio
- Higher NG conversion
- Lower CO₂ 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

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 Nm³/hr syngas

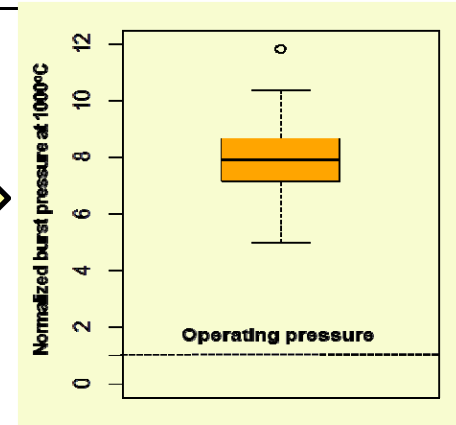
Successful integration of membranes into systems

Technology Development – Seal and Membrane



High temp burst test

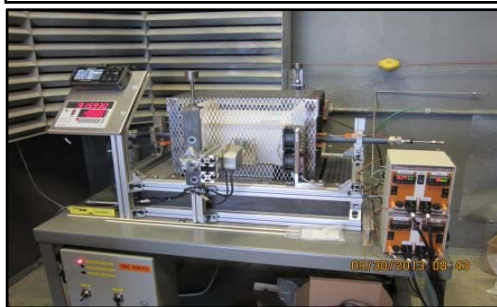
Pressure integrity:
> 4X safety factor



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

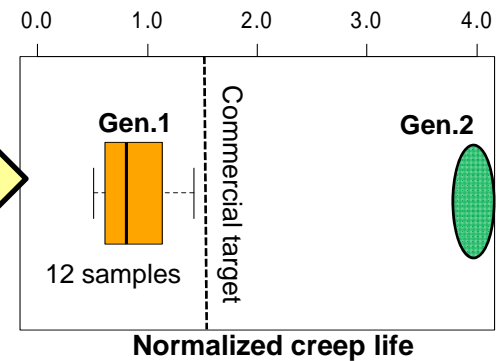


On-line laser creep test

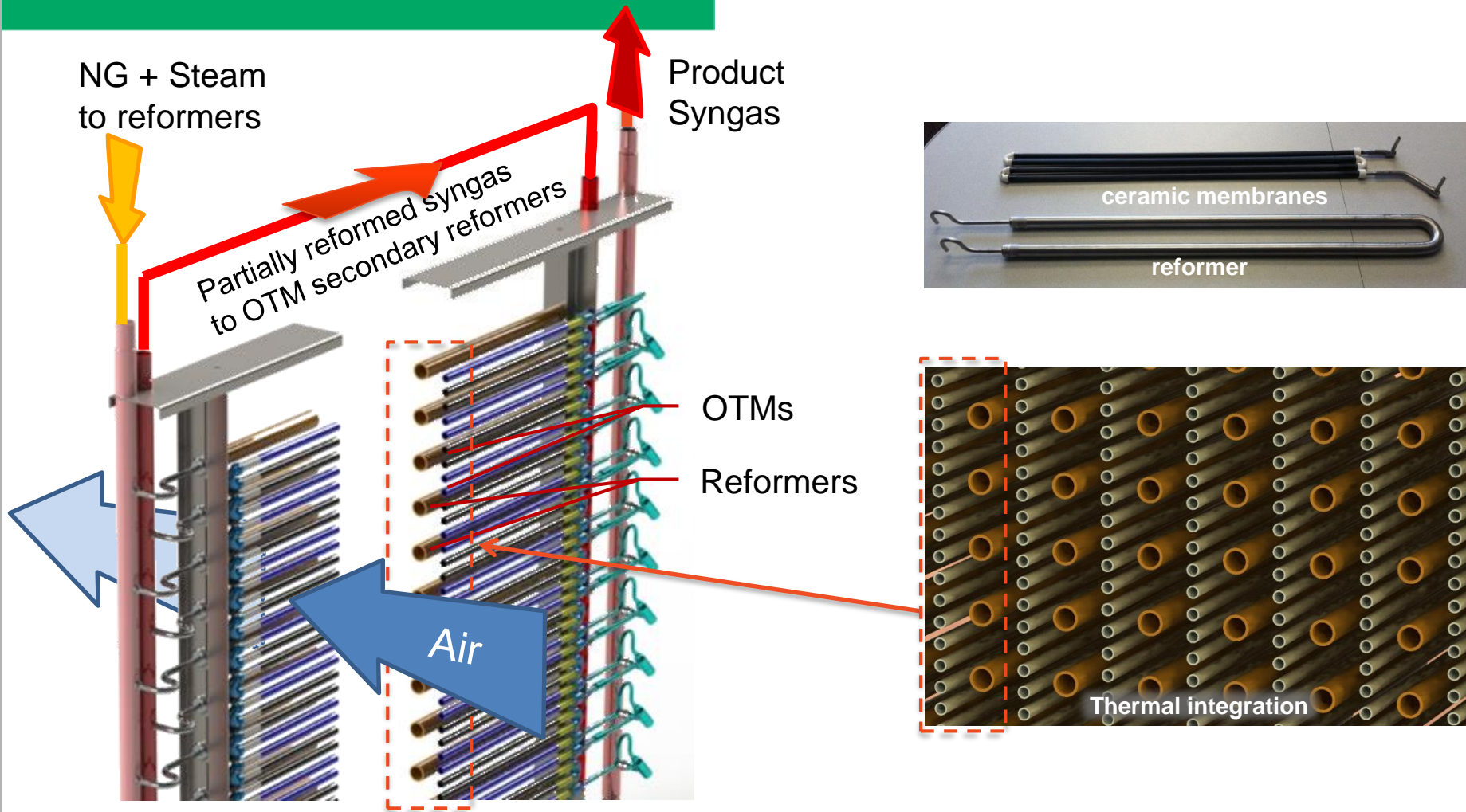


Creep/reliability test

~4X increase in
OTM creep life



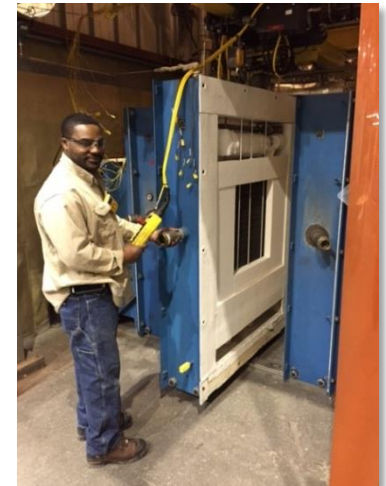
Integrated Combined Reformer Panel Array



Combined reforming in a single pass

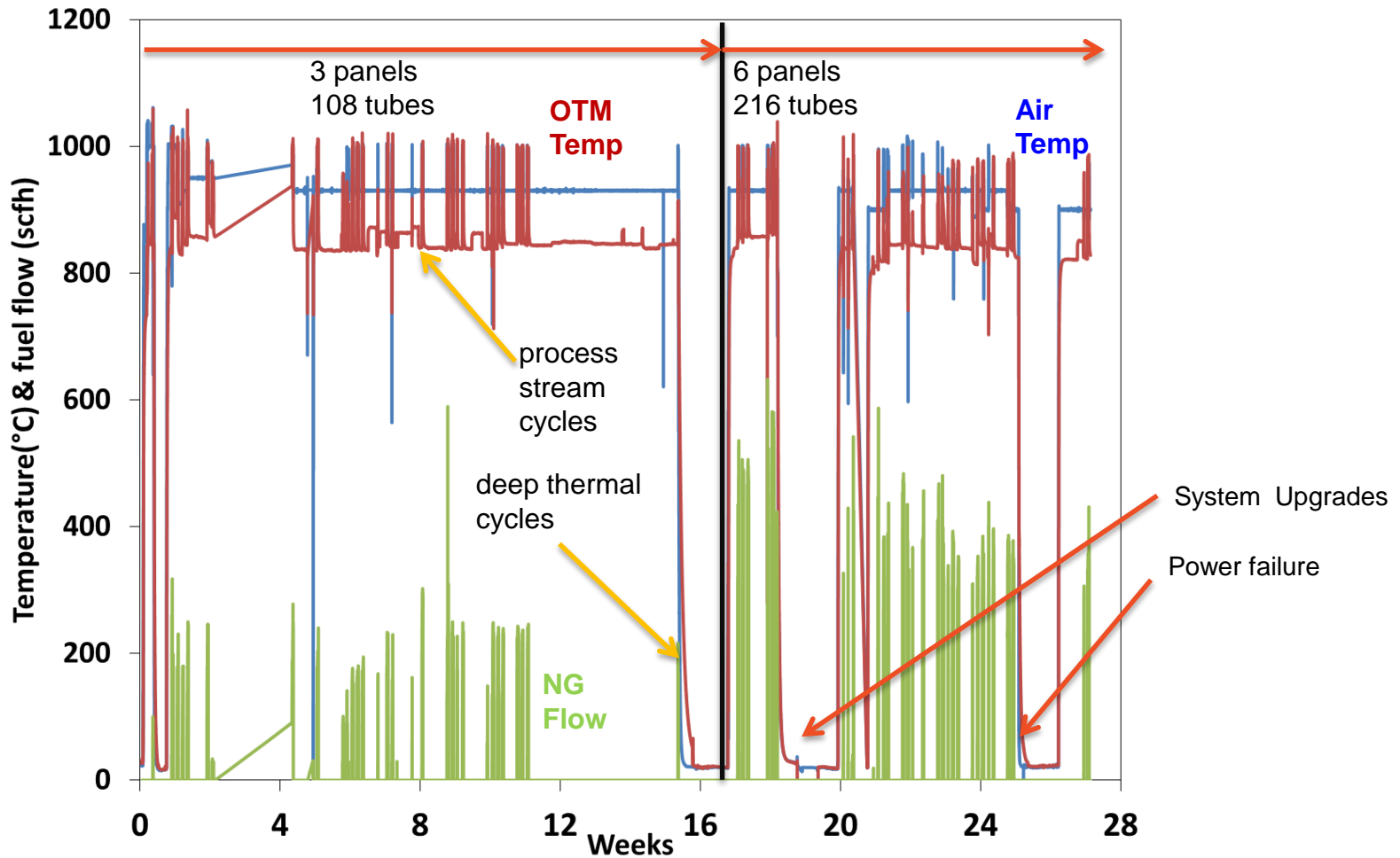
Reliable Operation of Development System

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



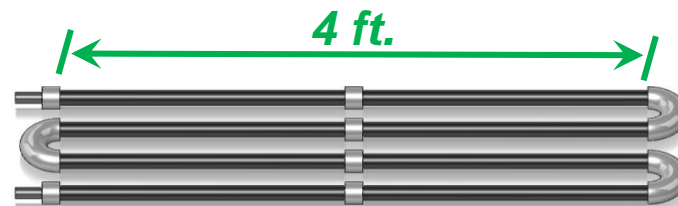
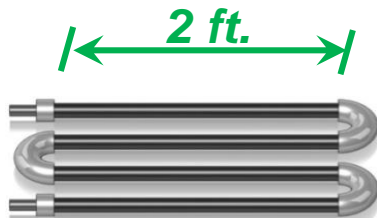
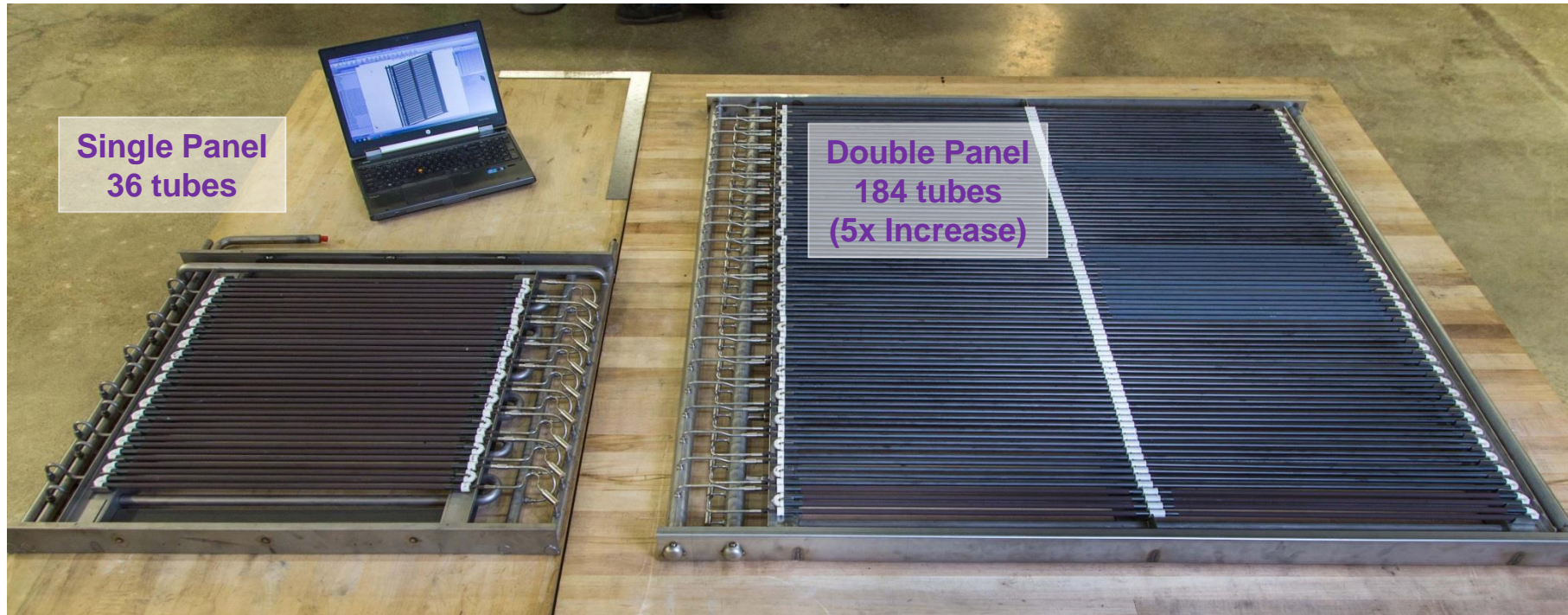
Technology ready for larger scale demonstration

OTM Development System



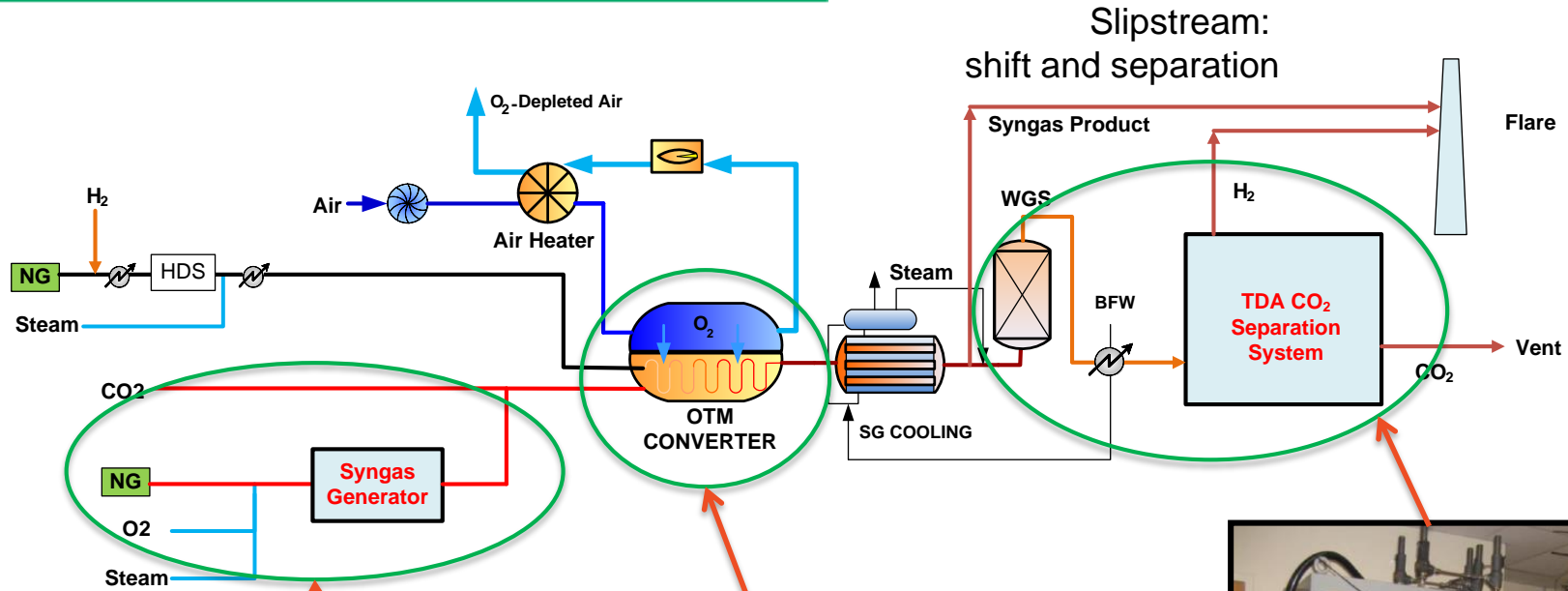
Panels have operated through multiple thermal, pressure, fuel cycles and shocks

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

□ 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

- ARRA Project
 - TEA of OTM-based NG-fired power cycle
- OTM-enhanced Gasification Project
 - Process simulation and TEA of OTM-enhanced IGCC process
 - Development of OTM with integrated catalyst for high pressure operation
 - Small-pilot scale test of OTM converter with TDA's WGS/CO₂ 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 opinions of authors expressed herein do not necessarily state or reflect those of the United States government or any Agency thereof.

Thank you!

