

Praxair's Oxygen Transport Membranes for Oxycombustion and Syngas Applications

NT43088

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Praxair At A Glance

27,000 employees
in more than **50** countries

FORTUNE
100
COMPANY
market capitalization

MORE THAN
63,000
hours contributed
to community
engagement efforts
benefitting
300,000 people

Applications
enabled twice
as many GHG
emissions to
be avoided as
were emitted

CR Magazine's
100 Best Corporate
Citizens List

\$12B in sales

TOTAL SHAREHOLDER RETURN
143%
Over the past five years

SIXTH YEAR
selected for the
CDP's Carbon
Disclosure
Leadership Index

Selected for **DOW JONES**
Sustainability World Index
for Eleventh Consecutive Year

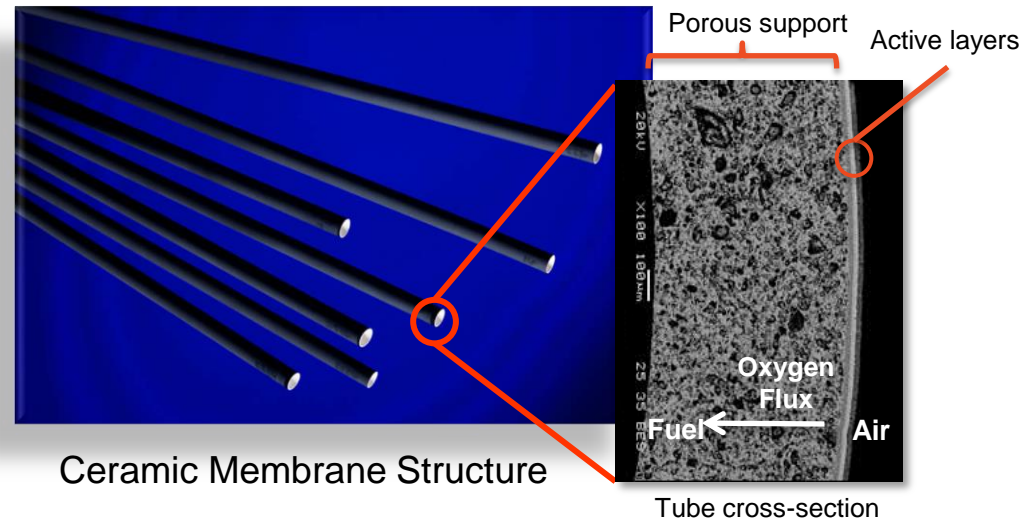
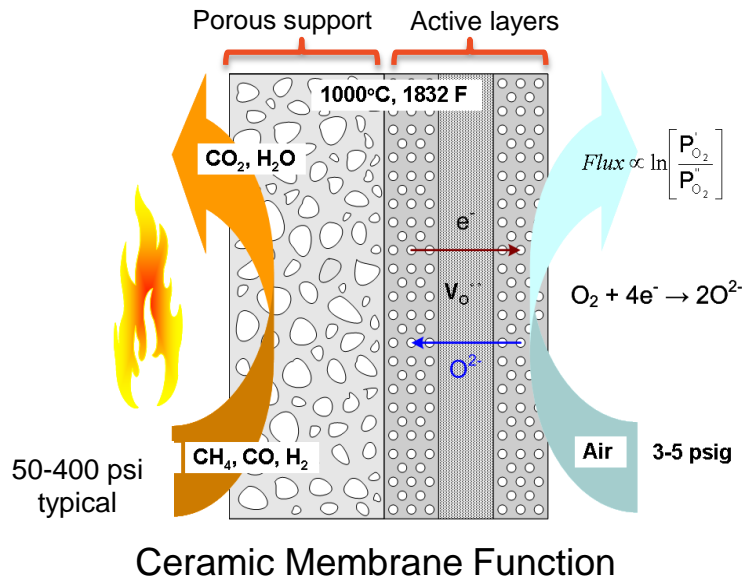
Praxair White Martins received the Best Innovator Award from A.T. Kearney for the 4th consecutive year



Presentation Outline

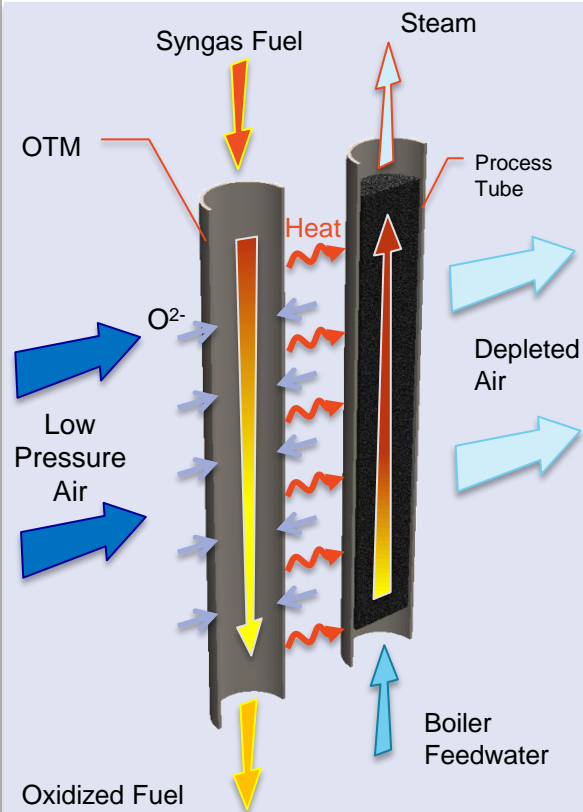
- OTM Technology and Process Integration
- Project Scope Overview
- Phase III Development Progress
- Power Cycle Update

Praxair Oxygen Transport Membranes (OTM)



Solid-state, perfect air separation and compression

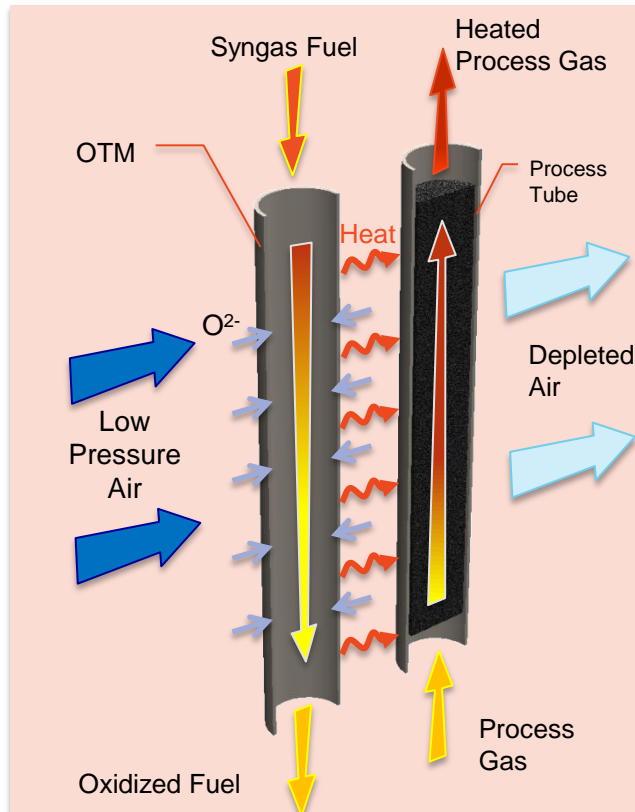
OTM Process Thermal Integration



OTM Boiler

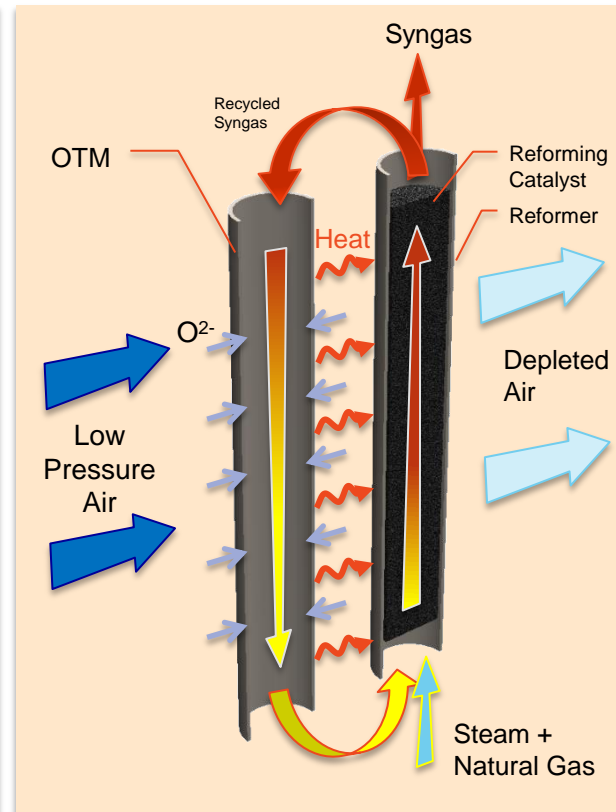
- Steam generation
- Enables power cycle w/CCS

US Patent Nos. 7,856,829 & 8,196,387



OTM Process Heater

- Process gas heating
- Enables oxycombustion power cycle w/CCS



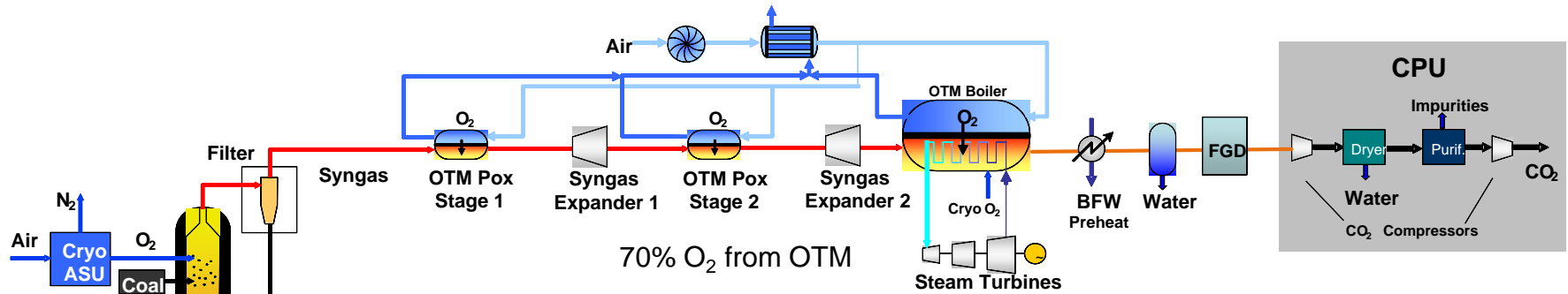
OTM Syngas

- Autothermal reforming of NG
- Enables downstream synthesis
- Enables NG oxycombustion power cycle w/CCS

US Patent Nos. 8,349,214

High temperature processes with integrated air separation

Praxair's Advanced Power Cycle



		Air-PC Case		
		Praxair/DOE No CCS SC	1 Main	
Case				
Net Efficiency		39.7	38.2	
Cost Basis (year)		3/2008	3/2008	
Plant Cost (\$/kW)		\$1,908	\$3,712	
	Coal Price (\$/MMbtu)			
Increase in COE over Reference	1.8		42.1%	\$37.66
	3		36.4%	\$38.23
	4		32.8%	\$38.68

\$/ton CO₂ captured

- Achievable goal of < 35% increase COE w/CCS
- < \$40/ton CO₂ removed

OTM technology enables economic utility scale power with CCS

Project Scope Overview

❑ Oxygen Transport Membrane Based OxyCombustion for CO₂ Capture from Coal Power Plants:

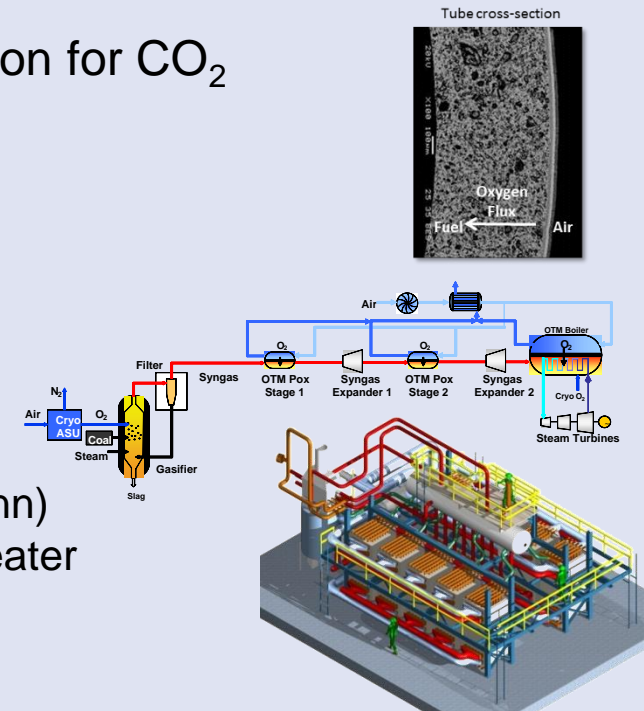
–Phase I (2007-2009)

- OTM development (materials, proof of concept)
- TEA: OTM-enabled coal power cycle w/CCS

–Phase II (2010-2012)

- Single tube testing on gasified coal syngas (U-Utah, UConn)
- Basic engineering design and cost OTM boiler/process heater

\$10.3MM, 65% DOE Share



❑ OTM for Industrial Applications (ARRA):

5yr. \$55MM, 63% DOE share

–Phase III (2010-2015)

- Develop robust, cost effective membranes
- Develop multi-tube modules for NG→syngas
- Engage world-class ceramics mfg. supplier
- Updated basic design for OTM boiler
- TEA: NG-fired oxycombustion power cycle with CCS



Saint-Gobain Ceramics Manufacturing

□ 43.2B € Revenue (2012)

–Experienced world class ceramic manufacturer

□ Competencies in critical areas:

–Ceramic powder manufacturing

–Industrial ceramic component manufacturing

–SOFC development experience

□ Phase III Development Subcontract

– Currently supplying membranes, seals, and ceramic subassemblies



Sealed OTM assemblies



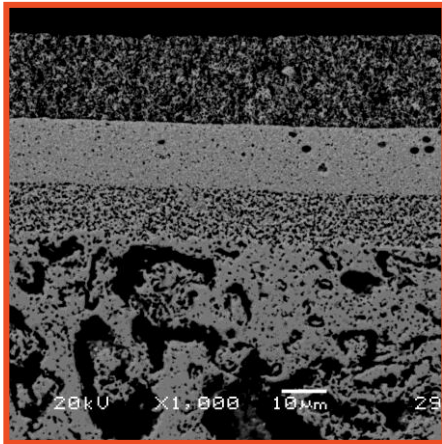
Saint-Gobain Furnace Investment

Focus on high-volume ceramics meeting cost targets

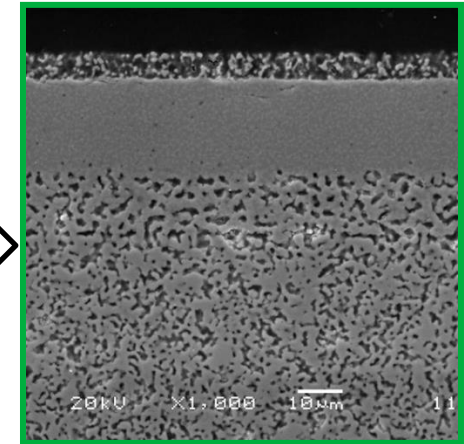
Gen.1 Membrane

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

Gen.2 Membrane



- Homogenous substrate
- Simplified, stable chemistry
- Thermal/chemical compatibility
- Improved manufacturing process



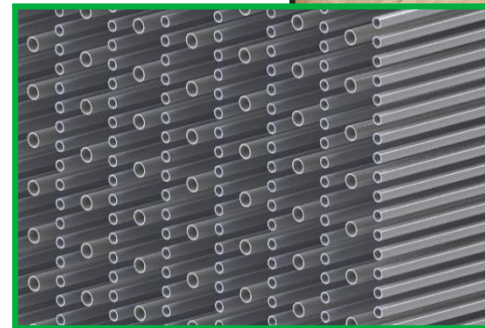
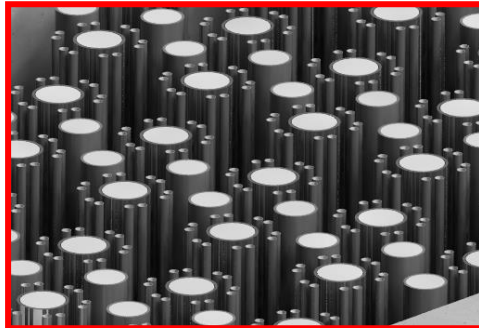
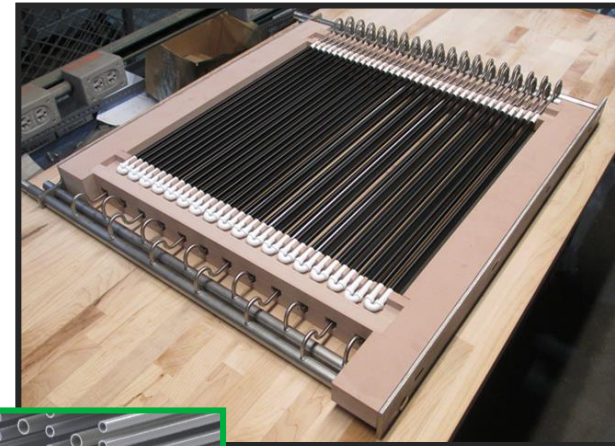
Membranes achieve early commercialization targets

Radial

- 2X membrane area / unit volume
- 60% less reformer metal
- Increased natural gas conversion

Panel Array

- Improved tube arrangement
- Small diameter reformer tubes
- Simplified manifolding
- Improved seals



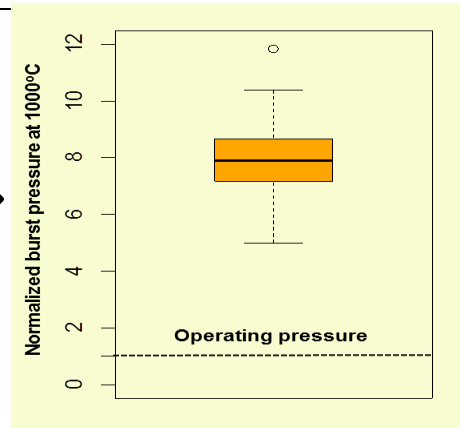
Panel Array module enables commercial-scale up

Phase III Progress: 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	8707	7	0
BAT # 02	6800	3	0
BAT # 03	6700	2	0

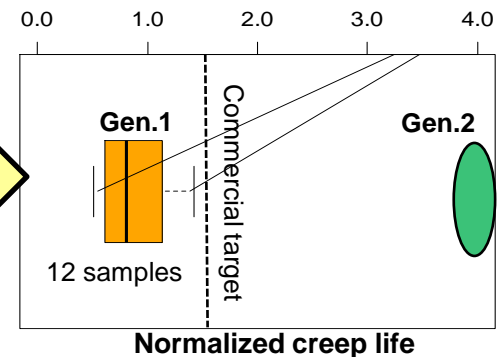


On-line laser creep test



Creep/reliability test

~4X increase in OTM creep life



Proven durability under required operating conditions

Test Systems Developed in Current Phase

Single Tube Testing → Module Testing → System Testing



Membranes can deliver requirements of the process

- Flux and fuel conversion demonstrated
- >20,000 hrs over 25 tubes
- Focus on Gen 2 membrane characterization at high pressure

Modules have shown excellent operational flexibility

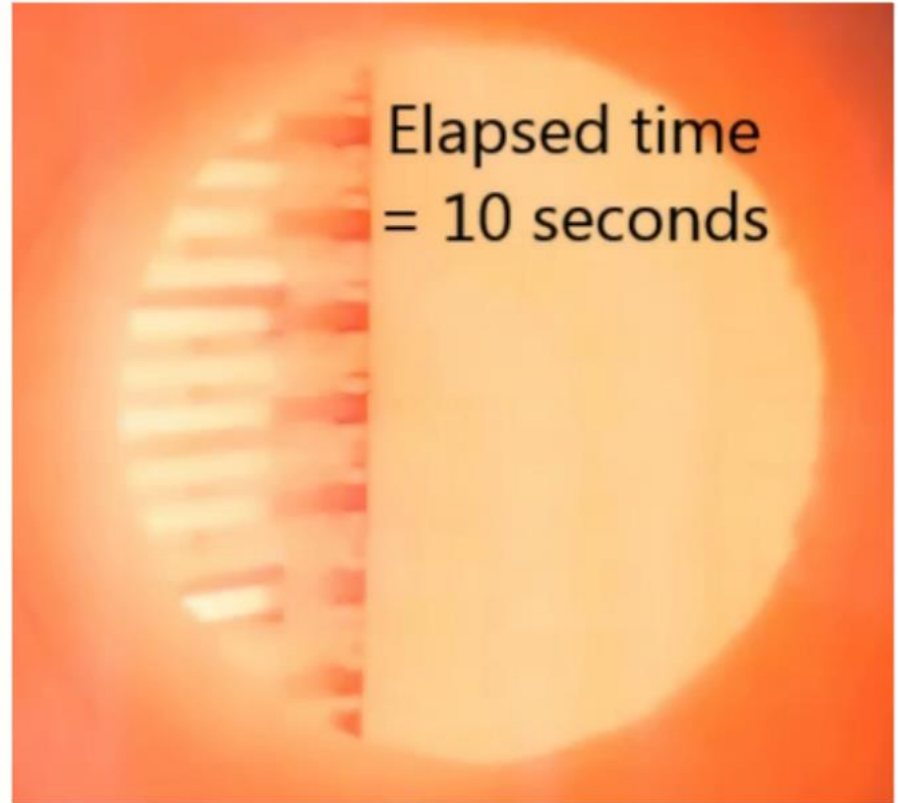
- 13 Modules tested (>200 OTM tubes)
- More than 4,700 hrs of flux testing
- >25 module thermal cycles
- Ceramics robust to thermal and chemical cycling

Successful multi-module syngas production (radial modules)

- Operating with 5 radial modules (60 OTM tubes)
- Representative commercial process elements
- Multiple successful heating / cooling cycles
- Capacity up to 190 Nm³/hr syngas

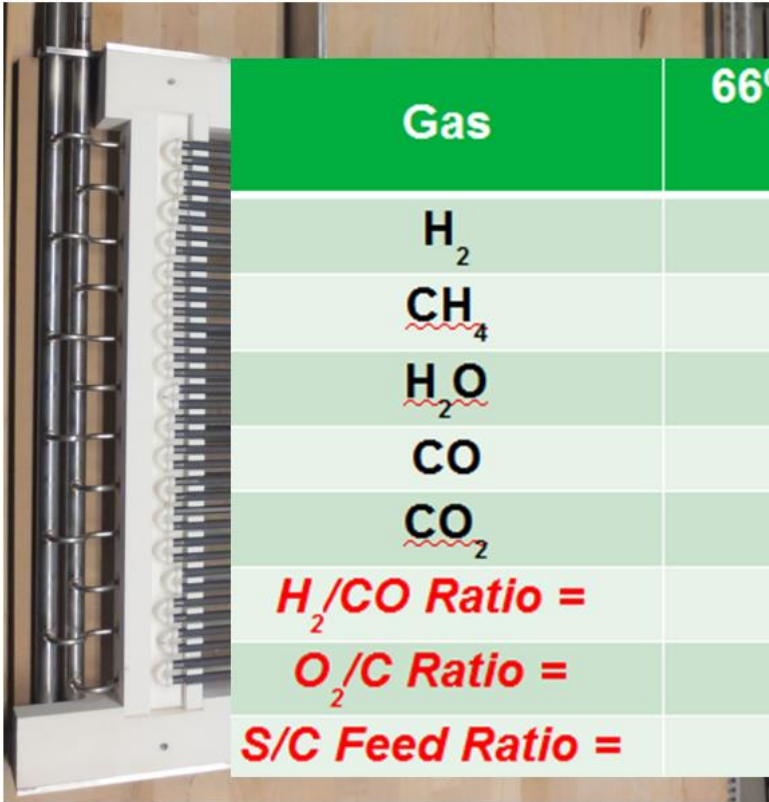
Successful integration of membranes into systems

Panel Array Operation



Syngas module robust to thermal cycles, trips, and transients

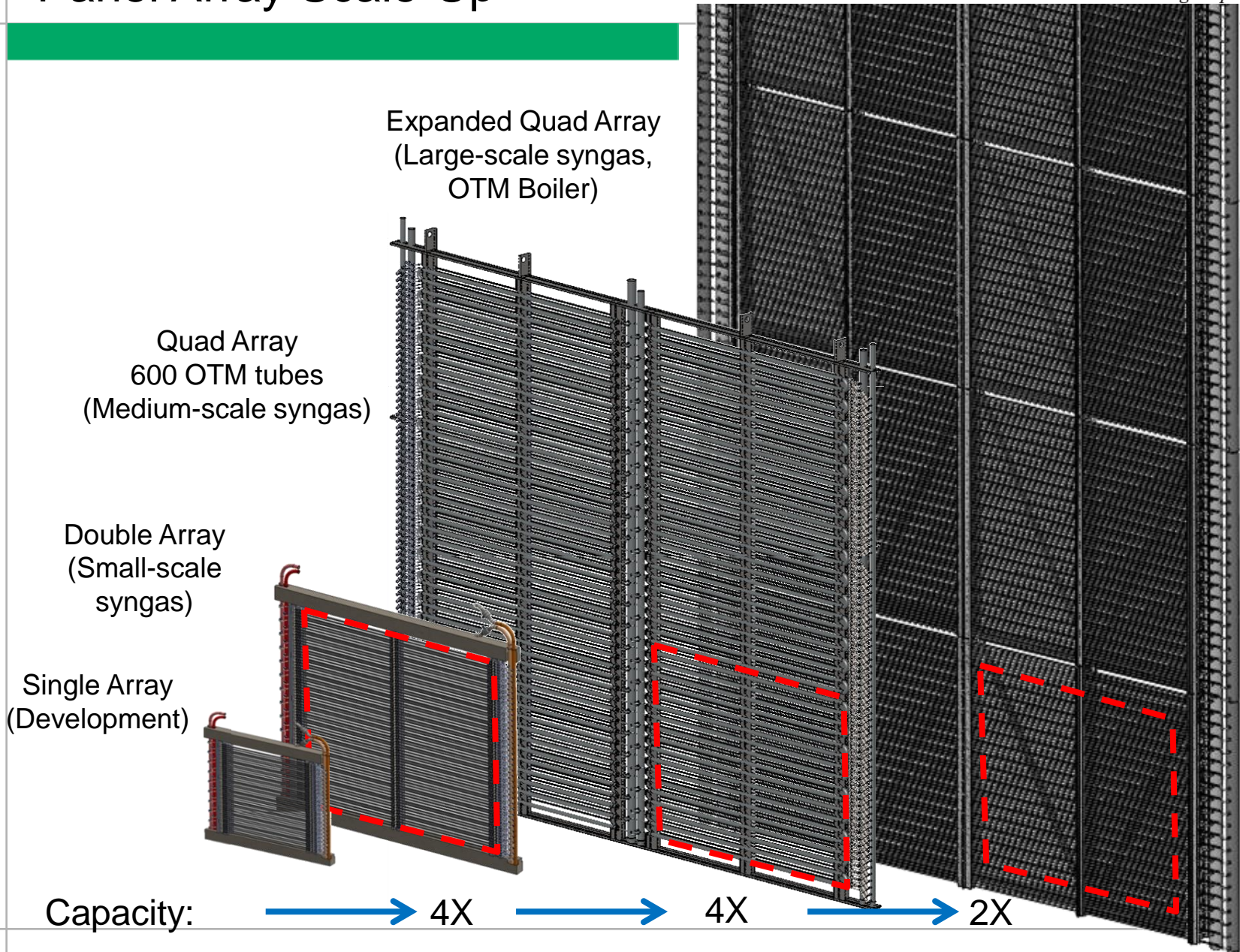
Panel Array Operation



Gas	66% NG + 34% CO ₂ Feed	100% NG Feed
H ₂	55.7%	70.5%
CH ₄	0.04%	0.13%
H ₂ O	0.00%	1.60%
CO	26.3%	21.6%
CO ₂	17.9%	6.20%
H₂/CO Ratio =	~ 2.12	~ 3.26
O₂/C Ratio =	~ 0.4	~ 0.38
S/C Feed Ratio =	~ 1.5	

Syngas module robust to thermal cycles, trips, and transients

Panel Array Scale-Up



Tubesheet Boiler

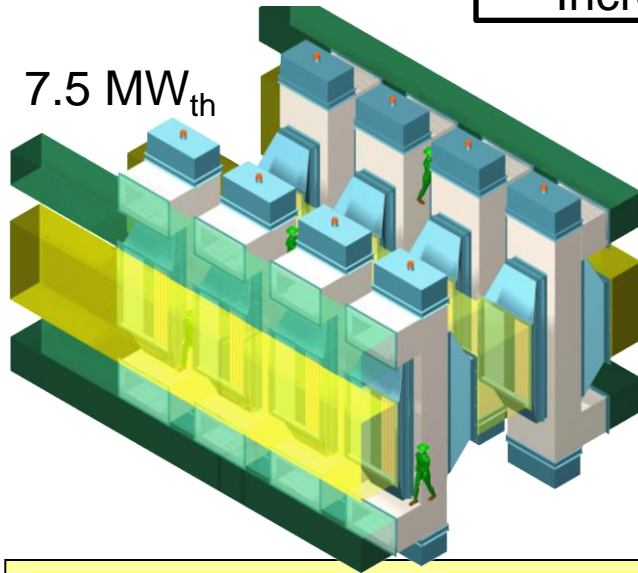
- 10X unit capacity
- 45% increased duty/unit volume
- 40% increased O₂/unit volume
- reduced capital cost

• Adopt panel array design

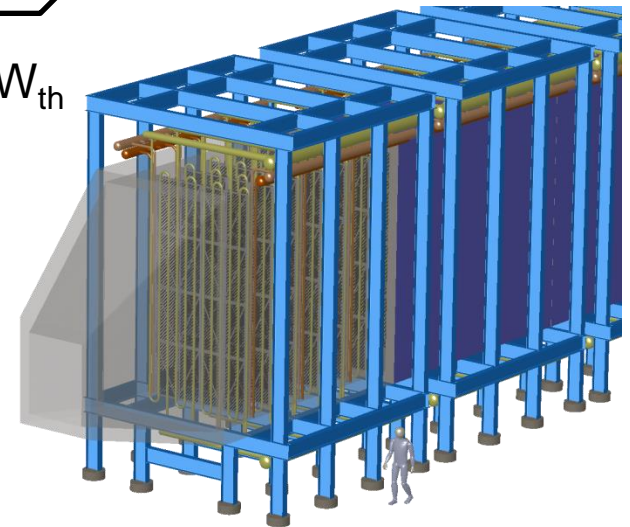
• Increase syngas pressure

• Increased module capacity

Panel Array Boiler

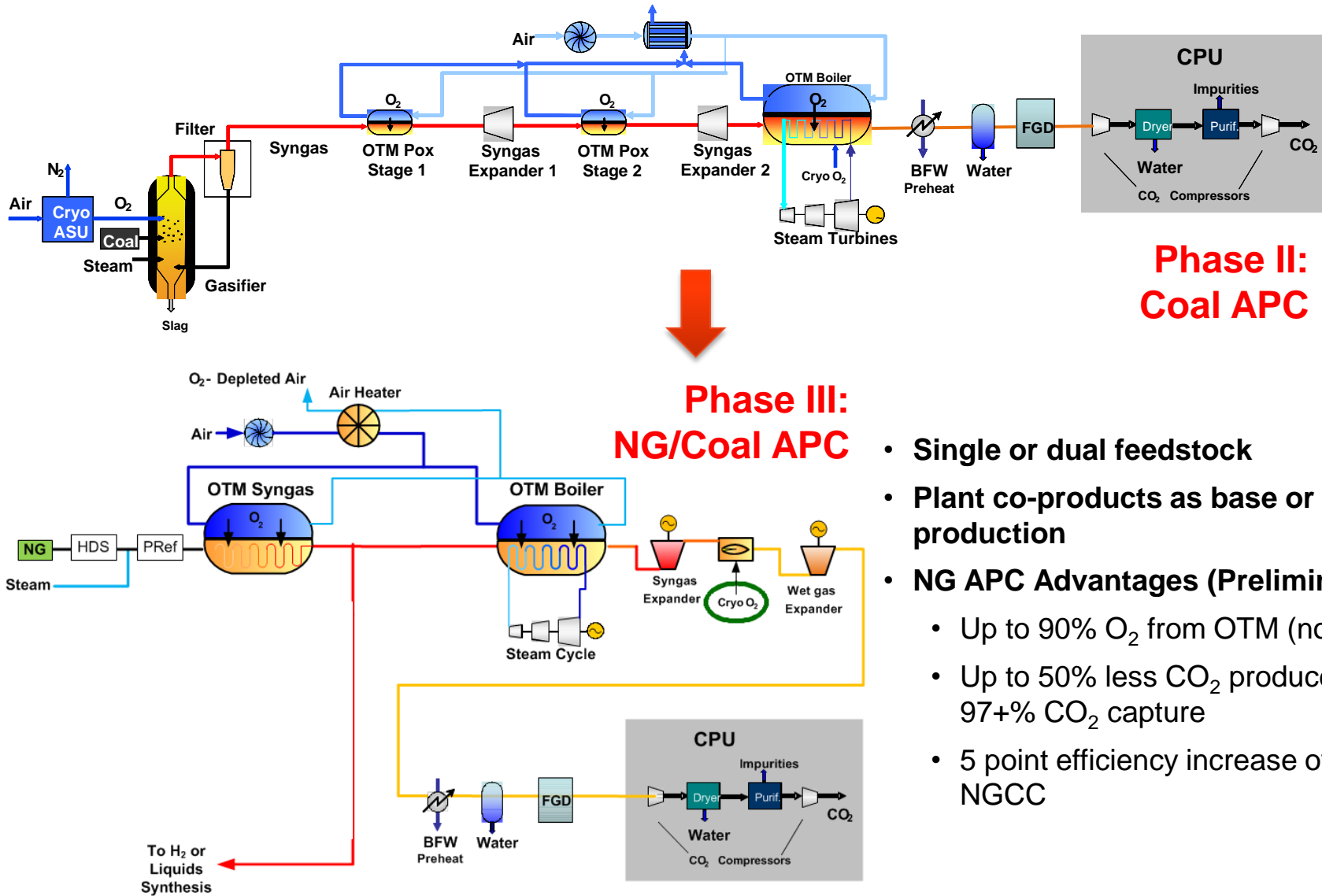


20-50 MW_{th}



Improved approach to large-scale power boiler

OTM Advanced Power Cycle (APC) Update



In Summary:

- **Key Results**

- Step change in membrane materials and mfg. process
- Demonstrated stability in coal-derived syngas
- Demonstrated high strength membrane 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 both chemicals synthesis and power w/CCS applications

- **Next Steps**

- Transition Gen 2 membranes into Panel Array modules
- Transition from Radial to Panel Array modules in syngas development system and walk capacity to 160,000 scfd syngas (1 TPD O₂)
- Update capital cost estimates for improved OTM boiler design
- Complete TEA for OTM-based NG-IGCC OTM

Acknowledgements

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Thank you!

