Robust & Energy Efficient Dual-Stage Membrane-Based Process for Enhanced Carbon Dioxide Recovery

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The Big Picture

Pre-Combustion Carbon Capture and Membrane Process

1. **US Energy Consumption:**
   Separation processes are ~43% of energy consumption in petroleum and refinery industries.

2. **Energy Efficiency:**
   Membrane process is considered one of the most energy efficient unit operations. Nevertheless, similar to conventional filters, a membrane process requires pressure (or other) energy to overcome the semi-permeable barrier to achieve separations.

3. **Synergy with Membrane Processes:**
   In-situ separations without heating/cooling offers great potential in improving energy efficiency. Further, process intensification can improve reaction efficiency and streamline the process.

IMPLICATIONS & SIGNIFICANCE

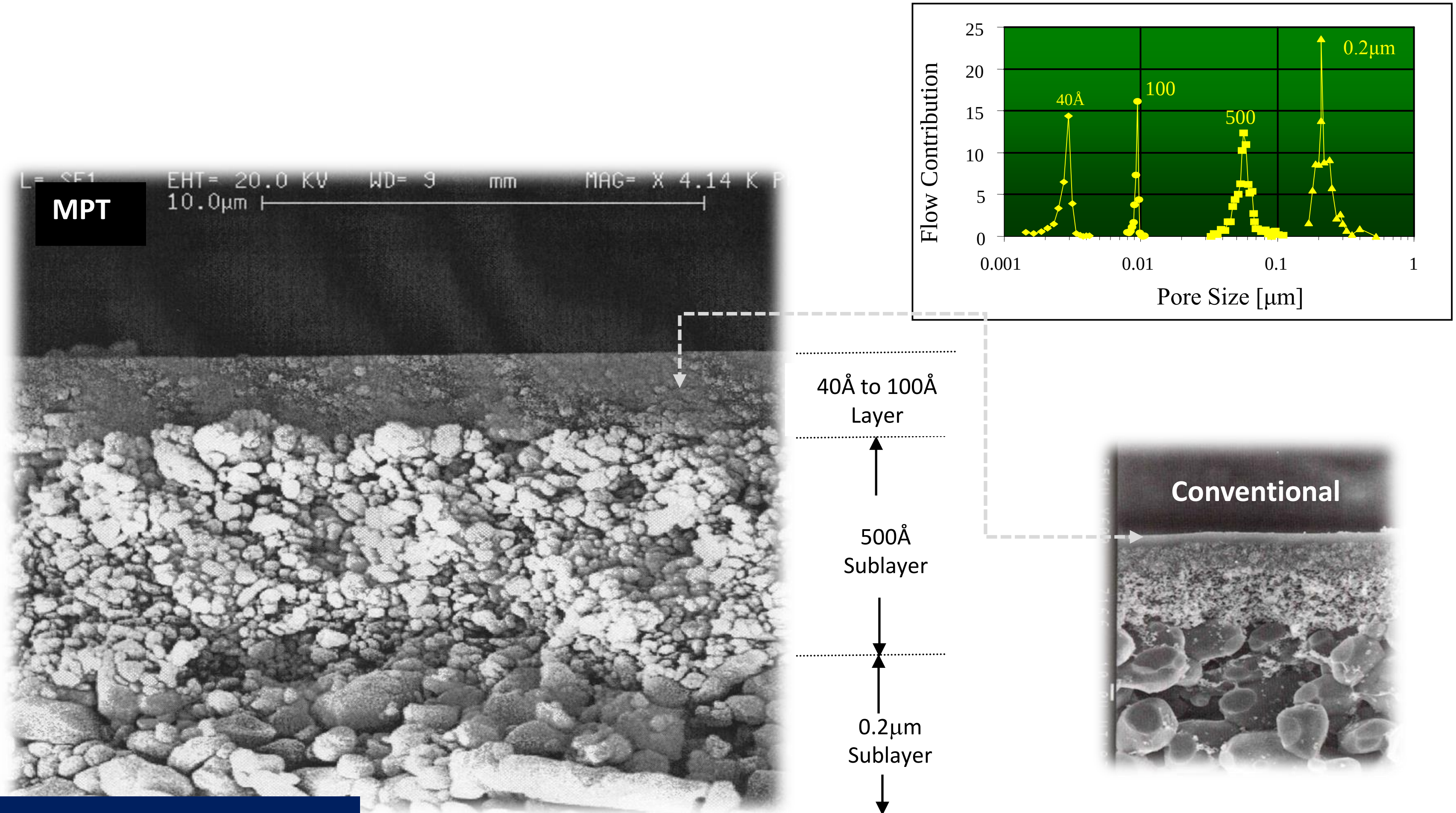
- **Pre-Combustion Carbon Capture** through H_2 separations and CO_2 capture via membranes can potentially take the full advantage of the above, i.e., ***in-situ separations***, ***process intensification***, and ***pressure energy*** available.

- **Inorganic membranes material stability** particularly under ***harsh environment***, **such as coal gasification,** is an ideal platform for us to pursue this mission – pre-combustion carbon capture.

- **As a US-based inorganic membrane manufacturer,** we have made a ***major advancement in this mission*** with our ceramic membrane products through this project.

MPT TECHNOLOGY BACKGROUND

Thin Film Deposition on Low Cost Substrate



Our Core Expertise/Technology

#1: Near perfect thin film deposition on less-than desirable but low cost porous tubular substrates

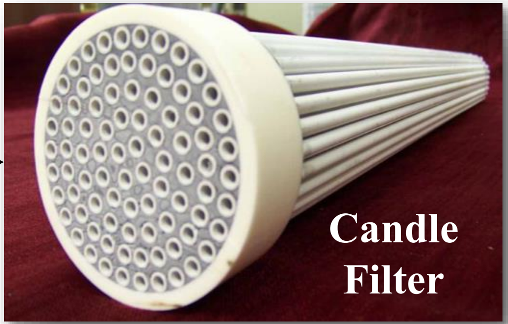
MPT TECHNOLOGY BACKGROUND

Multiple Tube Membrane Bundles – versatile, low cost

Example: conventional micro- and ultrafiltration

Example: porous heat exchangers & catalytic membrane reactors

Single tubes



Example: high pressure intermediate temperature gas separations

Example: Centerline permeate take-off for direct drop-in to commercial Codeline Vessels

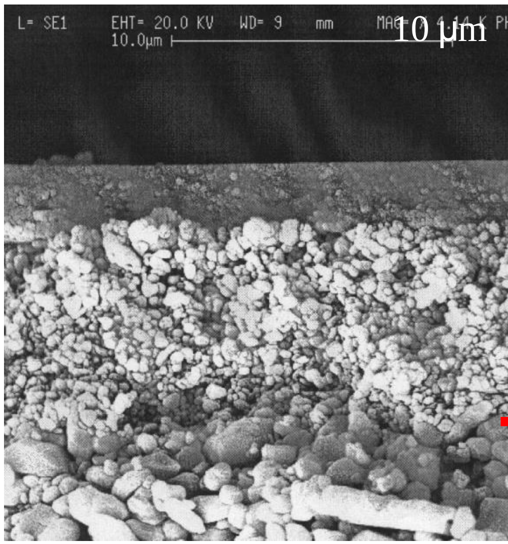
Our Core Expertise/Technology

#2: Packaging individual membrane tubes into commercially viable modules for field use.

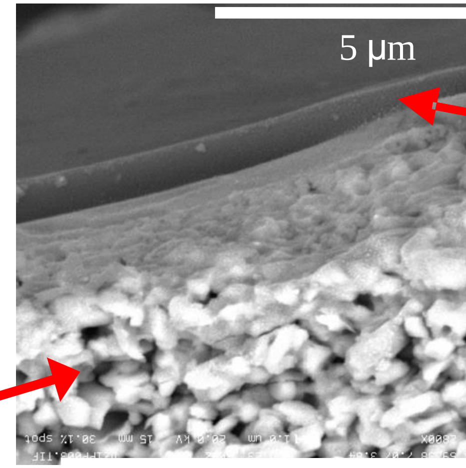
MPT Advanced Inorganic Membranes

Specific thin film deposition for advanced separations

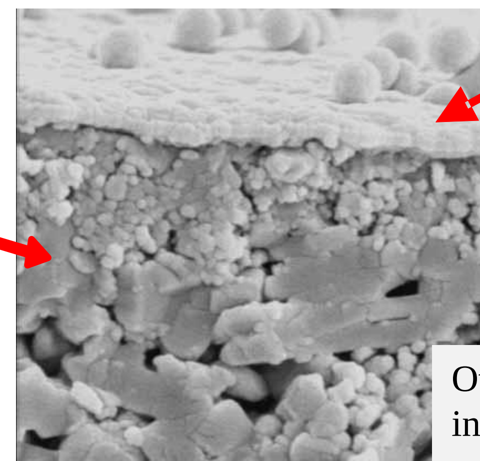
Ceramic Substrate



Ceramic Substrate



Carbon molecular sieve (porous, sulfur resistance)



Palladium (dense, excellent selectivity)

Others, including zeolites, flourinated hydrocarbons, etc.

- **Unique Features of Supported Membranes**
  Low cost, flexible, and convenient
- **Technical Challenges of Supported Membranes**
  Layer adhesion and defect control

MPT Technical Approach for IGCC/CCS

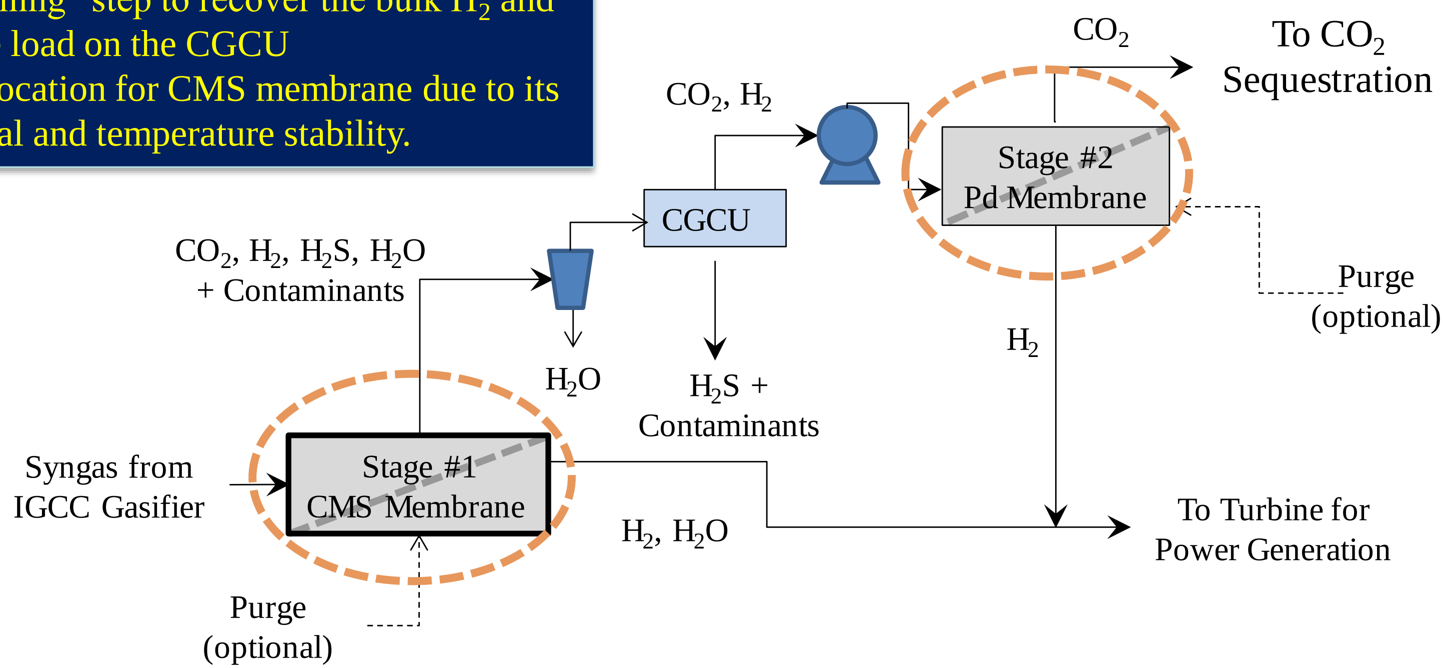
Dual Stage Membrane Process Scheme and Key Components

Pd-Alloy Membrane

1. High selectivity yields excellent residual H_2 recovery.
2. Ideal to achieve the CO_2 capture and purity targets.

CMS Membranes (coupled with WGS reactor)

1. Deliver enhanced CO conversion with reduced water consumption versus conventional WGS.
2. "Roughing" step to recover the bulk H_2 and reduce load on the CGCU
3. Ideal location for CMS membrane due to its material and temperature stability.



- ❑ Our unique two-stage process avoids the capital and compression costs associated with the conventional two stage operation.
- ❑ The strengths of CMS and Pd membranes are fully utilized while their weaknesses are compensated for by the synergy that is being created by this novel two-stage process.

MPT Dual Stage Membrane Process

Presentation Outline – Section 1

SECTIONS	SUB-SECTIONS	SPECIFIC TOPICS
1. Membranes	a. Carbon Molecular Sieve (CMS) Membranes	Permeance & Selectivity
		Thermal & Material Stability
	b. Palladium(Pd) Alloy Membranes	Permeance & Selectivity
		Material (Thermal + H_2) Stability
	c. Bundles & Housing	Bundle Engineering & Configuration
2. Process	a. Integrated Membrane Reactor or in Series	Process Configuration
	b. Modeling and Process Simulation	Mathematical Modeling
		WGS Reaction Kinetic Study
3. Field Tests	a. Previous Tests with 1st Gen CMS Bundle	Performance and Stability
	b. Current test with 2nd Gen CMS Bundle	Long Term Material Stability
	c. Verification of Model Prediction	Field Obtained Data vs Prediction
	d. Pd Membranes & Bundles	Performanc and Stability
	e. Pd Membrane Poisoned by Tar	Regeneration & Activity Restroation
4. TEA/EHS	a. Proposed Process Scheme	Block Flow Diagram
	b. Techno-economic Analysis (TEA)	Costs of Power & Carbon Capture
	c. TEA Sensitivity Analysis	Impact of Membrane Selectivity & Configuration
	d. Environmental, Health and Safety Analysis (EHS)	Evaluation on Key Separation and Manufacturing Processes

- ❑ Conclusions and Background infor on MPT Commercial Activities for Hydrogen Recovery
- ❑ (1) project milestones; (2) project success criteria; (3) Peer Review milestones; and (4) updated State-Point Data tables.

CMS Membrane Functional Performance

Typical Performance and Performance Targets

CMS Single Tube Characterization

CMS Membrane Characteristic	Preliminary Target to Achieve DOE Goals[1]	Laboratory Single Tubes Performance
Permeance, H_2 [GPU] @ **250°C, 20 psig**	550	420 to 1,100
Selectivity, H_2/X		
H_2/N_2	70	80 to >180
H_2/CO	70	70 to >130
H_2/CO_2	35	>65
H_2/H_2S	N/A[2]	>100 to 150[2]
H_2/H_2O	1.5	1.5 to 3

Notes:

1. Target performance is that required to achieve 90% CO_2 capture at 95% purity with 95% fuel utilization (H_2 + CO to the turbine).
2. At this selectivity, approximately 200 ppm H_2S in the fuel to turbine.

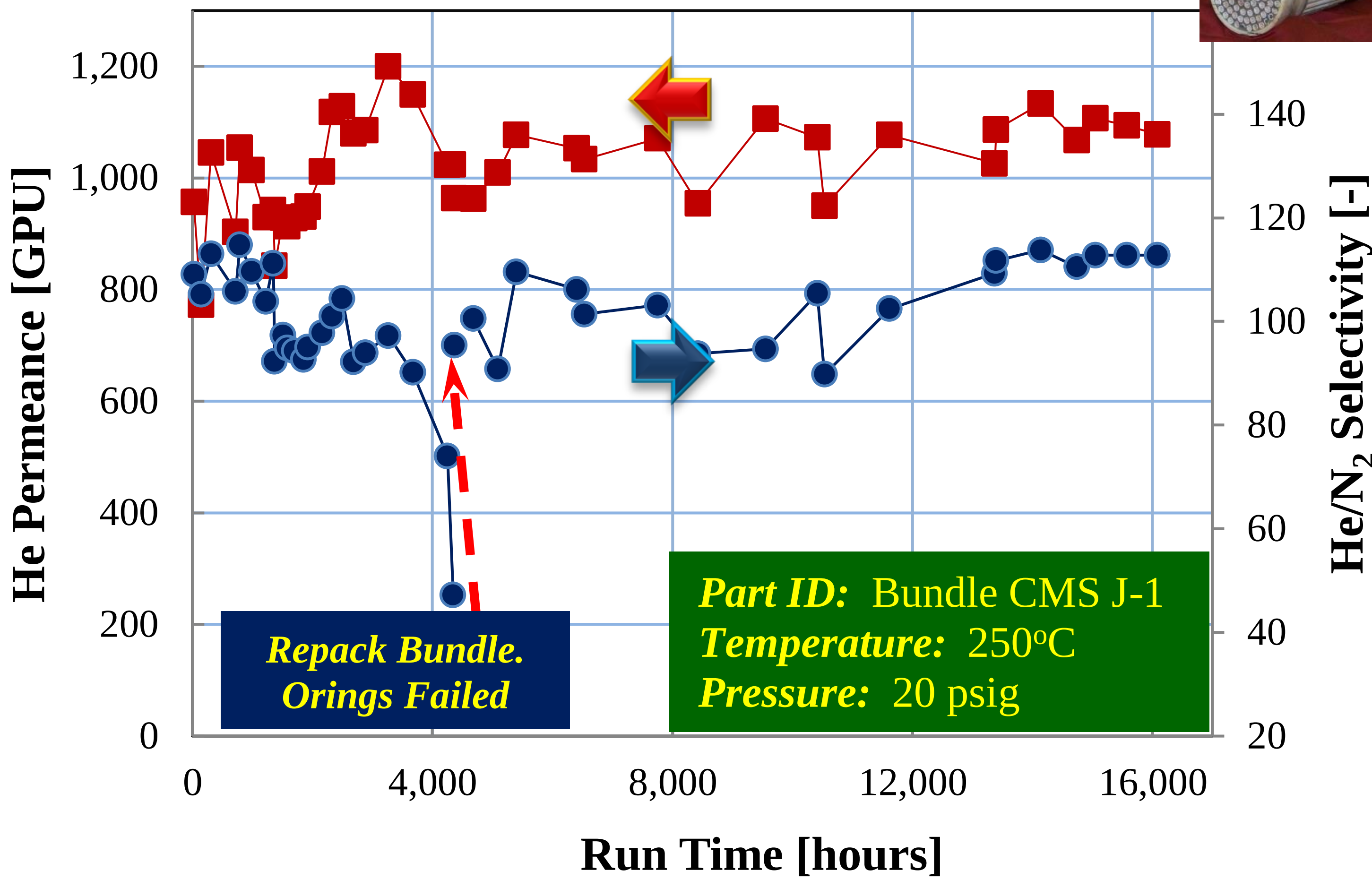
CMS 86-Tube Bundle Characterization

CMS Bundle ID	He Permeance [GPU]	He/N_2 Selectivity [-]
86-6	731	100
86-7	1,020	187
86-8	658	91
86-9	950	102
86-10	365	200
86-11	584	142
86-12	548	77
86-13	840	126
86-14	1,020	117
86-J1	973	120
86-MB1	421	122
86-MB2	665	87
86-MB3	438	85

CMS Membrane Long Term Stability

Key Technical Hurdles Focused on Long Term Stability (CMS Membrane)

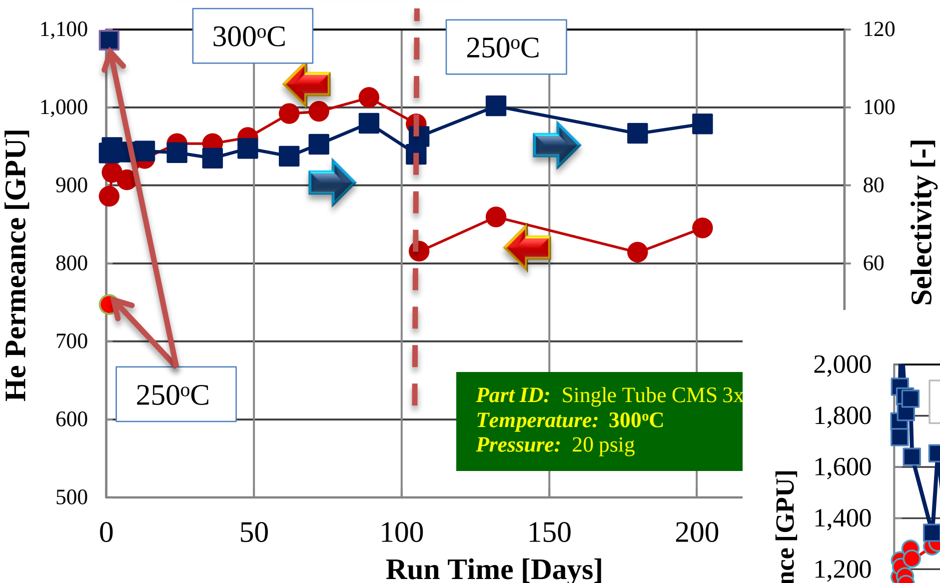
CMS 86 -Tube Bundle Long Term Stability (>16,000 hrs)



CMS Membrane Thermal Stability

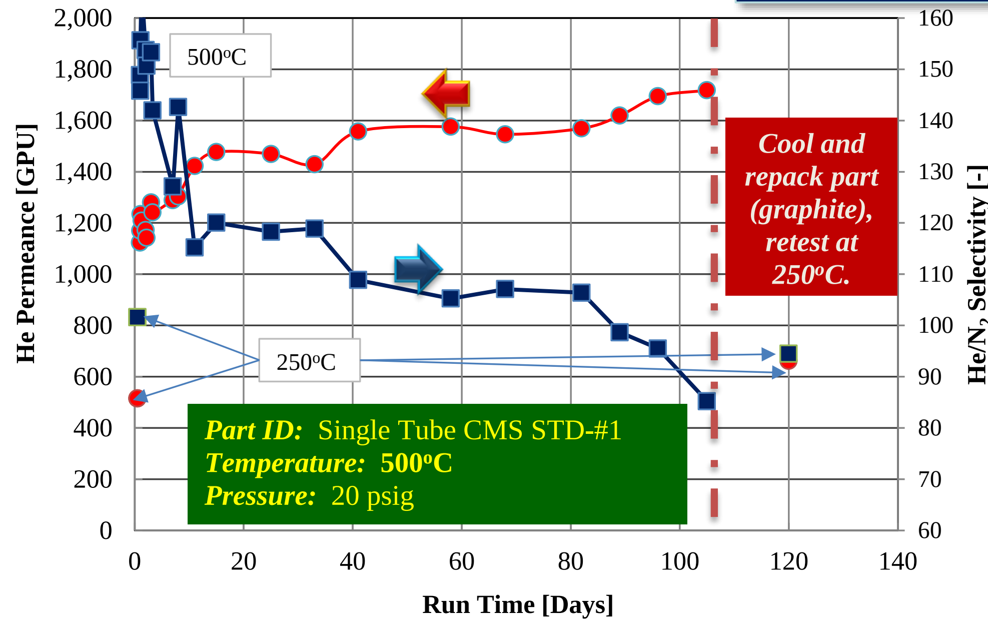
Key Technical Hurdles Focused on Long Term Stability (CMS Membrane)

300°C



High Temperature Excursions above the 250°C Design Temperature

500°C



CMS Membrane Material Stability

Contaminant Stability: CMS Membrane Actual Refinery Gas (higher hydrocarbons, NH_3, H_2S)

Chevron Pilot Testing Facility

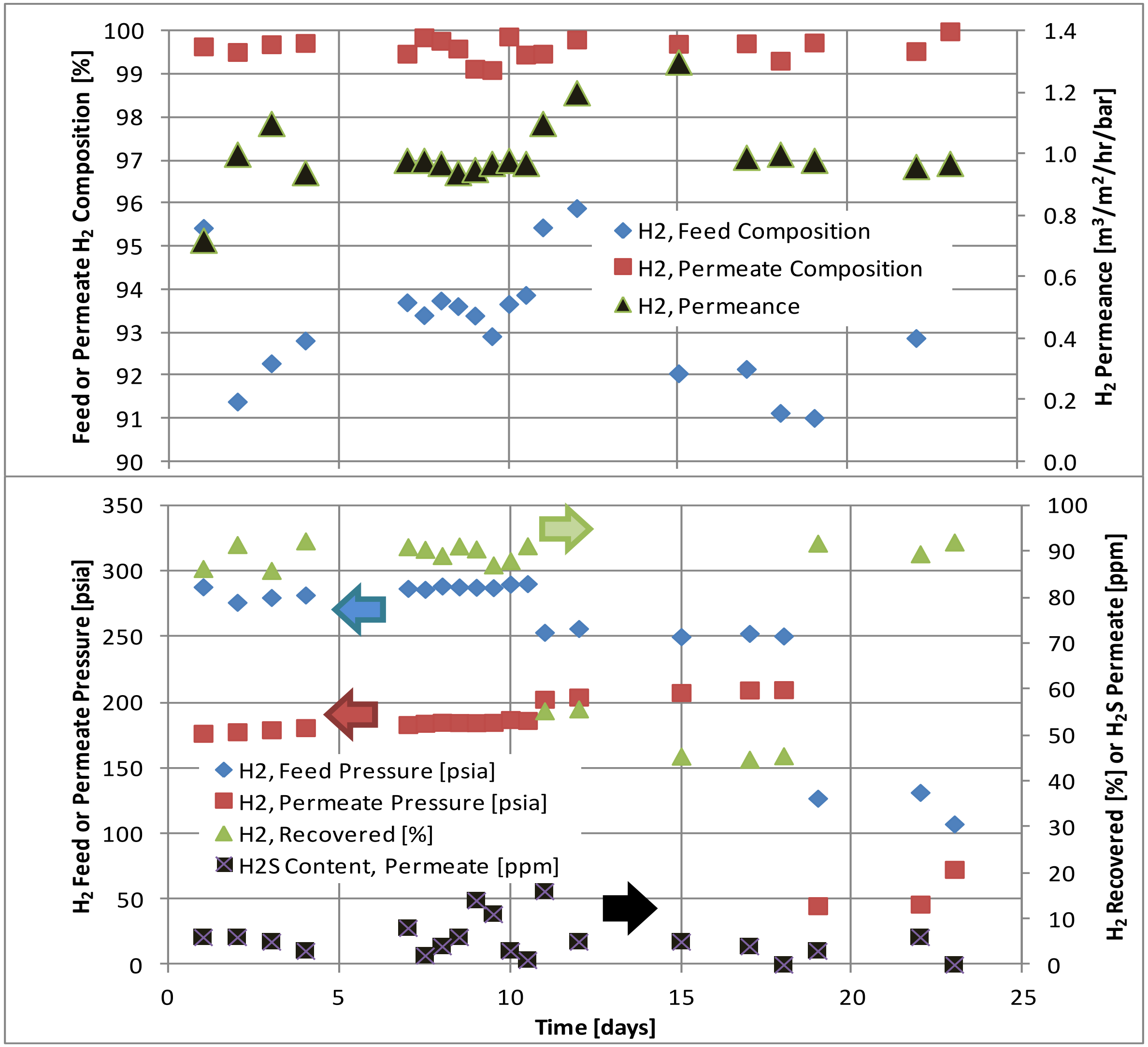
Membrane
CMS Tube

Operating Conditions
T~ 240°C
P~ 300 psig

Pretreatment
None.

Composition
H_2 ~ 90 to 95%
Hydrocarbon balance.

Trace Contaminants
NH_3 ~ 1,000ppm
H_2S ~ 15,000ppm



Pd-Alloy Membrane Functional Performance

Typical Performance and Performance Targets from Economic Analysis

Pd-Alloy Single Tube Characterization Overview

Pd-Alloy Membrane Characteristic	Preliminary Target to Achieve DOE Goals[1]	Laboratory Single Tubes Performance
Permeance, H_2 [GPU] @ **350°C, 20 psig**	3,470	1,750 to >5,500
Selectivity, H_2/X		
H_2/N_2	300	300 to >3,000
H_2/CO	300	300 to >3,000
H_2/CO_2	300	300 to >3,000
H_2/H_2S	N/A[2]	NA[2]
H_2/H_2O	300	300 to >3,000

Notes:
1. Target performance is that required to achieve 90% CO_2 capture at 95% purity with 95% fuel utilization (H_2 + CO to the turbine).
2. Feed gas to the Pd-alloy membrane has been pretreated to remove residual sulfur species in the CGCU.

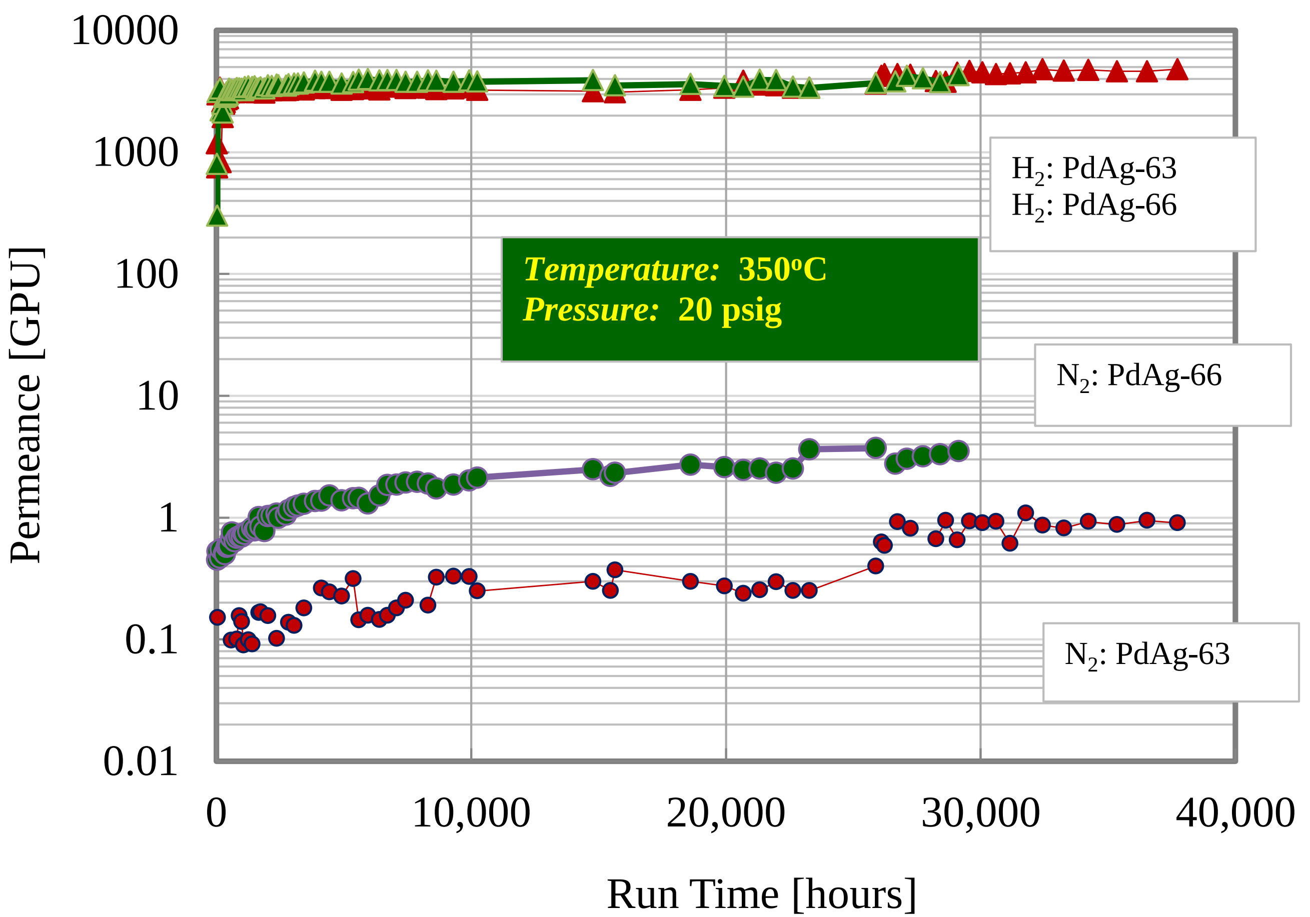
Pd/PdAg 12-Tube Bundle Characterization

Bundle ID	H_2 Permeance [GPU]	H_2/N_2
Pd-DCT-3	4,170	1,100
Pd-DCT-7	3,620	1,810
Pd-DCT-12	3,100	1,160
PdAg-DCT-27	4,750	2,260
PdAg-DCT-28	5,180	2,030

Pd-alloy Membrane Long Term Stability

Key Technical Hurdles Focused on Long Term Stability (Pd-alloy)

Pd-Alloy Pd-Ag (80/20) Long Term Stability (>35,000 hours)



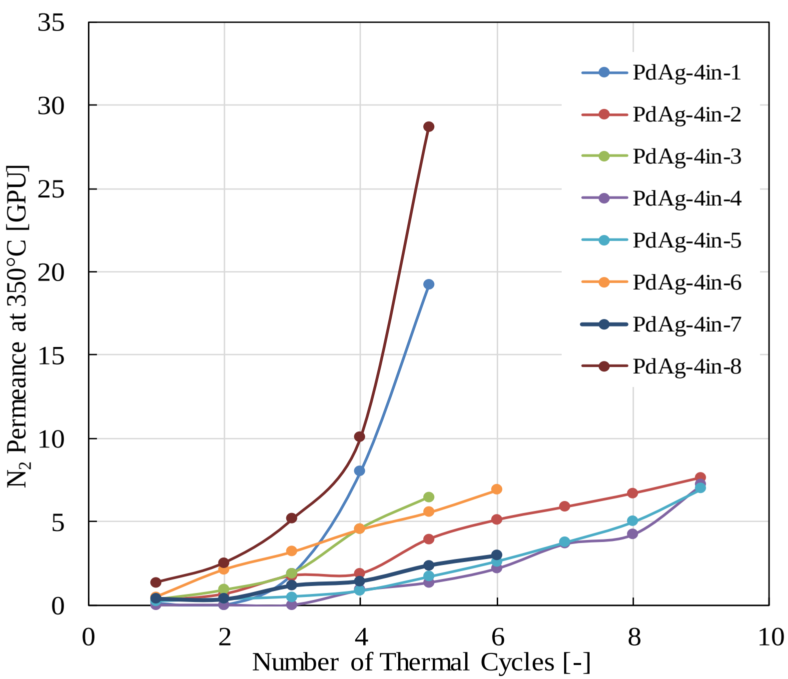
Pd-alloy Membrane Stability

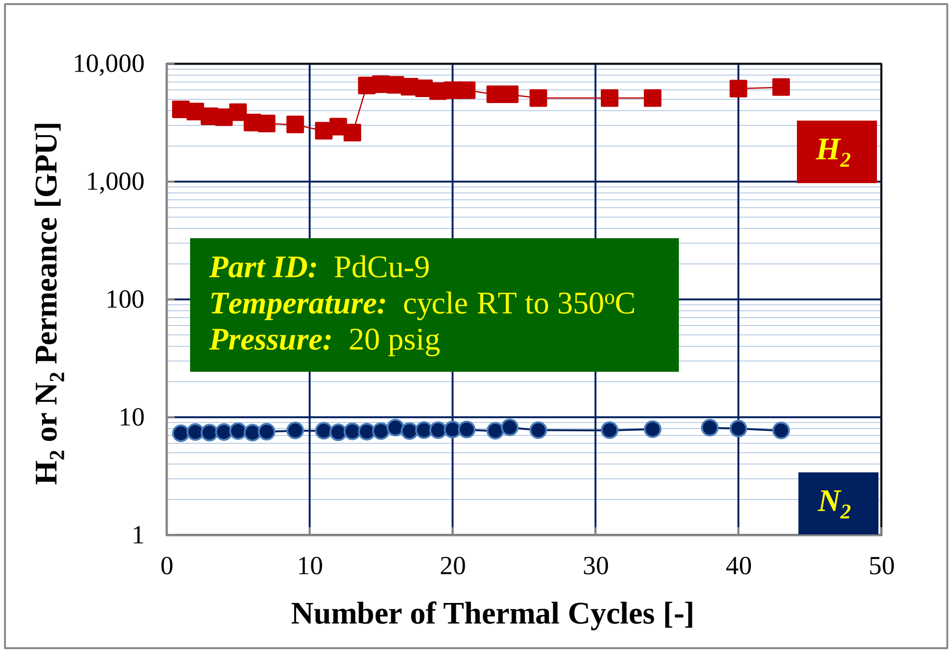
Key Technical Hurdle: Thermal Cycle Stability in H_2 (Pd-alloy)

Thermal Cycling in H_2: RT to 350°C

Pd-Ag (75/25)

Pd-Cu (60/40)





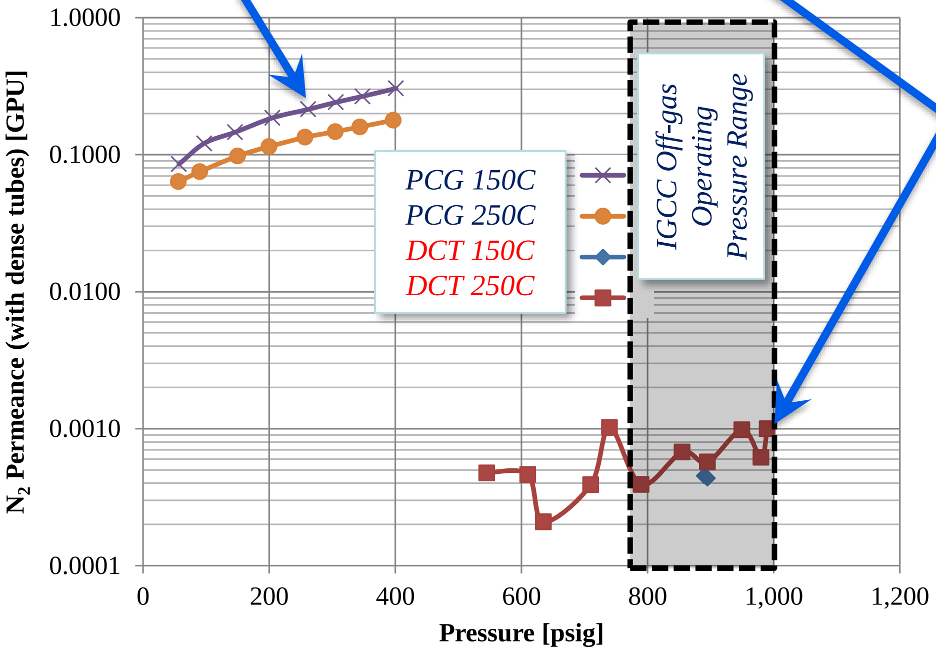
Multiple Tube Bundle Potting Development

High Pressure/Temperature Stability

Potted Ceramic/Glass (PCG)

Dense Ceramic Tube Sheet (DCT - CMS)

Dense Ceramic Tube Sheet (DCT-Pd Alloy)



Why PCG v. DCT?

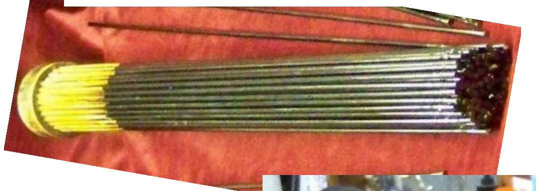
Performance, PCG v. DCT
Temperature [°C]: <300 v. >500
Pressure [psig]: <400 v. >1,100

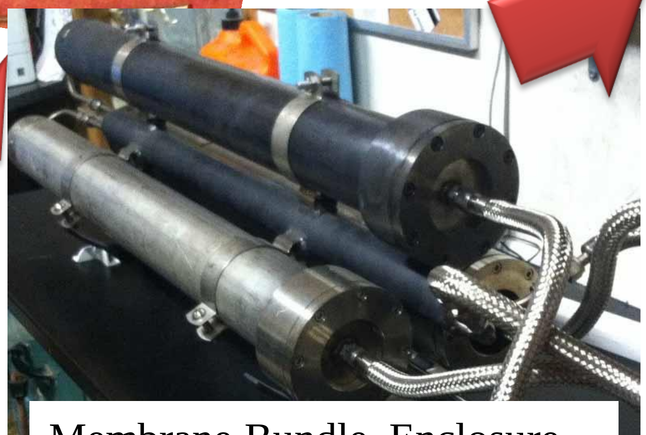
IGCC Operating Conditions
Temperature [°C]: 250 to 350
Pressure [psig]: >700 to 2,000

M&P Hydrogen Selective Membrane Modules

Multiple Membrane Bundle Modules

Membrane Bundle

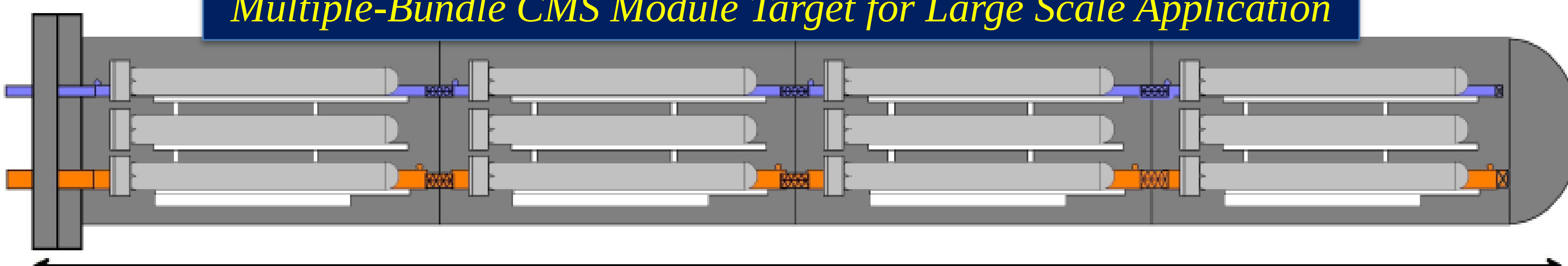




Membrane Bundle Enclosure

Multiple Bundle Module

Multiple-Bundle CMS Module Target for Large Scale Application



Total Pressure Jacket Length 200" of 24" Pipe, 4 sections of 7 Bundles connected with flexlines.

MPT Dual Stage Membrane Process

Presentation Outline – Section 2

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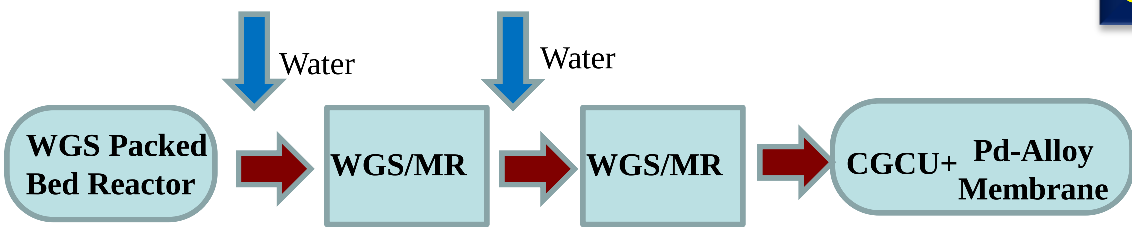
Process Simulation Results

Membrane + Reactor in series vs Integral Membrane Reactor

MR v. PBR-MS

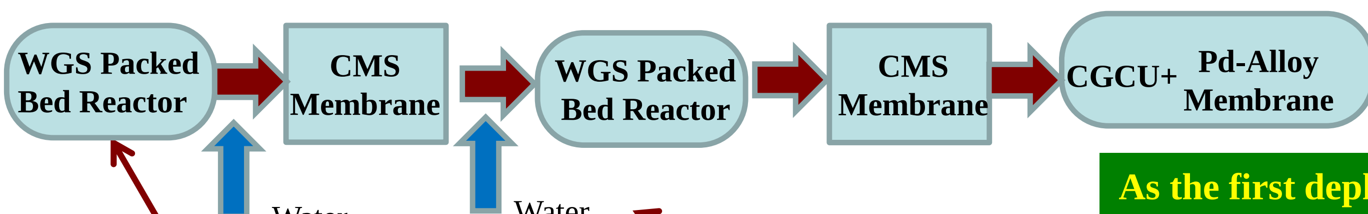
Area [m²]: 14,600 v. 16,500 (+12%)
CO_2 Recovery [%]: >90% (NC)
CO_2 Purity [%]: 93.5 to 94.5% (NC)

SCHEME 1
WGS/MR x n + Pd-Alloy Membrane



Based upon the operating condition of our proposed dual stage process, approximately 12% membrane surface area savings could be achieved with the integral membrane reactor according to our simulation.

SCHEME 2
(PBR + CMS Membrane) x n + Pd-Alloy Membrane



1. WGS PBR to pre-shift the syngas. Lose too much CO and H_2O to permeate in MR

2. Water injection for cooling due to reaction exotherm.

As the first deployment of such a membrane reactor process, we chose the series process scheme, which was also recommended by the industrial review panel.

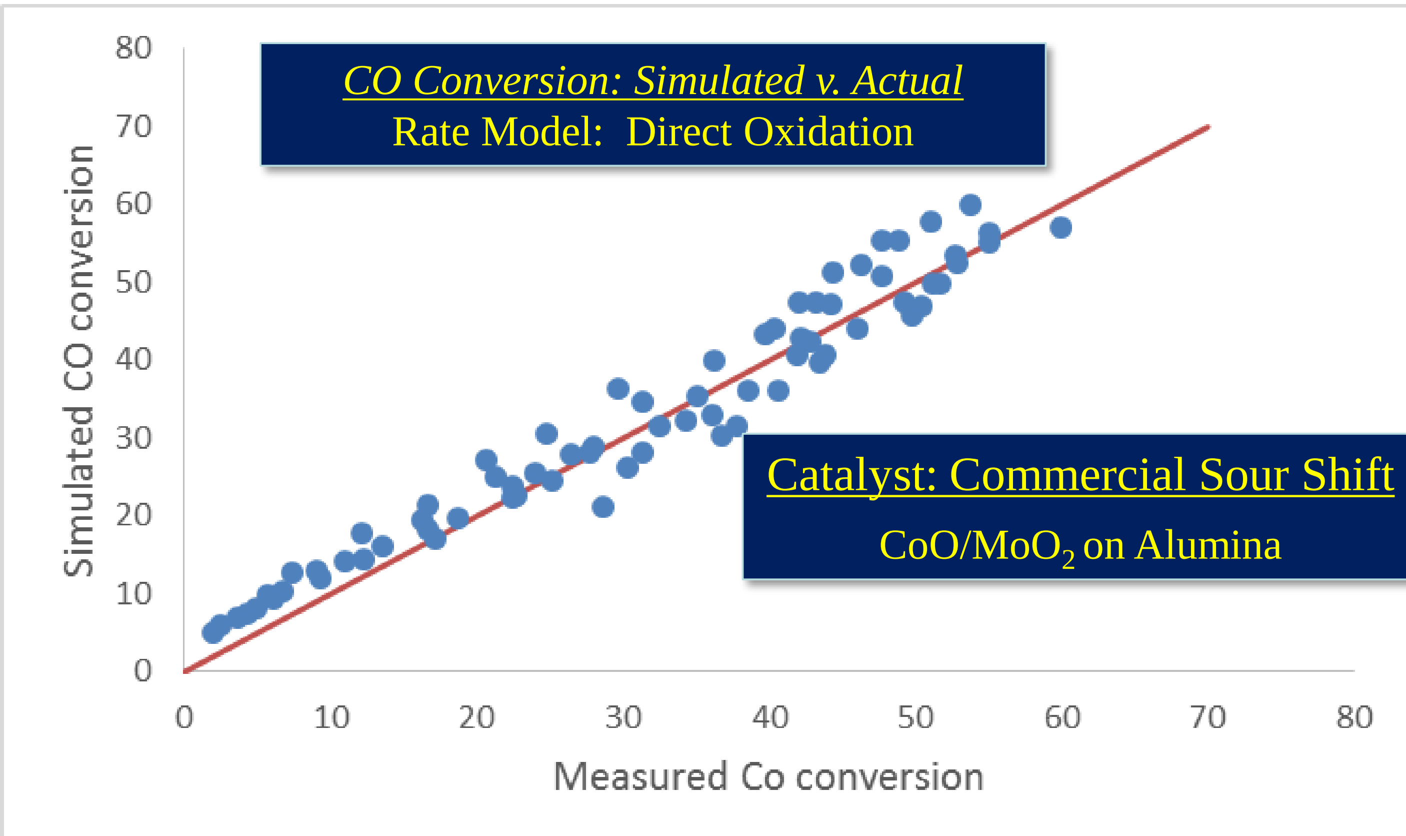
WGS-Membrane Reactor Model Development

WGS Reaction Kinetics at Elevated Pressure

Reaction Model Development

Operating Conditions: 220 to 300°C; up to 200psig

Rate Models: Formate Intermediate; Associative; Direct Oxidation



CO Conversion: Simulated v. Actual

Rate Model: Direct Oxidation

Catalyst: Commercial Sour Shift

CoO/MoO_2 on Alumina

Membrane Performance Model Development

Single Tube Mixed Gas Performance and Model Predictions

Membrane Model Development

CMS Membrane, 300°C, 200psig

Gas [-]	Feed Composition [vol%]	Mixed-gas Permeance [GPU]	Pure Gas Permeances [GPU]
H_2	28.2	**452**	**464**
CO	10.2	**10.2**	**10.2**
CH_4	8.2	**6.9**	**8.0**
CO_2	22.0	**16.8**	**17.5**
H_2S	0.48	**8.0**	**8.0**
H_2O	30.9	**343**	**372**

Typical Results for Single Tubes

1. Very good agreement with pure component data with single tubes.
2. Consistently see this in our laboratory with both CMS and Pd membranes.
3. Deviations observed at times but not common, not well understood.

MPT Single Tube CMS Membrane

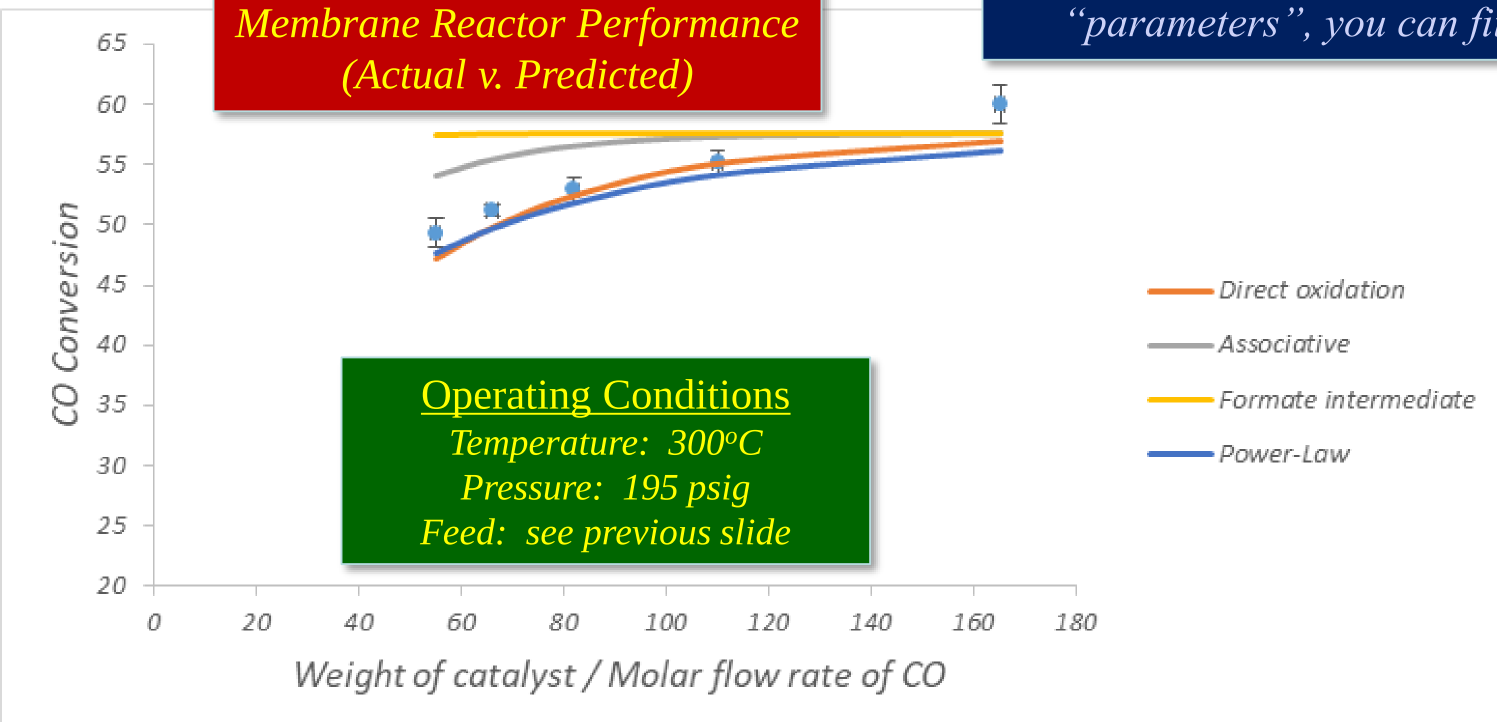
Candle Filter Configuration

WGS-Membrane Reactor Model

Combined Reaction and Membrane Models: Membrane Reactor

Membrane Reactor Module (Single Tube)

Membrane Reactor Performance (Actual v. Predicted)



Operating Conditions

Temperature: 300°C

Pressure: 195 psig

Feed: see previous slide

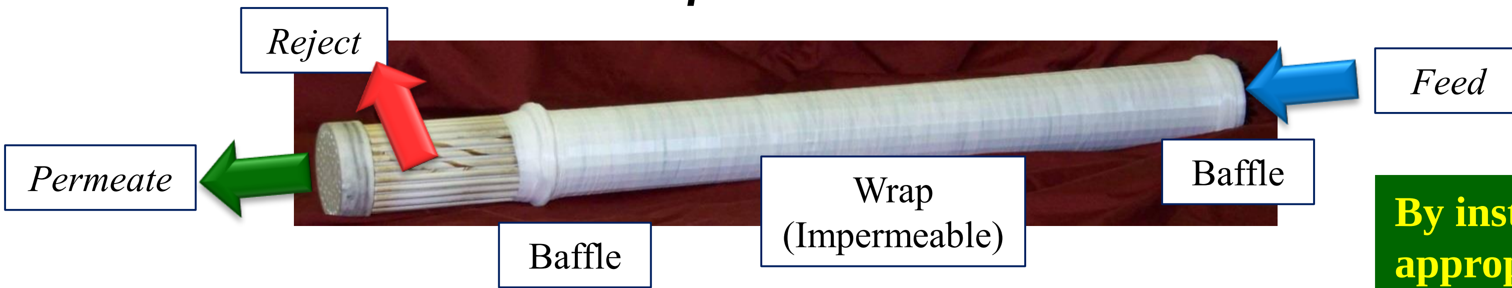
Predicted versus Actual Results

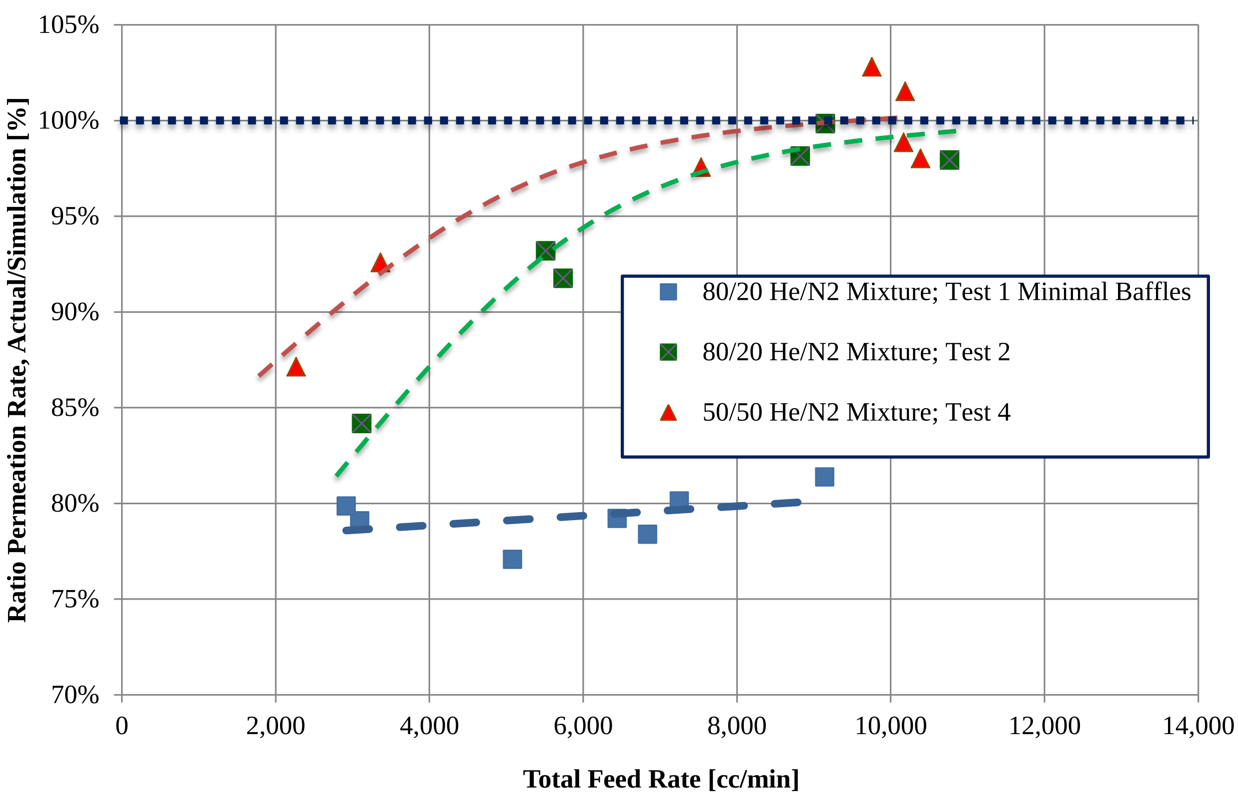
- ✓ *Very good agreement between model predictions and actual MR performance.*
- ✓ *DO mechanism superior model as expected from earlier kinetics study.*
- ✓ *Power law…if you add enough adjustable "parameters", you can fit any data set.*

Verification of Membrane Performance Modeling

Effect of Total Gas Feed Rate on Membrane Performance with Baffles

Ratio of Actual to Predicted Permeate Rates





By installing appropriate internal baffles, our mathematical model successfully predicted the gas separation performance for a multiple tube bundle *at a lower stage cut*, which is the most efficient operation model for a large scale operation.

MPT Dual Stage Membrane Process

Presentation Outline - Section 3

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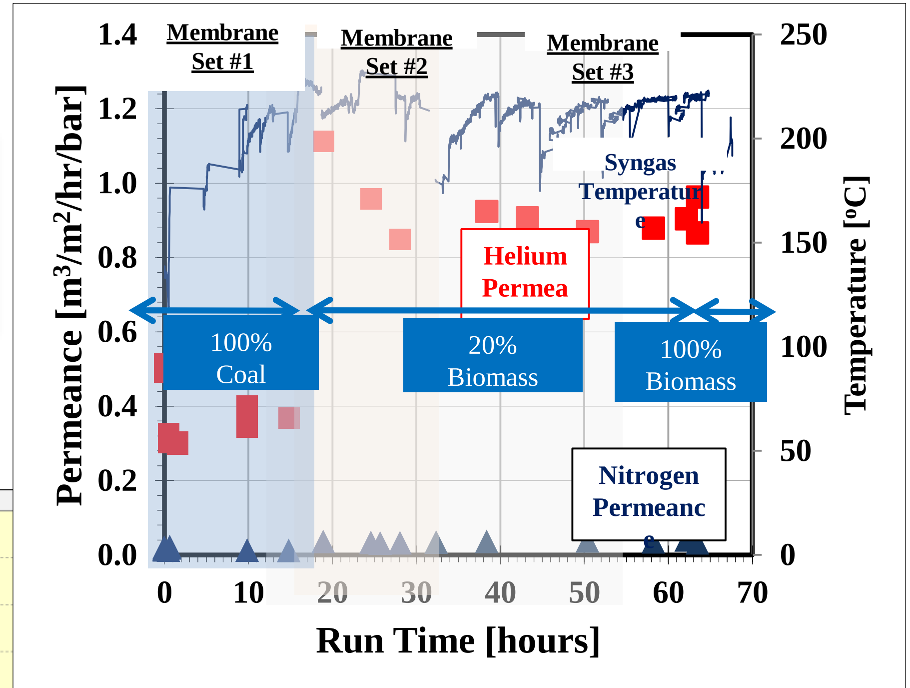
Our Previous Accomplishments in Field Tests at NCCC -1

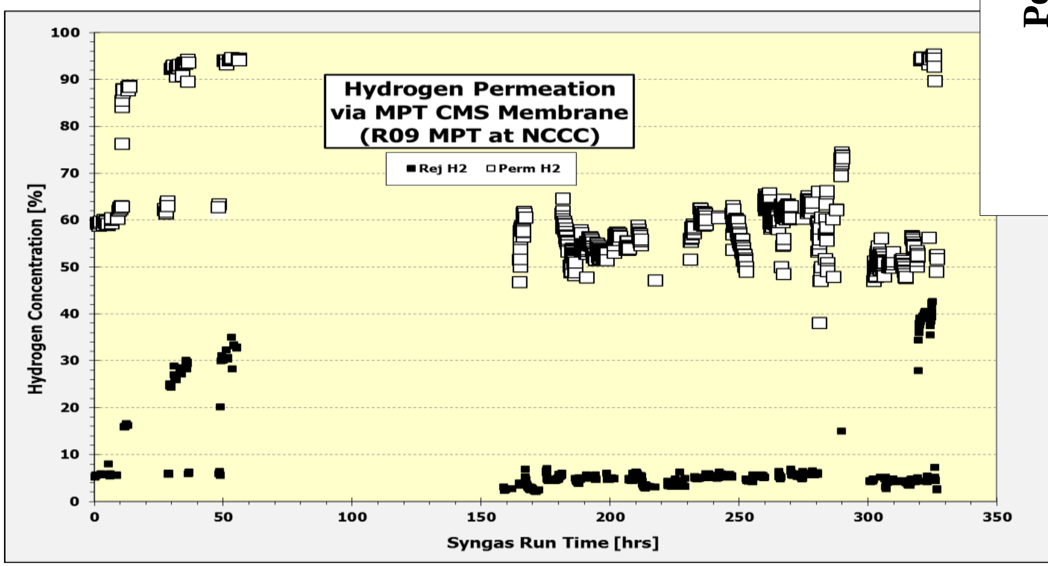
NCCC Testing: CMS Membranes Highly Stable in Coal Gasifier Syngas



Membrane Material Stability

CMS membrane shows high resistance to tar–like contaminants and sulfur at ≥250°C.

250°C and 250 psi Syngas with No Pretreatment



Membrane Perforamnce Stability

CMS membrane is stable with no pretreatment beyond particulate removal for a variety of gasifier feedstocks.

Our Previous Accomplishments in Field Tests at NCCC -2

NCCC Testing: CMS Bundles Highly Stable in Coal Gasifier Syngas

Testing Parameters

Membrane
86-tube CMS

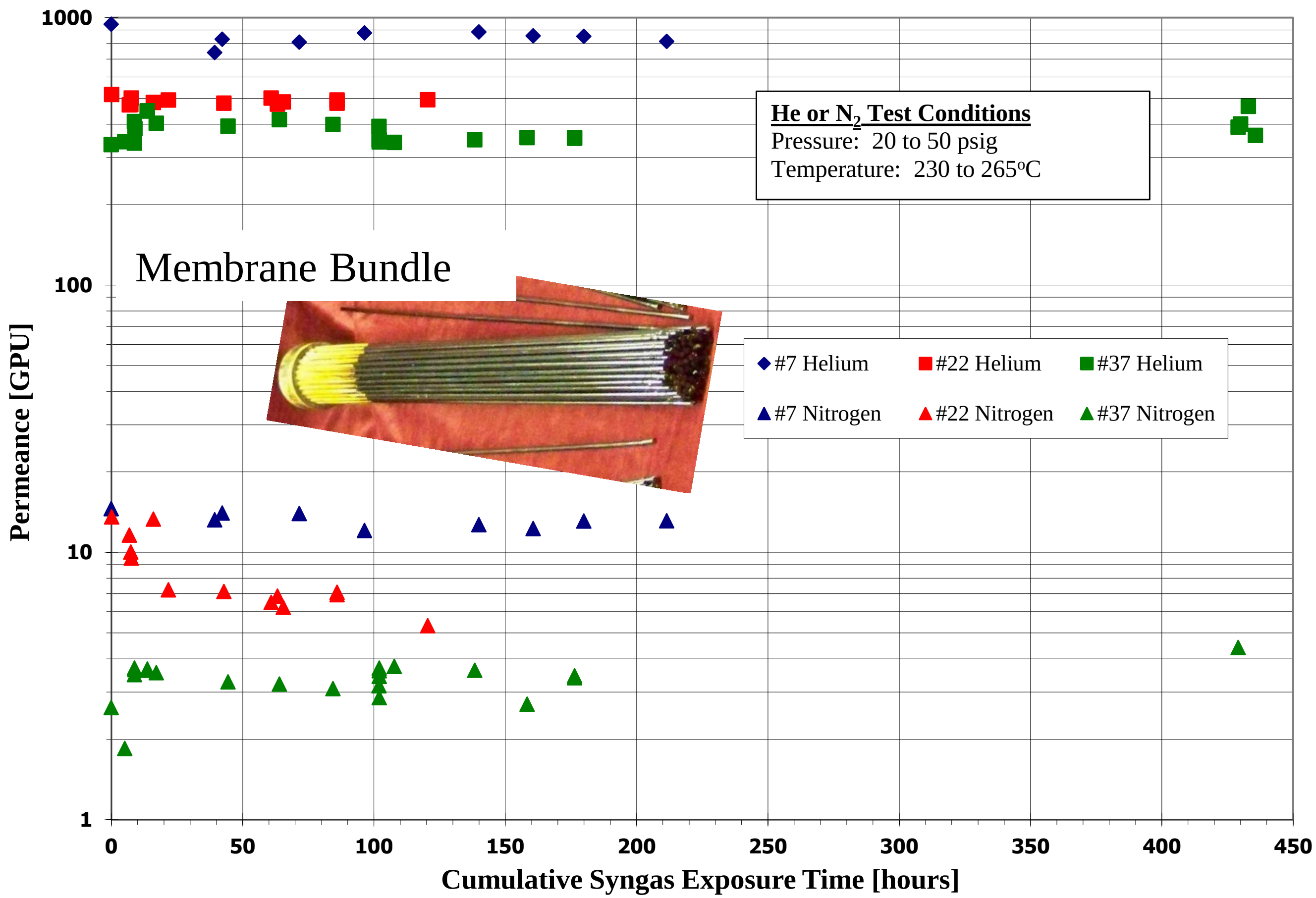
Operating Conditions
T~ 250 to 300°C
P~ 150 to 300 psig

Pretreatment
Particulate trap only, no other gas cleanup.

Composition
H_2 ~ 10 to 30%
CO ~ 10%
CO_2 ~10%
N_2,H_2O ~Balance

Trace Contaminants
NH_3 ~ 1,000ppm
Sulfur Species ~ 1,000ppm
HCl, HCN, Naphthalenes/Tars, etc.

NCCC Slip Stream Testing: No gasifier off-gas pretreatment



Performance stability of multiple tube CMS membrane bundles during H_2 recovery from NCCC slip stream testing. He and N_2 Permeances measured periodically during >400 hr test.

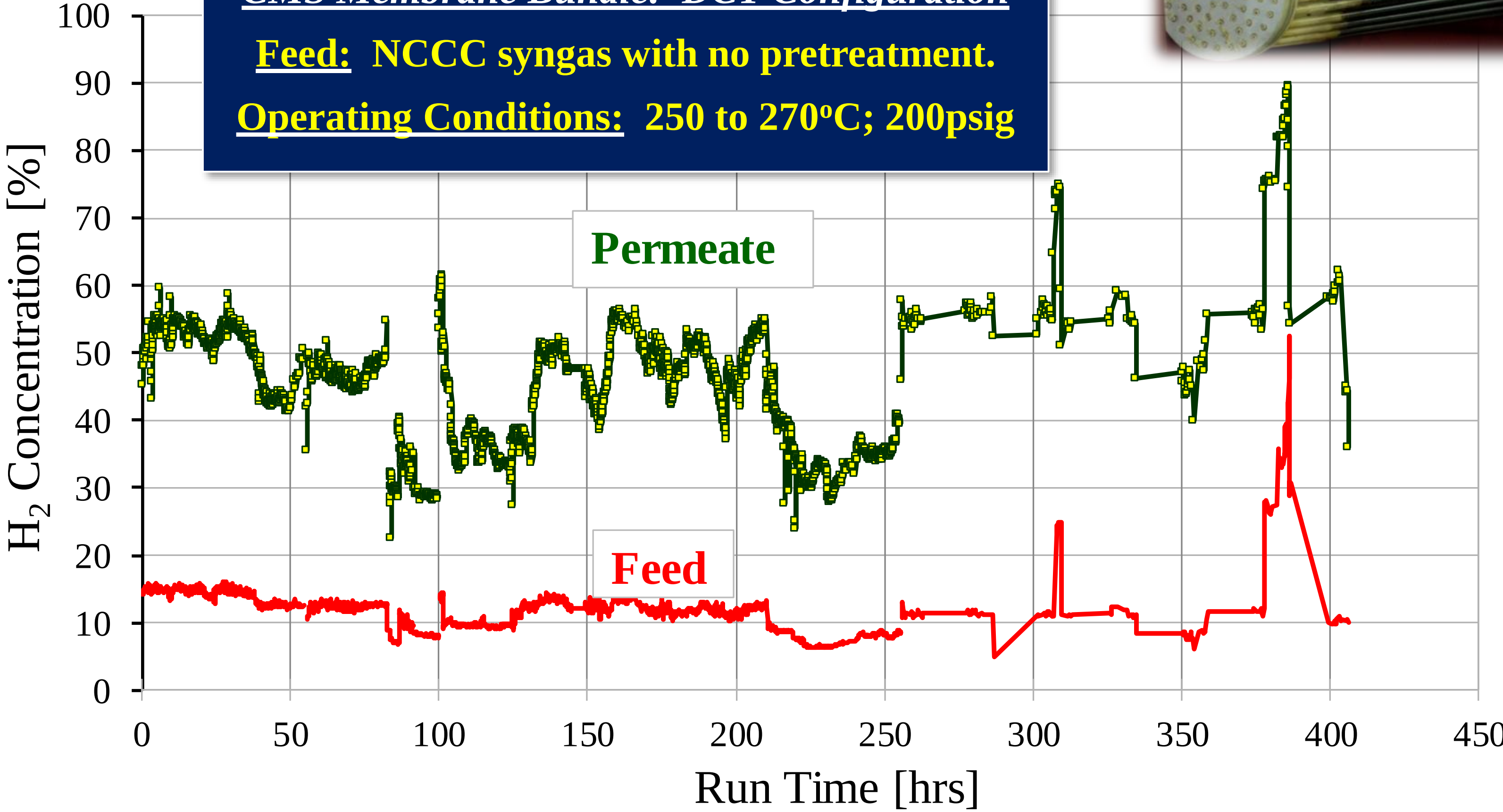
NCCC Testing: Dual Stage Membrane Process

Physical Integrity Test of CMS 57-Tube DCT Style Bundle

CMS Membrane Bundle: DCT Configuration

Feed: NCCC syngas with no pretreatment.

Operating Conditions: 250 to 270°C; 200psig



Through the >400 hrs testing at NCCC, the permeate composition is kept at relatively stable, indicating the physical integrity of the CMS membrane in the DCT style bundle.

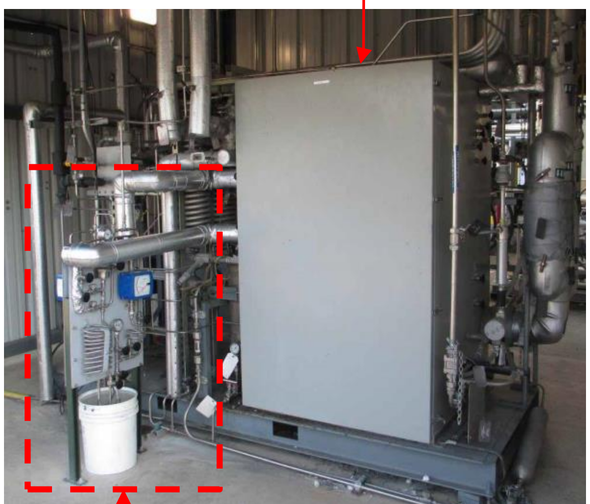
NCCC Testing: Predicting Membrane Performance

NCCC Testing: Improve Prediction of Membrane Performance

In-situ real time water composition analysis required

Added water capture units prior to recent NCCC testing round.

Membrane Test Cabinet



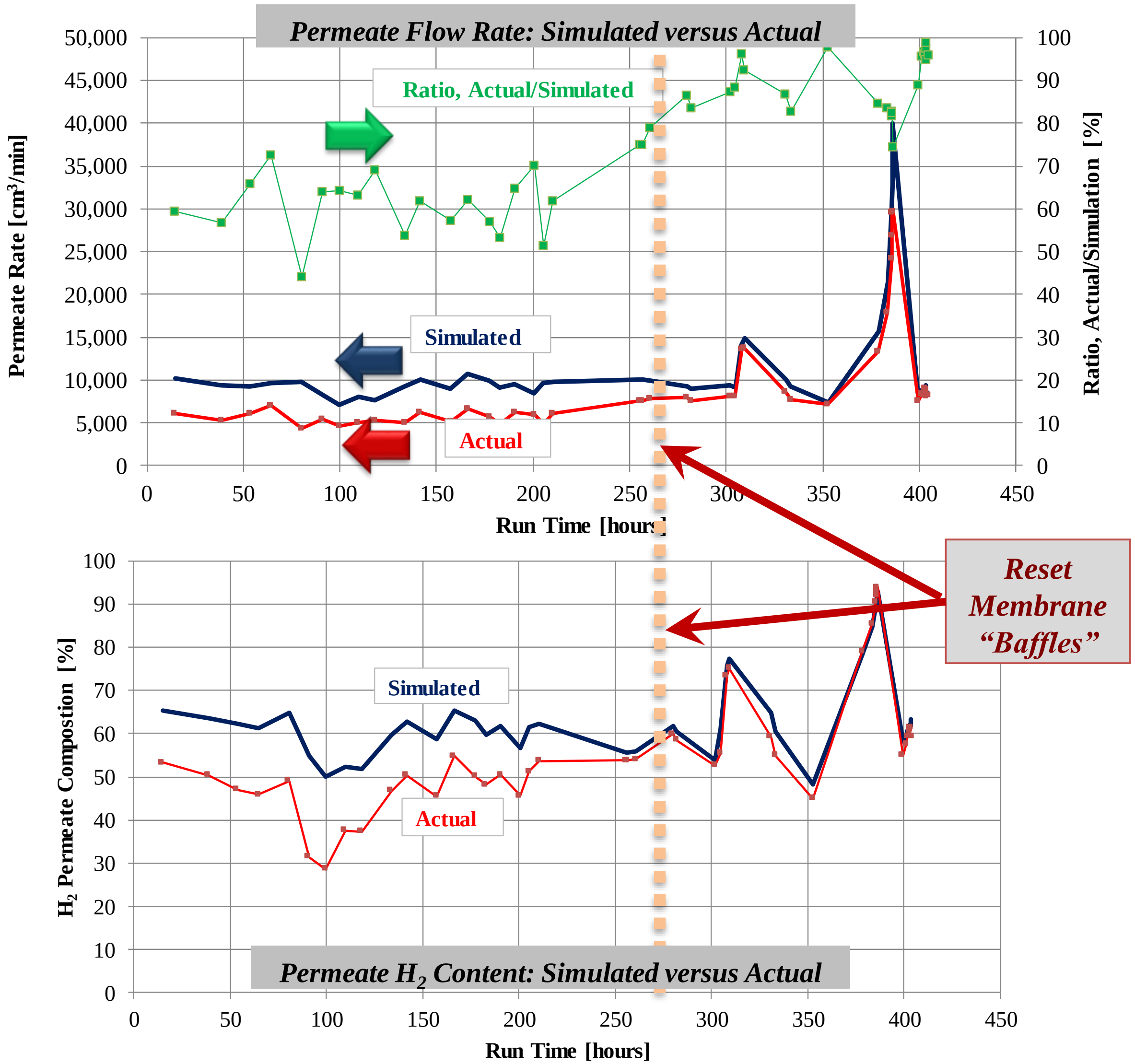
Water Capture Units

	NCCC Determined Raw Syngas Water	NCCC Shifted Syngas Water Content		MPT Water Collection Units				NCCC GC Dry Gas Mass Closure
				%	%	MPT Calculated %	NCCC/MPT Water Closure	
Time	%	WGS In	WGS Out	Perm	Reject	WGS Out	[%]	[%]
		22.3%	15.2%	51.8%	5.1%	11.6%	136.7%	101.8%
Day 1	6.2	16.2%	8.5%	39.5%	5.7%	8.8%	103.9% ✓	105.1%
		12.3%	4.3%	23.5%	3.6%	5.2%	123.3% X	102.0%
		12.3%	4.3%	16.1%	3.6%	4.5%	106.3% X	102.0%
		10.5%	6.6%	36.7%	2.2%	5.1%	77.5% X	107.1%
Day 2	8.4	10.6%	6.7%	23.2%	5.3%	6.5%	96.4% ✓	101.7%
		10.4%	6.4%	22.6%	9.1%	9.9%	154.4% X	101.6%
		10.5%	6.5%	28.6%	6.5%	7.9%	120.5%	101.6%
		10.4%	6.6%	27.3%	6.2%	7.4%	112.1% X	101.7%
		10.5%	6.6%	23.3%	7.0%	7.9%	119.6% X	101.2%
Day 3	8.1	7.5%	2.5%	19.9%	5.5%	6.6%	267.2% ?	99.5%
		7.5%	2.6%	37.2%	13.3%	15.1%	581.8% X	108.2%
Day 4	5.3	5.0%	1.7%	23.5%	0.2%	1.6%	98.4% ✓	102.3%
		5.0%	1.7%	13.6%	0.9%	1.5%	91.7% X	102.3%
Day 5	8.0	7.4%	2.7%	31.1%	0.6%	2.6%	98.5% ✓	103.0%

1. *Good agreement with NCCC "once per day" water content determinations.*
2. *Substantial water content variability outside this "once per day" window.*
3. *We now can determine accurate real time water composition in the membrane feed.*

CMS Membrane Performance Model Verification at NCCC

NCCC Testing: DCT-Style 57-tube CMS Membrane Bundle

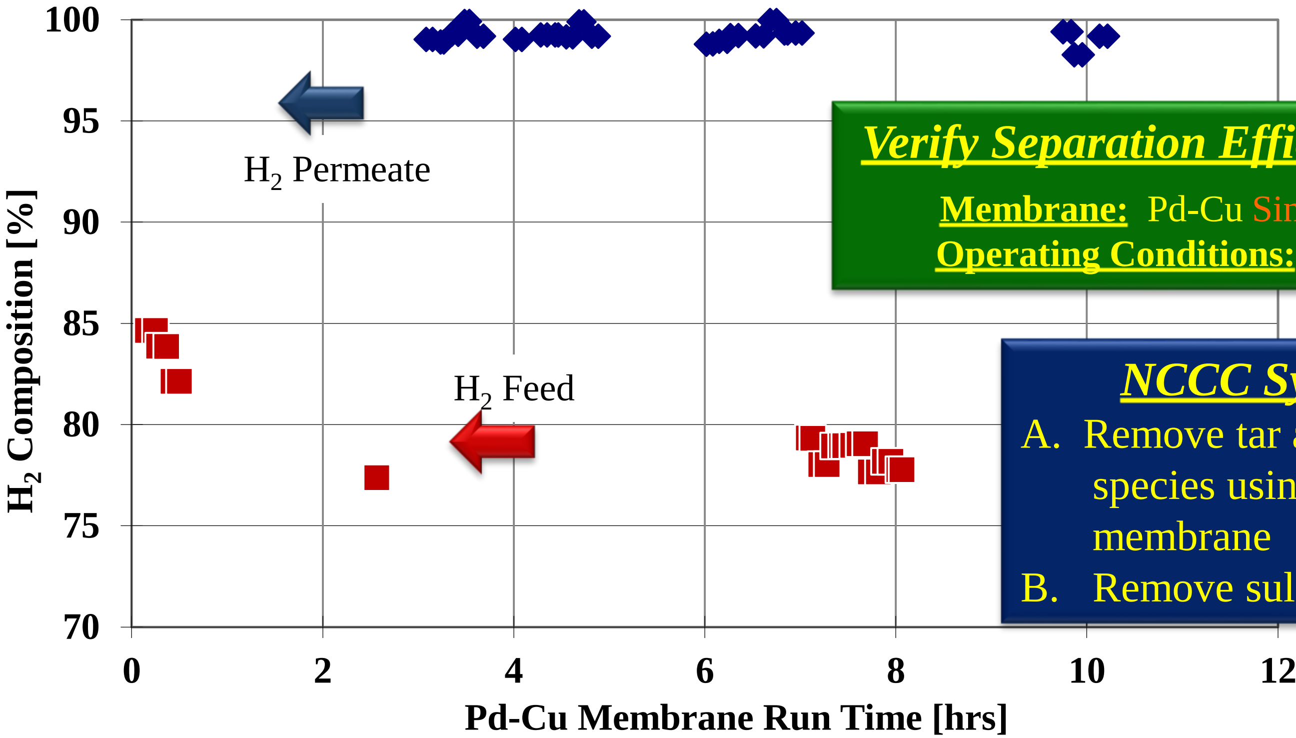


Actual v. Simulated Results

NCCC bundle test results indicate that the mathematical model prediction is consistent with the permeate composition obtained from NCCC with proper feed flow baffles and accurate gas phase (water) composition analysis.

Pd Alloy Membrane Challenge Testing at NCCC

Asymmetric Pd-alloy Membrane for Residual H_2 Recovery (Single Tube)



Verify Separation Efficiency at the NCCC

Membrane: Pd-Cu Single Tube, 24” length
Operating Conditions: 250°C, 25 to 45psig

NCCC Syngas Pretreatment

A. Remove tar and high molecular weight species using permeate from a CMS membrane
B. Remove sulfur via ZnO bed

Our Pd alloy membrane has demonstrated its ability to deliver high purity hydrogen from a “clean” syngas stream, indicating its stability for recovery of residual hydrogen in our two stage membrane process.

MPT Pd and Pd Alloy Challenge Testing at NCCC

Pd and Pd-alloy Bundles for Residual H_2 Recovery

Preliminary Membrane Performance

DCT-Style 12-tube Pd and Pd-Ag Membrane Bundles

Bundle integrity test is critical to the technical viability of an assymetric membrane, such as Pd thin film supported on ceramic substrate.

Preliminary Characterization Data

Membrane ID	Permeance [GPU]		H_2/N_2
	N_2	H_2	
Pd-DCT-3	3.8	4,170	1,100
Pd-DCT-7	2.0	3,620	1,810
PdAg-DCT-28	2.5	5,180	2,030

Pd Alloy Membrane Challenge Testing at NCCC

NCCC Testing: In-situ Membrane Bundle Performance

Testing Parameters

Membrane
12-tube Pd and Pd/Ag

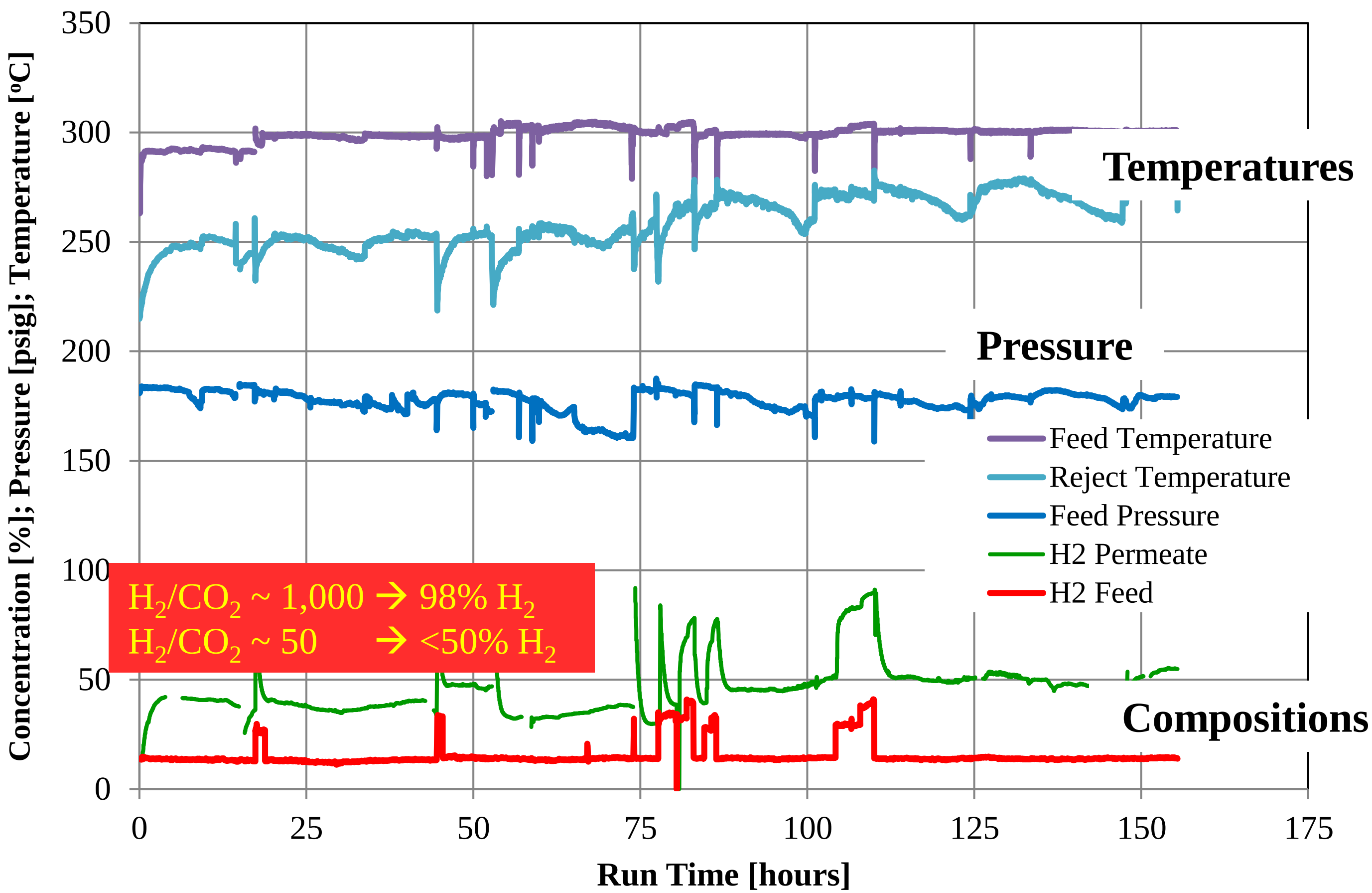
Operating Conditions
T~ 250 to 300°C
P~ 180 psig

Pretreatment
Sulfur removed
Sweet Shifted

Feed Composition
H_2 ~13% (spikes to ~30%)
CO ~ 1%
CO_2 ~15%
N_2,H_2O ~Balance

Trace Contaminants
Sulfur Species ~ 0ppm
NH_3 ~ 1,000ppm
HCl, HCN,
Naphthalenes/Tars, etc.

Slip Stream Testing with Sweet Shifted Gasifier Off-gas



The Pd and Pd alloy membrane bundles maintain their physical integrity through >150 hrs of cumulative testing at the NCCC.

Poison of Pd Membranes with Tar-containing Syngas

Summary of In-situ (NCCC) and Ex-situ Performance and Regeneration

Membrane ID	**Permeance [GPU]**		**H_2/N_2**
	N_2	H_2	
Pd-DCT-7 (pre-NCCC)	**2.0**	**3,620**	**1,810**
Pd-DCT-7 (in-situ NCCC)		*<300*	<50
Pd-DCT-7 (pure gas, periodic during NCCC test)	<2.0	400 to 500	<250
Pd-DCT-7-2 (lab, single tube, post-NCCC)	2.5	860	340
Pd-DCT-7-2 (lab, single tube, regenerated)	2.7	3,850	1,425

1. Performance decay is due to H_2 permeance reduction.
2. No membrane damage.
3. Fouling is reversible with regeneration.

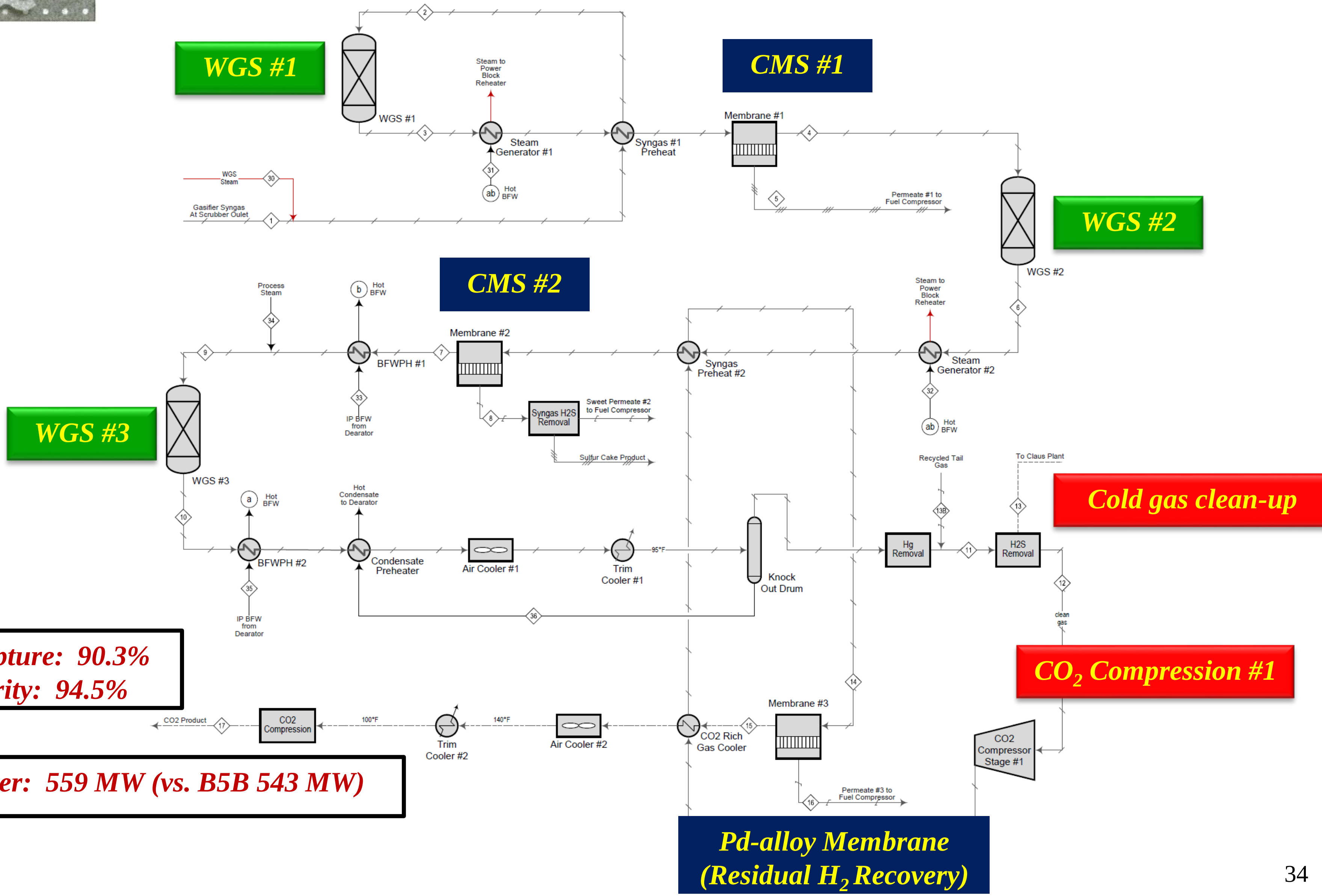
MPT Dual Stage Membrane Process

Presentation Outline – Section 4

SECTIONS	SUB-SECTIONS	SPECIFIC TOPICS
1. Membranes	a. Carbon Molecular Sieve (CMS) Membranes	Permeance & Selectivity
		Thermal & Material Stability
	b. Palladium(Pd) Alloy Membranes	Permeance & Selectivity
		Material (Thermal + H_2) Stability
	c. Bundles & Housing	Bundle Engineering & Configuration
2. Process	a. Integrated Membrane Reactor or in Series	Process Configuration
	b. Modeling and Process Simulation	Mathematical Modeling
		WGS Reaction Kinetic Study
3. Field Tests	a. Previous Tests with 1st Gen CMS Bundle	Performance and Stability
	b. Current test with 2nd Gen CMS Bundle	Long Term Material Stability
	c. Verification of Model Prediction	Field Obtained Data vs Prediction
	d. Pd Membranes & Bundles	Performanc and Stability
	e. Pd Membrane Poisoned by Tar	Regeneration & Activity Restroation
4. TEA/EHS	a. Proposed Process Scheme	Block Flow Diagram
	b. Techno-economic Analysis (TEA)	Costs of Power & Carbon Capture
	c. TEA Sensitivity Analysis	Impact of Membrane Selectivity & Configuration
	d. Environmental, Health and Safety Analysis (EHS)	Evaluation on Key Separation and Manufacturing Processes

Techno-economic Analysis (TEA)

Dual Stage Membrane Process Flow Diagram



CO_2 Capture: 90.3%
CO_2 Purity: 94.5%

Net Power: 559 MW (vs. B5B 543 MW)

Techno-economic Analysis (TEA)

Process Performance and Economics

Parameter	Baseline Case B5B*	MPT B5M-HP	Target	MPT vs B5B
Carbon Capture	90.0%	90.3%	90%	
CO_2 Purity	99.48%	94.5%	95%	
H_2 in Fuel	99.98%	98.7%	NA	
Net Power Production, MW	543	559	N/A	+3.0%
Cost of CO_2 Captured [$/tonne]	63.1	58.2	N/A	-8.0%
Cost of CO_2 Avoided [$/tonne]	91.6	82.0	N/A	-10.6%
COE no T&S [$/MWh]	135.4	130.1	N/A	-3.9%
Total as-spent Cost [$/kW]	4,782	4,621	N/A	-3.4%

* *Cost and Performance Baseline for Fossil Energy Plants. Volume 1b. Revision 2b, July 2015. DOE/NETL02015/1727. GEE IGCC with 2-stage Selexol*

Techno-economic Analysis: Sensitivity

Basic Approach and Concepts

Objective	Problem	Impact
Carbon Loss <10%	CMS permeates CO and CO_2	Miss Sequestration Target
Minimize Parasitic Loss: H_2 Fuel Compression	H_2 needs compressed (460psig) to the CT	Increased COE; Plant Size
Minimize Parasitic Loss: Steam Lost to Permeate	CMS permeates water Need makeup steam to WGS = Power loss at the ST	Increased COE; Plant Size

Techno-economic Analysis (TEA) Sensitivity

Sensitivity Considerations – 2011 Base Dollar

Case	Comments	Net Power Output [MWe]	Net Increase v. B5B [MWe]	Total COE no T&S [$/MWhr]	COE Increase v. B5A [$/MWhr]	Cost CO_2 Capture v. B5A [$/tonne]	Cost CO_2 Capture v. 12A [$/tonne]
MPT Base Cases							
MPT #2: B5M	2015 Base Case	554	11	134	31.4	38.2	62.9
MPT Sensitivity Cases (Demonstrated Performance)							
MPT #2: B5M-HP	2017 Optimized Permeate Pressu	559	16	130.1	27.5	33.5	58.2
MPT #3: B5M-HP.Sensitivity #1	Raise H2/CO2; Optimize Pressure	560	17	129.9	27.3	33.2	57.9
MPT Sensitivity Cases (Technical Challenge)							
MPT #4: B5M-HP.Sensitivity #2	Raise H2/H2O	569	26	127.8	25.2	30.7	55.4
MPT #5: B5M-HP.Sensitivity #3	N_2 Sweep CMS	569	26	127.8	25.2	30.7	55.4
MPT #6: B5M-HP.Sensitivity #4	N_2 Sweep Pd	572	29	127.1	24.5	29.9	54.6
MPT #7: B5M - Maximum Potential	No H2 Comprs; No steam loss	585	42	122.3	19.7	24.0	48.7
IGCC Base Cases							
IGCC Base Case (B5A)		622	NA	102.6	Base	Base	NA
IGCC Base Case with CCS (B5B)	2-Stage Selexol	543	Base	135.4	32.8	38.9	63.0
Conventional Base Cases							
Pulverized Coal, SC, Base (12A)		622	NA	82.3			NA
Pulverized Coal, SC w/CCS (12B)	2-Stage Selexol	550	NA	133.2			58.2

According to our sensitivity analysis, approx. 15% cost reduction in CO_2 capture (in comparison with the base case of IGCC with CCS) can be achieved with our existing technology and the proposed process. With the introduction of the “purge-able” module, up to 39% reduction in CO_2 capture cost can potentiall be achieved.

Environmental, Health and Safety (EH&S) Analysis

Our Approach

Our Approach

- **<u>Assess</u>** all major risks from product fabrication to final decommissioning/end of life.
- **<u>Identify Severity</u>** of a potential hazard for each major steps involved in our proposed process was evaluated with respect to **Environment & Health**, **Flammability**, or **Instability** **e**xposures.
- **<u>Predict Probability</u>** of the potential hazard occurrence.

Risk = f (Likelihood , Severity)

SEVERITY				
4	4	8	12	16
3	3	6	9	12
2	2	4	6	8
1	1	2	3	4
0	0	0	0	Review Instability
	1 Extremely Improbable	2 Extremely Remote	3 Remote	4 Probable
	PROBABILITY			

Risk Category

- "Minor" Risk
- "Major" Risk
- "Hazardous" Risk
- "Catastrophic" Risk

Risk ID	Risk Description	Severity		Liklihood	Safety Matrix*	Risk Mitigation Strategy/Comments
Membrane Production						
5A.102a.04	Methanol handling, and evaporation	Environment & Health	1	4	4	No extraordinary use. Common industrial chemical; standard handling and drying practice consistent with eg: paint finishing. Work under well-ventilated environment or with exhaust is recommended.
		Flamability	4	4	16	No extraordinary use. Common industrial chemical; standard handling and drying practice consistent with eg: paint finishing. Work under well-ventilated environment or with exhaust is recommended.
		Instability	0	1	0	

Environmental, Health and Safety (EHS) Analysis

Key EH&S Risks Identified in Our Proposed Dual Stage Process

Catastrophic Category

- CMS membrane subsystem: use of solvent methanol in the preparation of the carbon precursor.
- Pd membrane subsystem: use of hydrogen for membrane annealing.

Since methanol and hydrogen use are common in the industrial material preparation, their risk mitigation approaches are well established and readily available.

Hazardous Category

- CMS membrane subsystem: 5 areas
- Pd membrane subsystem: 3 areas

Primarily associated with the exposure to vapor emitted during the membrane material preparation.

Industrial standard practice in ventilation, exhaust collection and discharge is considered adequate.

Major Category (membrane process specific)

- The stability of the membrane seal through the long-term exposure.
  - ✓ *Our mitigation approach includes installation of the monitoring device during operation and implementation of regular maintenance. Thus, early detection can be identified and corrective actions can be taken timely.*
  - ✓ *Though "major" risk is assigned to the membrane seal according to our analysis, its impact to the operation is considered to be minor due to the "gradual" versus "sudden" failure mode.*

Conclusion: Thus, there is no reason to believe that a production process meeting the EH&S satisfaction cannot be established to commercialize the proposed technology and process.

MPT Dual Stage Process for IGCC with CCS

Conclusions

- **Meet the CCS Targets.** Synergy of the proposed Dual Stage Membrane (CMS and Pd-alloy) process meets or exceeds the performance targets required to deliver the DOE CCS goals.
- **Long Term Membrane Stability.** The CMS (250^{o}C) and Pd-alloy (350^{o}C) membrane tubes and bundles (full ceramic) have been demonstrated to be stable in thousands of hours of thermal stability testing.
- **CMS Membrane Highly Stable in Gasifier Off-gas at the NCCC.** The CMS membrane bundle has been shown to be stable in various tests for hundreds of hours of exposure to synthetic and actual coal gasifier syngas with only particulate pretreatment.
- **Pd/Pd-alloy Membrane Undamaged at NCCC.** The Pd/Pd-alloy membrane is not damaged at the NCCC in sulfur free off-gas. Fouling occurs on exposure to "tar" like species which will not be present in the proposed process downstream of the Cold Gas Cleanup Unit.
- **Extreme pressures.** >1,000psig can be achieved with our DCT-style bundles making them suitable for the proposed IGCC with CO_2 capture environment.
- **Power Production Increased.** Base Case net power production for the process is 553MWe, 1.8% above the NETL base case. Optimization can boost this by +6 to +18 MWe (+2.9 to 5.2%). Base Case total capital cost for the process is $32MM (3%) below the NETL base case.
- **CO_2 Capture Cost.** About 15% reduction in comparison with the base case of IGCC/CCS. Sensitivity analysis indicates that ~39% reduction can potentially be achieved with the introduction of a purge-able membrane module

Project Overview

Summary of Progress on Project Milestones and Success Criteria

ID	Milestone Description and Success Criteria	Comment
A	Generation of performance database. (Show >90% CO conversion and >70% H_2 recovery at target operating conditions).	*Completed.*
B	Verification of the mathematical model. (Demonstrate model deviation from actual performance <20%).	*Completed.*
C	Operation under extreme pressure.	*Completed.*
D	Conceptual design of the CMS/MR. (Complete conceptual design of the WGS/MR).	*Completed.*
E	Field test on real syngas. (Conduct >720 hours of actual syngas testing).	*Completed.*
F	Design and Engineering Analysis. (Complete the process design for >90% capture and 95% purity).	*Completed.*
G	Economic and Environmental Analysis. (Complete the TEA and EHS)	*Completed.*

ID	Milestone Description	Comment
RC1	Add partner with power plant expertise.	*Completed.*
RC2	Down-select WGS and membrane configuration.	*Completed.*
RC3	Down-select from N_2 purge option based upon technical feasibility.	*Completed.*
RC4	Down-select Pd-Cu or Pd-Ag for bundle NCCC testing.	*Completed.*
RC5	Consider Pd material potential supply problems.	*Completed.*

Point State Details

Summary of CMS Membrane Point State - 2017

	Units	Value
Materials Properties (CMSM)		
Materials of Fabrication for Selective Layer	—	Carbon Molecular Sieve (CMS)
Materials of Fabrication for Support Layer	—	Alumina
Nominal Thickness of Selective Layer	µm	2 to 3
Membrane Geometry	—	Tubular
Max Trans-Membrane Pressure	Bar (psig)	Tubes: >75 (1,100) DCT Tube Sheet: >75 (1,100)
Hours Tested Without Significant Degradation	—	Single Tube Thousands of hours in various challenge conditions (steam, H_2S, vapors, etc). Multiple Tube (50 to 85) Bundles >16,000 hours in thermal stability testing >1,000 hours in untreated coal gasifier off-gas
Manufacturing Cost for Membrane Material	$\$/m^2$	<750
Membrane Performance (CMSM)		
Temperature	°C	250 to 300
H_2 Pressure Normalized Flux	GPU or equivalent	H_2: 550 to 900
H_2/H_2O Selectivity	—	2 to 4
H_2/CO_2 Selectivity	—	>50
H_2/H_2S Selectivity	ppm	>100
Type of Measurement	—	Mixed gas

Point State Details

Summary of Pd Alloy Membrane Point State - 2017

	Units	Value
Materials Properties (Pd membrane)		
Materials of Fabrication for Selective Layer	—	Pd-Ag Alloy
Materials of Fabrication for Support Layer	—	Alumina
Nominal Thickness of Selective Layer	µm	2 to 5
Membrane Geometry	—	Tubular
Max Trans-Membrane Pressure	Bar (psig)	Tubes: >75 (1,100) DCT Tube Sheet: >75 (1,100)
Hours Tested Without Significant Degradation	—	Single Tube >35,000 hours in thermal stability challenge test. Multiple Tube (12) Bundles 150 hours in pre-treated coal gasifier off-gas
Manufacturing Cost for Membrane Material	$/m^2	<1,200
Membrane Performance (Pd-alloy membranes)		
Temperature	°C	250 to 400
H_2 Pressure Normalized Flux	GPU or equivalent (at 20 psig)	2,000 to >5,500
H_2/H_2O Selectivity	—	1,000 to >5,000
H_2/CO_2 Selectivity	—	1,000 to >5,000
H_2/H_2S Selectivity	ppm	NA
Type of Measurement	—	Mixed Gas