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

DE-FE0013064

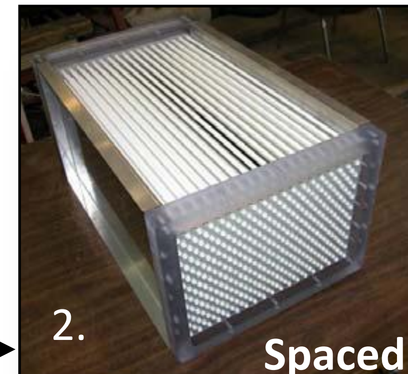
- Dr. Paul KT Liu, Media and Process Technology Inc.
  1155 William Pitt Way, Pittsburgh, PA 15238
- Professor Theo T. Tsotsis, University of Southern California
- Dr. Eric C. Wagner, Technip Stone & Webster Process Technology, Inc.

MPT Commercial Ceramic Membranes

Various Multiple Tube Elements – versatile, low cost

Single tubes

Ex: conventional MF & UF



Ex: porous heat exchangers & catalytic membrane reactors

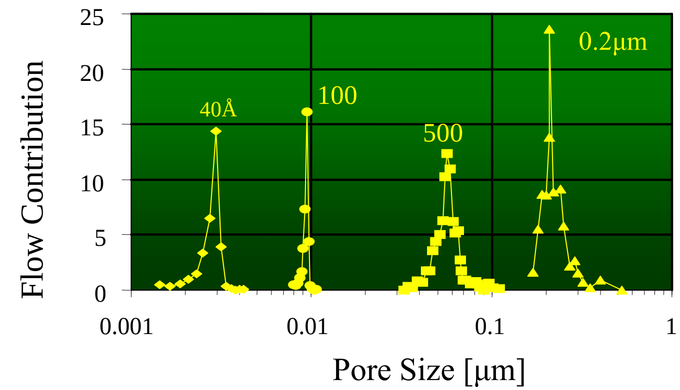
Ex: high pressure intermediate temperature gas separations

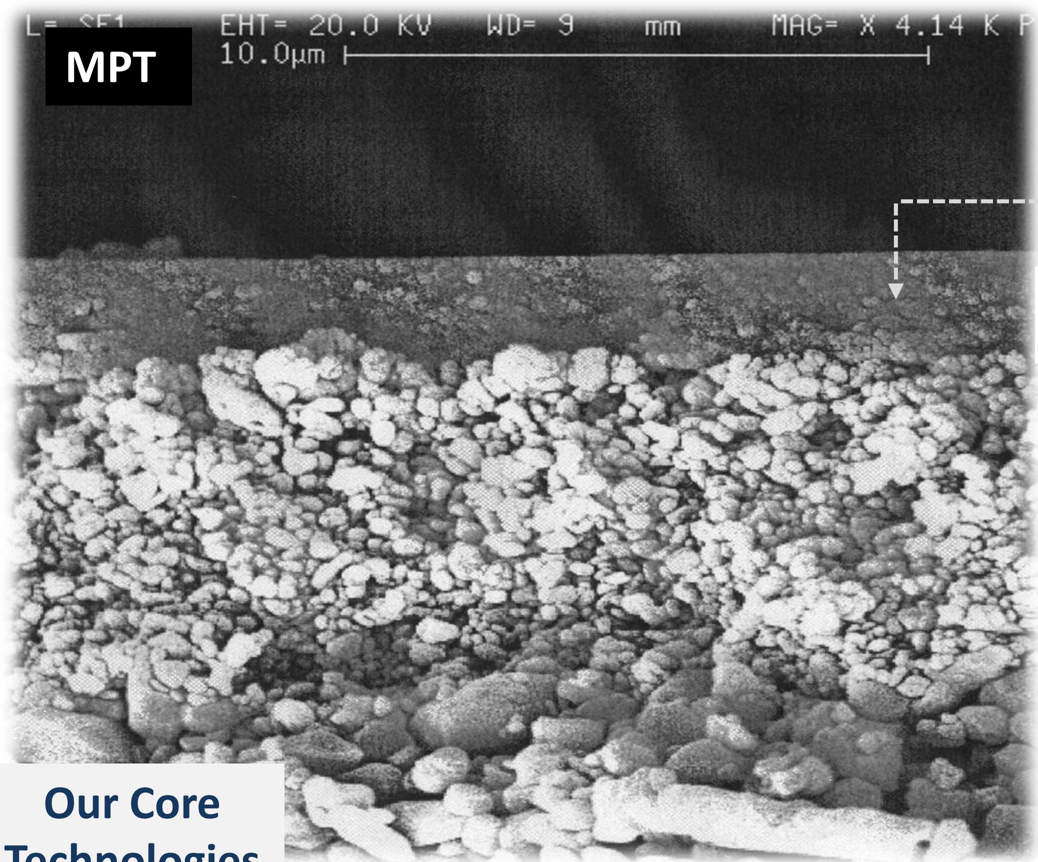
Our Core Technologies

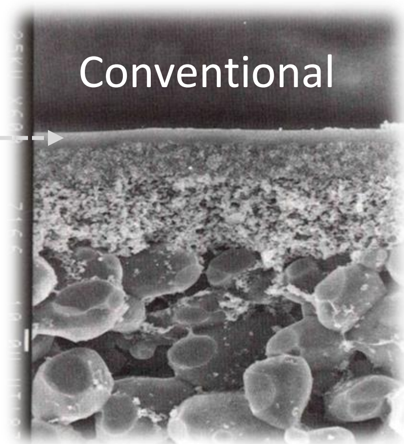
1. Packaging membrane tubes into commercially viable modules for field use.

MPT Commercial Ceramic Membranes

Our Low Cost vs Conventional Expensive Tubular Substrate







Our Core Technologies

2. depositing a near perfect thin film on less-than desirable, but low cost porous substrate.

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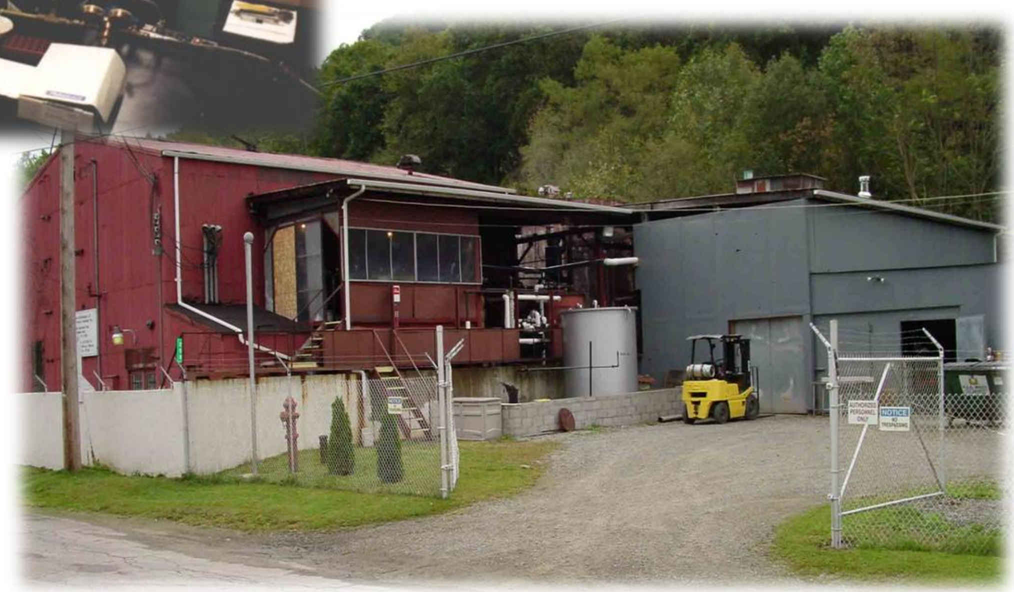
Our Facilities

R&D Facility
Pittsburgh, PA

Production/ Field Testing Facility
Leechburgh, PA



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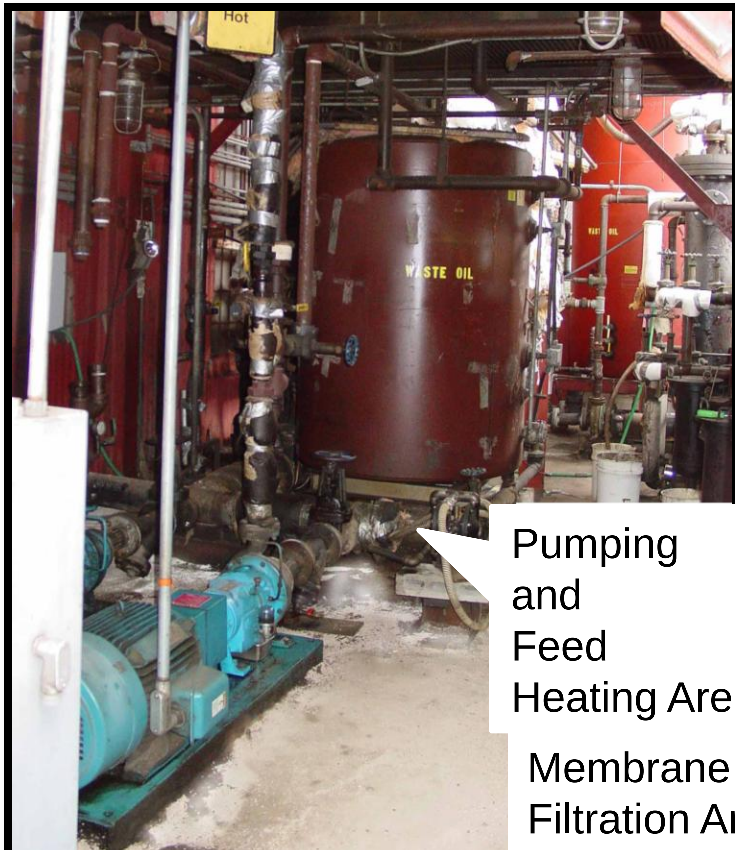
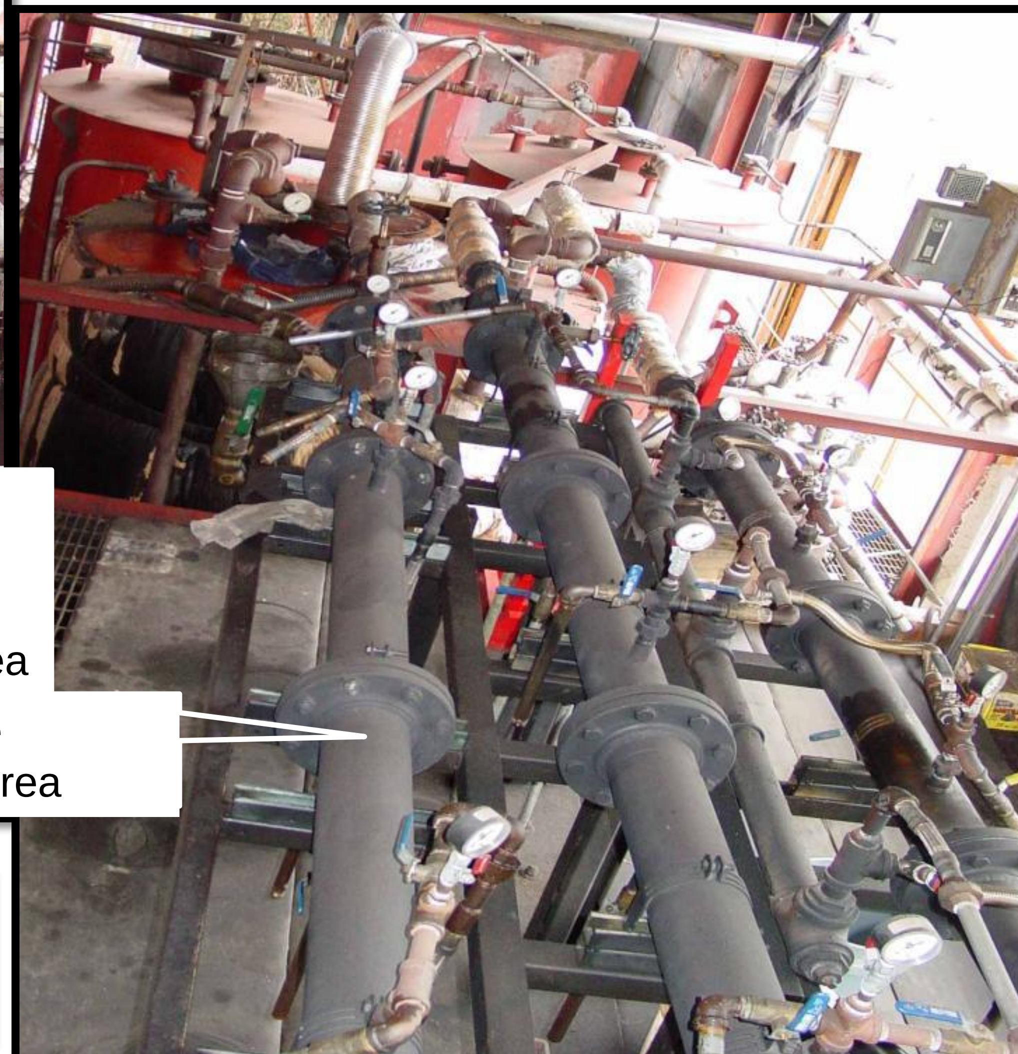
Waste Motor Oil Filtration for Recycle and Reuse using MPT Ceramic Membrane





Our ceramic membrane performs effectively at 25-200°C and >100 psi for liquid filtration.

Our Ceramic Membrane-based Process as End-of-The-Pipe Treatment

an effective, economical and simple tool for biodiesel producers
to adapt to lower quality feedstock

Major Unit Operations
Biodiesel Production from Generic Feedstock

Feedstock
Ex.: soybean oil,
waste cooking oil,

→ Esterification

↓ Trans-esterification

← Separation
Neutralization
Purification

as end-of-the-pipe treatment to meet the CSFT (cold soak filtration test) without using selective adsorbents.

- Projected biodiesel production in US is 1 bgy in 2013.

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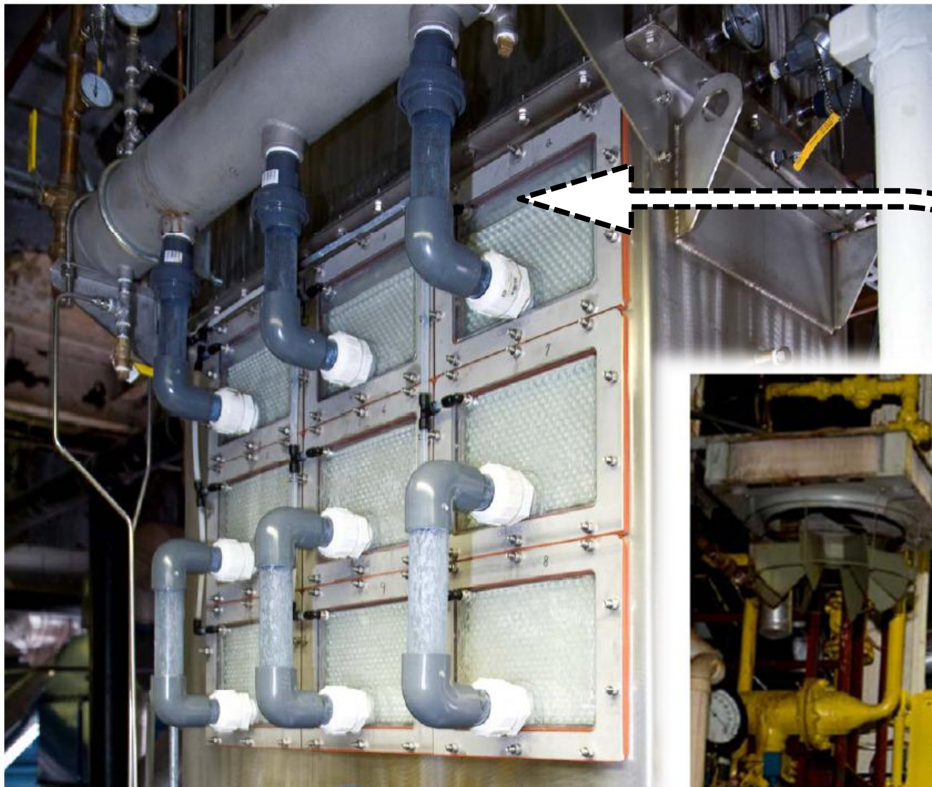
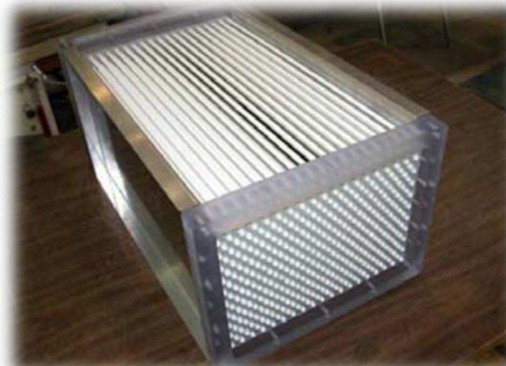
MPT Commercial Ceramic Membranes

Vapor phase applications: energy and water recovery from combustion flue



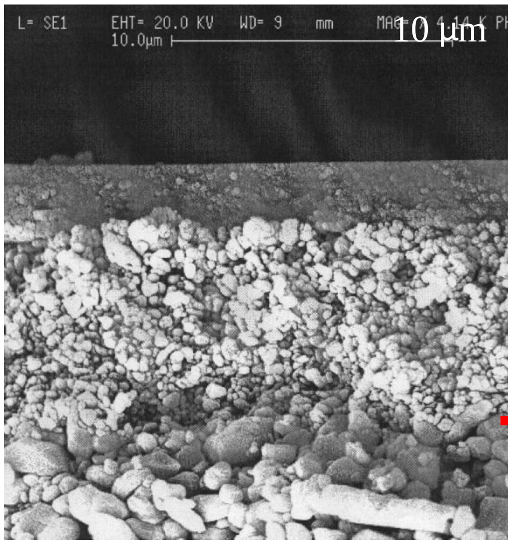


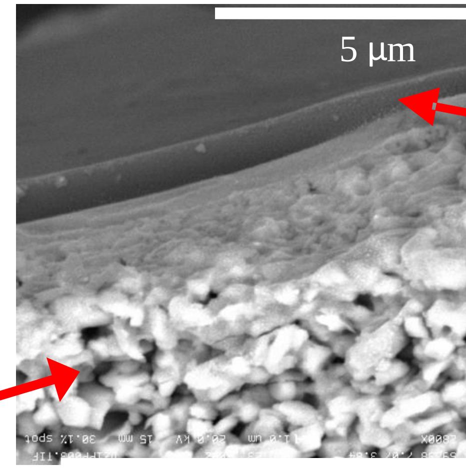
As a porous heat exchanger, our ceramic membrane has demonstrated the enhancement of boiler efficiency from ~80 to >90%

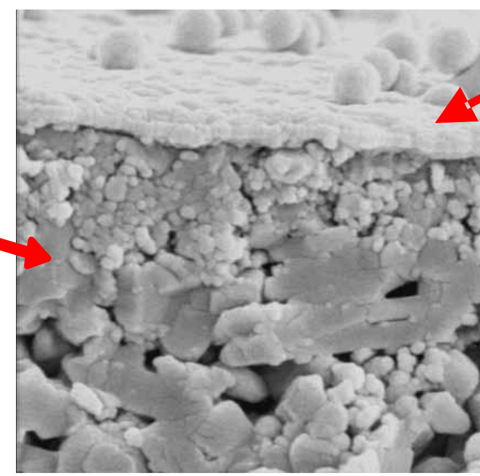
MPT Advanced Inorganic Membranes

Specific thin film deposition for advanced separations

Inorganic Substrate







Others, including zeolites, flourinated hydrocarbons, etc.

Unique feature of
<u>Supported Membranes</u>
Low cost,
e.g., no Pd supply challenge

MPT Advanced Inorganic Membranes

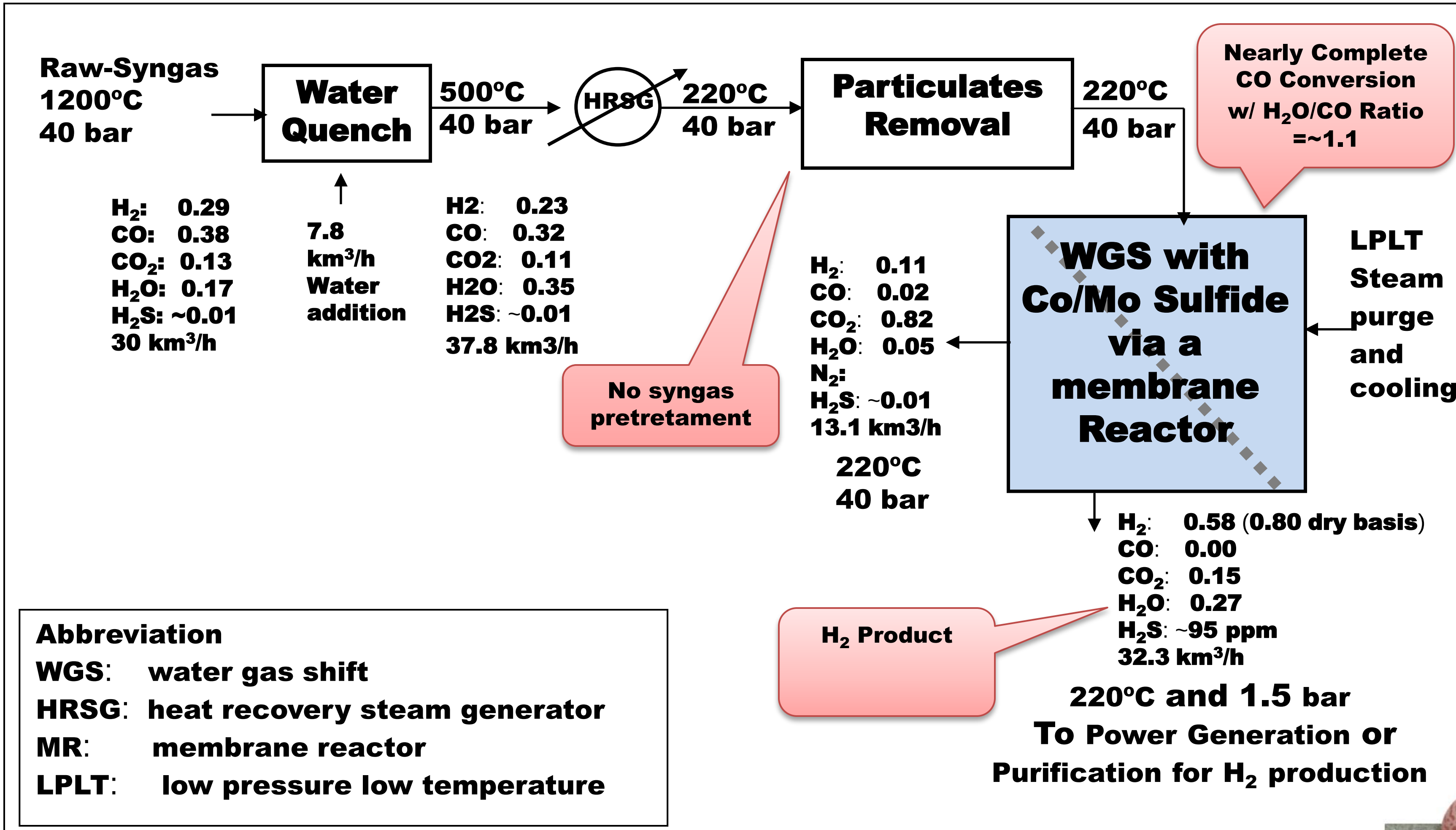
CMS and Pd Membrane Elements

CMS thin film deposition on various elements

Pd thin film deposition on various elements

Block Flow Diagram for the One Box Process for H_2 production and/or power generation

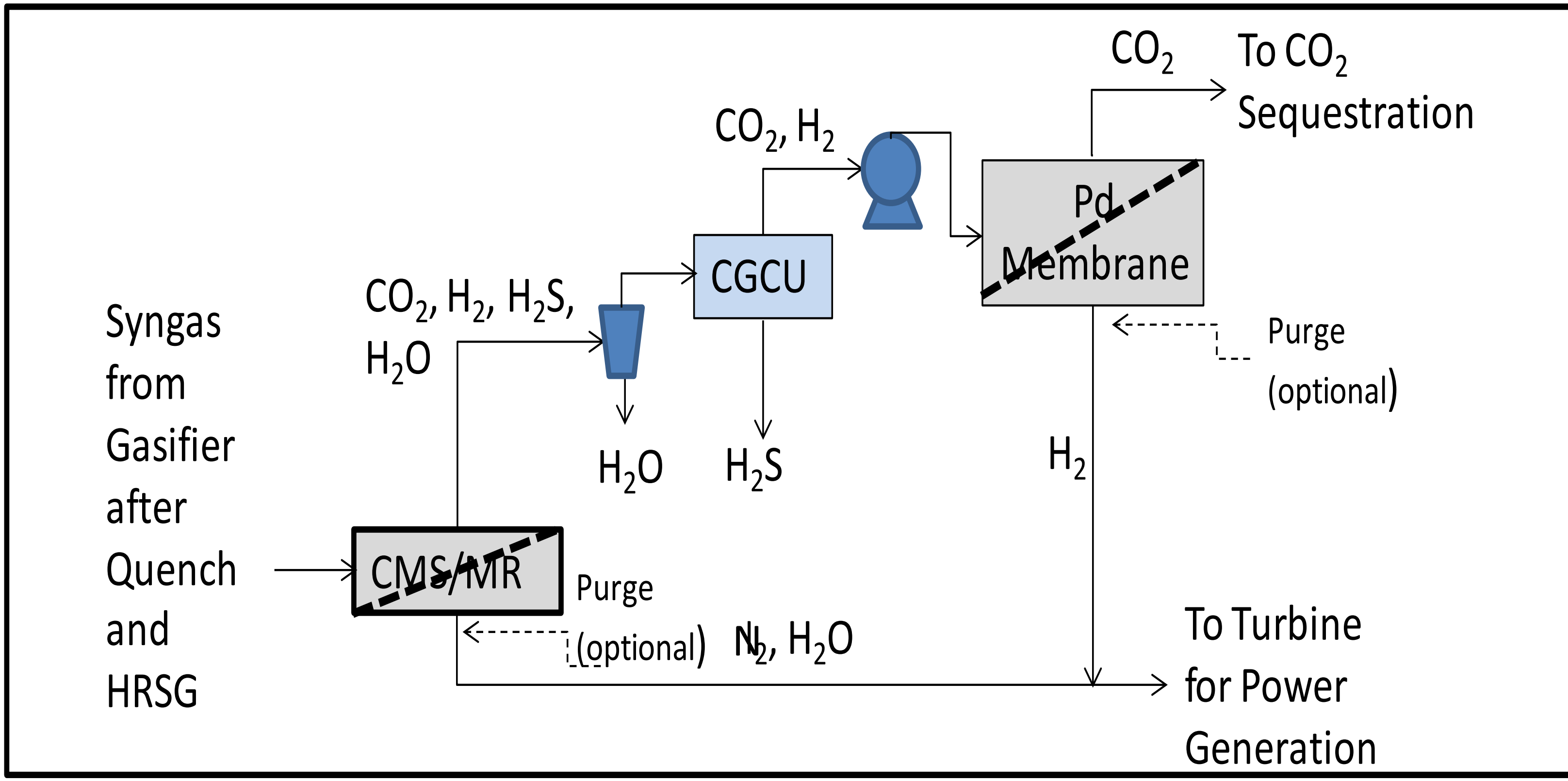
Basis: 300 MW IGCC plant (simplified, unoptimized, for illustration purposes only)



H_2 selective carbon molecular sieve (CMS) membranes as **one-box process** that accomplishes the warm gas clean-up of coal-derived syngas, the WGS and H_2 recovery in one single unit.

MPT Advanced Inorganic Membranes

Dual Stages for IGCC with CCS



- ❑ **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 Advanced Inorganic Membranes

Preliminary Economic Analysis for IGCC + CCS via Dual Stage

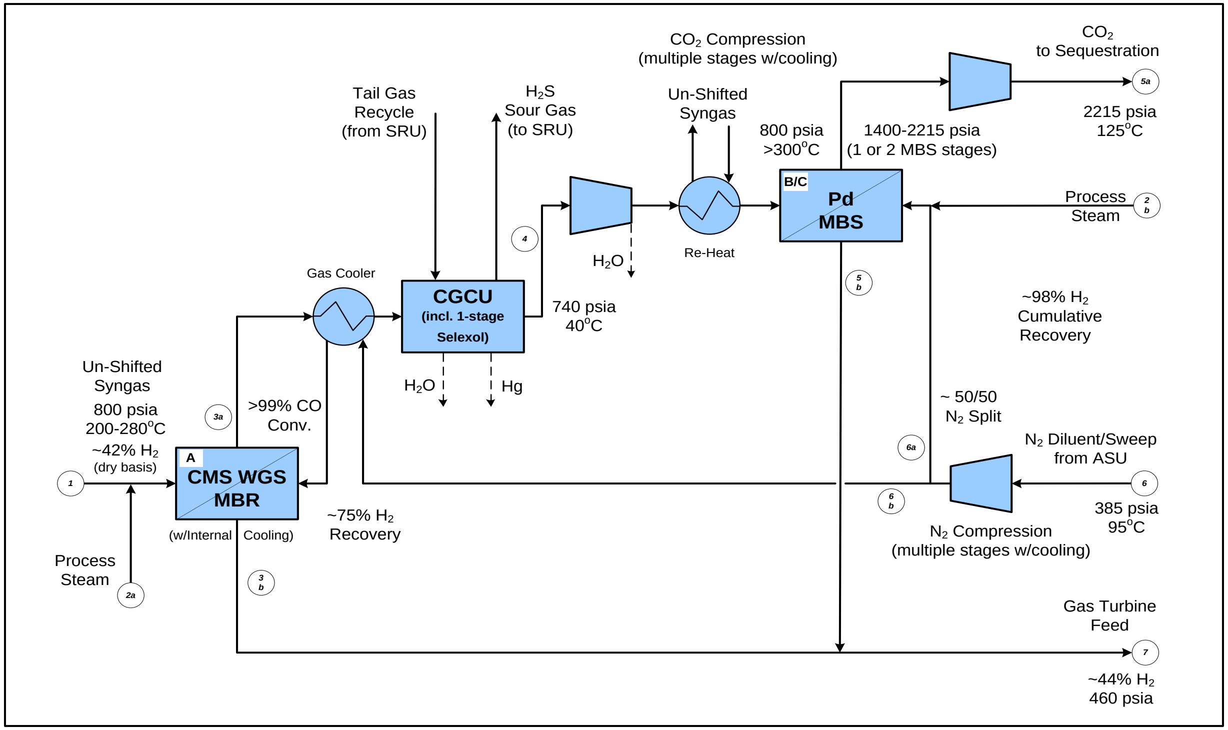


Table 1 Process Schemes Selected for Performance and Economic Analysis for Power Generation

Case Descriptions	Production		HHV	Required Selling Price				CO_2	CO_2
	Electricity	Hydrogen	Efficiency	Electricity	Hydrogen	Electricity	Hydrogen	Capture	Avoided
	MWh/Ton	M SCF/Ton	%	mills/kWh	$/MM Btu	% Increase		%	$/tonne
1a: IGCC w/o CCS - 1-Stage Selexol™ (base case)	2.66	-	39.0	76.3	-	-	-	0	-
2a: IGCC w/CCS - 2-Stage Selexol™	2.23	-	32.6	105.5	-	38	-	90	42.46
3a: IGCC w/CCS - CMS & Pd Membranes & 1-Stage Selexol™	2.37	-	34.6	95.1	-	25	-	98	24.64

Note : *Avoided Cost* = $(COE/MWh_{\text{w/capture}} - COE/MWh_{\text{w/o capture}}) / (\text{tonne } CO_2 \text{ emitted}/MWh_{\text{w/o capture}} - \text{tonne } CO_2 \text{ emitted}/MWh_{\text{w/capture}})$;

for H_2 production, COE is replaced with the RSP of H_2 and the basis of MWh is replaced by M SCF.

Ref.: Cost and Performance Baseline for Fossil Energy Plants, Volume 1: Bituminous Coal and Natural Gas to Electricity, DOE/NETL-2010/1397, Revision 2, November 2010.

Kick-off Meeting for DE-FE0013064

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

1. **Introduction/Background of The Contractor and The Project (MPT)**

2. **1st Stage: CMS Membrane for Bulk Contaminants Removal and Bulk Hydrogen Recovery (MPT)**
   - ❑ *Current Technology Status; Potential Technical Challenges; Proposed Technical Activities*

3. **1st Stage: CMS Membrane as WGS Membrane Reactor (USC)**
   - ❑ *Current Technology Status; Potential Technical Challenges; Proposed Technical Activities*

4. **2nd Stage: Pd Membrane for Enhanced Hydrogen Recovery through CO_2 Compression Train for CCS (MPT)**
   - ❑ *Current Technology Status; Potential Technical Challenges; Proposed Technical Activities*

5. **Engineering, Economics and Environmental Analysis (Technip)**

M&P H_2 Selective CMS Membranes

Mixture Separations with Our CMS Membrane at 250°C

Gas mixture composition

Gas	Permeance $m^3/(m^2\ h\ bar)$	Separation Factor (S.F.)
(1) $H_2:CO:CO_2:CH_4:H_2S = 39.5\%:15.2\%:32.4\%:12.2\%:0.7\%$		
H_2	1.37	1.0
CO	0.02	68.5
CO_2	0.05	27.4
CH_4	0.01	137.0
H_2S	0.01	137.0
(2) $H_2:CO:CO_2:CH_4:H_2S = 45.36\%:4.52\%:38.91\%:11\%:0.21\%$		
H_2	1.40	1.0
CO	0.02	70.0
CO_2	0.04	35.0
CH_4	0.01	140.0
H_2S	0.01	140.0
(3) $H_2:CO:CO_2:CH_4:H_2O:H_2S = 42.45\%:4.233\%:36.4\%:10.29\%:6.43\%:0.197\%$		
H_2	1.56	1.0
CO	0.02	78.0
CO_2	0.05	31.2
CH_4	0.01	156.0
H_2O	1.1	1.4
H_2S	0.01	156.0

Though selectivity is not as high as some competitive polymeric and metallic membranes (Pd-based), our CMS membrane is inert and robust, and is suitable for intermediate temperature applications

M&P H_2 SELECTVE CMS MEMBRANES

QA/QC Performance Testing of CMS Full Scale Bundles

CMS Bundles: 86 tube, 3.25" Collar, Full Ceramic

QA/QC Testing Conditions

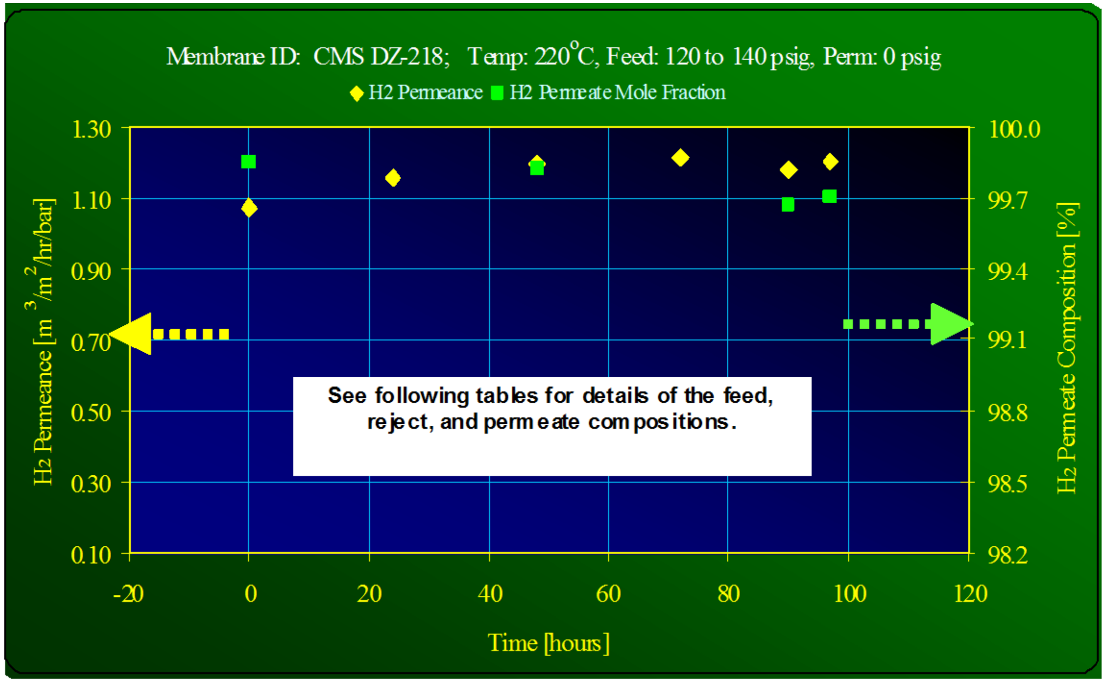
Temperature: 220 to 250°C

Pressure: 20 to 50psig

Membrane ID	He Permeance [$m^3/m^2/hr/bar$]	N_2 Permeance [$m^3/m^2/hr/bar$]	He/N_2 Selectivity [-]	Comments
3-1 to 3-5	Off-spec bundles. Initial facility setup and deposition trials.			
3-6	2.0	0.020	100	
3-7	2.8	0.015	187	
3-8	1.8	0.020	91	
3-9	2.6	0.025	102	
3-10	1.0	0.005	200	Overdeposited
3-11	1.6	0.011	142	
3-12	1.5	0.020	77	Repair of damaged tubes
3-13	2.3	0.018	126	
3-14	2.8	0.025	117	

CMS Membrane Field Testing

Membrane performance is stable in a 100 hour challenge test conducted at a refinery pilot facility using VGO hydrocracker off-gas in the presence of significant H_2S, NH_3, and higher hydrocarbon contamination.



Gas Stream Compositions, Stage Cut and H_2 Recovery During the VGO Hydrocracker Pilot Test

At time = 3 hours				
Gas	Composition [%]			H_2/Slow Selectivity
	Feed	Reject	Permeate	
H_2S	5.2	32.0	0.03	163
H_2	89.9	38.9	99.88	1
C_1	2.1	12.2	0.08	123
C_2	0.88	5.4	0.01	~600
C_3+	1.88	11.6	ND	>1,000
Stage Cut		85%		
H_2 Recovery		92%		

At time = 100 hours				
Gas	Composition [%]			H_2/Slow Selectivity
	Feed	Reject	Permeate	
H_2S	4.8	24.5	0.16	74
H_2	90.8	50.6	99.70	1
C_1	1.9	9.9	0.06	123
C_2	0.81	4.2	0.01	~600
C_3+	1.66	10.7	ND	>1,000
Stage Cut		80%		
H_2 Recovery		85%		

Milestone #4

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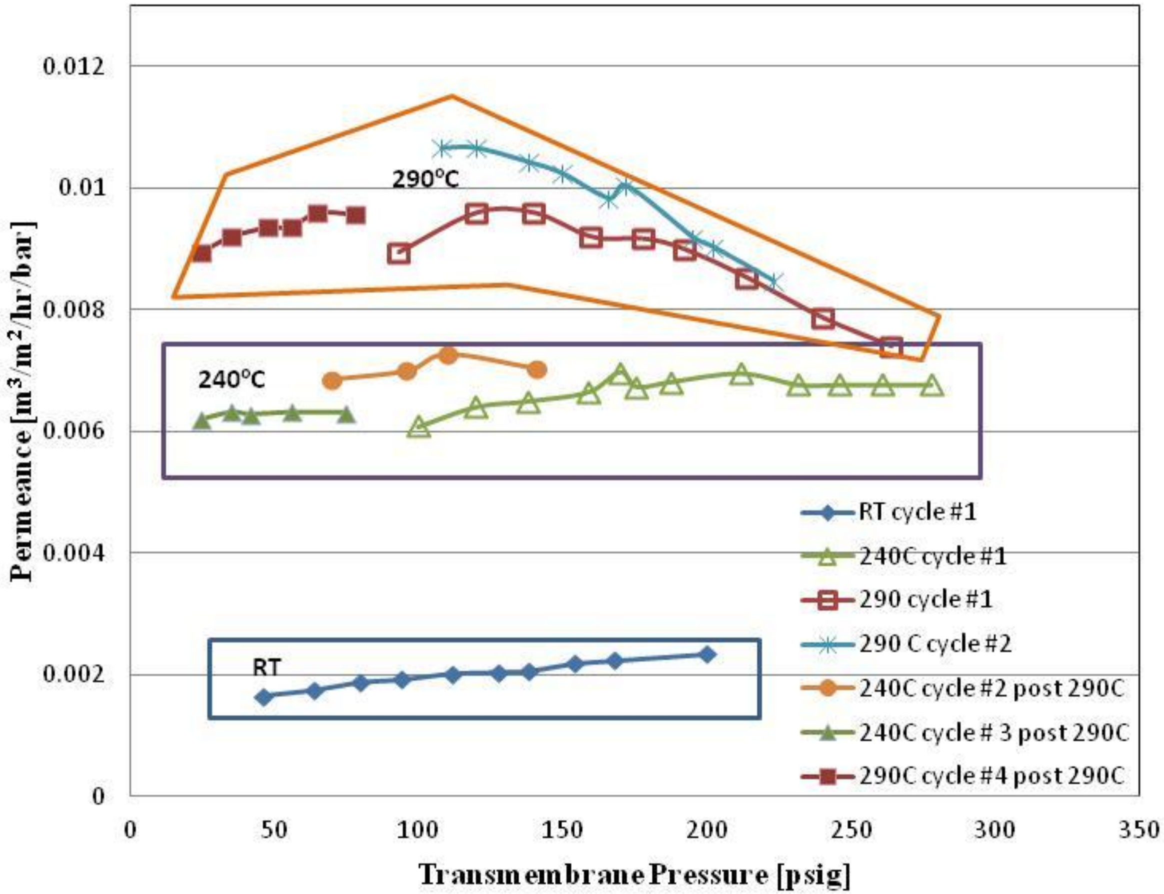
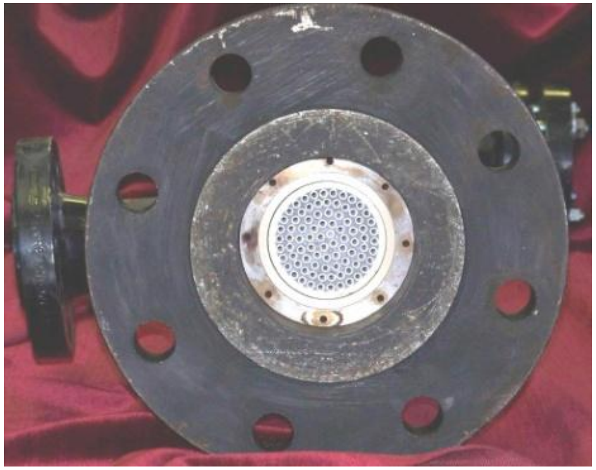
MPT H_2 Selective CMS Membranes

86-tube CMS Bundle in Pilot Scale Module

CMS Tube Bundle N_2 Permeance versus Temperature and Pressure



CMS Bundle in High Pressure Housing



MPT H_2 Selective CMS Membranes

Testing Results: Slip Stream from NCCC (PSDF) Coal/Biomass Gasifier

PSDF Field Test Objectives

Demonstrate hydrogen production/recovery from coal gasifier off-gas.

Gasifier Off-gas Composition to the CMS Membrane:

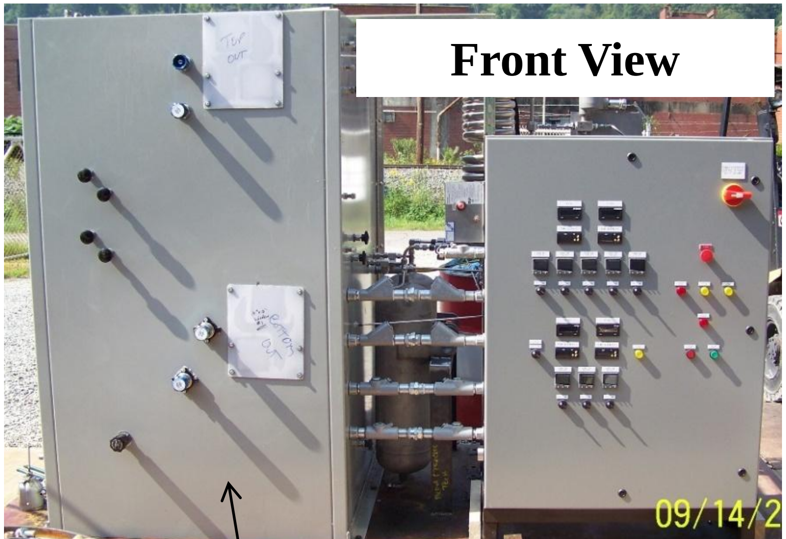
H_2 Content ca. 10 to 30%, balance primarily CO_2, N_2, CO.

The trace contaminants typically encountered at PSDF includes:

- NH_3 ~1000ppm
- Sulfur Species ~1000ppm
- HCl < 5ppm
- HCN ~20ppm
- Naphthalenes (and other condensable higher hydrocarbons) also high concentration contaminant

MPT H_2 Selective CMS Membranes

NCCC (PSDF) Field Test Unit



Front View

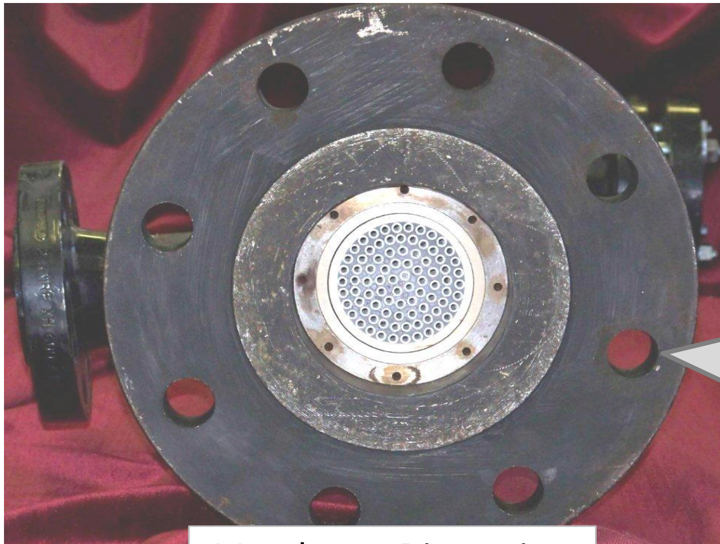
Cabinet for Membrane Bundles

Installed NCCC

The Unit meets Class 1, Div.2 requirement. The field test is scheduled to begin on Oct 15, 2011 for two months at US DOE’s NCCC testing facility, to be fed with actual coal gasifer off-gas directly to our membrane without pre-treatment.

MPT H_2 Selective CMS Membranes

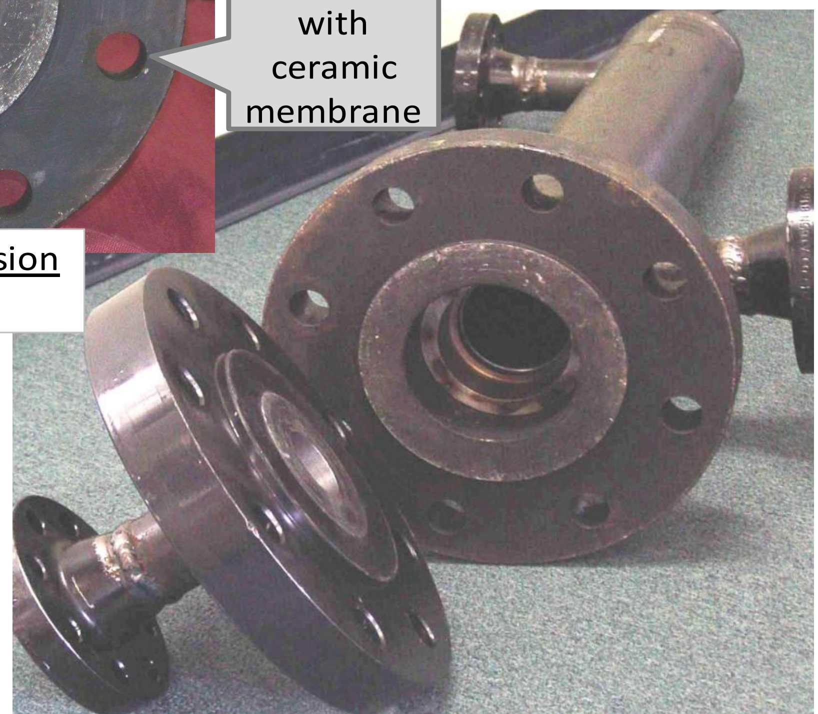
CMS Membrane Bundle in Field Test Module



M&P Full-Scale Hydrogen Selective Membrane and Housing Rated for 1000 psi use

End view
packed with ceramic membrane

Membrane Dimension
3” dia x 30”L



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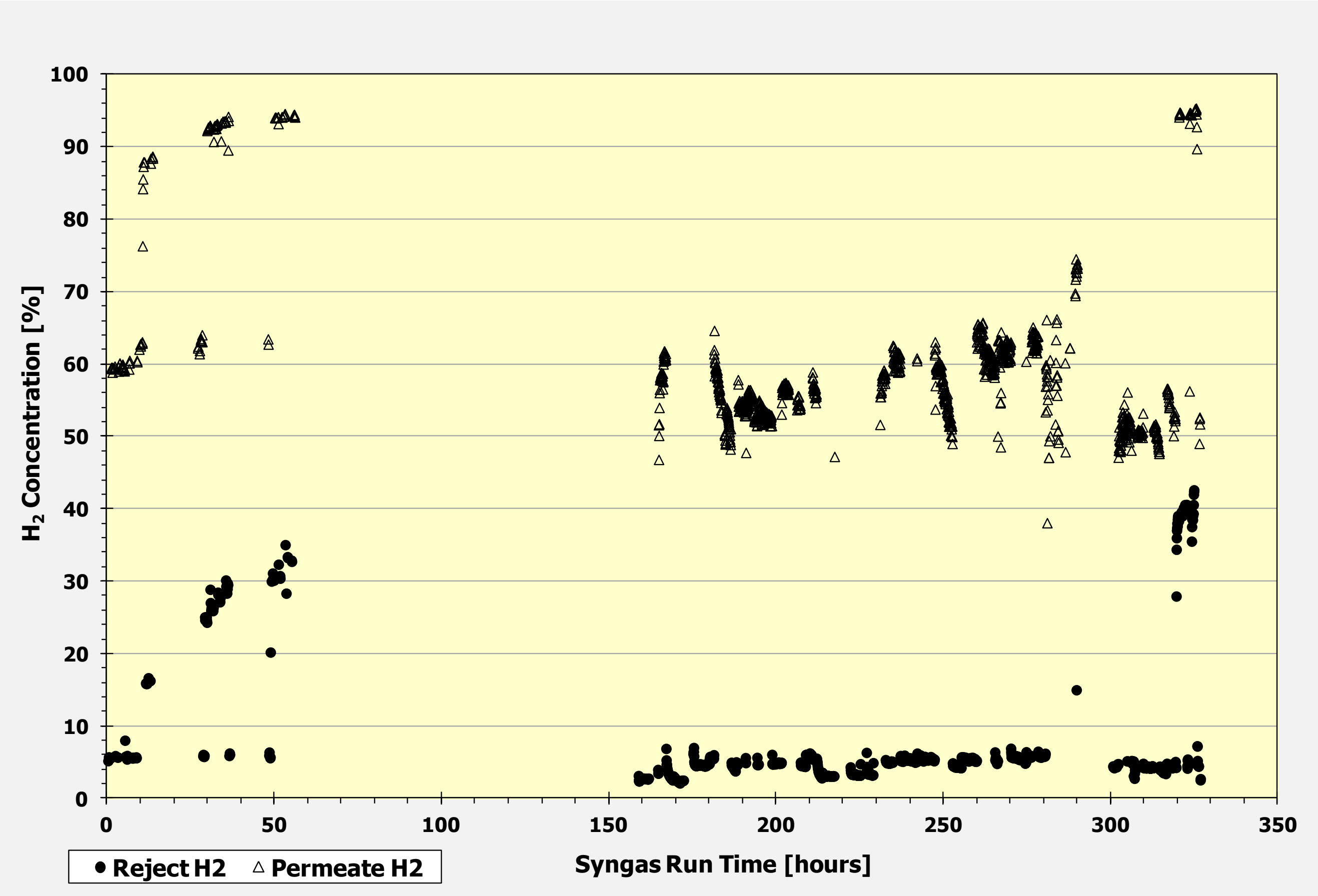
MPT H2 Selective CMS Membranes

Performance of a CMS Bundle at NCCC (PSDF)



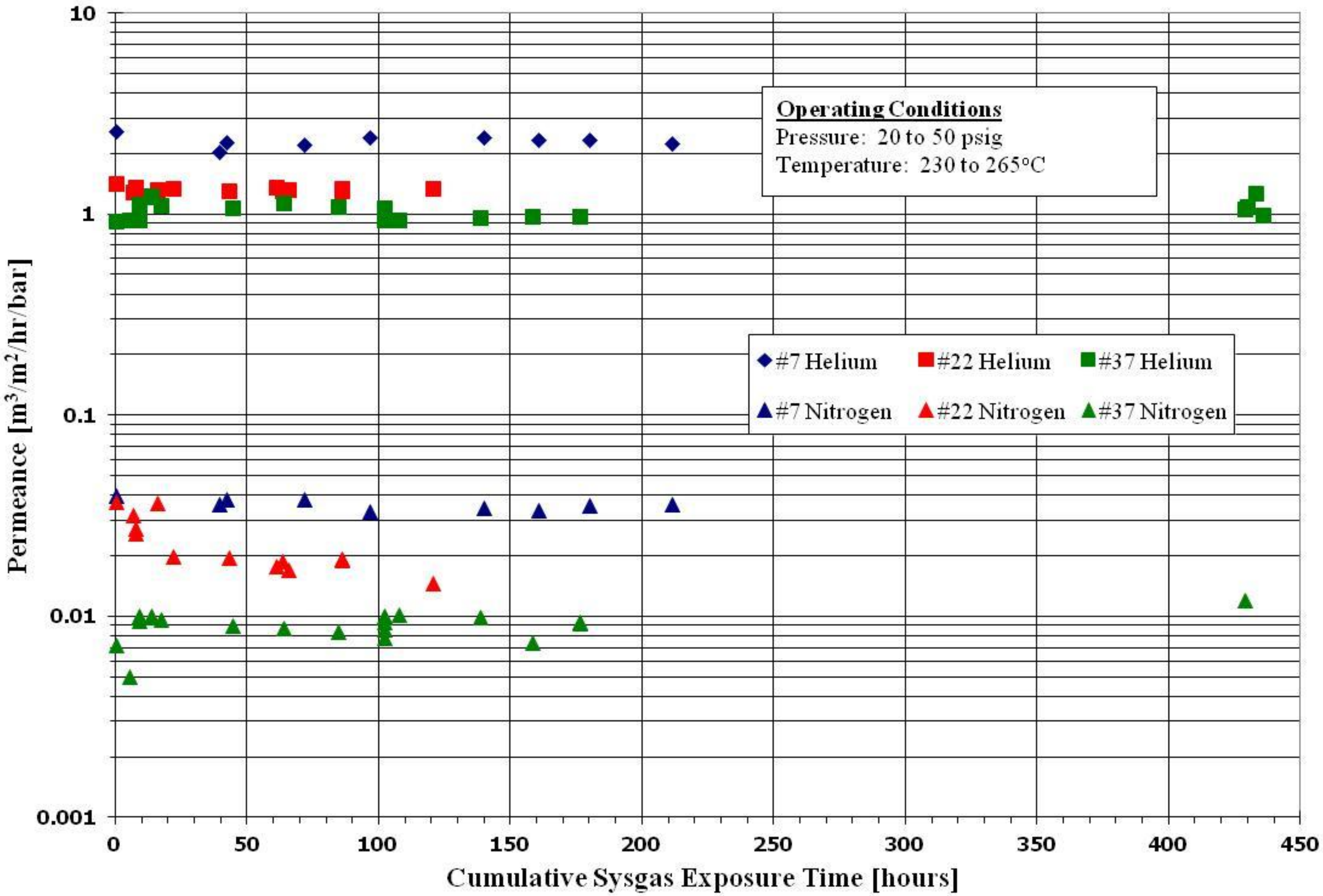
Hydrogen was enriched from 20-30% to >90-9%, consistent with the prediction based upon single components obtained in the lab.

Hydrogen concentration (dry-basis) in the permeate and reject sides during the testing of the "full-scale" CMSM module fed with air blown coal-fed gasifier off-gas at ~250 °C and ~14.8 bar. The feed rate was maintained in the range of 150 to 250 l/min. The typical feed composition during this run is 6.49% H_2, 74.03% N_2, 9% CO, 9% CO_2, 0.9% CH_4, and 312 ppm H_2S. During the beginning (2-50 hr) and the ending periods (near 350 hr), the feed was artificially spiked with bottled hydrogen to simulate the feed hydrogen concentration of the oxygen-blown gasifier to the "one-box" process.

MPT H_2 Selective CMS Membranes

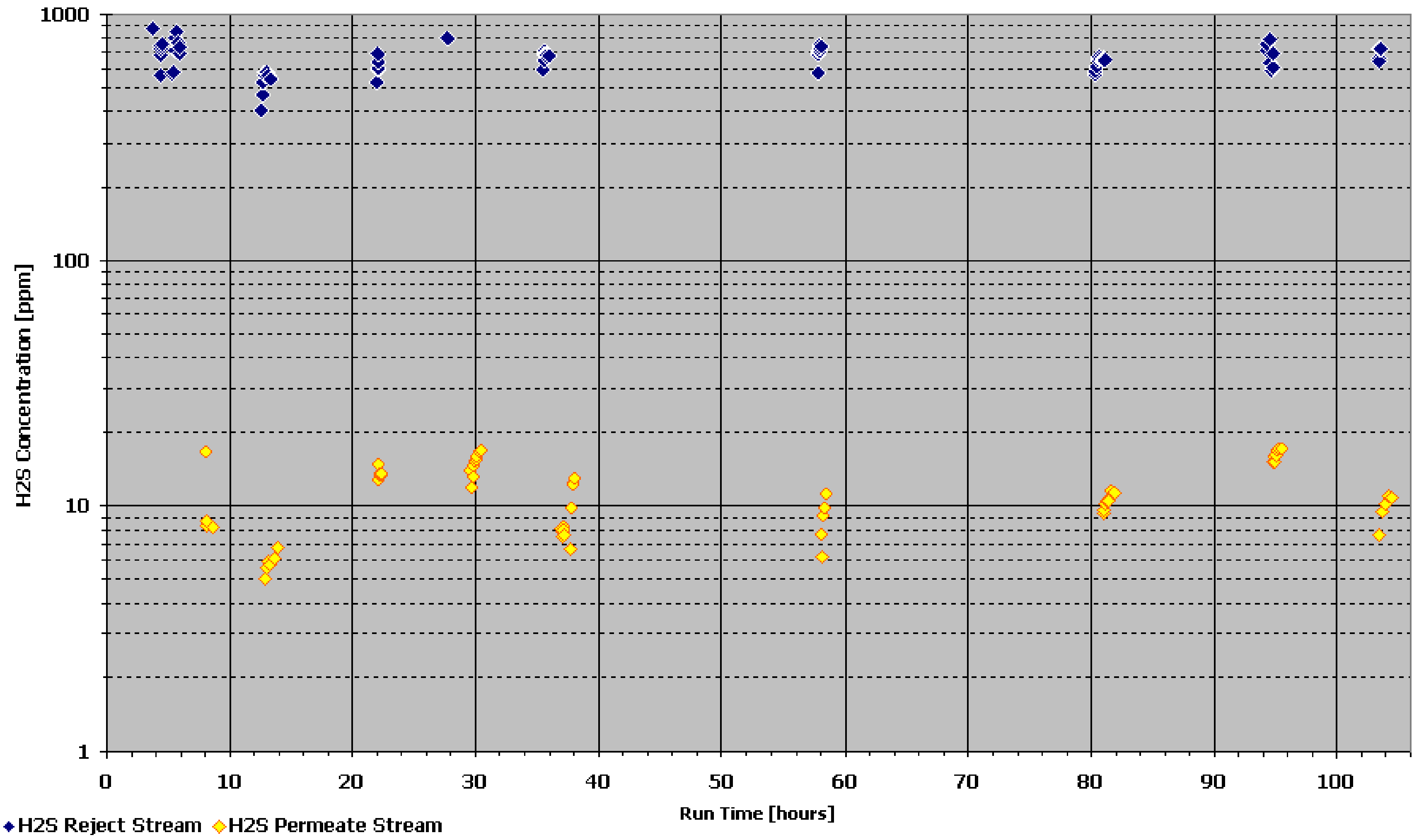
Performance Stability of the B3-7 Bundle

He and N_2 Permeance Stability Following Gasifier Off-gas Exposure



MPT H_2 Selective CMS Membranes

H_2S Removal with the B3-7 Bundle



1st Stage, CMS Membranes as a WGS Membrane Reactor (WGS-MR): Current Technology Status

- CMS membranes tested for pressures up to 60 psig and temperatures up to 300 ^{o}C in the WGS/MR in the presence of simulated coal-derived syngas containing NH_3, H_2S and model organic vapor and tar compounds
- Kinetics of sulfided Co-Mo WGS catalyst tested for the same region of pressure/temperature conditions
- Both membranes and catalysts performed well and stably for continuous experiments lasting more than 6 weeks
- WGS/MR model developed and used successfully to model the experimental data

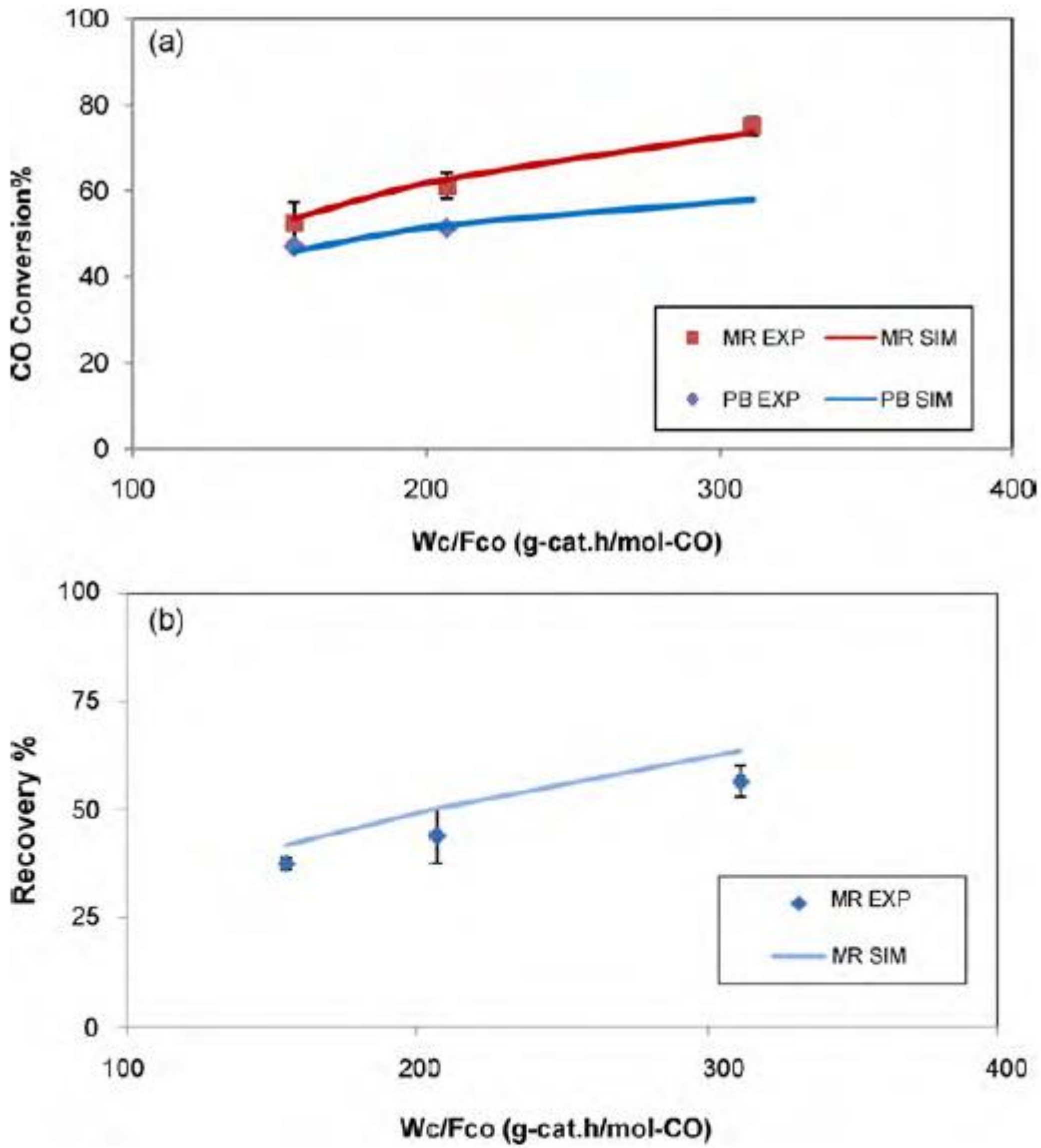


Fig. 10. Comparison of the experimental (a) conversion and (b) recovery with the model predictions at $T = 300\,^\circ C$, $P = 5$ atm and sweep ratio = 0.3 using CMS#2.

Comparison of Experimental Results vs. Model Predictions for WGS/MR using CMS Membranes (Co/Mo Sulfided Catalyst)

CO Conversion and Hydrogen Recovery

Temperature (°C): 300	
Pressure (atm): 5	
Weight of catalyst (g): 12	
W/F_{CO} (g-cat.h/mol-CO): 150 -311	
Feed Composition	
H_2:CO:CO_2:CH_4:H_2O:H_2S 2.6:1:2.14:0.8:1.2:0.05	

J. Membr. Sci., *363*, 160 (2010); *Ind. Eng. Chem.*, 10.1021/ie402603c (2014)

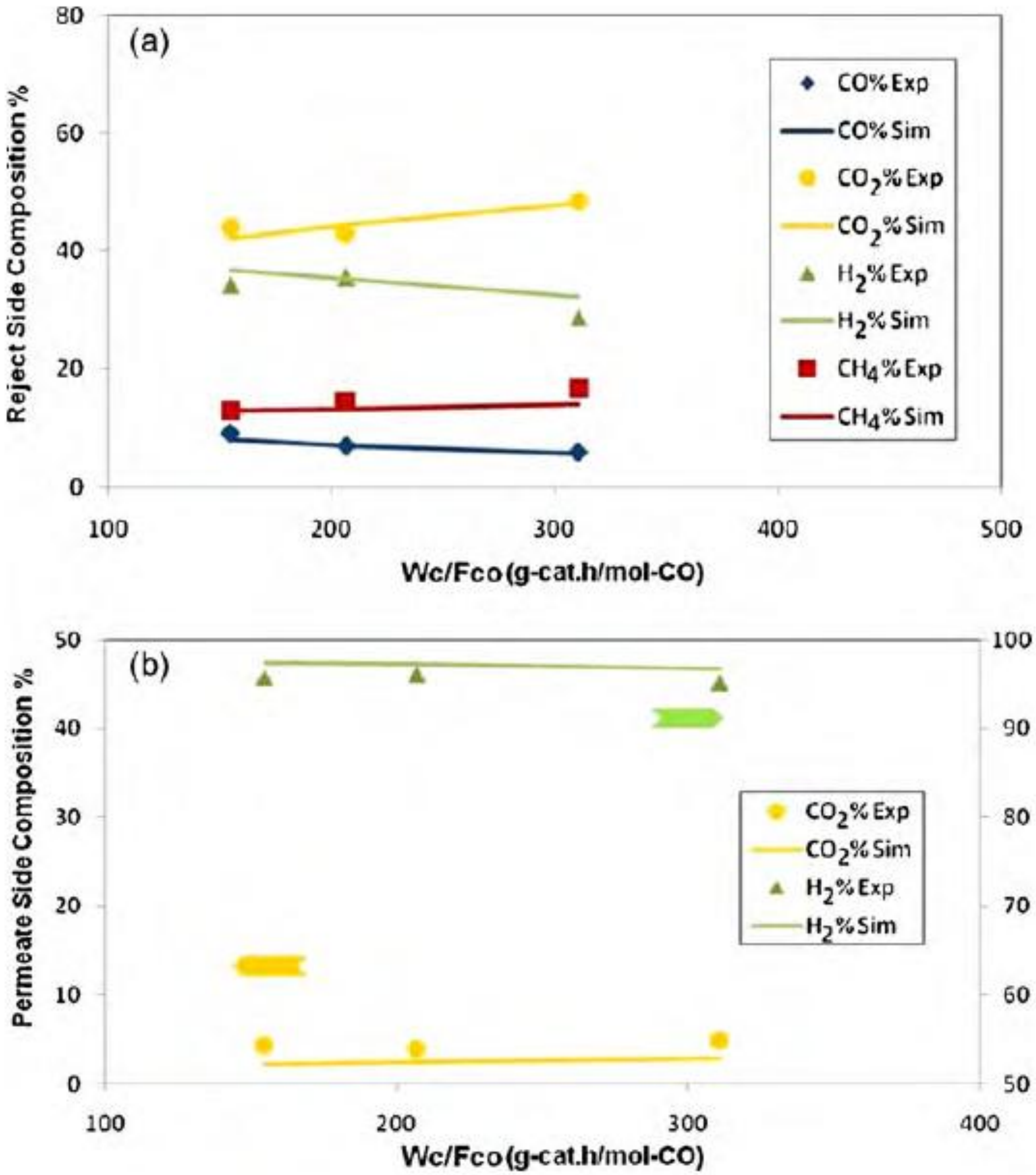
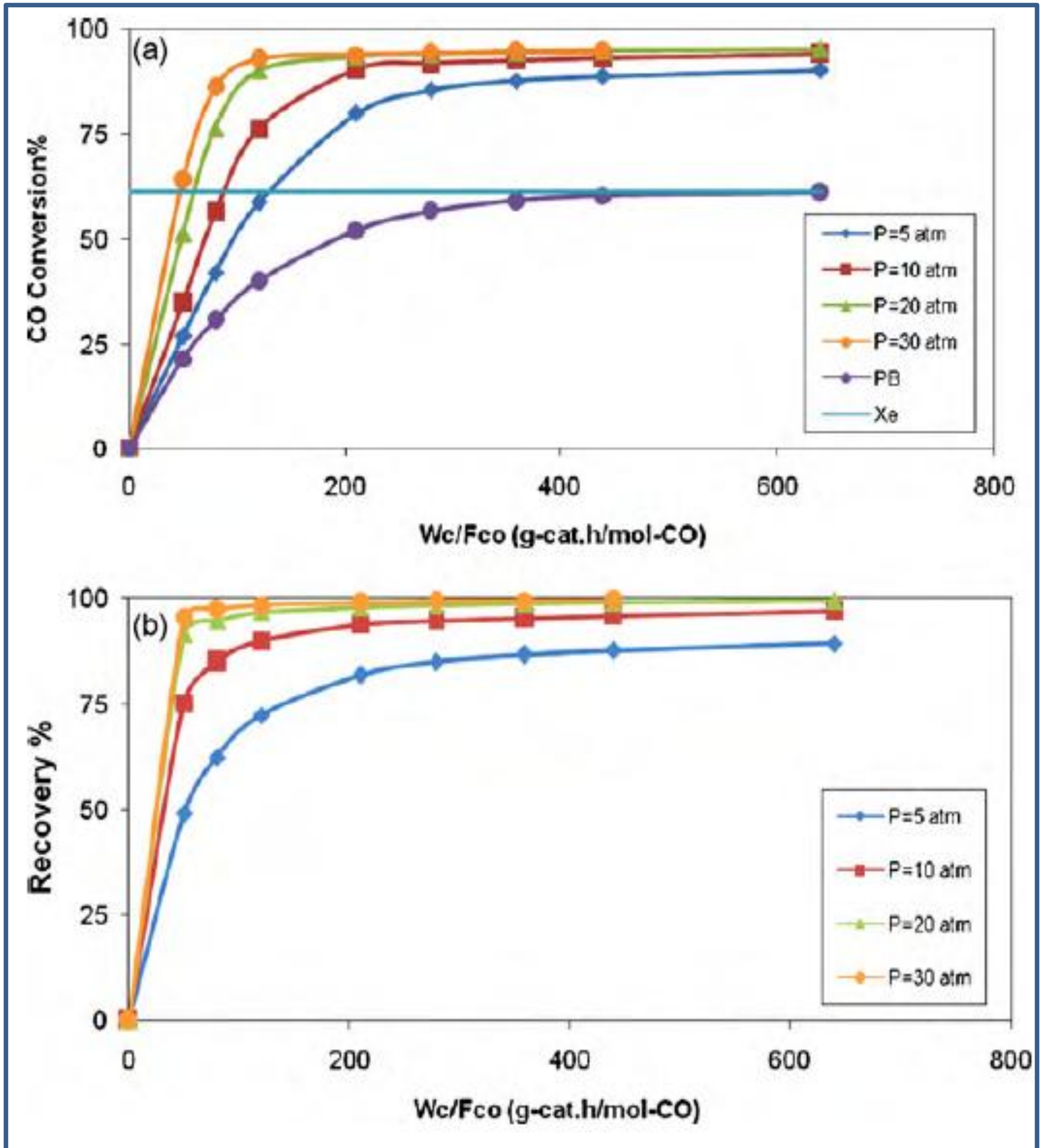


Fig. 6. Compositions of (a) reject and (b) permeate side at *P* = 3 atm and sweep ratio = 0.3.

Comparison of Experimental Results vs. Model Predictions for WGS/MR using CMS Membranes (Co/Mo Sulfided Catalyst)

Reject and Permeate Stream Compositions

J. Membr. Sci., *363*, 160 (2010); *Ind. Eng. Chem.*, 10.1021/ie402603c (2014)



Simulations for WGS/MR using a CMS Membrane Under a Coal Gasification Environment

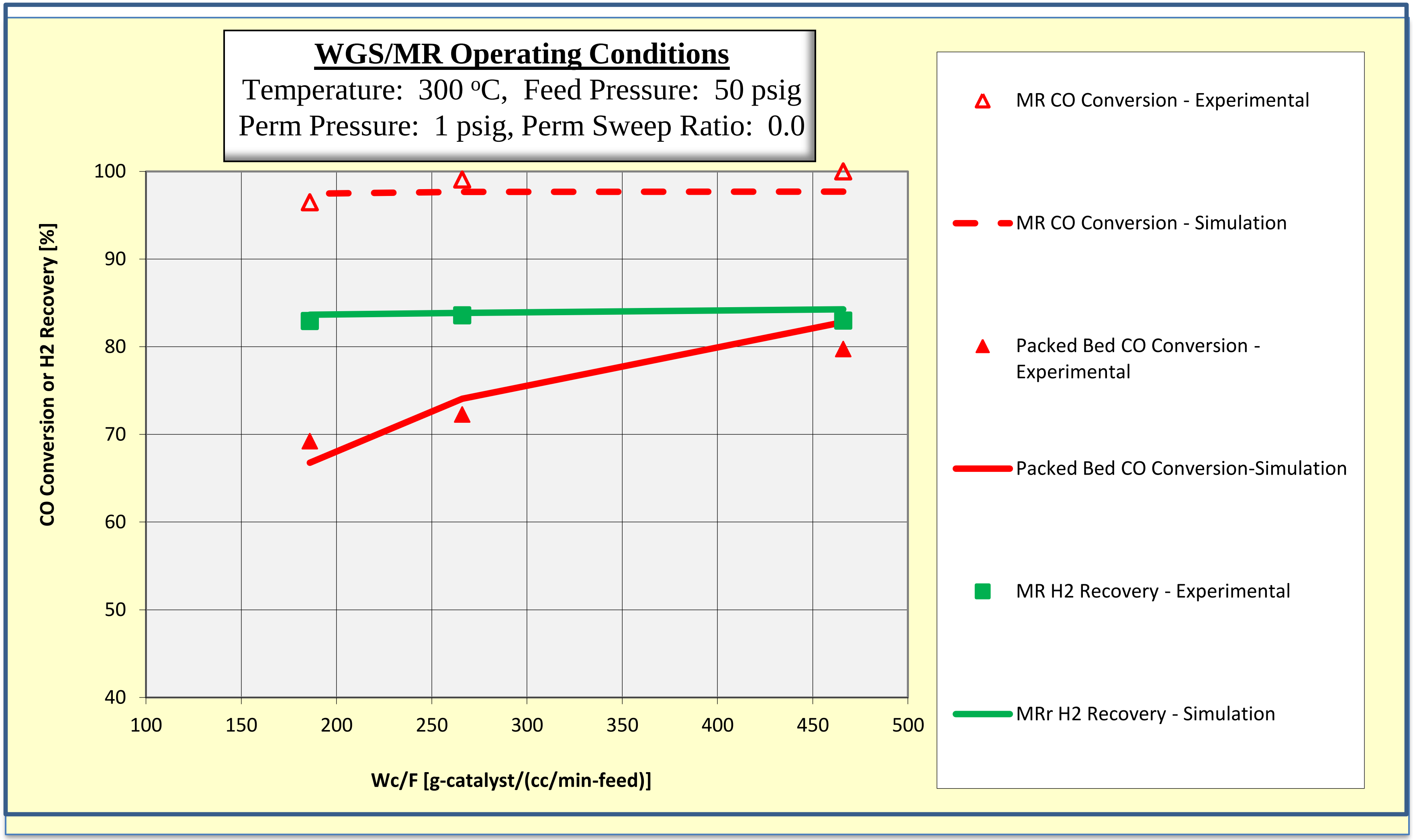
(Co/Mo sulfided Catalyst)

Effect of Pressure on the CO Conversion and Hydrogen Recovery

J. Membr. Sci., 363, 160 (2010); *Ind. Eng. Chem.*, 10.1021/ie402603c (2014)

WGS-LTS Membrane Reactor using a Palladium Membrane

Experimental results using methane steam reformate *at 50 psig and with no sweep*



- Our experimental results demonstrate >99% conversion and >99.9% purity at >83% hydrogen recovery is possible by our WGS-MR using Pd membranes.

J. Membrane Science ,390, 32 (2012)

1st Stage, CMS Membranes as a WGS Membrane Reactor (WGS-MR): Proposed Technical Activities

1. **Task 2. Establish Performance Database for CMS-WGS/MR**
   - *Subtask 2.1: Modification of the Present Laboratory-Scale WGS/MR System*
   - *Subtask 2.2: Generation of the Performance Database*
   - *Subtask 2.3: Verification of the Existing Mathematical Model and Simulations of the Performance of the Bench-Scale System*

2. **Task 5. Evaluate Gas Permeation and Catalytic Reaction CMS Membrane as WGS Membrane Reactor**
   - *Subtask 5.1: Experimental Verification*
   - *Subtask 5.2: Membrane and MR Simulation Support*

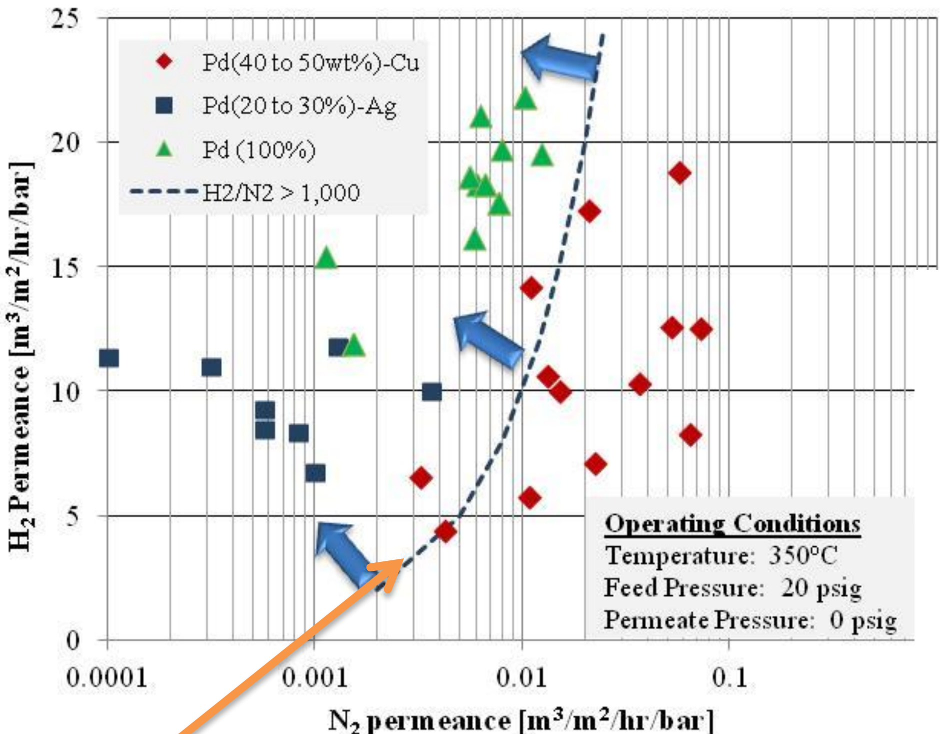
3. **Task 7. Provide Technical Support for Process Design and Engineering Study**

4. **Task 8. Provide Technical Support for Environmental and Economic Analyses**

MPT H2 Selective Pd Alloy Membranes

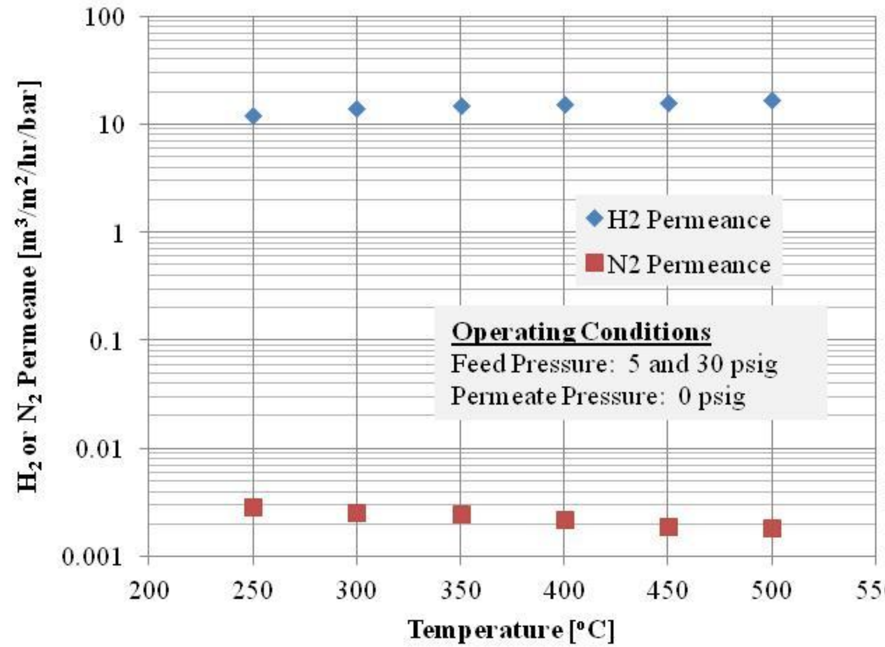
General Performance: H_2 and N_2 Permeance

H_2 and N_2 Permeance for Various Parts and Alloys



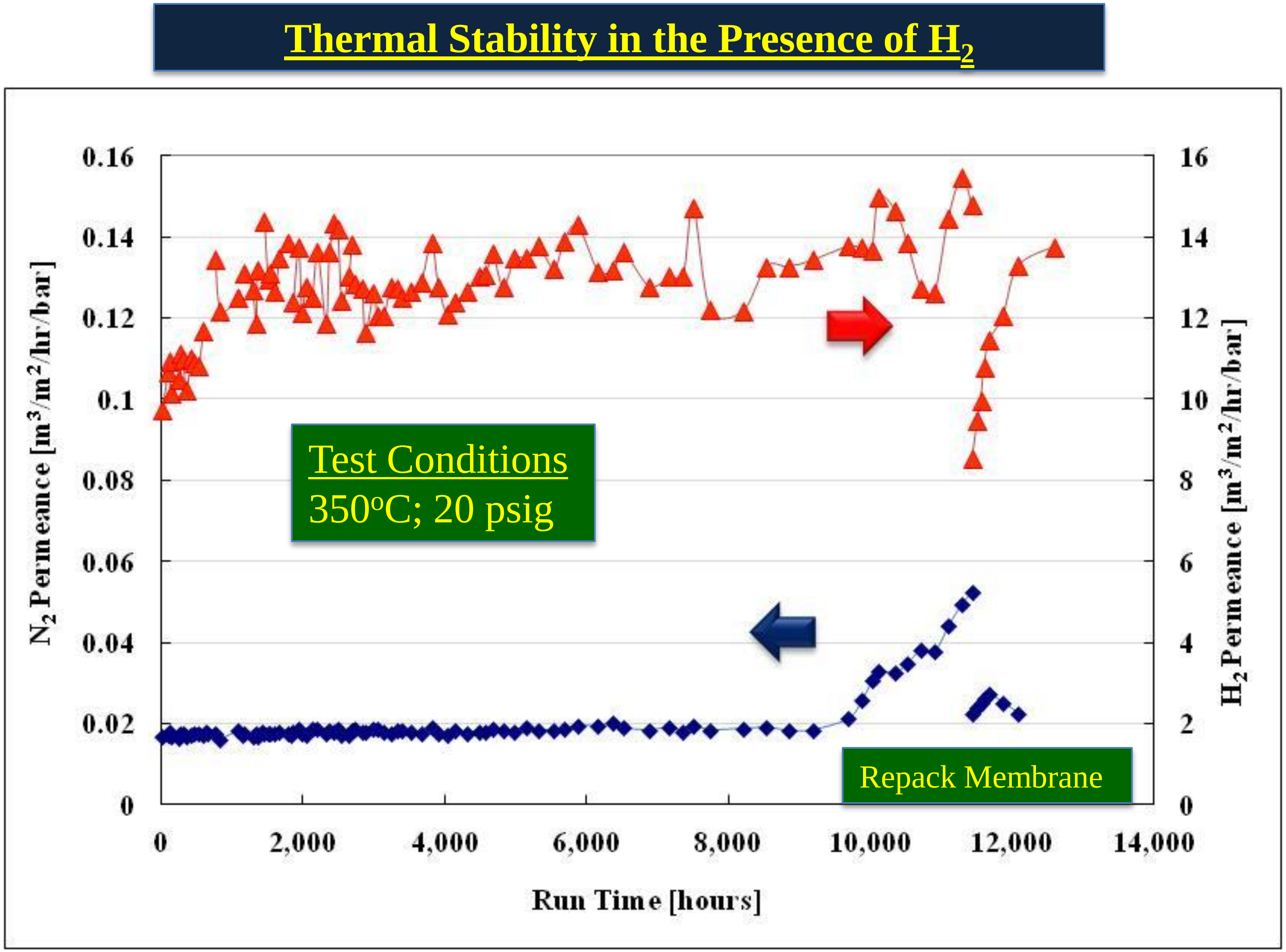
H_2/N_2 = 1,000

H_2 and N_2 Permeance Temperature Dependences for a Typical Pd Membrane



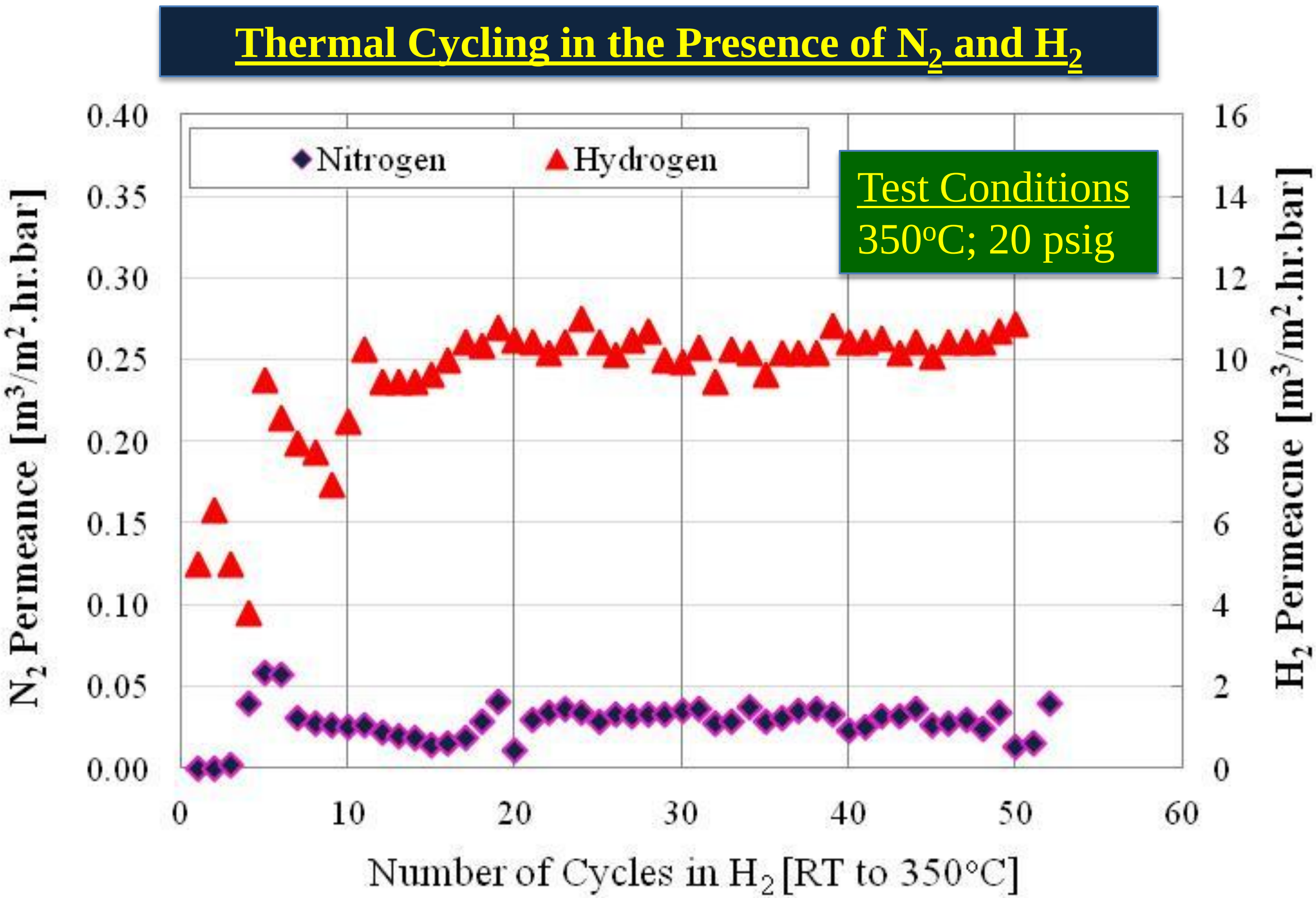
MPT H_2 Selective Pd Alloy Membranes

Long Term Thermal Stability in the Presence of H_2



MPT H_2 Selective Pd Alloy Membranes

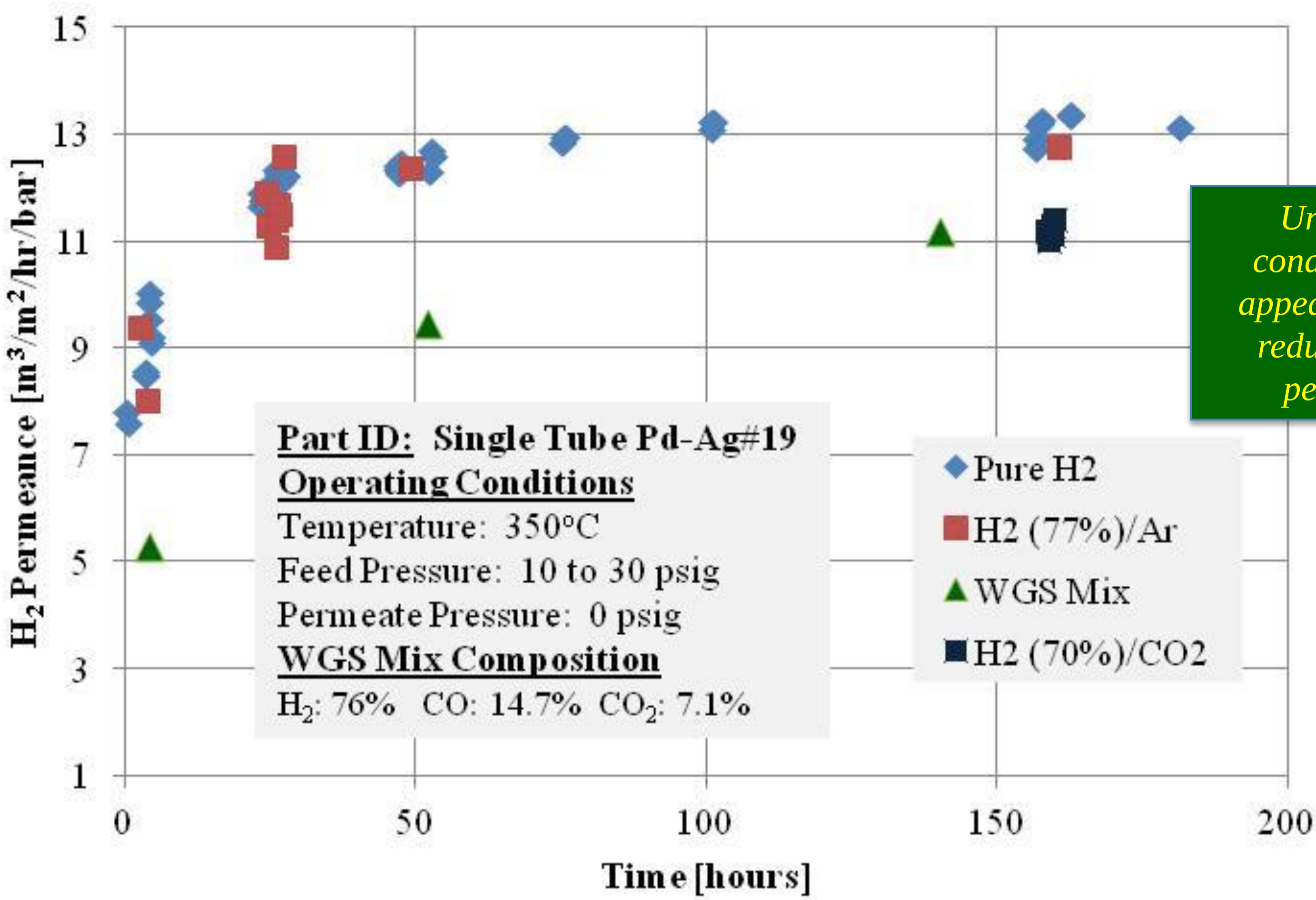
Simulated Startup and Shutdown Operation. Pd-Cu Alloy Membrane



MPT H_2 Selective Pd Alloy Membranes

Mixed Gas Testing

H_2 Permeance in Various Mixed Gas Systems



Under these conditions, CO_2 appears to yield a reduction in H_2 permeance.

MPT H_2 Selective Pd Alloy Membranes

Multiple Tube Bundles for Fuel Cell Applications

High Pressure Tube Sheet

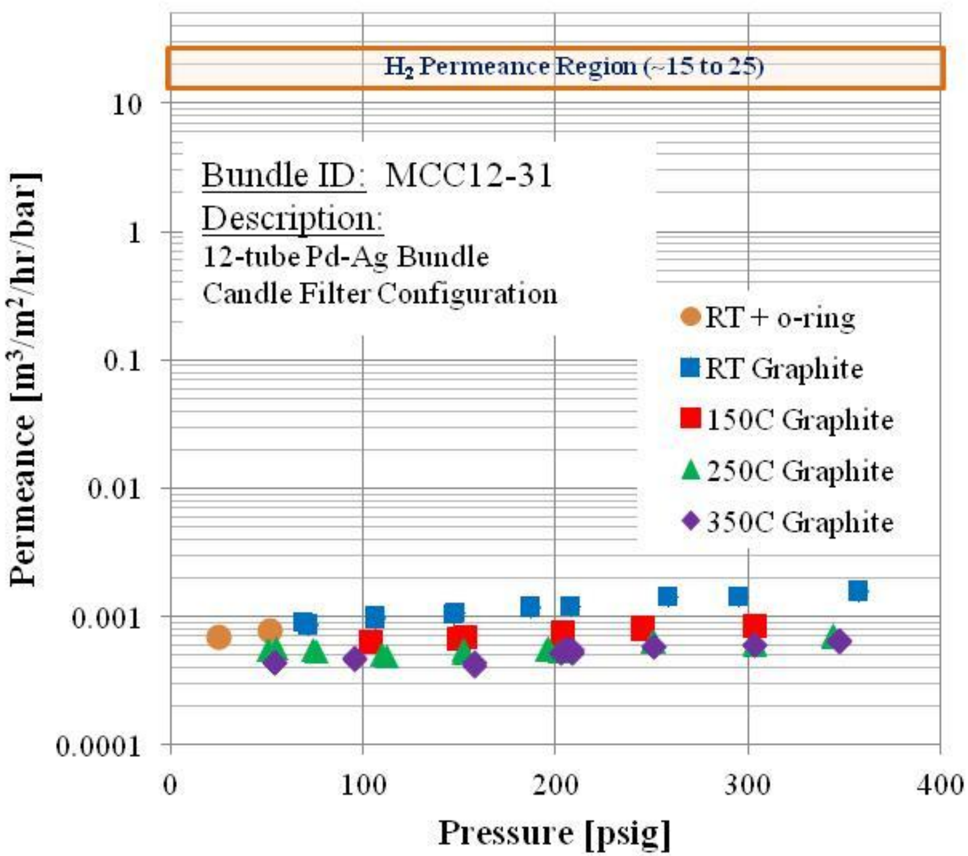
Pd Bundle and Ceramic Tube Sheet

2nd Generation Module Design

Latest Module Design with Graphite Packing

High Performance Package

N_2 Flux (Leak Rate) v. Pressure and Temperature



MPT H_2 Selective Pd Alloy Membranes

Performance Benchmarking: Competing substrates

Porous Stainless Steel (PSS) Supported Composite Pd Membranes

PSS: Single Tube Membrane Performance

Table 1 – Characteristics of composite Pd and Pd–Au membranes tested at NCCC.

Membrane #		Thickness Pd–Au μm	He leak at 25 °C $Ncm^3\ min^{-1}\ bar^{-1}$	H_2 permeance at 450 °C $Nm^3\ m^{-2}\ h^{-1}\ bar^{-0.5}$	H_2/He selectivity 450 °C, $\Delta P = 1$ bar
M-01[a]	After 1st plating	6.9–0	0.5	31.7	>1563
	After 2nd plating	8.2–0.16	<0.1[b]	27.8[c]	N.A.
M-03	After 1st plating	5.9–0	9	27.7	>218
	After 2nd plating	7.0–0.2	<0.1[b]	26.1[c]	N.A.
M-04	After 1st plating	12–0	2.2	22.3	>248
	After 2nd plating	13.2–0	<0.1[b]	20.7[c]	N.A.

a M-01 weld nuggets were plated with an extra 10 μm thick Au layer.
b 0.1 $Ncm^3\ min^{-1}\ bar^{-1}$ detectable minimum leak.
c Estimation taking into account Pd thickness and support mass transfer resistance.

Ma et. al., International Journal of H_2 Energy, 37 (2012) 14577-14568.

MPT Ceramic: Multiple Tube Bundle Performance

MCC12-31 (12 tube bundle)	2x ELP	~5	NA	35 to 45 at 350°C	>3,000

MPT H_2 Selective Pd Alloy Membranes

Overall Comparison: Pd-PSS vs Pd-Ceramic of Ours

Disadvantages/Limitations of Pd-PSS Composite Membranes

Costly substrate: Sintered fine powdered metal in H_2 atmosphere.

"Poor" quality substrate: Multiple references describe problems and attempted solutions.

Intermediate Layer problems: Delamination and high surface roughness.

Thick Pd Layer: …to overcome the substrate and intermediate layer problems.

End seals and joints. Leaking and failure at the Pd layer/substrate end seals. Unproven technology.

Lower flux: Thick Pd layer yields lower flux.

High operating temperature: …to overcome the lower flux problems.

MPT H_2 Selective CMS Membranes

CMS Membrane Challenge Areas:

- ***Optimize Pore Size Tuning***

  Pore size tuning to maximize H_2 permeance with the rejection of H_2S; thus, hydrogen extraction can be maximized in Stage I for turbine applications

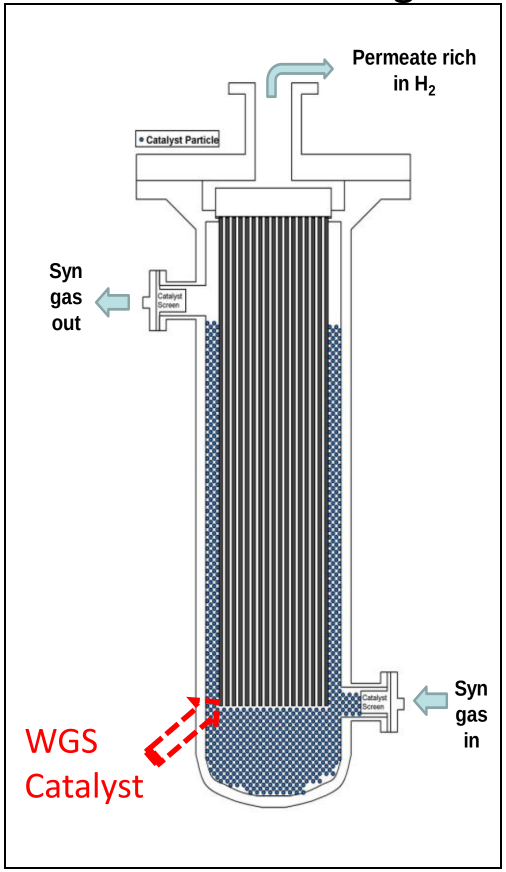
- ***Reactor Design and Catalyst Packing***

  Our current designs focus on a solid positive seal, consistent flow path, and optimized free flow distribution. While it does have space for catalyst to be loaded into the vessel, it is not optimized for use as a reactor bed.

  Improvements in reactor design and catalyst packing should include:

  - catalyst bed flow distribution optimizations
  - ability to monitor internal bed conditions
  - efficient catalyst loading/unloading capability
  - and others

Current MR usage



1st Stage, CMS Membranes as a WGS Membrane Reactor (WGS-MR): Potential Technical Challenges

- Catalysts and membranes may not perform adequately in the high-pressure region
- Reaction kinetics derived at low pressures may not fit high-pressure experimental data
- Mathematical model may need to be revised to describe MR experiments at high pressures

MPT H_2 Selective Pd Alloy Membranes

Pd Membrane Challenge Area A: Very Large Surface Area Requirements

Pd Challenge #A: H_2 Recovery in CCS = Enormous Scale Membrane Application

Objective: Minimize the Membrane Area and Cost

Approach

Minimize the Pd Layer Thickness

1. **Higher flux**
2. **Less metal**

Delivers

a. **Smaller scale**
b. **Overall cost reduction is 2-fold**

Requires Maximized (Optimized) Substrate Flux

1. **High flux Pd requires very high flux substrates**
2. **Defects more problematic**
3. **Strength may suffer (thinner substrate)**

MPT H_2 Selective Pd Alloy Membranes

Composite Membrane Engineering: Next Generation Substrates

Larger pore size higher flux substrates under development

Table A-1. H_2 permeances obtained with Pd thin films supported on MPT commercial and experimental ceramic substrates

Parameters / Substrates	Overall H_2 Permeance [$m^3/m^2/hr/bar^{0.5}$]	Apparent Substrate Resistance Contribution [%]	Ideal Selectivity H_2/N_2 [-]	Substrate Pore Size [μm]
MPT Commercial Ceramic Tube	36.8	66	>5,000	0.5
MPT High Permeance Substrate	55.8	48.4	350 to 500	2
MPT Developmental Substrate	104	3.8	100 to 150	10

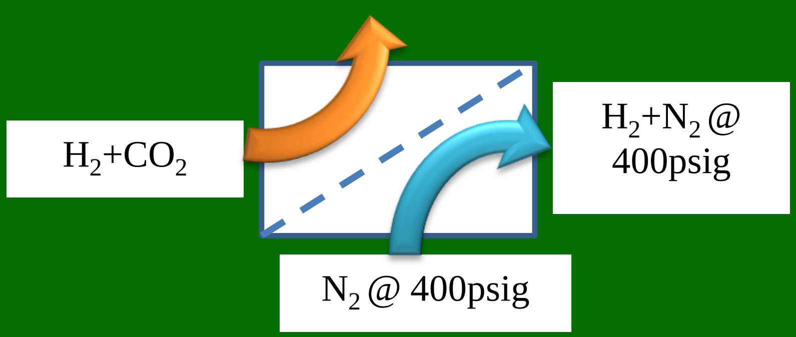
MPT H_2 Selective Pd Alloy Membranes

Pd Membrane Challenge Area B: Permeate Sweep with Inert Gas and/or Steam

Challenge B: Prefer High Pressure H_2 as Turbine Fuel Supply

Pd Membrane Permits Selective Transfer of H_2 to High Pressure Sweep Gas

Approach



Concepts: Example

Bundle Open Both Ends

Task	Yr I 1	Yr I 2	Yr I 3	Yr I 4	Yr II 1	Yr II 2	Yr II 3	Yr II 4	Yr III 1	Yr III 2	Yr III 3	Yr III 4	Cost per Task ($)	Cost per BP ($million)
	BP 1						BP 2			BP 3				
Task 2.0 Establish performance database for CMS-WGS/MR (USC)													200,000	1.15
Subtask 2.1 Modification of the present lab-scale WGS?MR system	■	■												
Subtask 2.2 Generation of performance database			■	■	■ A									
Subtask 2.3 Verification of existing mathematical model						■ B								
Task 3.0 Preparation of CMS membane reactor for bench scale test (MPT)													577,595	
Subtask 3.1 Optimization of CMS membrane separation performance	■	■	■	■										
Subtask 3.2 Conceptual design on CMS membrane/module/housing to function as a WGS/MR	■	■	■	■ D										
Subtask 3.3 Fabrication and evaluation of CMS-WGS/MR				■	■	■								
Subtask 3.4 Technical input for membrane reactor design/fabrication (Technip)	■	■	■	■	■	■								

ID	Title	Planned Date	Verification Methods
A	**Generation of the performance database**	12th	Report with the database including parameters listed in p. 39 of FOA
B	**Verification of the mathematical model**	18th	Report summarizing the deviation for all tests performed
D	**Conceptual design for the CMS/MR**	12th	CAD drawing of the MR, and parameters listed in p. 39 of FOA

Task	Yr I				Yr II				Yr III				Cost per Task ($)	Cost per BP ($million)
	1	2	3	4	1	2	3	4	1	2	3	4		
	BP 1						BP 2			BP 3				
Task 4.0 Prepare a Pd alloy membrane separator for the 2nd stage hydrogen recovery (MPT)							■	■					140,721	0.67
Task 5.0 Evaluate gas permeation and catalytic reaction under extremely high pressure (USC)													50,000	
Subtask 5.1 Experimental Verification							■	■ C						
Subtask 5.2 Membane and membrane reactor simulation support														
Task 6.0 field test with the CMS-WGS/MR and Pd membrane gas separator (MPT)													293,936	
Subtask 6.1 Operation of the bench-scale membrane reactor							■	■	■					
Subtask 6.2 Long term operation stability							■	■	■ E					

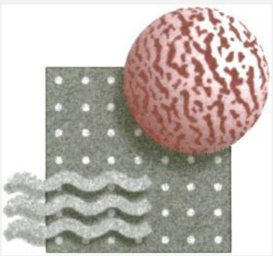
ID	Title	Planned Date	Verification Methods
C	**Operation under extreme pressure**	24th	including parameters listed in p. 39 of FOA
E	**Field test**	24th	Test report including updated parameters listed in p. 39

Task	Yr I				Yr II				Yr III				Cost per Task ($)	Cost per BP ($million)
	1	2	3	4	1	2	3	4	1	2	3	4		
	BP 1						BP 2			BP 3				
Task 5.0 Evaluate gas permeation and catalytic reaction under extremely high pressure (USC)													50,000	0.68
Subtask 5.2 Membane and membrane reactor simulation support														
Task 7.0 Conduct process design and engineering study (Technip & MPT & USC)												F	273,881	
Task 8.0 Conduct Economic and Environmental Analyses (Technip & MPT & USC)												G	273,881	

ID	Title	Planned Date	Verification Methods
F	**Design and Engineering Analysis**	36th	analysis according to the format in Attachment 3 requested by this FOA
G	**Economic and Environmental Analysis**	36th	analysis according to Attachment 3&4 requested by this FOA format

Total Budget: $2.5 millions

>20 year Experience in High Temperature High Pressure Membrane-based Gas Separations

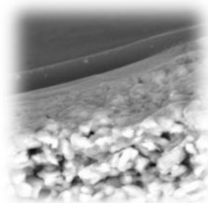


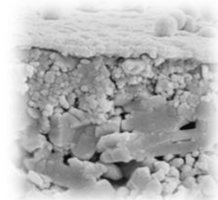
- A Commercial Ceramic Membrane Manufacturer
- A Ceramic Membrane Module & Housing Designer

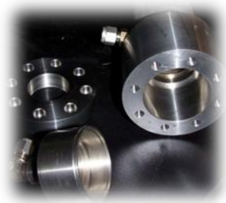
- Transport Phenomena for Fluid through Porous Media
- A Reaction Engineer specializing in Membrane Reactor

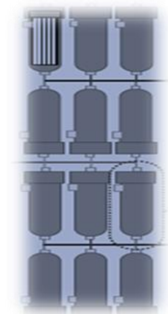
USC VITERBI SCHOOL OF ENGINEERING

One-Box Process









Field Implementable High Temperature Membrane-based Gas Separation Process

Bench (small pilot) Scale Field Test with Real Coal-derived Syngas

⊕

Engineering, Economic, & Environmental Analysis

Technip

(formerly KTI)

the world leader in the design and construction of the conventional hydrogen production facilities

Next Step: Field Test/Demonstration