Critical Component/Technology Gap in 21st Century Power Plant

Gasification Based Poly-generation:

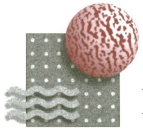
Advanced Ceramic Membranes/Modules for Ultra Efficient H_2 Production/CO_2 Capture for Coal-Based Poly-generation Plants

DE-FE0031930

Carbon Management Project Review Meeting

9-1-2023

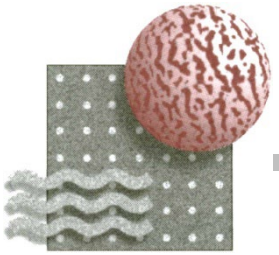
- **Dr. Richard J. Ciora, Jr. ,** Media and Process Technology Inc., Pittsburgh, PA
- **Professor Theo Tsotsis,** University of Southern California, Los Angeles, CA



Media and Process Technology Inc.

USC VITERBI SCHOOL OF ENGINEERING

U.S. DEPARTMENT OF ENERGY | NETL NATIONAL ENERGY TECHNOLOGY LABORATORY



MPT TECHNOLOGY BACKGROUND

Project Overview

Program: *DOE/FE "Critical Components for the 21st Century Power Plant"*

Funding: *Project Budget/Cost Share: $2.38M (DOE: $1.91M; Cost Share: $0.47M)*

Overall Project Performance Dates: *October 1, 2020 - September 30, 2023 (36 months); 1-year No Cost Extension to September 30, 2024*

Project Participants:

- *Media and Process Technology Inc…Membrane manufacturer/supplier and technology developer (POC: Dr. Richard Ciora)*
- *University of Southern California.…Membrane and system modeling (POC: Professor Theo Tsotsis)*

Overall Project Objectives:

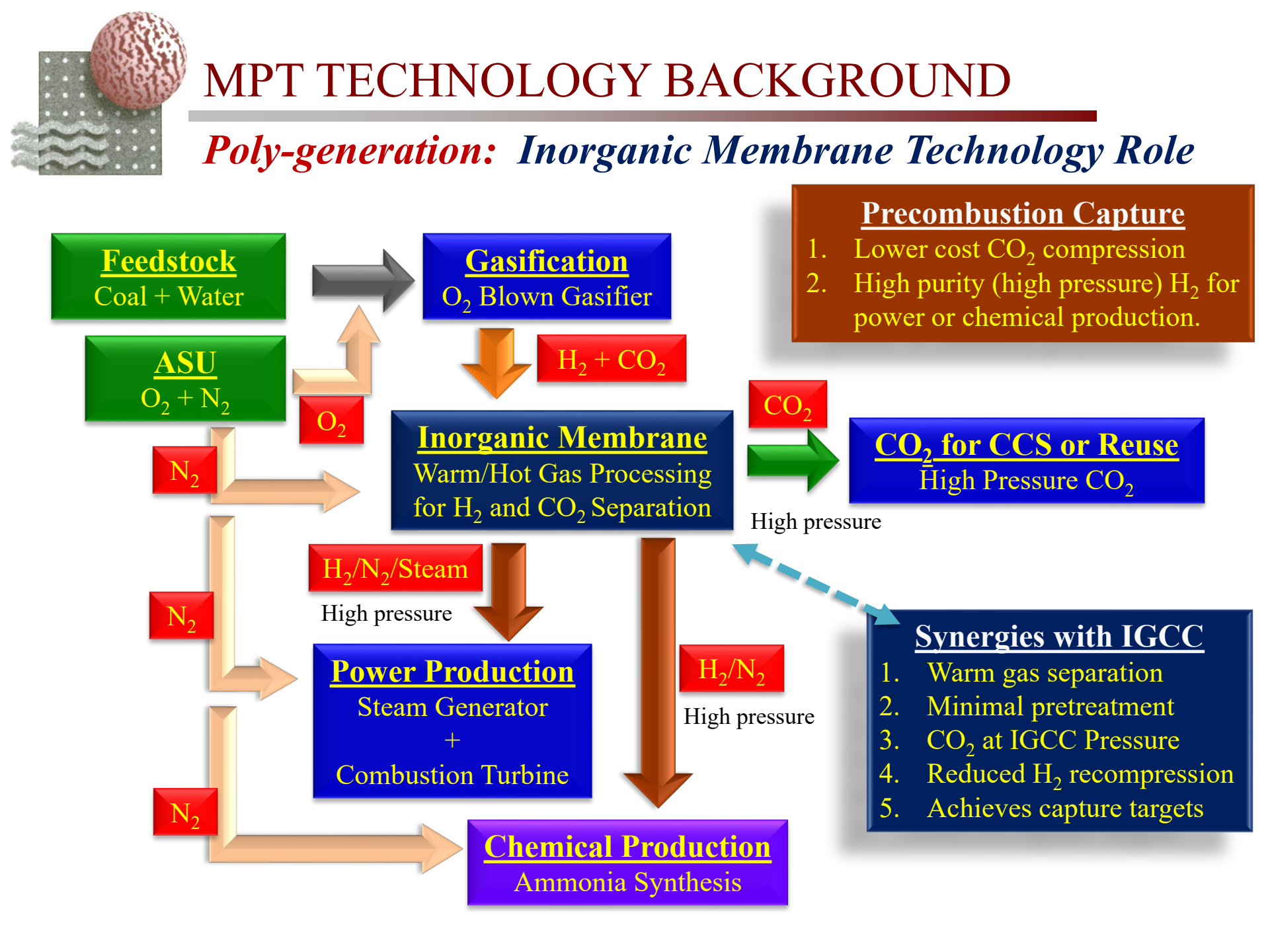
Perform R&D to enable emerging inorganic membrane technology in Poly-generation based precombustion CO_2 capture.

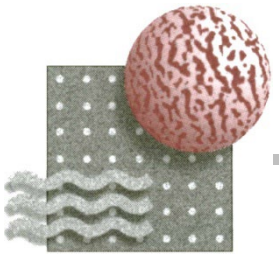
(i) Develop & fabricate a full ceramic multiple tube bundle w/ permeate purge capability.

(ii) Fabricate multiple bundle housing/module as a pre-commercial scale unit.

MPT TECHNOLOGY BACKGROUND

Poly-generation: Inorganic Membrane Technology Role





Poly-generation: Advanced Inorganic Membranes

Project Objectives and Technical Program Summary

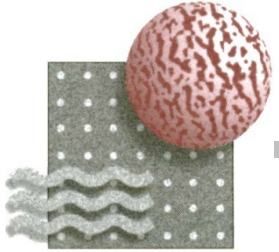
Primary Objective

Develop a permeate sweep/purge capable full ceramic multiple tube membrane bundle and multi-bundle module.

- ✓ This capability represents a Critical Technology Gap for advanced inorganic membranes in pre-combustion CO_2 capture.
- ✓ This capability is required to achieve the >30% COE cost savings target over baseline.
- ✓ Target operating conditions of 200 to >350°C and at up to 800 psig.

Technical Program Summary

- ➢ Develop and fabricate a permeate purgeable multiple tube bundle
- ➢ Design and fabricate a multiple bundle housing with appropriate seals
- ➢ Conduct a range of challenge tests to demonstrate bundle/housing stability
- ➢ Conduct long term performance stability testing at the target operating conditions
- ➢ Develop CFD model to predict membrane performance and inform module configuration
- ➢ Update the DSMP TEA for Poly-generation



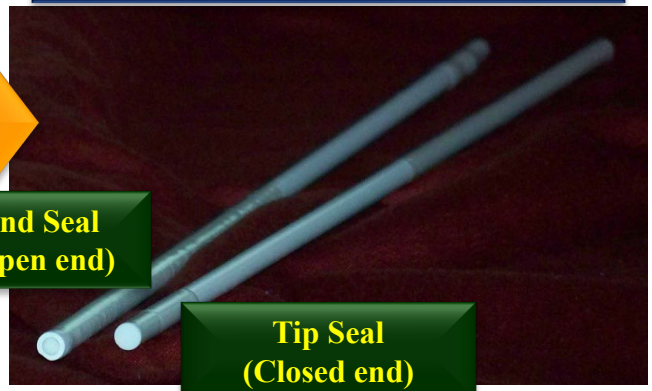
M&P TECHNOLOGY BACKGROUND

Advanced Inorganic Membranes

- Wide range of membranes technologies
- Multiple tube bundles
- High temperature (>500°C)
- High pressure (>1,000psig)
- Stepping stone from the laboratory to field/commercial scales.

Ceramic Tube Extrusion

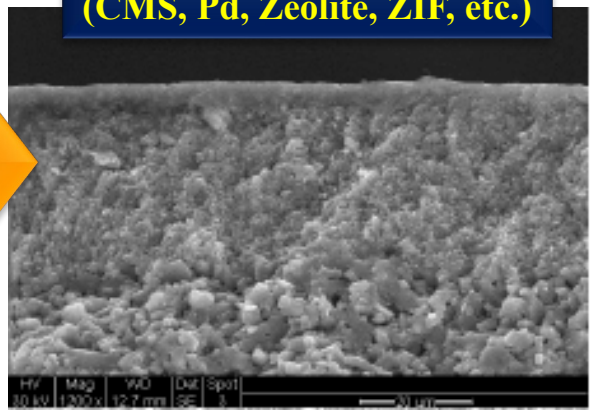
Intermediate Layer Deposition + Non-porous Tip and End Seals



End Seal (Open end)

Tip Seal (Closed end)

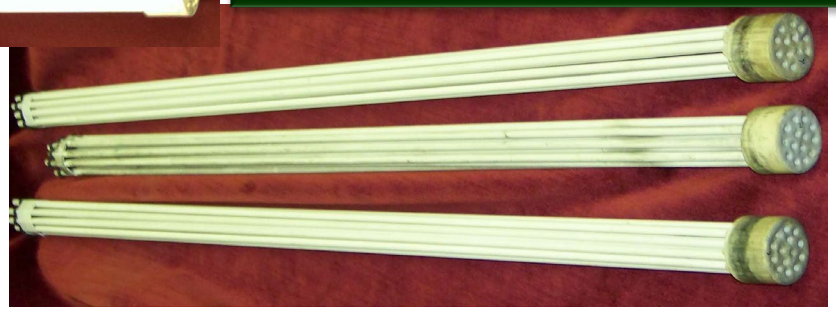
Active Layer Deposition (CMS, Pd, Zeolite, ZIF, etc.)



Carbon Molecular Sieve Membrane

Package into Multiple Tube Bundle

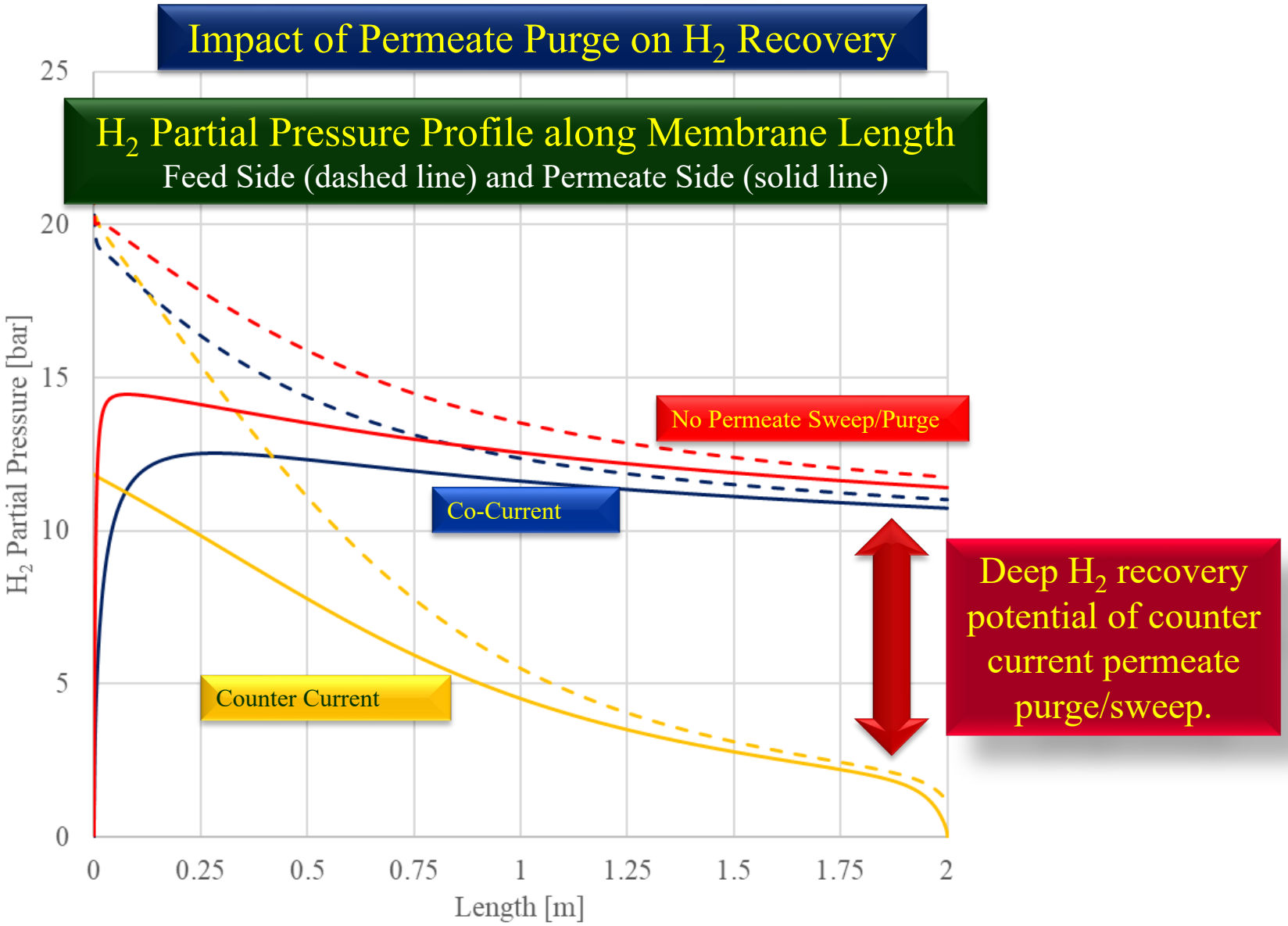
NaA, NaY, and MFI Zeolite Membranes

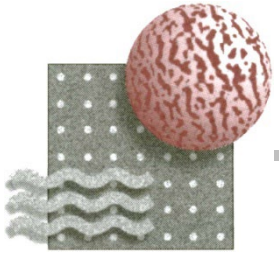


Pd-alloy Membrane

Poly-generation: Advanced Inorganic Membranes

Motivation. ***Permeate Purge Capable, Dual End Open***





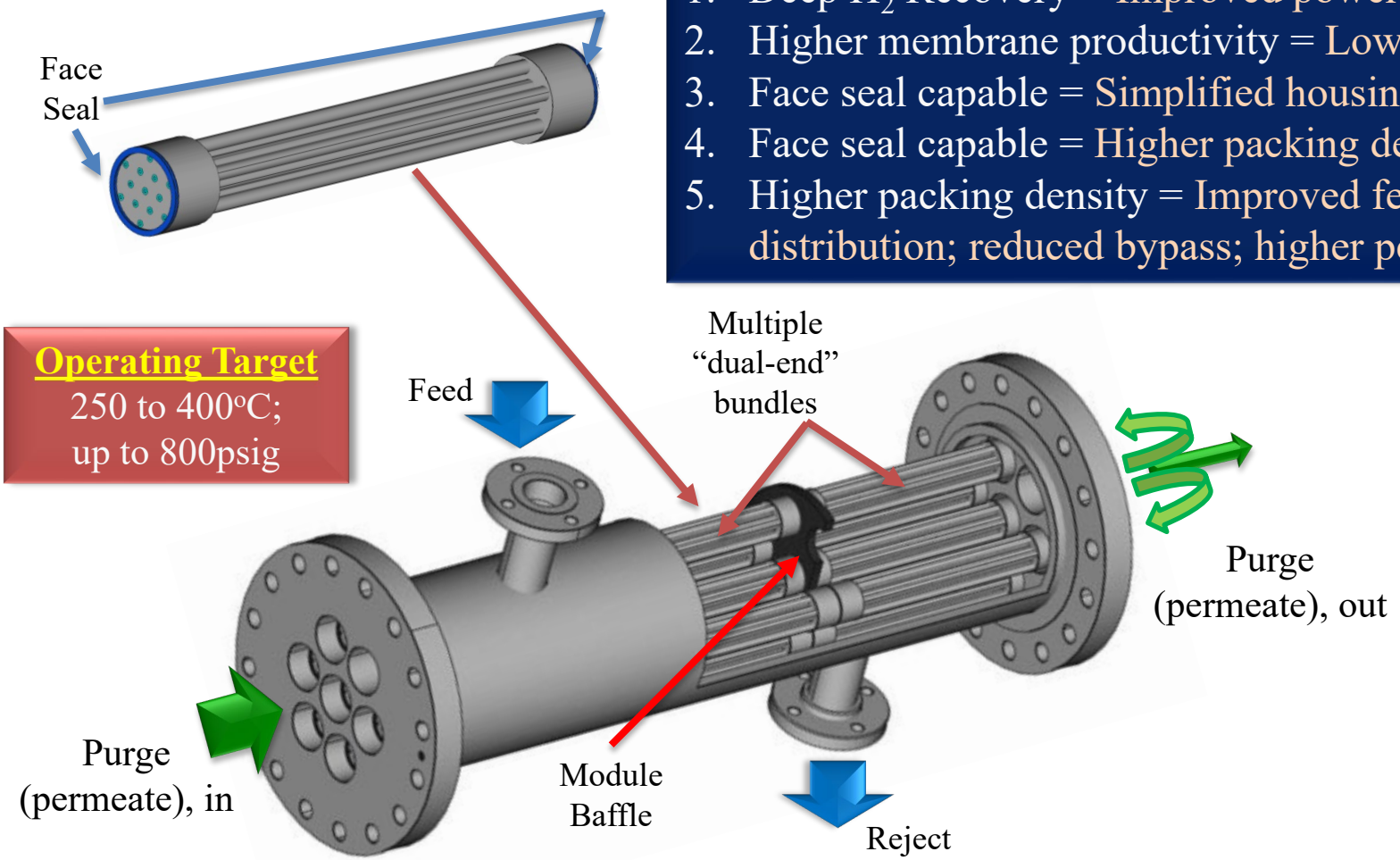
Poly-generation: Advanced Inorganic Membranes

Permeate Purgeable; Face Seals; Multiple Bundle Housings

Advantages of Dual End Permeate Purgeable

1. Deep H_2 Recovery = Improved power production.
2. Higher membrane productivity = Lower cost.
3. Face seal capable = Simplified housing design.
4. Face seal capable = Higher packing density.
5. Higher packing density = Improved feed flow distribution; reduced bypass; higher performance.

Operating Target
250 to 400°C;
up to 800psig



Poly-generation: Advanced Inorganic Membranes

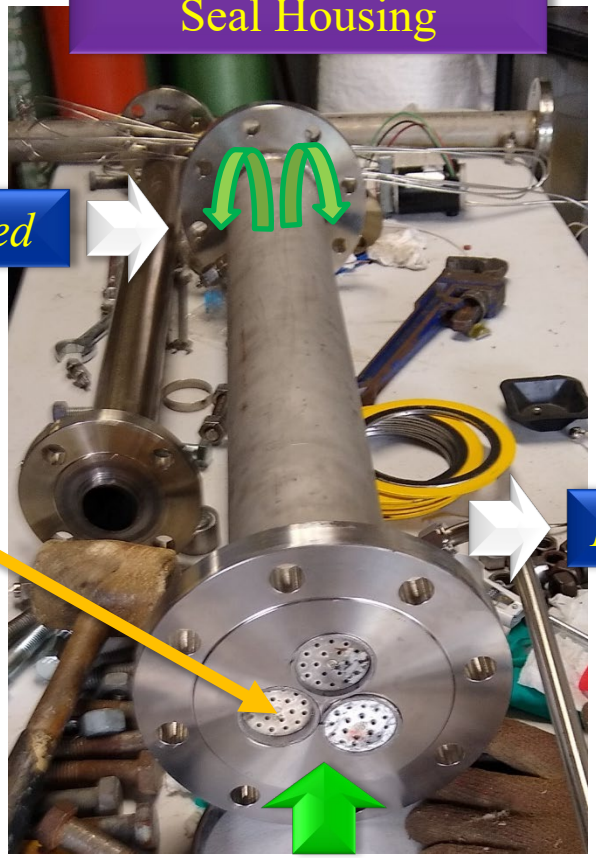
Current Status. Multiple Membrane Bundle Housing

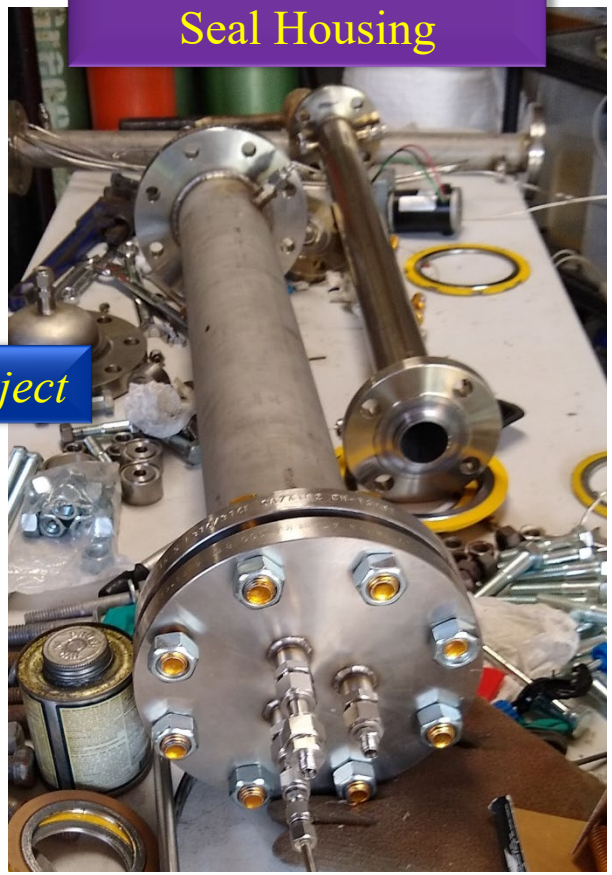
"First-of-its-kind"

Dual End CMS Membrane Bundles

Multiple Bundle Face Seal Housing

Multiple Bundle Face Seal Housing





Feed

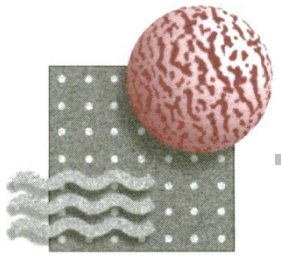
Reject

Permeate with Centerline Purge

Dense Tube Centerline Purge Port

Poly-generation: Advanced Inorganic Membranes

Project Structure…Team Member Roles and Tasks



BP1

Task 2. Design and Fabricate Permeate Purgeable Full Ceramic Multi-tubular Bundles (Q1– Q6)

Task 3. Design and Fabricate Membrane Housings for Multiple Bundles (Q1 – Q4)

Task 4 Conduct Mathematical and CFD Modeling (Q1– Q6)

Subtask 2.1 (Primary Design) *Prepare Dual Ended Bundles with Improved QC on Tubes and Optimization on Tube Sheet (Q1 – Q6)*

Subtask 2.2 (Secondary Design) *Improve Existing Candlefilter Design with U-tube or Concentric Tube Configuration as Back-up Candidate (Q3 – Q6)*

Subtask 4.1 *Conduct CFD Modeling on Module and Internal Configuration (Q1– Q4)*

Subtask 4.2 *Conduct Mathematical Modeling and Optimization of Purgeable Membranes (Q4– Q6)*

GO/NO GO

BP2

Task 5 Prepare CMS and Pd Alloy Membrane Tubes and Bundles (Q7-Q9)

Task 6 Evaluate the Operating Envelope of Module Comprising Two Bundles in Housing (Q7-Q9)

Subtask 4.3 *Technical Support for CFD and Separation Performance Modeling (Q8– Q12)*

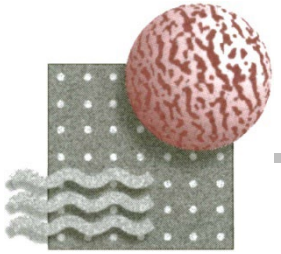
Task 7 Test Prototype Multiple Bundle Module (Q8-Q11)

Task 1. Project Management and Planning (Q1– Q12)

Task 8 Update the TEA to Confirm Cost Savings and Prepare the Final Report (Q11 – Q12)

Legend

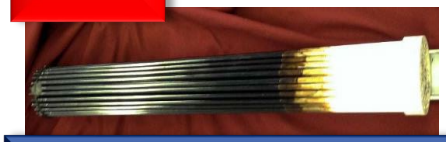
- Media and Process Technology Inc.
- University of Southern California
- Sequence of Events
- Coordination between Events



Poly-generation: Advanced Inorganic Membranes

Project Overview: BP1, BP2, NCE

BP1

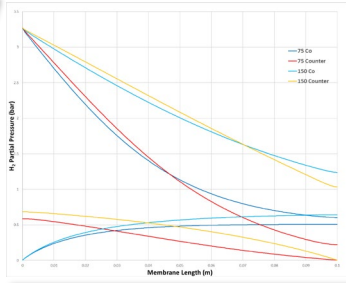


Candle Filter, Full Ceramic

Dual End, Full Ceramic

Radial

Face



COMSOL Model Basic Development

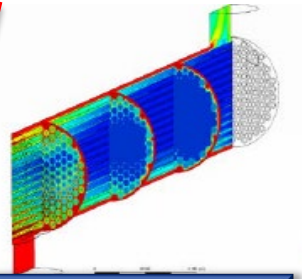
BP2

Dual End

Functional Dual End

Single Bundle, Radial Seal

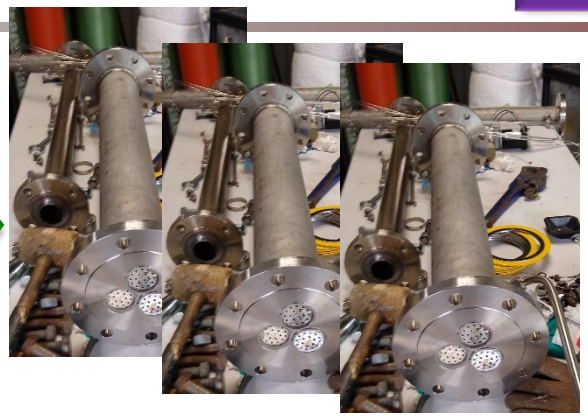
Multiple Bundle, Face Seal



COMSOL Model Flow Distribution + Housing Design

NCE

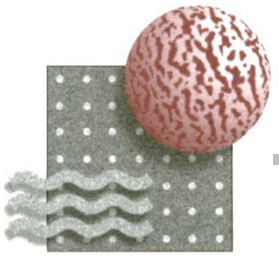
Multiple Bundle, Face Seal



Long Term Performance and Challenge Testing in Multiple Bundle Membrane Housings

+

Predictive Performance Modeling



Poly-generation: Advanced Inorganic Membranes

Milestone Progress. BP2

Mile-stone	Milestone Description	Target Completion	Current Status	% Completion
I	Complete the CFD modeling of the dual ended bundle and multiple bundle module in U-bend and permeate sweep modes with recommendations for internal baffle and other flow management devices.	Q11	*Status:* Continuing "bundles in parallel" model development and simulation in multiple bundle housings. Simulation of Polygeneration WGR+Membrane for PFD, HMB, TEA update. *Remain:* a. 6x Series/parallel bundles in module. b. Bundle and housing design/optimization.	~90%
J	Prepare the CMS & Pd-Ag membrane tubes and 6x dual end bundles that meet the minimum leak and compression targets.	Q9	Pd tubes, >120 of 120 (100% completion) CMS tubes, >120 of 120 (100% completion) Pd and CMS Bundles: 6x each (100% Complete)	100%
K	Complete the shakedown and performance testing in permeate sweep mode.	Q7	Pd and CMS bundle performance verification in permeate sweep mode complete.	100%
L	Complete the testing of the 3 to 4 (6) bundles as base modular unit.	Q11 (Q12)	*Status:* - Testing of the multiple bundle housing (underway) - Mixed gas testing with permeate sweep (underway) Remain: a. Two bundle in series testing. b. Six bundle series/parallel testing.	Bundle: ~100% Testing: ~40% Overall: 50%
M	Update the TEA for the new module design and process configuration with update for the Poly-generation scheme.	Q12	*Status:* • PFD and HMB process model simulation in DWSIM. *Remain:* Update the PFD and TEA	10%

Technical Progress: BP1

Milestone D/E. Fabricate Permeate Purgeable Bundles (complete)

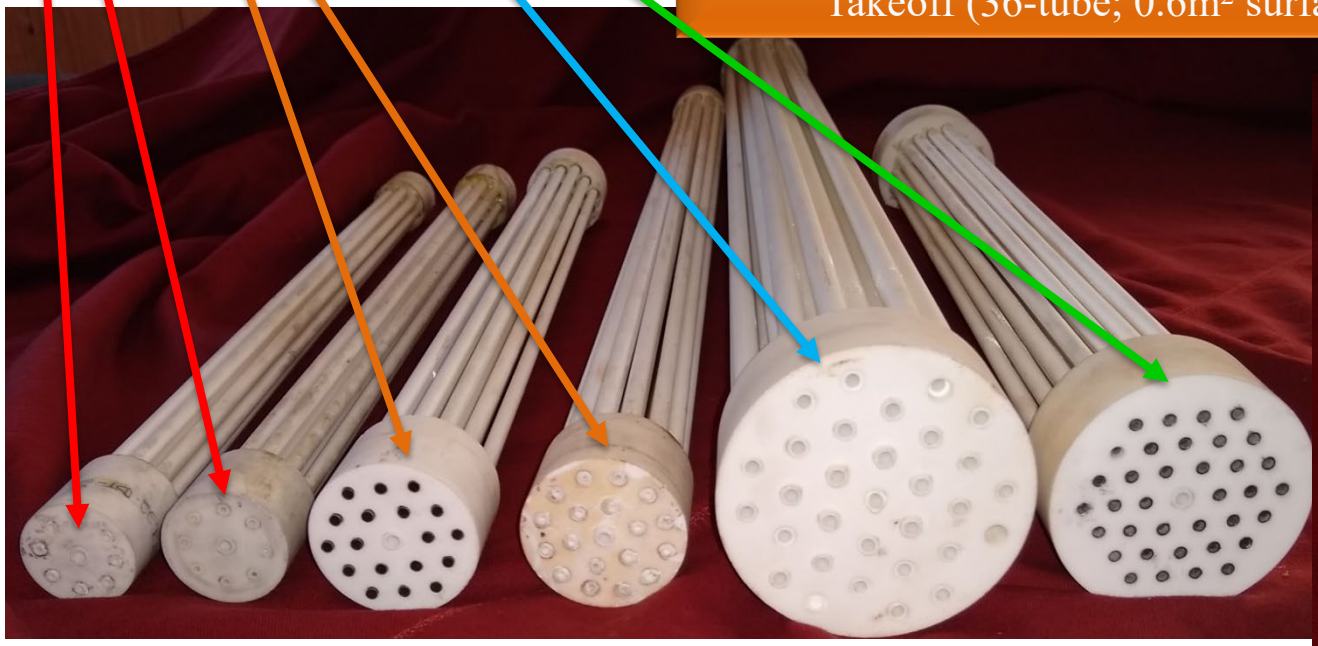
1.5": 18 x 5.7mm Dense/Porous Tube w/ Centerline Permeate Takeoff

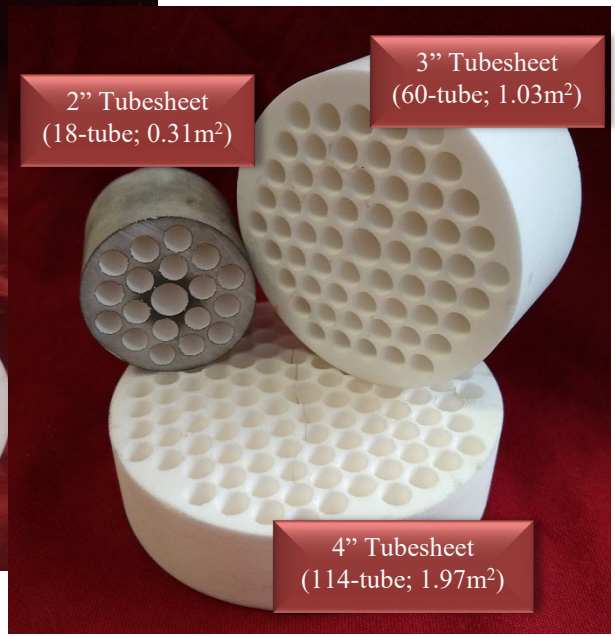
"First-of-its-kind"

2": 12 x 8.6mm Tube Dense/Porous Tube w/Centerline Permeate Takeoff

3": 4x 8.6mm Dense Tube w/Centerline Permeate Takeoff

2.5": 1x 5.7mm Porous Tube w/Centerline Permeate Takeoff (36-tube; 0.6m^2 surface area at 38")





Technical Progress: BP1

Milestone D/E. Challenge Test Permeate Purgeable Bundles

	Thermal Cycling, "Unloaded"					Thermal Cycling,in Housing			Pressure Cycling, in Housing		
Membrane ID	**250°C**	**400°C**	**450°C**	**Membrane ID**	**Housing/Seal**	**250°C**	**400°C**	**450°C**	**250°C**	**400°C**	**450°C**
PGI.5-PTA-1	13	(101) 160	25	PGI.5-PTA-1	Single Face, Metal	28	27	24		6	6
PGI.5-PT-2	0	(114) 173	0	PGI.5-PT-2							
PGI.5-PT-3	0	(91) 150	23	PGI.5-PT-3							
PGI.5-DT-2	8	63	2	PGI.5-DT-2							
PGI.5-DT-3	8	62	23	PGI.5-DT-3							
PGI.5-DT-6	0	0	34	PGI.5-DT-6							
PGI.5-DT-7	0	0	0	PGI.5-DT-7	Radial, Graphite	30					
PGI.5-DT-8	1	6	0	PGI.5-DT-8	Radial, Graphite	10					
PGI.5-DT-9	0	7	0	PGI.5-DT-9	Dual Face, Metal	10					
(PGI.5-DT-9)	0	0	0	(PGI.5-DT-9)	Single Face, Oring	10					
PGI.5-DT-10	0	4	0	PGI.5-DT-10	Dual Face, Metal	9	3	7		3	
PGI.5-DT-11	0	13	12	PGI.5-DT-11							
PGI.5-DT-12	0	12	24	PGI.5-DT-12	Dual Face, Oring				67		
PGI.5-DT-14	0	0	0	PGI.5-DT-14	Dual Face, Oring				39		
PGI.5-DT-15	0	0	0	PGI.5-DT-15	Dual Face, Oring				20		
PGI.5-DT-16	0	0	0	PGI.5-DT-16	Dual Face, Oring				75		
PGI.5-DT-6	0	34	16	PGI.5-DT-6							
PGI.5-DT-13	0	0	0	PGI.5-DT-13							
PGI.75-DT-1	0	27	0	PGI.75-DT-1	Radial, Graphite		8		9	(27) 62	
PGI.75-DT-2	0	24	0	PGI.75-DT-2							
PGI.75-DT-3	0	10	0	PGI.75-DT-3	Dual Face, Oring				6		
PGI.75-DT-4	0	8	0	PGI.75-DT-4	Dual Face, Oring				6		
PGI.75-DT-7	0	0	0	PGI.75-DT-7	Dual Face, Oring				29		
PGI.75-DT-8	0	0	0	PGI.75-DT-8	Dual Face, Oring				3		
PGI.75-DT-9	0	0	0	PGI.75-DT-9	Dual Face, Oring				26		
PGI.75-DT-10	0	0	0	PGI.75-DT-10							
PGI.75-DT-11	0	0	0	PGI.75-DT-11							
PGI.75-DT-12	0	0	0	PGI.75-DT-12	Dual Face, Oring				(0) 53		
PGI.75-DT-13	0	0	0	PGI.75-DT-13	Dual Face, Oring				(0) 53		
PGI.75-DT-14	5	(3) 6	0	PGI.75-DT-14							
PGI.75-PT-2	5	(3) 6	0	PGI.75-PT-2							
PG2-PT-1	0	0	33	PG2-PT-1	Radial, Graphite		9	24		4	
PG2-PT-2	0	6	8	PG2-PT-2							
PG2-PT-3	0	0	8	PG2-PT-3	Radial, Graphite			22		15	
PG2-PT-4	0	0	8	PG2-PT-4							
PG2-DT-1	0	4	22	PG2-DT-1							
PG2-DT-2	0	28	0	PG2-DT-2							
PG2-DT-7	0	0	0	PG2-DT-7	Radial, Graphite	21	12			17	
PG3-DT-1	12	8	0	PG3-DT-1							
PG3-DT-2	4	58	0	PG3-DT-2							
PG3-PT-1	0	(64) 125	0	PG3-PT-1							
PG3.5-DT-5	10	58	0	PG3.5-DT-5							
PG3.5-DT-6	2	0	0	PG3.5-DT-6							
Totals	68	1,052	238		***Totals***	118	99	117	412	116	6

Key
PGxx-yy-ID#
xx: Bundle Diameter
yy: DT = Dense Tube
PT = Porous Tube

BP1 Dense and Porous Tube Bundle Challenge Testing

Test Modes

1. **Thermal Cycle (T/C); unloaded**
2. **T/C; constrained = radial or face seal housings**
3. **T/C; constrained; pressure cycled**

Results Summary

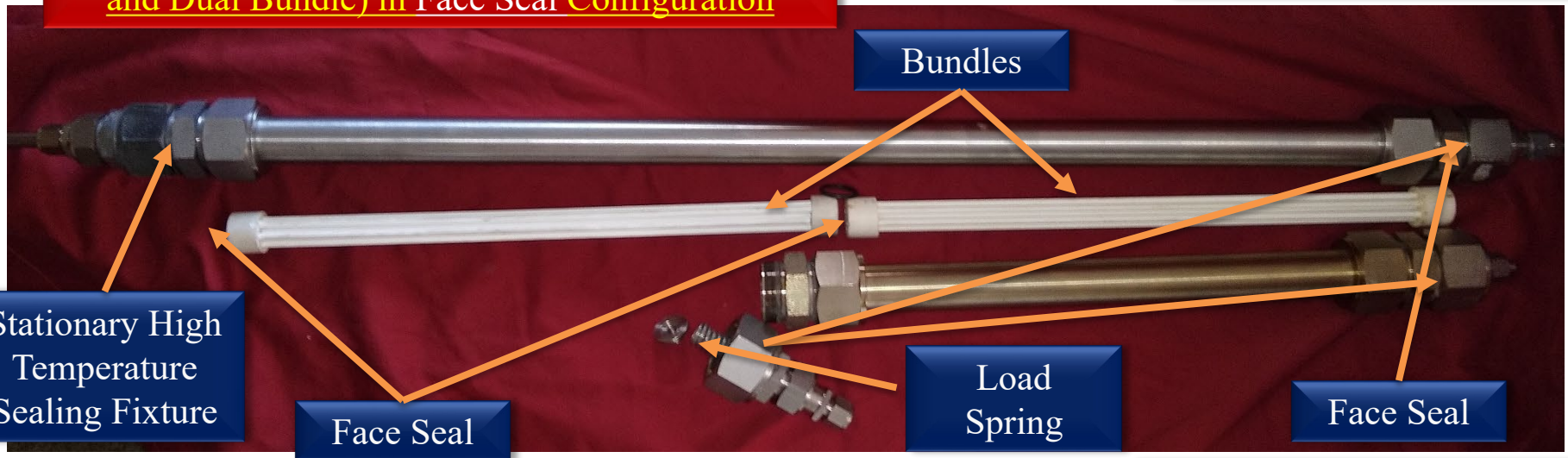
1. 43 Successful Dual End Bundles
2. Dense and Porous Tube
3. >1,300 T/C unloaded
4. >300 T/C loaded housing
5. >500 T/C loaded, pressurized

Technical Progress: BP1

Milestone F/G. Dual End Bundle Housing Fabrication (complete)

2" Dual End Full Bundle Housing (Single Bundle and Dual Bundle) in Face Seal Configuration

"First-of-its-kind"



2" Dual End Bundle Radial Seal Housing

1.5" Dual End Bundle Radial Seal Housing

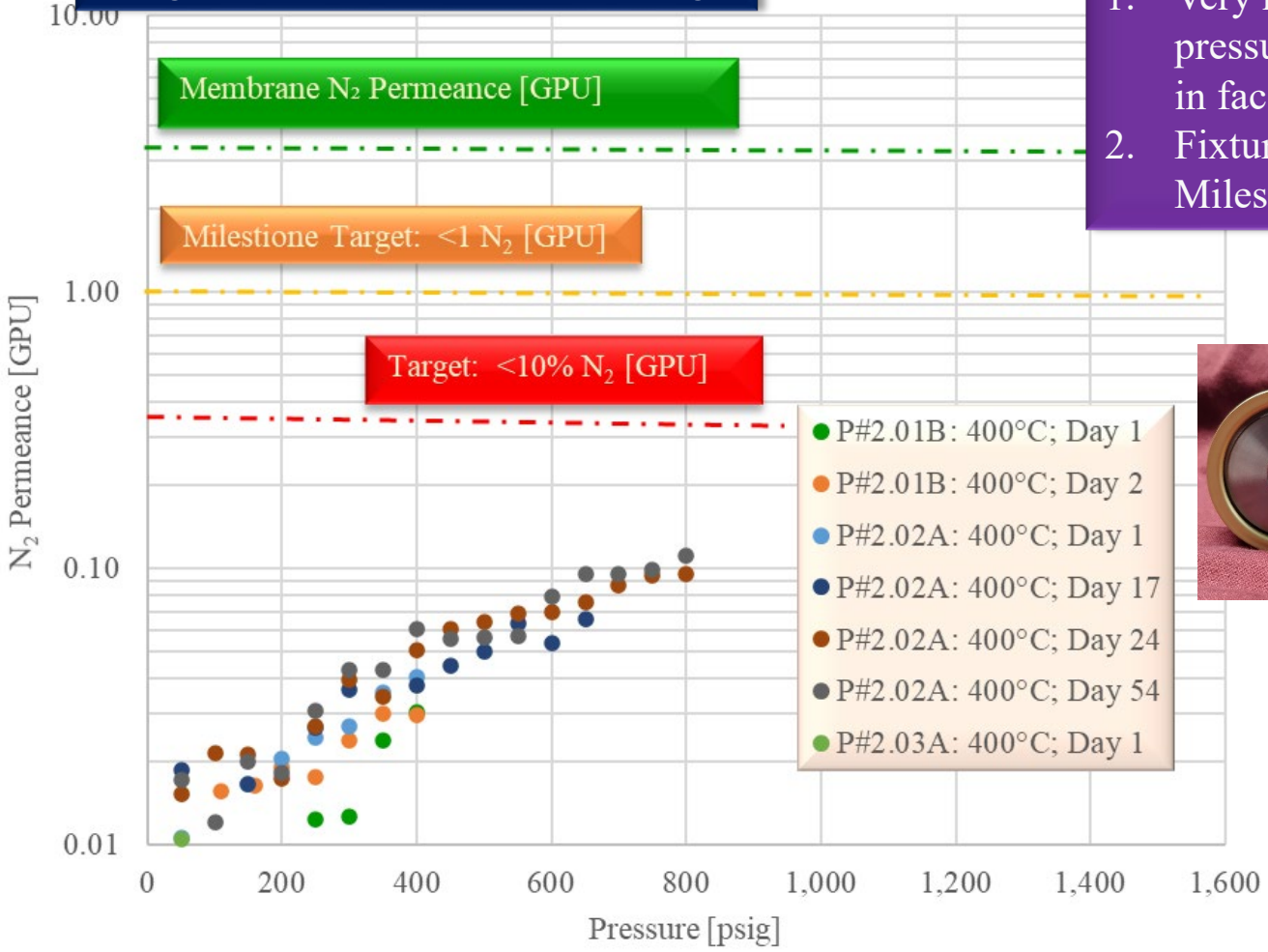
3" Dual End Bundle Radial/Face Seal Housing

Technical Progress: BP1

Milestone F. Face Seal Configuration Challenge Testing (complete)

High Temperature Face Seal Housing

High Pressure Performance Testing



Results Summary

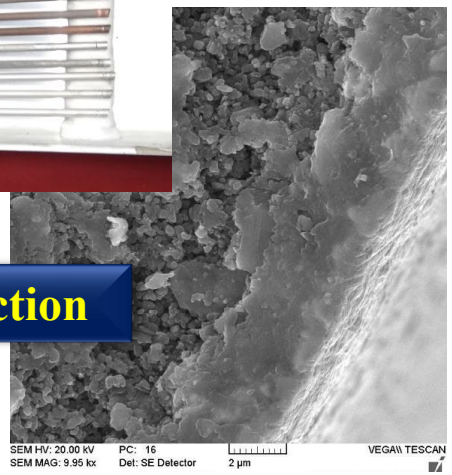
1. Very high temperature and pressure capability demonstrated in face seal configuration.
2. Fixture leak rates well below the Milestone F and "stretch" target.

Technical Progress: BP2

Milestone J. Pd and CMS Membrane Tube Fabrication (Complete)

Dual End Pd Tubes

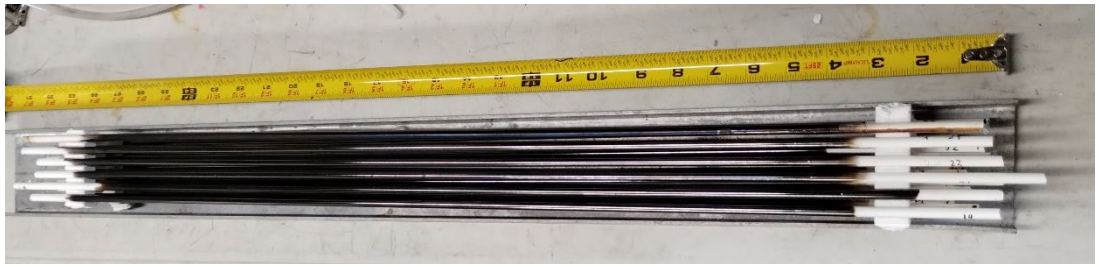
A. Complete >120 tubes.
B. Performance Average:
   H_2 [GPU]: 3,700
   H_2/N_2 [-]: >29,000



SEM Cross Section

Dual End CMS Tubes

A. Complete >120 tubes.
B. Performance Average:
   He [GPU]: ~400
   He/N_2 [-]: >250
C. Outliers (~20 tubes)
   He [GPU]: ~550 to 700
   He/N_2 [-]: >300



Technical Progress: BP2

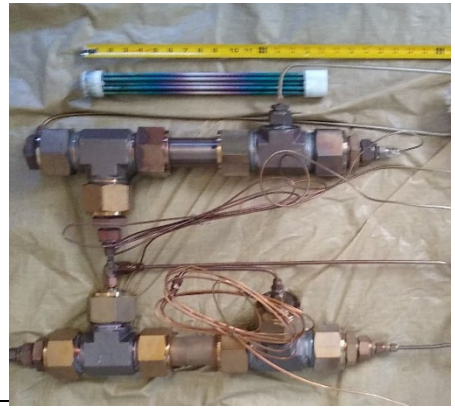
Milestone L. Pd Multiple Tube Bundle Fabrication (Complete)

Pd Membrane Bundle Performance. QC Testing

Target performance: (i) >75% of Average Single Tube Performance; (ii) N_2 Leak Rate <5 GPU

PdB19T.01

	Temp [°C]	H_2 [GPU]	N_2 [GPU]	H_2/N_2 [-]	Comment [-]
Average Single Tube Performance	350	1,059	1.0	1,059	
Bundle PdB19T.01					
Day 9	331	464	2.2		
Day 16	331	469	2.4	192	
Day 17	331	N/A	2.6		
Day 17	331	912	2.5	367	Post Air Purge
	>75%?	86.1%	2.49	<5 GPU	
Day 18	336	559	3	215	
Day 21	338		2.9		
Day 21	338	986	2.7	368	Post Air Purge
	>75%?	93.1%	2.68	<5 GPU	



PdB19T.02

	Temp [°C]	H_2 [GPU]	N_2 [GPU]	H_2/N_2 [-]	Comment [-]
Average Single Tube Performance	350	3,850	0.2	25,667	
Bundle PdB19T.02					
Day 1	350	2,617	1.31		
Day 1	350	3,637	1.34	2,712	
	>75%?	94.5%	1.34	<5 GPU	Post Air Purge
Day 2	350	2,898	1.28	2,257	
Day 7	350	1,145	1.27	904	
Day 7	350	3,261	1.24	2,623	Post Air Purge
	>75%?	84.7%	1.24	<5 GPU	

PdB19T.03

Tube ID [-]	Temp [°C]	H_2 [GPU]	N_2 [GPU]	H_2/N_2 [-]	Comment [-]
Average Single Tube Performance	350	3,850	0.2	25,66	
Bundle PdB19T.03					
Day 1	350		0.88		
Day 4	350	1,403	0.91	1,547	
Day 4	350	2,083	1.02	2,052	Post Air Purge
Day 13	308	1,290	1.34	962	
Day 13	308	2,536	1.33	1,909	
	>75%?	65.90%	1.33	<5 GPU	
Day 14	308	973	1.36	717	
Day 14	308	2,847	1.32	2,156	Post Air Purge
	>75%?	74.00%	1.3	<5 GPU	
Day 17	311	1,322	1.37	963	
Day 17	311	3,141	1.38	2,278	Post Air Purge
	>75%?	81.60%	1.38	<5 GPU	
Day 20	311	1,394	1.48	939	
Day 20	311	3,275	1.43	2,287	

PdB19T.04, .05, .06

Tube ID [-]	Temp [°C]	H_2 [GPU]	N_2 [GPU]	H_2/N_2 [-]	Comment [-]
Average Single Tube Performance	350	N/A	N/A	N/A	
Bundle PdB19T.04					
Day 1	RT	N/A	13.55	N/A	
	350	N/A			
Bundle PdB19T.05					
Day 1	RT	N/A	1.95	N/A	
Day 4	350	3,200	1.17	<5 GPU	
Bundle PdB19T.06					
Day 1	RT	N/A	1.65	N/A	
Day 3	350	4,300	0.94	<5 GPU	

On-spec

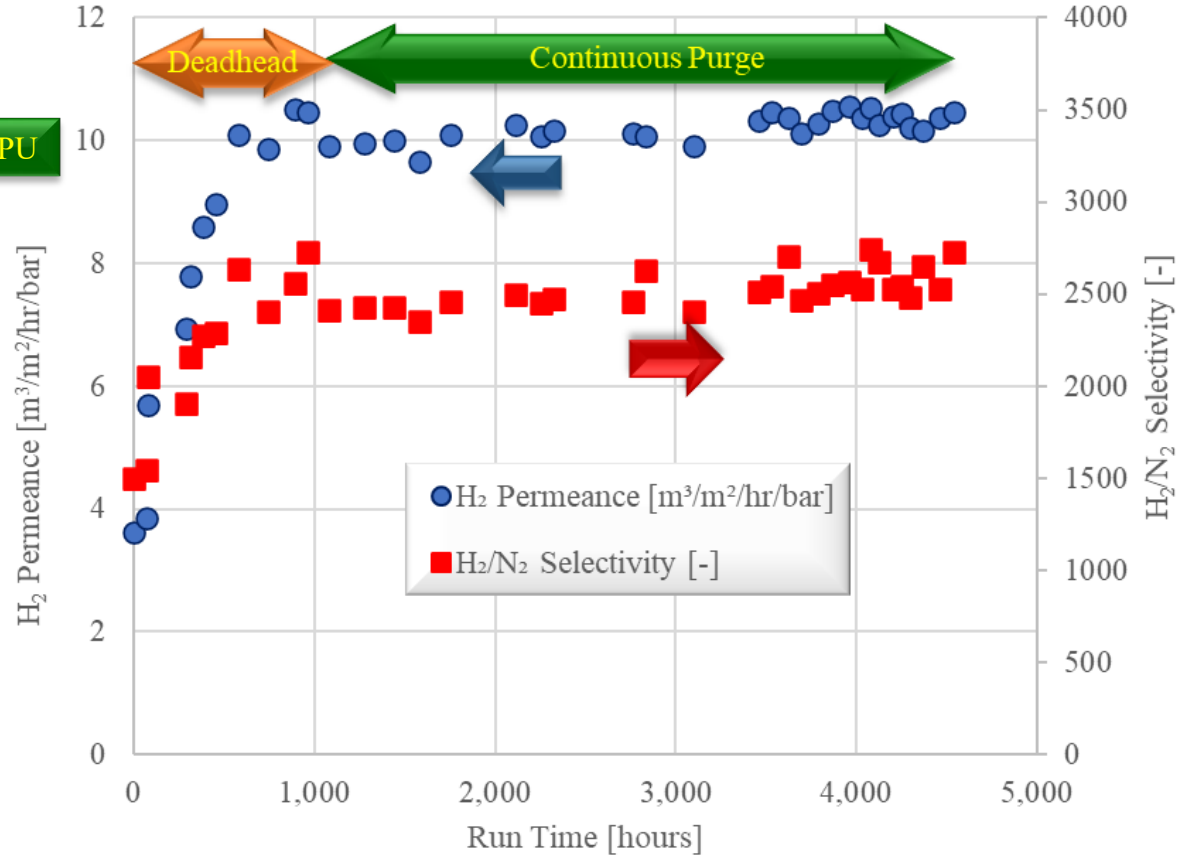
Technical Progress: BP2

Milestone L. Pd Bundle Challenge Testing (Complete; on-going)

Long Term Performance Stability Testing

PdB19T.03

~3,650 GPU



Technical Progress: BP2

Milestone L. CMS Multiple Tube Bundle Fabrication (Complete)

CMS Membrane Bundle Performance. QC Testing

Target performance: (i) >75% of Average Single Tube Performance; (ii) N_2 Leak Rate <5 GPU

CMS DB19T.01

		He [GPU]	N_2 [GPU]	He/N_2 [-]	Comment [-]
Average Single Tube Performance	RT	N/A	4.1		
	250	361	1.4	254	
Bundle CMS.DB19T.01					
Day 1	RT	N/A	11.3		
	250	214	6.3	34	High N_2
Day 2	250	275	6.7	41	Overnight N_2 purge
He Permeance Ratio [%]		76.2	[He permeance on spec; N_2 permeance high]		
Bundle CMS.DB19T.01 (post polishing)					
Day 3	250	166	1.98	84	
Day 5	250	147	1.96	75	

CMS DB19T.04

		He [GPU]	N_2 [GPU]	He/N_2 [-]	Comment [-]
Average Single Tube Performance	RT	N/A	0.8		
	250	351	1.6	224	
Bundle CMS.DB19T.04					
Day 1	RT	N/A	5.9		
Day 1	250	N/A	14.8		Out of range for N2.
He Permeance Ratio [%]		N/A	[He and N_2 permeance on-spec]		
Patch Tubesheet Leak					
Day 1	RT	N/A	1.8		
Day 1	250	N/A	1.6		Out of range for N2.
He Permeance Ratio [%]		N/A	[He and N_2 permeance on-spec]		

CMS DB19T.05

	[°C]	He [GPU]	N_2 [GPU]	He/N_2 [-]	Comment [-]
Average Single Tube Performance	RT	N/A	0.9		
	250	385	1.3	289	
Bundle CMS.DB19T.05					
Day 1	RT	N/A	3.0		
	250	N/A	3.7		
	250	346	3.8	92	N2 purge.
Day 3	250	370	3.6	104	N2 purge.
He Permeance Ratio [%]		96.2	[He and N_2 permeance on-spec]		

CMS DB19T.03

		He [GPU]	N_2 [GPU]	He/N_2 [-]	Comment [-]
Average Single Tube Performance	RT	N/A	0.9		
	250	351	1.6	224	
Bundle CMS.DB19T.03					
Day 1	RT	N/A	0.4		
	250	221	1.3	170	
Day 3	250	262	1.3	198	Start N2 purge.
Day 7	250	300	1.3	224	N2 purge.
Day 16	250	244	1.4	169	
Day 21	250	286	1.4	201	
Day 22	250	290	1.4		
Day 29	250	301	1.4	215	
He Permeance Ratio [%]		85.6	[He and N_2 permeance on-spec		

CMS DB19T.06

	[°C]	He [GPU]	N_2 [GPU]	He/N_2 [-]	Comment [-]
Average Single Tube Performance	RT	N/A	1.4		
	250	344	1.3	258	
Bundle CMS.DB19T.06					
Day 1	RT	N/A	1.8		
	150		2.4		
	250	372	3.3	114	N2 purge.
	250	367	3.3	112	N2 purge.
	250	365	3.0	123	N2 purge.
neance Ratio [%]		106.2	[He and N_2 permeance on-spec]		
	250	365	3.0	123	N2 purge.

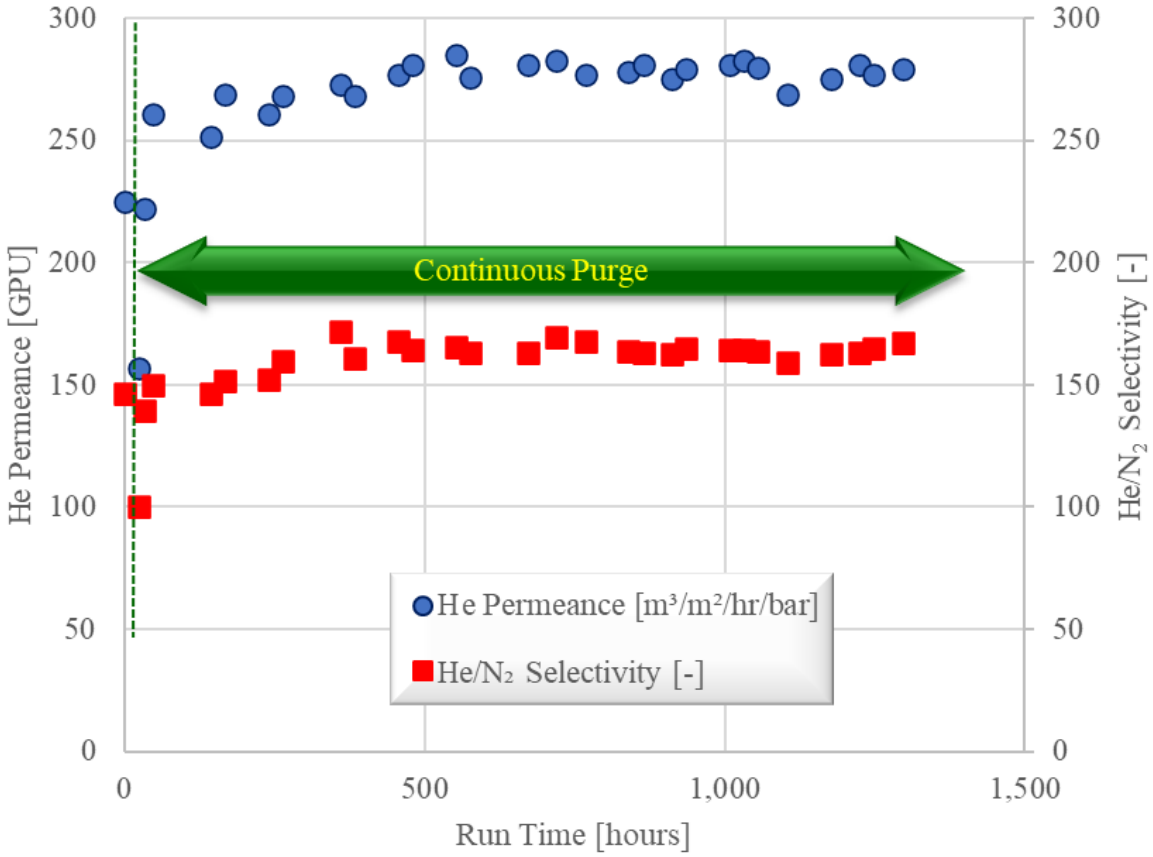
CMS DB19T.02

		He [GPU]	N_2 [GPU]	He/N_2 [-]	Comment [-]
Average Single Tube Performance	RT	N/A	2.5		
	250	339	1.6	217	
Bundle CMS.DB19T.02					
Day 1	RT	N/A	1.6		
	250	225	1.5	147	
Day 2	250	270	1.6	170	Overnight N_2 purge
He Permeance Ratio [%]		79.6	[He and N_2 permeance on-spec]		

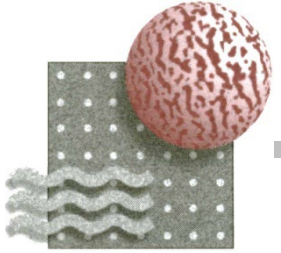
Technical Progress: BP2

Milestone L. CMS Bundle Challenge Testing (Complete; on-going)

Long Term Performance Stability Testing (Face Seal Housing Configuration)



CMS DB19T.03



Technical Progress: BP2

Milestone L. Mixed Gas with Sweep Testing (Complete; on-going)

CMS DB19T.02
Mixed Gas with Sweep (Ar)
(Feed: 30/70 He/N_2; T: 250°C)

Part ID [#]	Feed Pressure [psig]	Sweep Rate [cc/min]	Actual Permeate Rate [cc/min]	Predicted Permeate	Error Actual/ Model [%]	Actual Reject He [%]
CMS DB19T.02						
No sweep	65	0	707	556	127.3	18.6
Co-current	65	308	1,035	1,081	95.8	16.4
Counter	65	308	1,124	1,040	108.1	12.3
No sweep	65	0	406	359	113.2	14.2
Co-current	65	308	714	778	91.8	11.6
Counter	65	308	863	820	105.2	5.5
No sweep	100	0	758	809	93.8	13.3
Co-current	100	308	1,131	1,179	95.9	11.5
Counter	100	308	1,280	1,212	105.6	9.2
No sweep	100	0	696	722	96.4	13.0
Co-current	100	308	1,006	1,122	89.6	10.5
Counter	100	308	1,136	1,119	101.5	7.2

PdB19T.03
Mixed Gas with Sweep (Ar)
(Feed: 30/70 H_2/N_2; T: 340°C)

Part [#]	Feed Pressure [psig]	Sweep Rate [cc/min]	Actual Permeate Rate [cc/min]	Predicted Permeate Rate [cc/min]	Stage Cut	Error Actual/ Model [%]	Actual Reject H_2 [%]
PdB19T.03							
No Sweep	51.5	0	2,386	2,404	9.3	99.2	23.5
No Sweep	50.8	0	2,393	2,355	9.2	101.6	23.7
No Sweep	50.5	0	2,372	2,279	9.4	104.0	24.1
Co-current	51.5	751	4,511	4,297	17.8	105.0	19.1
Co-current	51.0	751	5,172	5,172	20.8	100.0	19.8
Counter	50.0	751	4,571	4,260	17.6	107.3	14.8
Counter	50.0	752	4,752	4,334	17.7	109.7	14.1

A. Reject Purity: Counter current purge delivers substantial reduction in fast gas reject purity (higher recovery).

B. Model Predictions: COMSOL model permeate rate in reasonably good agreement with actual performance.

Technical Progress: BP2

Milestone L. Mixed Gas with Steam Sweep (on-going)

Steam Sweep for Pressurized H_2 (permeate) Delivery
(Feed: H_2/CO_2 at 50/50; T: 359°C)

Run ID [-]	Run Mode [-]	Feed Press [psig]	Perm Press [psig]	Feed [cc/min]	Reject [cc/min]	Total Perm Flow [cc/min]	Sweep Flow [cc/min]	Sweep Free Perm Flow [cc/min]	Target Reject Gas [-]	Actual Reject Comp [%]
Steam sweep										
374	Sweep	56.5	0	1,589	1,024	1,221	656	566	CO_2	84
378	Sweep	57.0	0	1,635	1,085	1,106	556	550	CO_2	84
383	No Sweep	57	0	1,442	1,001	441	0	441	CO_2	78
Steam sweep at elevated permeate pressure.										
418	Sweep	91.5	0	1,896	1,127	2,756	1,987	769	CO_2	N/A
419	Sweep	91.8	52	1,625	1,164	2,521	2,060	461	CO_2	N/A
422	Sweep	91.9	56	1,63	1,171	2,550	2,090	460	CO_2	N/A
No sweep at elevated permeate pressure.										
426	No Sweep	89.5	0	1,793	1,125	668	0	668	CO_2	N/A
430	No Sweep	89.9	23	1,474	1,221	253	0	253	CO_2	N/A
431	No Sweep	90	35.8	1,3	1,354	42	0	42	CO_2	N/A
432	No Sweep	90	43	1,320	1,320	0	0	0	CO_2	N/A

A.

B.

A. High productivity with sweep versus no sweep cases: Sweep enables deeper H_2 recovery under the same operating conditions.

B. Steam sweep of the permeate at elevated pressure: H_2 delivery at high purity and compressed to high pressure.

Technical Progress: BP2

"First-of-its-kind"

Milestone L. Multiple Bundle Module Testing (on-going)

1st Bundle Shakedown Testing in the 3-Bundle Housing

CMS DB19T.04
Mixed Gas Testing
(Feed: 70/30 He/N_2; T: 250°C)

Feed Pressure [psig]	Actual Permeate Rate [cc/min]	Predicted Permeate Rate [cc/min]	Error Permeate Actu Mod [-]	Stage Cut [%]
45.0	1,110	1,056	1.05	65.9
45.0	1,095	1,142	0.96	58.0
45.0	1,180	1,304	0.91	49.7
45.0	1,371	1,438	0.95	46.0
65.2	1,800	1,676	1.07	68.8
65.2	1,734	1,945	0.89	52.2
65.2	1,915	2,143	0.89	46.8
80.1	2,125	2,140	0.99	64.4
80.1	2,284	2,555	0.89	51.2
63.0	2,013	1,823	1.10	66.1
63.0	1,729	1,717	1.01	62.5
63.9	1,544	1,621	0.95	61.3
63.9	1,528	1,533	1.00	64.3

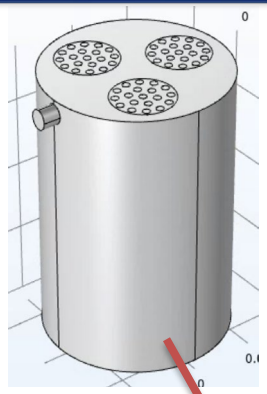
A.

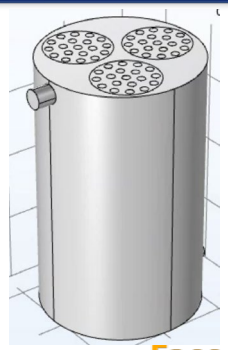
A. Good agreement between actual and predicted permeate rate in the multiple bundle housing: Error typically under 5% with some excursions to 10%. Consistent with single bundle housing results.

Technical Progress: BP2

Milestone I/M. COMSOL Model Predictions (on-going)

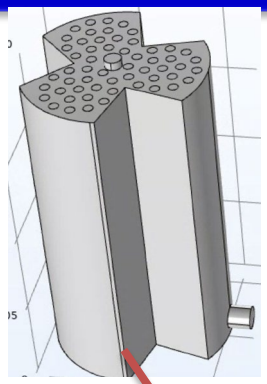
Three Bundle in Parallel Modeling

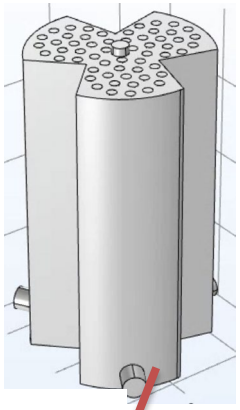




Face seal
(63.9 %)

Baffled with Side Entry/Center Take-off





72.8%

73.8%

Ideal
(74.4 %)

H_2 Recovery

55 60 65 70 75

Radial seal
(59.4 %)

Baffled
(68.9%)

Base Case

Composition: 50/50 He/N_2
Pressure: 100psig feed; 0 psig permeate
Feed Rate: 257cc/min per tube
He Permeance: 1 $m^3/m^2/hr/bar$ (365 GPU)
He/N_2 Selectivity: 100
He Recovery, **Ideal**: 74.4%

Baffled with Side Entry/Exit

Hybrid Baffled with "Multiple" Side Entry/Center Take-off

Technical Progress: BP2

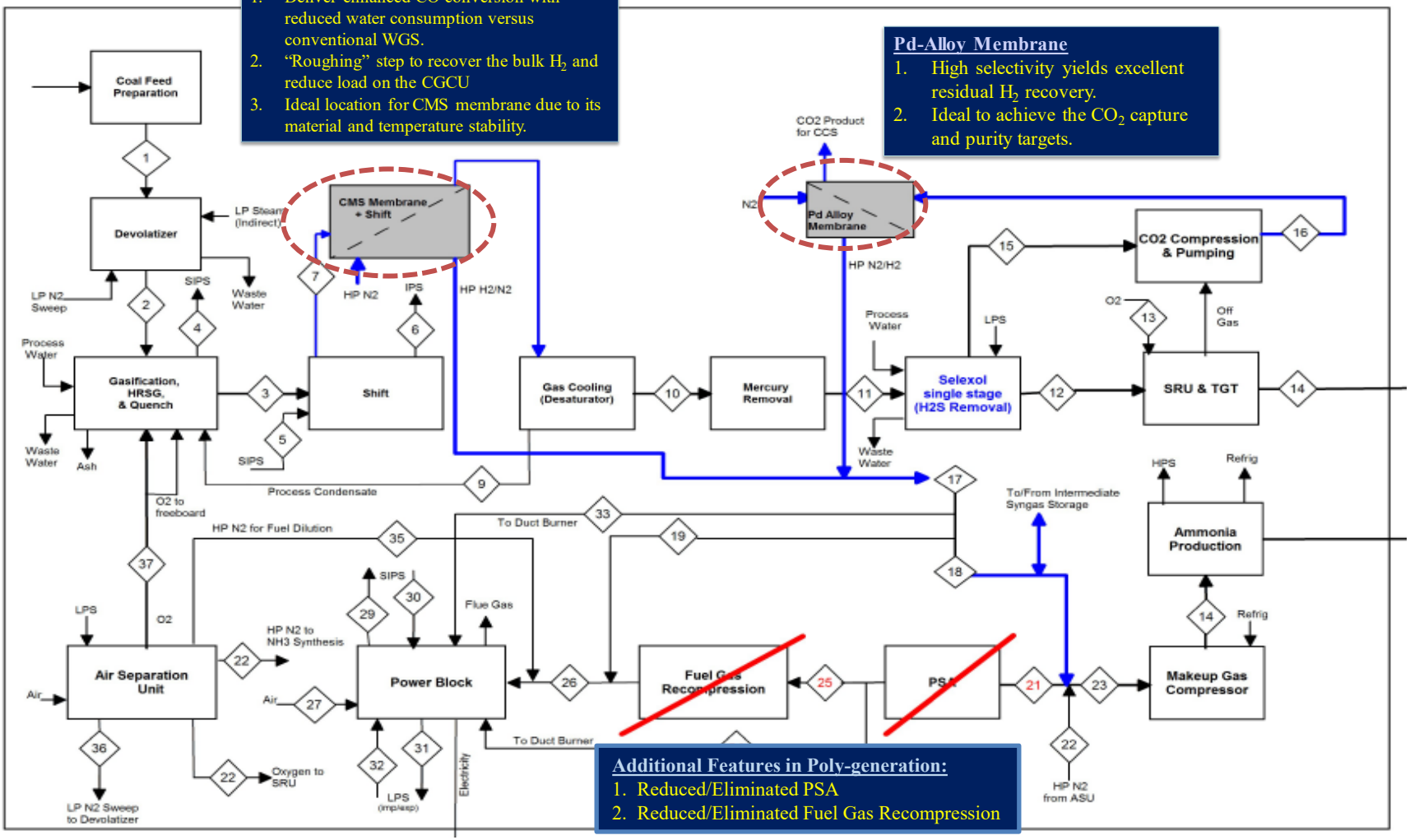
Milestone M. Poly-generation PFD and TEA Update (on-going)

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.

Pd-Alloy Membrane

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

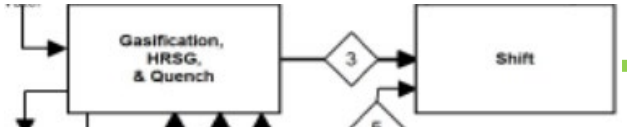


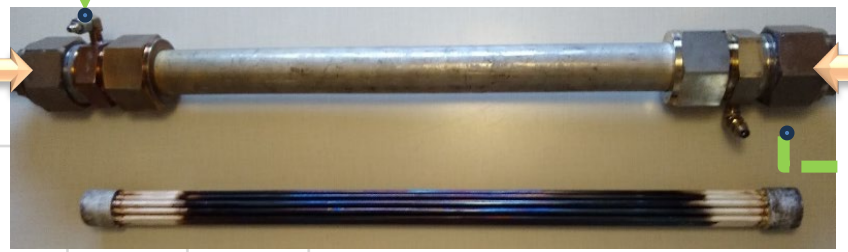
Additional Features in Poly-generation:

1. Reduced/Eliminated PSA
2. Reduced/Eliminated Fuel Gas Recompression

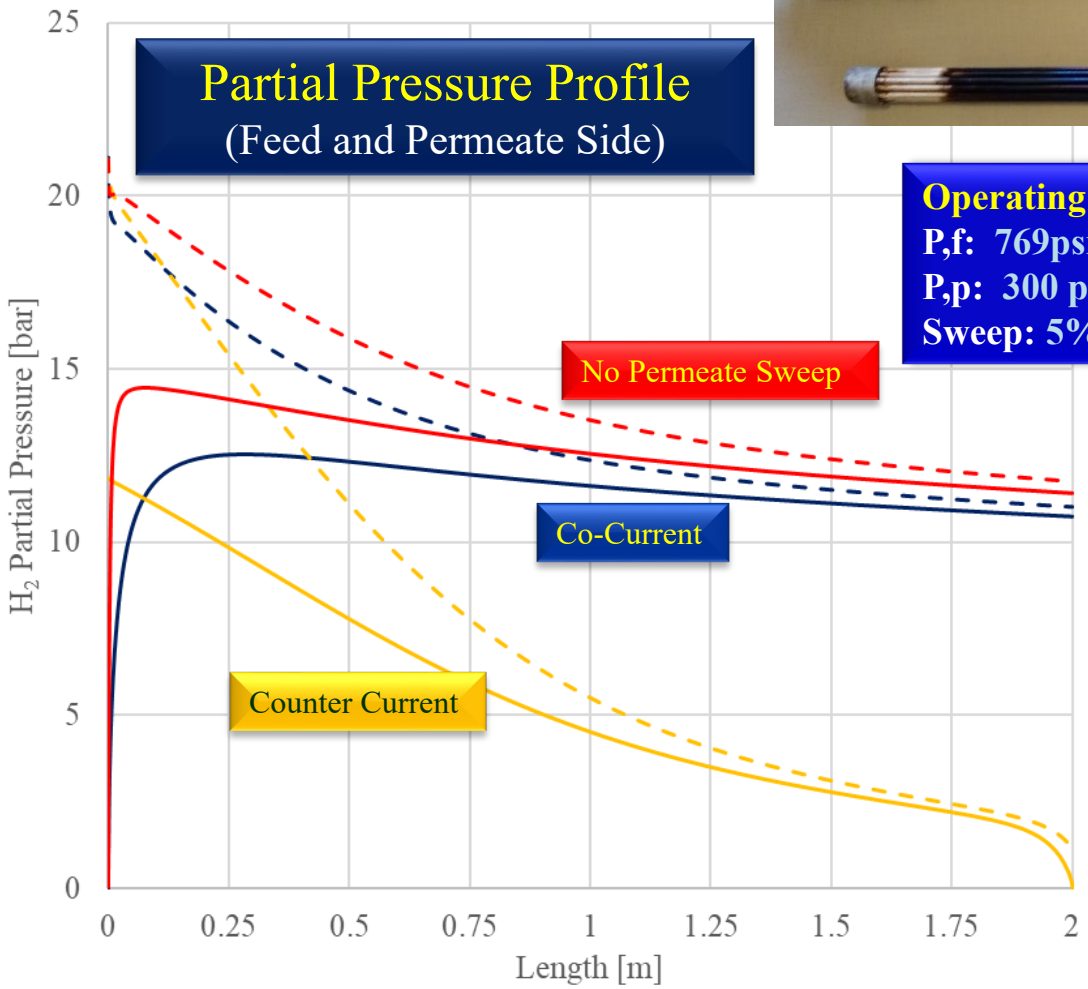
Technical Progress: BP2

Milestone I/M. Sweep Modeling for TEA Update (on-going)





Partial Pressure Profile
(Feed and Permeate Side)



Operating Conditions
P,f: 769psig
P,p: 300 psig
Sweep: 5% of feed rate

Feed Composition
H_2: 40.5%
CO_2: 27%
H_2O: 24.9%
CO: 5.9%
Other: Balance

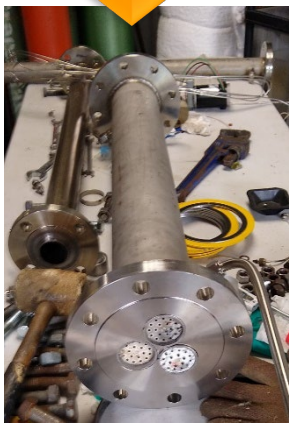
A. Deep H_2 Recovery on Counter Current Sweep: Counter current purge delivers substantial improvement in H_2 recovery.

B. Ultimate result…substantial cost reduction: Reduced membrane area; more efficient purge gas utilization; increased power production → >30% reduction in COE for CO_2 capture

Summary. BP1/BP2

Summary of Project Status and Successes

1. **Dual End Bundle Fabrication and Mechanical Challenge Testing (BP1).** Successfully fabricated 43 dual end purgeable dense and porous tube bundles at up to 3" diameter ("first-of-its-kind"). No failures in over 2,000 challenge tests up to 450°C.
2. **Bundle Seal Leak Performance Testing (BP1).** Demonstrated bundle seal leak rates well below the 1 GPU target in radial and face seal style housings at temperatures to 400°C and pressures to 800psig ("first-of-its-kind").
3. **Pd and CMS Dual End Bundles (BP2).** Six of each type; 18-tube + center-line permeate purge. ("first-of-its-kind").
4. **Performance Evaluated Pd and CMS Dual End Bundles (BP2).** Bundle mixed gas testing with co-/counter current permeate sweep ("first-of-its-kind").
5. **Performance Evaluated First 3-bundle Housing (BP2).** Good agreement with model predictions with the first CMS membrane bundle ("first-of-its-kind").
6. **Developed a COMSOL based CFD Model for Membrane Performance Prediction (BP1/BP2).** Successfully predicted the mixed gas performance of the 18-tube membrane bundles with permeate sweep. Targeting multiple bundle housing design optimization, performance modeling, and Poly-generation process development/TEA.

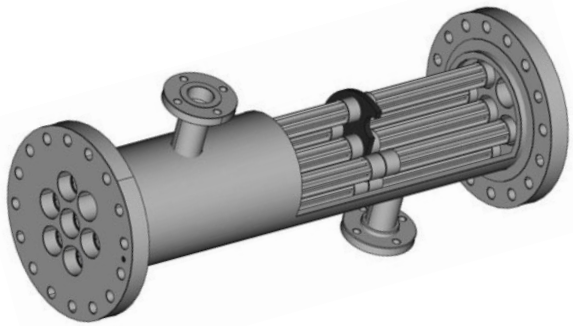


Project. BP2/NCE

Next Step

1. **Complete the testing of the first multiple bundle in parallel housing (3-bundle) with permeate sweep.** Battery of mixed gas testing with permeate sweep demonstration of the 3-bundle in parallel housing. Simulated gasifier off-gas with N_2 and steam permeate sweep.
2. **Fabricate and conduct testing with additional multiple bundle housings.** Additional 3-bundle and a 6-bundle housing (3-parallel x 2-series).
3. **FOCUS: Conduct long term challenge testing with multiple bundle housings.** Confirm the performance and mechanical stability of the bundles, seals, and overall housing design.
4. **COMSOL CFD Model for Membrane Performance Prediction.** Large scale housing design optimization; Poly-generation process and TEA development.
5. **Fabricate the first 4" (~2m^2) dual end bundle.** Demonstrate/highlight scalability.

50MW = ~1,000m^2 CMS Membrane Area



21 Bundle at 2m^2 each (4")
50MW = 24 Housings

Acknowledgements

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Questions?