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

- **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

MPT TECHNOLOGY BACKGROUND

Project Overview

Program: ***DOE/FE "Critical Components for 21st Century Power Plants of the Future"***

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)***

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.

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.

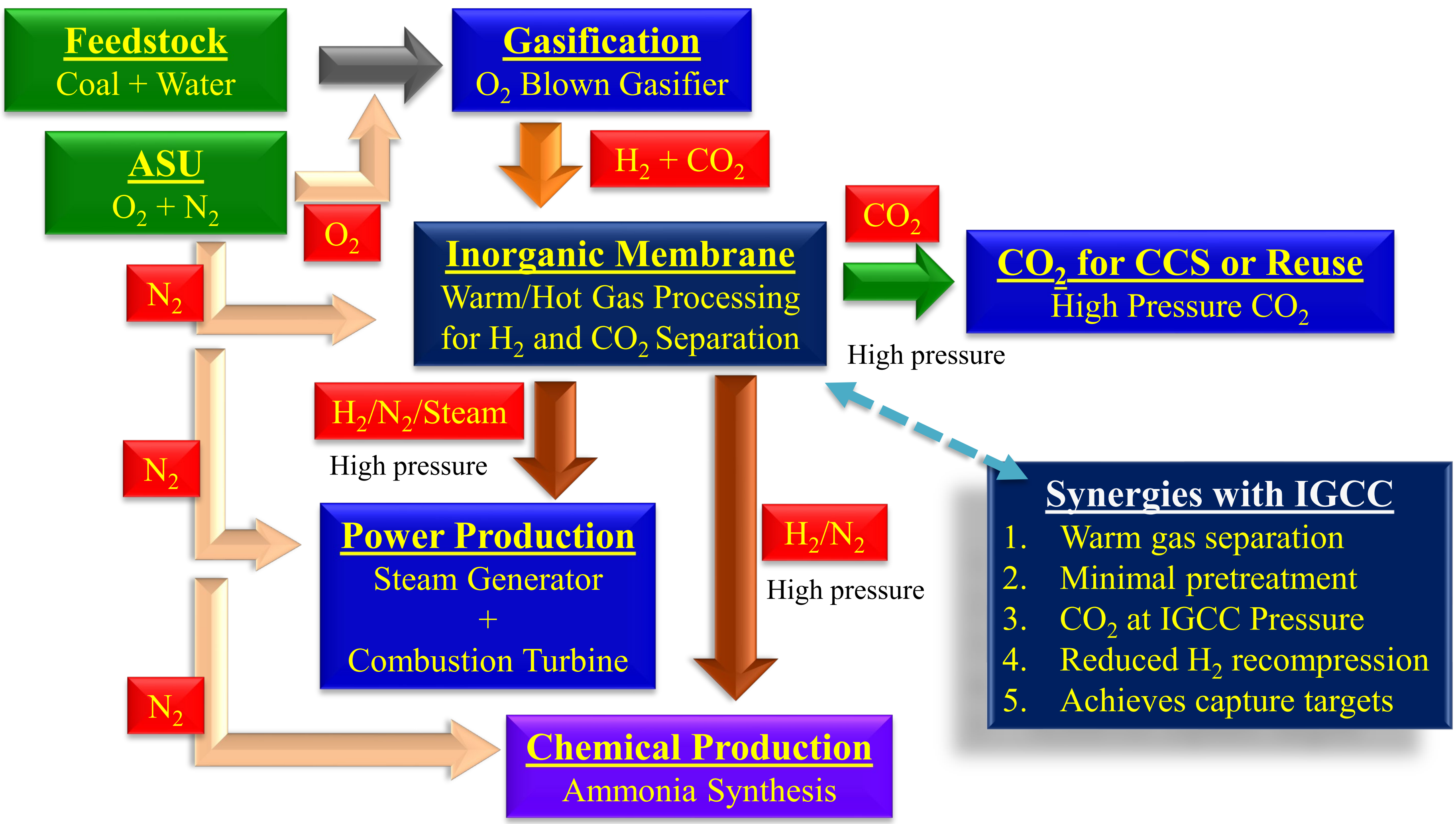
- ✓ This capability represents a Critical Technology Gap for advanced inorganic membranes in pre-combustion CO_2 capture.
- ✓ This capability is required to achieve the >30% COE cost savings target over baseline.
- ✓ Target operating conditions of 200 to >350°C and at up to 800 psig.

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

MPT TECHNOLOGY BACKGROUND

Poly-generation: Inorganic Membrane Technology Role



MPT TECHNOLOGY BACKGROUND

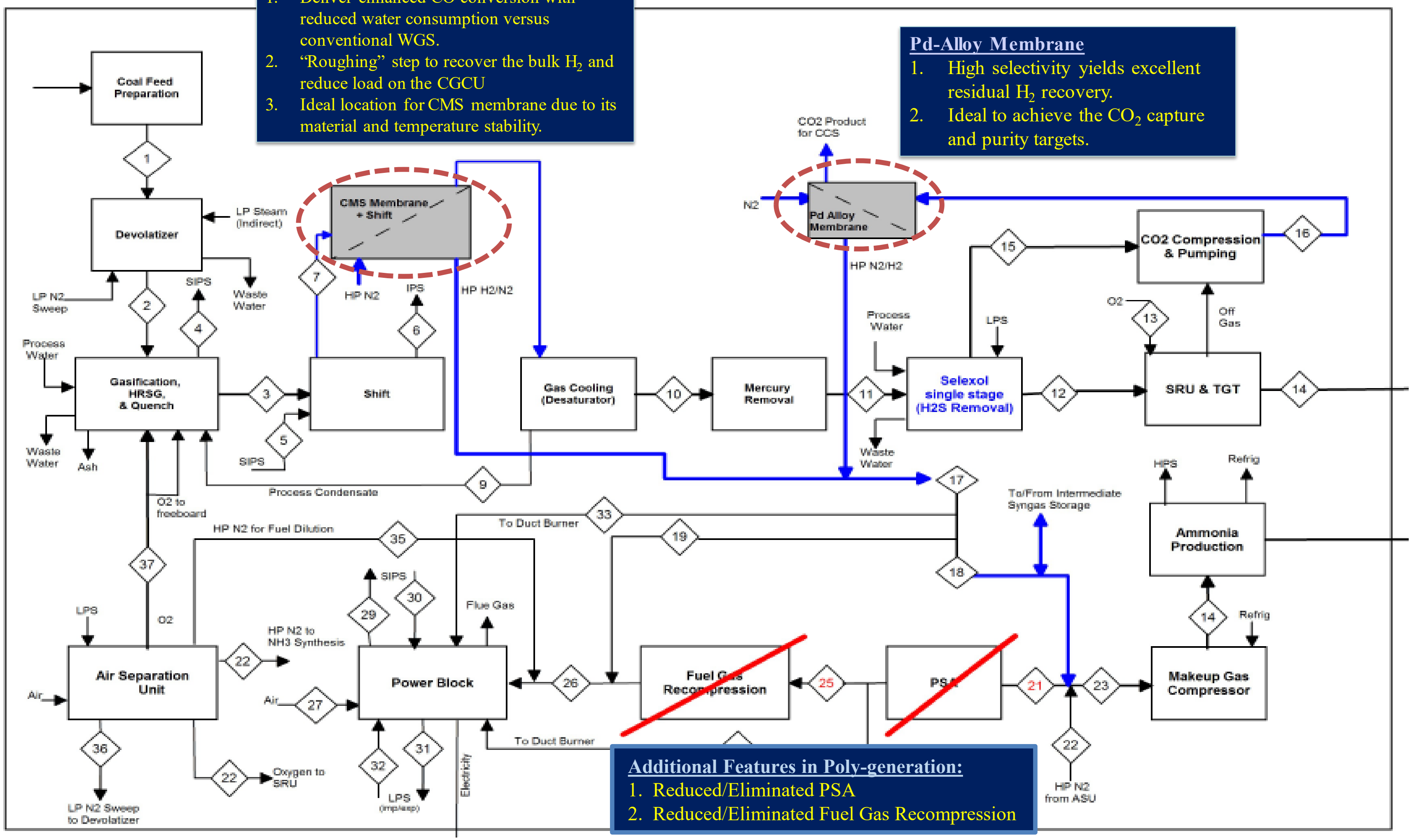
Poly-generation: Dual Stage Membrane Process (DSMP)

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

MPT TECHNOLOGY BACKGROUND

Technology Point State: Candle-filter Configured Multi-tube Bundle

CMS for H_2 Recovery in "Dirty" Gas Systems

Na-A and Na-Y Zeolite for Azeotrope Dehydration

MFI Zeolite for Gas Separation

MPT Ceramic Membrane Supports Offer

- 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.

Pd-Alloy for H_2 Recovery

Candle-filter

- ✓ **Simple Scale-up**
- ✓ **Simple Module**
- ✓ **"Stress-free"**

- But -

No Permeate Sweep

MPT TECHNOLOGY BACKGROUND

Project Motivation: "Technology Gap"

Implementation of the DSMP in Poly-generation

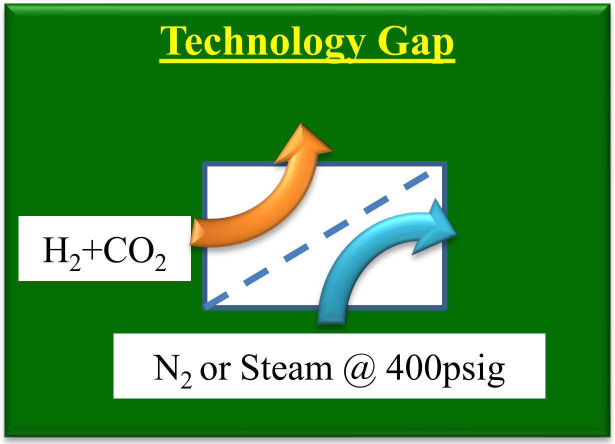
MPT Technology Baseline and Advantages

- ✓ *Enabled "Bench-scale" Inorganic Membrane Technology Demonstration*
- ✓ *Scale-up included CMS, Pd-alloy, and Zeolite-based membranes*
- ✓ *Confirmed High Performance in Pre-combustion Capture*
- ✓ *Demonstrated Highly Stable in Hot/Warm "Live" Gas Processing (ie: NCCC)*
- ✓ *TEA Show the DSMP Process Can Deliver Target CO_2 Capture Efficiency*
  - *>90% Capture at ~95% Purity*

What's Missing: The Technology Gap

Required: *Permeate Sweep/Purgeable Membrane and Module*

- ➢ *Enables meeting of the COE reduction targets*
- ➢ *Simplifies and streamlines module design*
- ➢ *Reduces system cost and footprint*



MPT TECHNOLOGY BACKGROUND

Project Motivation: TEA Impact/Advantages

DSMP Economics in Pre-combustion CO_2 Capture

DSMP TEA Development Based Upon:

1. Actual membrane performance results with
2. Multiple tube membrane bundles in
3. Live gas testing at the NCCC in the
4. Actual/expected operating conditions.

DSMP Achieves DOE CO_2 Targets

>90% capture at ~95% purity

Poly-generation: Additional Impacts

Reduce/eliminate PSA in NH_3 Synthesis

Minimize "fuel gas" recompression

Case	Comments	Net Power Output [MWe]	Net Increase v. B5B [MWe]	Total COE no T&S [$/MWhr]	COE Increase v. B5A [$/MWhr]	COE Reduction v. B5B [%]	Cost CO_2 Capture v. B5A[1] [$/tonne]	Cost CO_2 Capture v. B5B [% Reduction]
MPT Dual Stage Membrane Process Base Cases								
MPT Case: B5M-HP.S1	Candle Filter Bundle Configuration	560	17	129.9	27.3	16.9%	33.2	14.7%
MPTCase: B5M-HP.Purgeable	Permeate Purgeable Bundle Configuratio	582	39	120.3	17.7	46.0%	21.5	44.6%
IGCC Base Cases								
IGCC Base Case (B5A)	IGCC with No CO2 Capture	622	NA	102.6	Base	NA	Base	NA
IGCC Base Case with CCS (B5B)	IGCC with 2-Stage Selexol	543	Base	135.4	32.8	Base	38.9	Base

DOE/NETL Report 2015/1727 – *Cost and Performance Baseline for Fossil Energy Plants*, Volume 1b Rev 2b, July 31, 2015

Technology Background

Media and Process Technology Inc. (M&P)
1155 William Pitt Way
Pittsburgh, PA 15238 - 1678

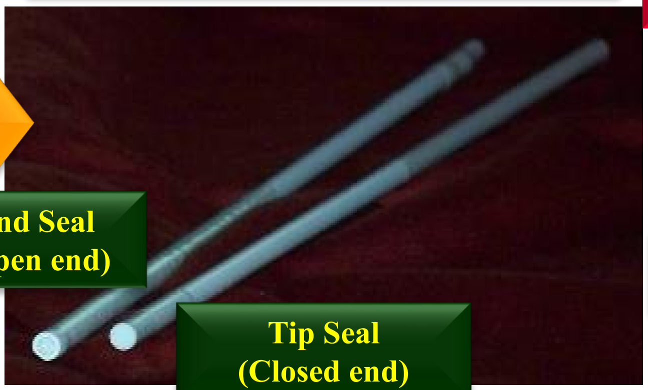
MPT TECHNOLOGY BACKGROUND

Advanced Inorganic Molecular Sieving 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

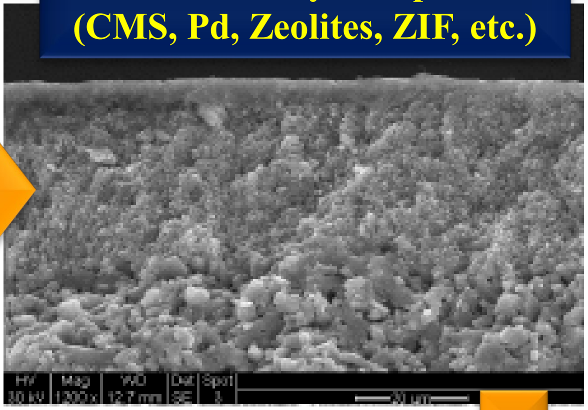
Intermediate Layer Deposition + Non-porous Tip and End Seals



End Seal (Open end)

Tip Seal (Closed end)

Thin Active Layer Deposition (CMS, Pd, Zeolites, ZIF, etc.)



Package into Multiple Tube Bundle

MPT 57-tube Bundle (Carbon Molecular Sieve Membrane)

M&P TECHNOLOGY BACKGROUND

Precombustion: Advanced Inorganic Membranes

Testing Parameters

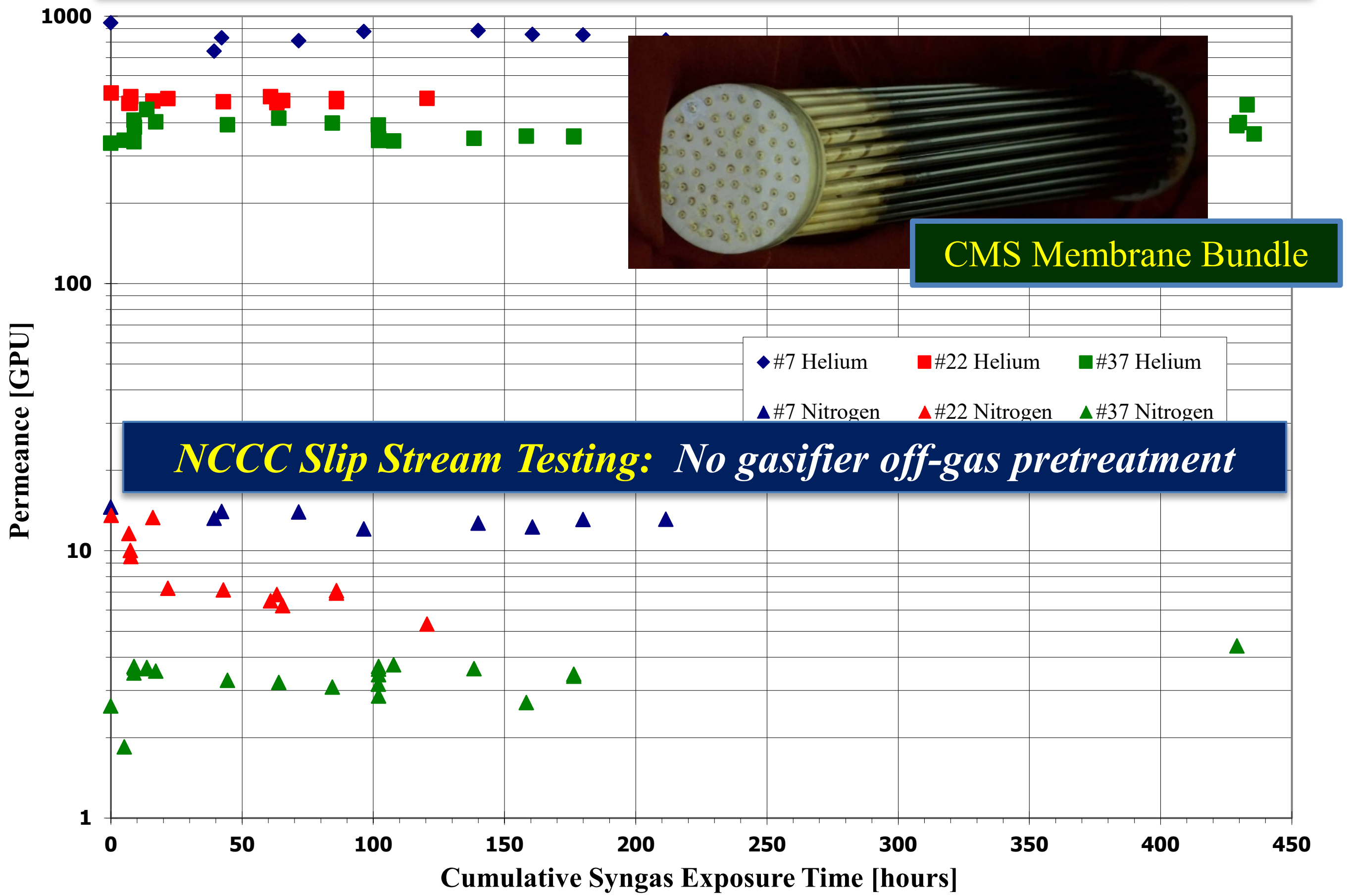
Operating Conditions
T~ 250 to 300°C
P~ 150 to 300 psig

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.

Carbon Molecular Sieve (CMS) Membrane Background
Performance Stability



Project Technical Scope and Approach

Media and Process Technology Inc. (M&P)
1155 William Pitt Way
Pittsburgh, PA 15238 - 1678

Poly-generation: Advanced Inorganic Membranes

Project Tasks and Schedule

Tasks and Milestones	Start Date	End Date	Q1	Q2	Q3	Q4	Q5	Q6	Q7	Q8	Q9	Q10	Q11	Q12
			Budget Period 1 10/1/2020 - 3/31/2022						Budget Period 2 4/1/2022 - 9/30/2023					
Task 1.0 - Project Management and Planning	10/1/2020	9/30/2023	■	■	■	■	■	■	■	■	■	■	■	■
Task 2.0 - Fabricate Permeate Purgeable Full Ceramic Multi-tubular Bundles	10/1/2020	3/31/2022	■	■	■	■	■	■						
Task 3.0 - Design and Fabricate Housing for Single Bundles	4/1/2021	3/31/2022			■	■	■	■						
Task 4.0 - Conduct Mathematical and CFD Modeling	10/1/2020	3/31/2022	■	■	■	■	■	■						
Subtask 4.1 - Conduct CFD Modeling on Module and Internal Configuration	4/1/2021	9/30/2021			■	■								
Subtask 4.2 - Conduct Mathematical Modeling and Optimization of Purgeable Membranes	10/1/2020	3/31/2022	■	■	■	■	■	■						
Subtask 4.3 - Technical Support for CFD & Separation Performance Modeling	4/1/2022	9/30/2023							■	■	■	■	■	■
Task 5.0 - Prepare CMS and Pd Alloy Membrane Tubes and Full-scale Bundles	4/1/2022	12/31/2022							■	■	■			
Task 6.0 – Evaluate the Operating Envelope of Module Comprising Two Bundles in Housing	4/1/2022	6/30/2022							■					
Task 7.0 - Test Prototype Full-scale Multiple Bundle Module	7/1/2022	6/31/2023								■	■	■	■	
Task 8.0 - Update the TEA to Confirm Cost Savings and Prepare the Final Report	4/1/2023	9/30/2023											■	■

Poly-generation: Advanced Inorganic Membranes

Technical Approach: Milestones-Go/No-Go: Overall

BP1

- Fabricate 3 to 4 multiple tube permeate purgeable full ceramic bundles.
- Target size is 1.5" up to 4" diameter; 20 to 38" length.
- Leak free/mechanically stable on thermal cycle challenge testing in "free" and "constrained" (in housing) configurations.
- Fabricate the first operational housing for purgeable single membrane bundles.
- Bundle leak rate <1 GPU N_2 at 250^{o}C and 400psig up to 400^{o}C and 800psig.
- CFD modeling of the dual ended bundles incorporating feed flow distribution, mixed gas permeate take-off, permeate purge, and recommendations for housing design.

BP2

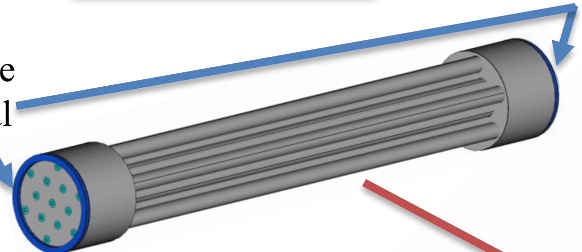
- Fabricate of up to 200 CMS and/or Pd-alloy membranes with target H_2/N_2 selectivity of >100 and >1,000, respectively.
- Fabricate up to four purgeable multiple tube bundles from CMS and/or Pd-alloy tubes at a minimum diameter of 1.5"; 20 to 38" length.
- Bundles meet the N_2 leak rate spec of <1 and 5 GPU (CMS and Pd-alloy).
- Demonstrate bundle gas separation performance at the membrane operating conditions (250°C and/or 350°C, respectively, for the CMS and Pd-alloy bundles).
- Completed long term mechanical/performance stability testing of 6 to 12 months with the multiple tube permeate purgeable bundles at the target operating conditions.
- Updated the DSMP TEA for Poly-generation.

Poly-generation: Advanced Inorganic Membranes

Permeate Purgeable; Multiple Bundle Housing and Seals

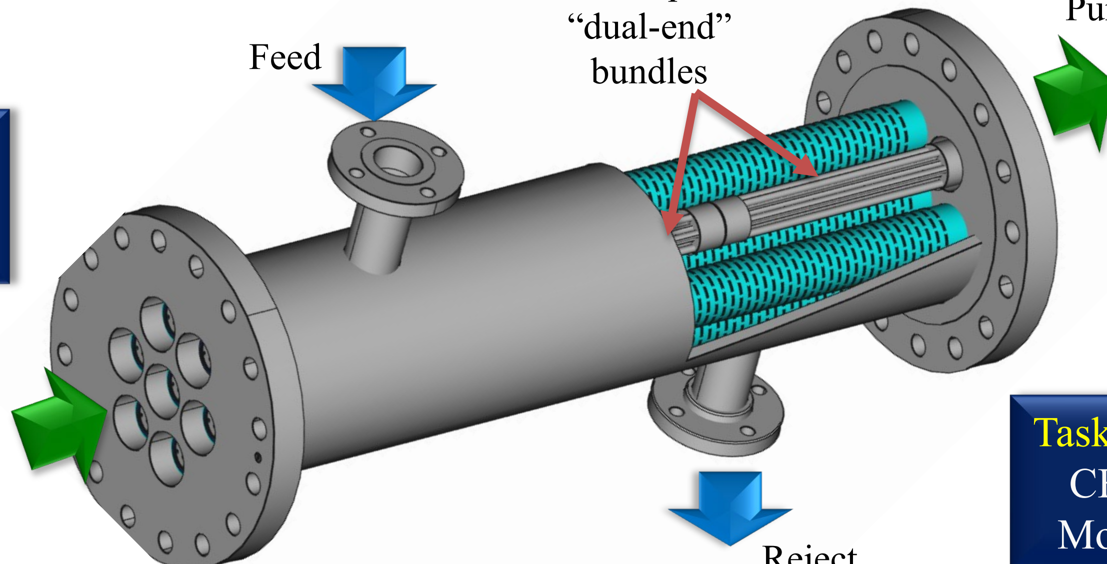
BP1 Activities

Operating Target
250 to 400^{o}C; up to 800psig



Task 2. Dual End Permeate Purgeable Bundle Fabrication and Testing

Task 3. Single Bundle Seal and Housing Development



Task 4. Permeation and CFD Mathematical Model Development

BP2 Activities

Task 5. CMS and/or Pd-alloy Dual End Bundle Fabrication
Task 6. Single Bundle Performance Evaluation
Task 7. Multiple Bundle Housing Development and Testing
Task 8. Process Flow Diagram and TEA Update

Poly-generation: Advanced Inorganic Membranes

Technical Approach: Concepts and Milestones: BP1

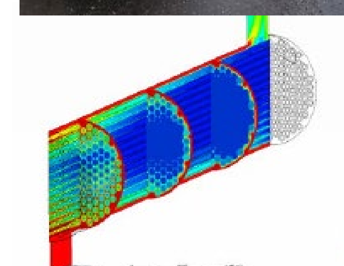
Task 2. Dual End Bundle Development
Milestone d: Dense tube bundles (9/21).
Milestone e: Porous tube bundles (3/22).

Project Activities/Milestones
- 1.5" to 4" diameter (4 to 80+ tube)
- Thermal cycle stability to 400°C
- Constrained/mechanically loaded T/C stability (in housing)

Task 3. Housing and Seal Development
Milestone f: Single bundle housing (6/21).
Milestone g: Multiple bundle housing. (3/22)

Project Activities/Milestones
- Transition to face seal design
- Multiple bundles in series
- Add multiple bundles in parallel

Task 4. Mathematical Model Development
Milestone h: Single bundle housing.
Milestone i: Multiple bundle housing.



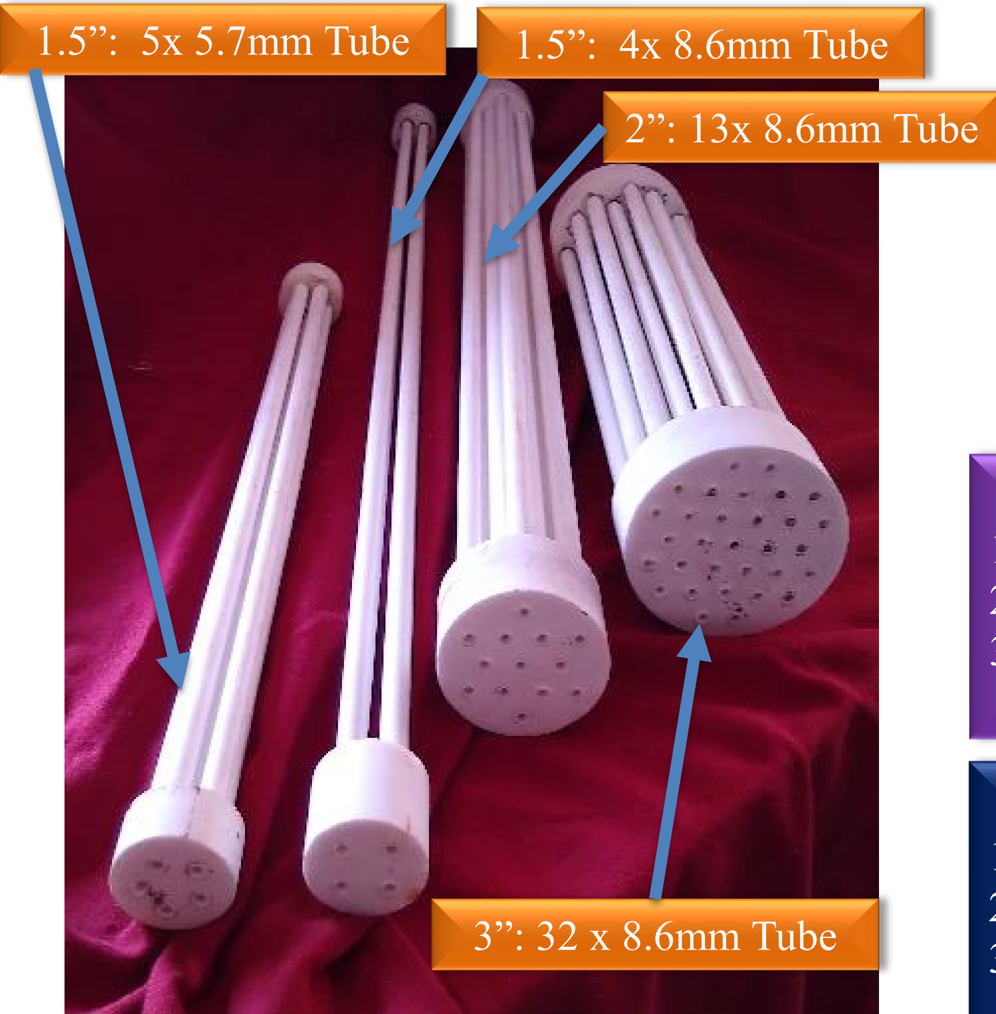
Project Activities/Milestones
- Feed flow distribution, multiple tube
- Incorporate permeation/separation
- Multiple bundle in series/parallel

Project Progress and Status

Media and Process Technology Inc. (M&P)
1155 William Pitt Way
Pittsburgh, PA 15238 - 1678

Technical Approach: BP1

Task 2. Fabricate Permeate Purgeable Dual End Bundles



Task Objectives

- ✓ *Fabricate multiple tube dual end bundles*
- ✓ *Scale-up from 3-tube 10” long prototype*
- ✓ *Target diameter is 1” up to 4” bundles*
- ✓ *Nominally 7- and 80-tube, respectively.*
- ✓ *Target length is >20 to 38”*
- ✓ *Initial focus Dense Tubes*
- ✓ *Transition to Porous Tubes*
- ✓ *BP2 follow-up with CMS and/or Pd-alloy*

Results Summary

1. Dense and porous tube dual ended bundles.
2. 1.5 to 3” diameter at up to 38” length
3. No bundle failure on thermal cycle testing in free and constrained configurations.

Milestone Progress

1. Minimum bundle target 1.5” x 38” completed.
2. 3” prototype underway (4” to follow).
3. Porous tube bundle transition underway; fabricated and challenge tested.
4. Bundle leak rates <<1 GPU (unmeasurable).

Technical Approach: BP1

Task 2. Performance Test Permeate Purgeable Bundles

Thermal Cycle Challenge Testing with and without Housing

Bundle ID	Description	Cycles to 250°C	Cycles to 400°C	Cycles to 450°C
**DT5-1 (1.5")	5x 8.6mm tube; 18"	22[6]	46	25
DT5-2 (1.5")	5x 8.6mm tube; 38"	8	63	2
DT4-1 (1.5")	4x 8.6mm; 32"	8	40	23
**DT4-2 (1.5")	5x 8.6mm tube; 18"	0[12][6]	43	
**DT4-7 (1.5")	5x 8.6mm tube; 18"	8 [19]	43	
DT4-7 (1.5")	5x 8.6mm tube; 12"	N/A	34	
**PT7-1 (1.5")	7x 5.7mm tube; 18"	13[0]	46	25
PT4-1 (1.5")	4x 8.6mm tube; 18"	N/A	20	
PT7-3 (1.5")	7x 5.7mm tube; 18"	N/A	7	
DT13-1 (2")	13x 8.6mm tube; 12"	4	25	22
DT13-2 (2")	13x 8.6mm tube; 12"	N/A	28	9
**DT13-5 (2")	13x 8.6mm tube; 28"	3 [3]		
**PT13-1 (2")	13x 8.6mm tube; 28"	4 [5]		

Dual Bundle **Face** Seal Housing

Single Bundle **Face** Seal Housing

Single Bundle **Radial** Seal Housing

Results
"Free T/C": No failures in >400 T/C

** Transitioned to "constrained" challenge testing.

DT: Dense Tube
PT: Porous Tube

Technical Approach: BP1

Task 2. Performance Test Permeate Purgeable Bundles

Radial Seal Housings

Dual Ended Full Bundle Housing (Single Bundle) in Radial Seal Configuration

Thermal Cycle Challenge w/Mechanical Constraint

1st Level of Mechanical Constraint: Housing with O-ring or Graphite Packing

DT13-5 (2")
PT13-1 (2")

2" Dual End Bundle in Housing

Dense Tube: 3 T/C
Porous Tube: 5 T/C

Furnace

DT-7 (1.5")

1.5" Dual End Bundle in Housing

Dense Tube: 19 T/C

Test Conditions

1. Ambient Pressure
2. 250°C Thermal Cycling
3. Housing with O-ring seals
4. Housing with Graphite seals

Results

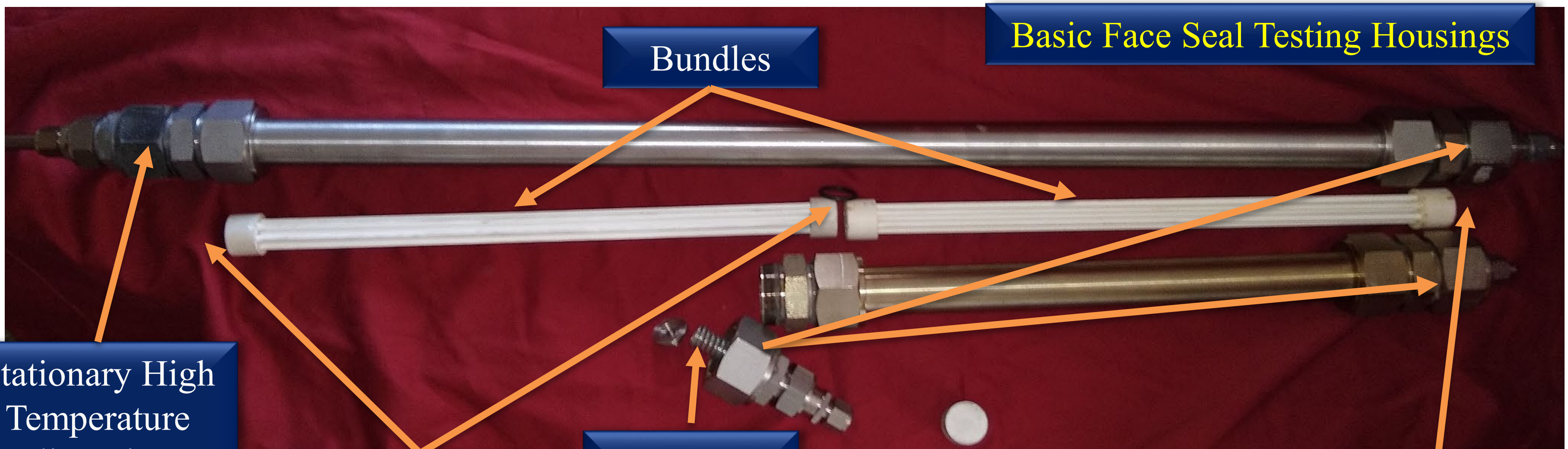
"Constrained T/C": No bundle failures in 27 thermal cycle to 250°C (2" and 1.5" bundles).

Technical Approach: BP1

Task 2. Performance Test Permeate Purgeable Bundles

Face Seal Housings

Dual Ended Full Bundle Housing (Single Bundle and Dual Bundle) in Face Seal Configuration



Three Dual End Bundles in Testing

Dual Bundle Housing
DT5-1 (1.5”) and DT4-2 (1.5”)

Single Bundle Housing
PT7-1 (1.5”)

Results
“Constrained T/C”: No failures in 13 T/C to 250°C (1.5” bundles).

Technical Approach: BP1

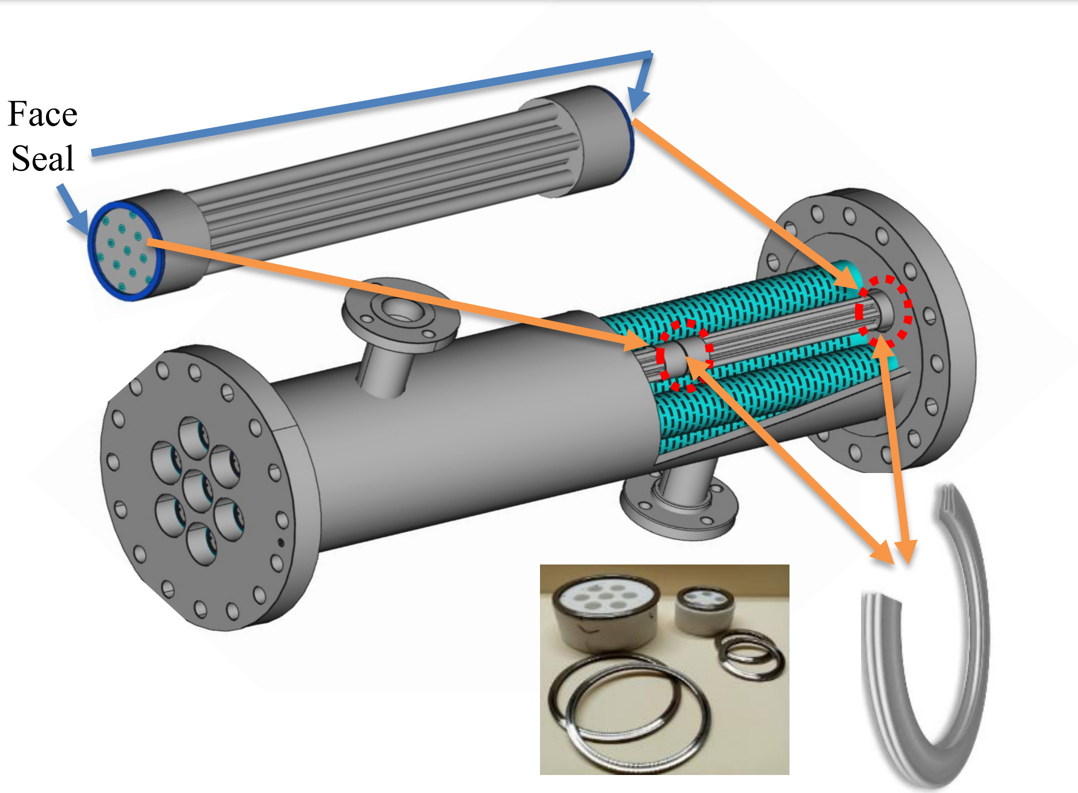
Task 3. Purge Capable Module and Seals Design and Fabrication

Milestone f. Fabricate first prototype housing for single dual end bundle.

Milestone g. Fabricate multiple bundle housing with bundle interconnects.

Two Fundamental Housing Design Concerns/Restrictions

- ✓ *Minimize stress between the ceramic bundle and steel housing.*
- ✓ *Develop bundle interconnects that maintain axial compression.*



Solution #1

Transition to Face Seal

Jet Seal E-series Metallic Seal

- ✓ *Liquid/gas sealing*
- ✓ *High cyclic deflection*
- ✓ *700°C, 10,000 psi*
- ✓ *Bundles in compression*
- ✓ *Higher packing density v. radial seal*

Solution #2

"Floating" or U-bend Header

- ✓ *Minimize bundle to module stress*

Technical Approach: BP1

Task 3. Purge Capable Module and Seals Design and Fabrication

1.5" Ceramic Tube Sheet

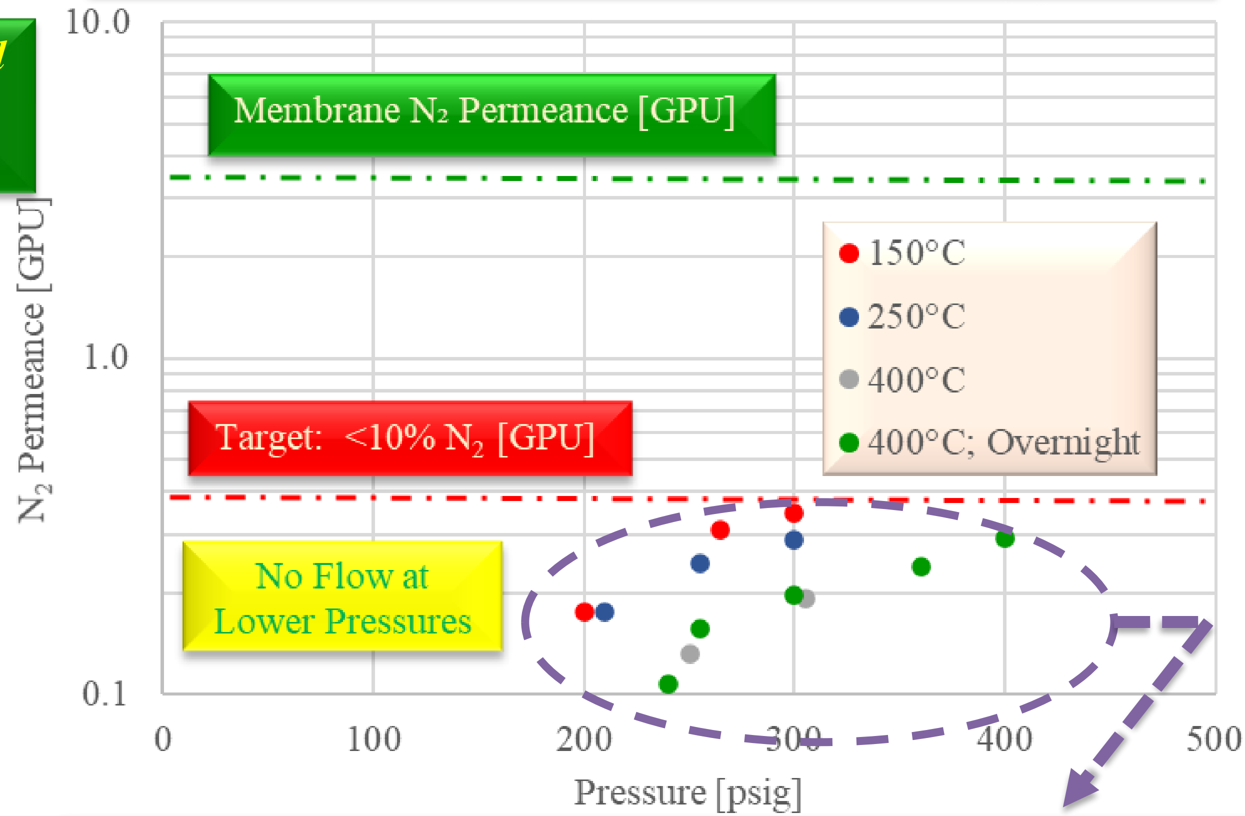
Metal E-seal

Metal Seal Base

Swagelok Ferrule Set

Face Seal (Metal E-seal) Performance Testing

Target: Leak rate <10% of CMS Membrane N_2 Permeance



Results

A. Low leak rate demonstrated up to 400psig and 400°C.

B. Exceeds BP1 Milestone Target of <1 GPU

Technical Approach: BP1

Task 4. Conduct Mathematical and CFD Modeling

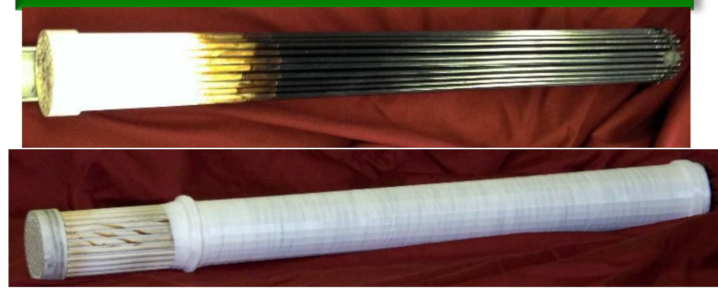
Task Objectives

- ✓ *Develop CFD model to simulate feed flow distribution*
- ✓ *Incorporate CFD model into gas separation models*
- ✓ *Use modeling to inform bundle/module configuration*

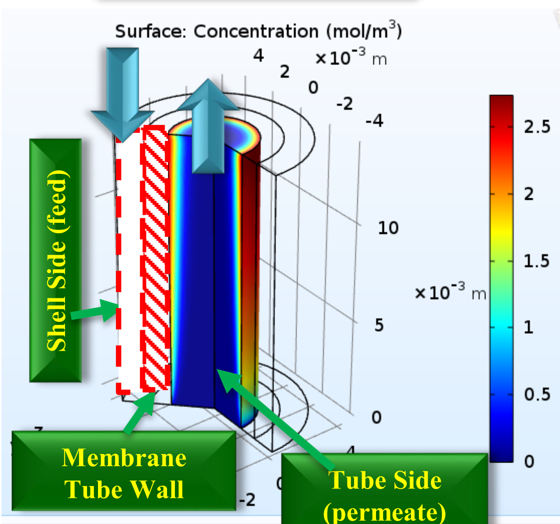
Target Performance

- ➢ *Verify mixed gas separation with model predictions*

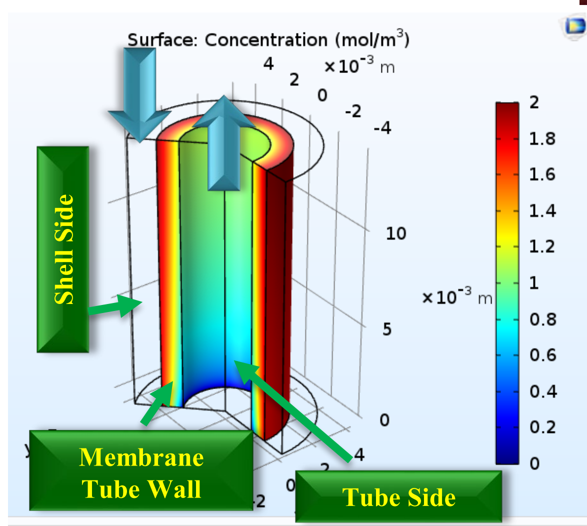
Previous Work: CMS Membrane
Pre-combustion Capture
Baffles for Feed Flow Distribution



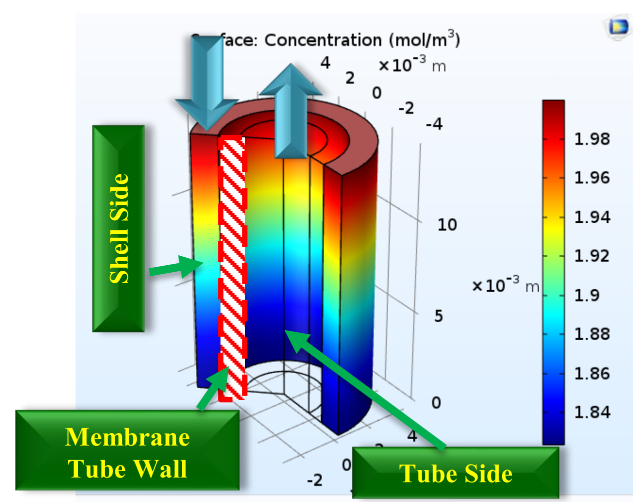
Tube Side



Membrane



Shell Side



Results

A. Single tube velocity and concentration profiles modeled.

Project Technical Program
Future Testing and Commercialization

Media and Process Technology Inc. (M&P)
1155 William Pitt Way
Pittsburgh, PA 15238 - 1678

Technical Approach: BP2 and Beyond

Future Work

In this Project (BP2)…

- *Gas Separation Membranes*. Extend the current technical success to high performance gas separation membranes (Carbon Molecular Sieve; Pd-alloy)
- *Multiple Bundle Module.* Demonstrate a high packing density permeate purgeable module targeting multiple bundles in series and parallel configuration in a single housing.
- *Performance Evaluation.* Short and long term performance evaluation of the full module in single bundle and multiple bundle configurations.
- *Process Design and TEA Updates*. Complete an update of the Poly-generation process design and TEA incorporating the new module configuration.

Next Project…

- Performance testing in actual gas stream of a multiple bundle module.
- For example, University of Kentucky CAER facility coal/biomiass gasifier.

Scale-up Potential…

- This project addresses a key commercialization hurdle ("Technology Gap") faced by novel inorganic membranes… a scale-up pathway that is cost effective and technically sound.

Commercial Potential…

- ✓ Potential commercial application areas are wide ranging for inorganic membranes and include H_2 production and separation; chemical synthesis in membrane reactors; solvent dehydration via pervaporation/vapor permeation; solvent recovery and separation via nanofiltration.

Technical Approach: BP1

Project Summary

Project Driver

- *Pre-combustion Capture.* Inorganic membranes have been demonstrated to be highly effective for and ideally suited to for pre-combustion capture.
- *Capture Basics.* >90% CO_2 Capture at ~95% Purity
- *Economics.* >40% Reduction in COE and COC versus baseline.
- *Poly-generation.* DSMP modified IGCC/Polygen well suited to co-production of NH_3. Minimize PSA and Fuel Gas recompression.
- *Technology Gap.* Permeate purge capability with N_2 or steam is assumed in various TEA developments but not available in practice.

Solution

- Dual End Full Ceramic Purgeable Multiple Tube Membrane Bundles
- Face seals for high packing density in multiple bundle series/parallel configuration.

Key Results

- Demonstrated multiple tube permeate purgeable bundle fabrication.
- Multiple tube bundles mechanically stable in various challenge tests to 450^{o}C.
- Metallic face seals show leaks rate <10% of the membrane N_2 permeance (400^{o}C; 400psig).

Take-away

- ✓ Inorganic membranes have tremendous promise in a wide range of applications, yet remain benchtop novelties due to a lack of a support for commercial scale-up.
- ✓ The ceramic bundle/module under development in this project solves this "Technology Gap".

Questions?

Media and Process Technology Inc. (M&P)
1155 William Pitt Way
Pittsburgh, PA 15238 - 1678

Appendix

Media and Process Technology Inc. (M&P)
1155 William Pitt Way
Pittsburgh, PA 15238 - 1678

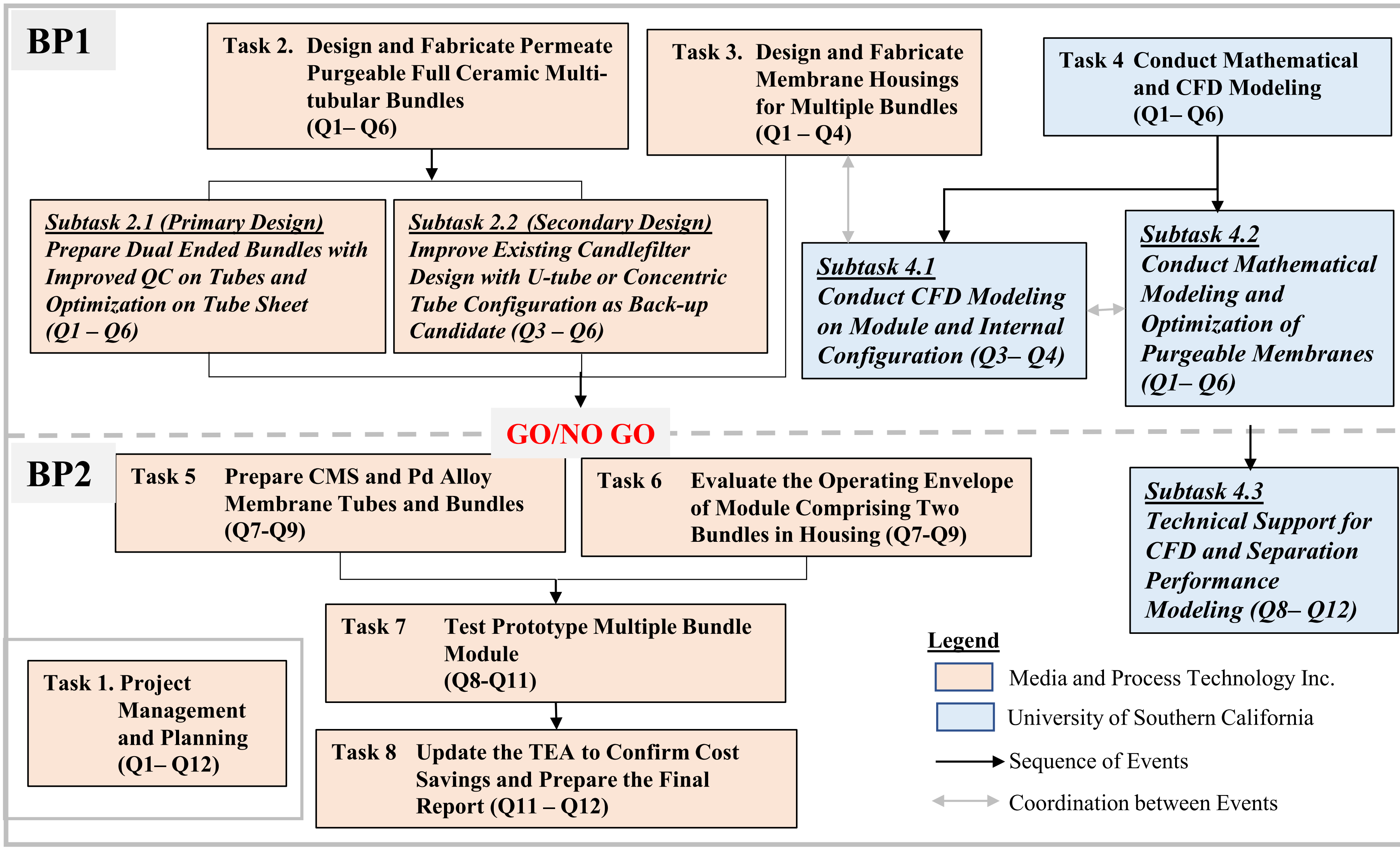
Poly-generation: Advanced Inorganic Membranes

Project Team

Team Member	CV/Capabilities	Responsibilities
	MPT has nearly 30 years of experience in inorganic membrane materials and process development in high temperature, high pressure, aggressvive chemicals gas and liquid separations. Since 2003 MPT has been a commercial manufacturer and supplier of ceramic membrane technology into a wide range of ultrafiltration applications.	Project management; membrane bundle and housing development; performance testing; TEA update
USC VITERBI SCHOOL OF ENGINEERING	Professor Tsotsis at USC has over 40 years of experience in membrane and adsorbent preparation/characterization, reaction engineering, reactor design, and the modeling of transport in complex porous media. He is the author/co-author of over two hundred and fifty technical publications and several book chapters.	CFD model development and bundle/module performance verification; TEA update

Poly-generation: Advanced Inorganic Membranes

Project Structure…Team Member Roles and Tasks



Poly-generation: Advanced Inorganic Membranes

Project Timeline and Milestones: BP1

Tasks and Milestones	Start Date	End Date	Q1	Q2	Q3	Q4	Q5	Q6
			Budget Period 1 10/1/2020 - 3/31/2022					
Task 1.0 - Project Management and Planning	10/1/2020	9/30/2023	■	■	■	■	■	■
Milestones								
-a Updated PMP finalized			♦					
-b Kickoff meeting, annual/final reports completed			♦			♦		
-c Technology Maturation Plan completed.			♦					
Task 2.0 - Fabricate Permeate Purgeable Full Ceramic Multi-tubular Bundles	10/1/2020	3/31/2022	■	■	■	■	■	■
Milestones								
- d Complete the preparation of the dual ended full ceramic dense tube bundle						♦		
- e Complete the preparation of the dual ended full ceramic porous tube bundle								♦
Task 3.0 - Design and Fabricate Housing for Single Bundles	4/1/2021	3/31/2022			■	■	■	■
Milestones								
- f Fabricate first prototype single bundle housing with dual end seal design.					♦			
- g Fabricate the first prototype multiple bundle housing incorporating the dual end seals and connector components								♦
Task 4.0 - Conduct Mathematical and CFD Modeling	10/1/2020	3/31/2022	■	■	■	■	■	■
Subtask 4.1 - Conduct CFD Modeling on Module and Internal Configuratic	4/1/2021	9/30/2021			■	■		
Subtask 4.2 - Conduct Mathematical Modeling and Optimization of Purgeable Membranes	10/1/2020	3/31/2022	■	■	■	■	■	■
Subtask 4.3 - Technical Support for CFD & Separation Performance Modeling	4/1/2022	9/30/2023						
Milestones								
- h Complete the CFD modeling and experimental verification of single dual end bundle in mixed gas permeance with permeate sweep						♦		

ID	Verification Method
a	PMP file
b	Presentation file/report documents
c	TMP file
d	Photographs and test data of bundles included in quarterly report
e	Photographs and test data of bundles included in quarterly report
f	Schematics, photographs, description of module in quarterly report
g	Schematics, photographs, description of module in quarterly report
h	Results reported in the quarterly report

Poly-generation: Advanced Inorganic Membranes

Project Timeline and Milestones: BP2

			Budget Period 2					
			4/1/2022 - 9/30/2023					
Tasks and Milestones	Start Date	End Date	Q7	Q8	Q9	Q10	Q11	Q12
Task 4.0 - Conduct Mathematical and CFD Modeling								
Subtask 4.3 - Technical Support for CFD & Separation Performance Modeling	4/1/2022	9/30/2023						
Milestones								
- i Complete the CFD modeling of the dual ended bundle and multiple bundle module in U-bend and permeate sweep modes with flow management recommendations							♦	
Task 5.0 - Prepare CMS and Pd Alloy Membrane Tubes and Full-scale Bundles	4/1/2022	12/31/2022						
Milestones								
- j Prepare up to 200 CMS and/or Pd (-alloy) membranes (30" long) and pot into bundles					♦			
Task 6.0 – Evaluate the Operating Envelope of Module Comprising Two Bundles in Housing	4/1/2022	6/30/2022						
Milestones								
- k Complete the shakedown and performance testing of the two-bundle modules and housing			♦					
Task 7.0 - Test Prototype Full-scale Multiple Bundle Module	7/1/2022	6/31/2023						
Milestones								
- l Complete the testing of the 3-4 bundles as base modular unit							♦	
Task 8.0 - Update the TEA to Confirm Cost Savings and Prepare the Final Report	4/1/2023	9/30/2023						
Milestones								
- m Update TEA for the new module design and process configuration								♦

ID	Verification Method
i	Results reported in the quarterly report
j	Reported in the quarterly report
k	Photographs and test results reported in quarterly report.
l	Results reported in the quarterly report
m	Results reported in the quarterly report
QR	Quarterly Report files
FR	Draft Final Report file

Project Risk Management

Media and Process Technology Inc. (M&P)
1155 William Pitt Way
Pittsburgh, PA 15238 - 1678

Poly-generation: Advanced Inorganic Membranes

Risk Management: Technical

Perceived Risk	Risk Rating (Low, Med, High)			Mitigation/Response Strategy
	Probability	Impact	Overall	
Technical/Scope Risks				
Mechanical failure of the dual end bundle due to internal thermal or other stress.	Med	High	Med	Extensive and wide-ranging program is proposed to overcome this problem. Previous experience with full ceramic bundles provides the materials and fabrication knowledge base to transition to the dual ended purgeable membrane bundle. A back-up solution with a smaller diameter bundle is offered.
Mechanical failure of the dual end bundle due to external stresses associated with module seals and thermal expansion mismatch.	Med	High	Med	A range of flexible seal and housing configurations is proposed to overcome this problem. No back-up solution is necessary since parts suggested are commercial products, which have been practiced under similar operating conditions.
Seal lifetime problems and premature failure due to gasifier off-gas contaminants.	Low	Med	Med	Work closely with seal manufacturers who have extensive experience in a wide range of aggressive operating conditions and a range of materials options. Identify problem contaminants and materials solutions via accelerated challenge testing.
Non-ideal flow and feed maldistribution in the proposed housing	Low	Low	Low	CFD modeling to be used to recommend baffle type and location. Significant practical commercial experience in gas separation and heat exchanger design can be incorporated. A back-up solution is offered which comprised enhanced baffling in the presence of armored ceramic bundles.
Residual sulfur components expected from the Selexol (one stage) impact significantly Pd-Ag performance.	Low	Med	Low	Move to more sulfur resistant alloy such as Pd-Cu or others. A back-up solution is offered, which include fixed bed warm gas cleanup for residual sulfur removal as a guard bed for the Pd membrane, or installation of additional membranes to compensate for the permeance loss.

Poly-generation: Advanced Inorganic Membranes

Risk Management: Other

Perceived Risk	Risk Rating (Low, Med, High)			Mitigation/Response Strategy
	Probability	Impact	Overall	
Financial, Cost/Schedule Risks:				
Budgetary issues, i.e., not enough funds to complete a certain Task	Low	Low	Low	Seek DOE guidance and approval for shifting funds from less critical tasks and consolidating certain activities
Pd Membrane production budget constraints due to metal cost and/or low on-spec ratio	Low	Med	Low	Reduce the number of tubes required via increased bundle tube spacing and/or reduced bundle diameter.
Delays in delivery of equipment/parts from vendors	Low	Med	Med	Improve coordination with vendors. Seek alternate vendors.
Resource Risks:				
Equipment malfunction	Low	Low	Low	Wide range of back-up systems available at MPT. Significant experience in system construction if additional back-up is needed.
Personnel performance issues	Low	Low	Low	Address/remedy performance issues. Replace personnel, if need arises. Most employees have been with MPT for >10years.
Overspending of the allocated budget for the proposed application	Low	Low	Low	Our monthly accounting report will alert us to overspending problems. MPT has significant experience in these projects and very reliable cost estimating practices.
ES&H Risks:				
ES&H issues develop	Low	High	Low	Identify problem(s) causes and take remedial actions. Retrain personnel, if human factor is involved.
Management and Planning and Oversight Risks:				
Lack of effective and timely coordination to get the tasks completed in time according to project needs.	Low	High	Low	Weekly project review meetings and daily project coordination is practiced. MPT is the only contractor on this project.
IP ownership issues develop	Low	Low	Low	MPT will own all IP