U.S. DEPARTMENT OF ENERGY | Energy Efficiency & Renewable Energy

ADVANCED MANUFACTURING OFFICE

Membrane Technology Workshop Summary Report

Final Report

November 2012
Workshop held on July 24, 2012
Rosemont, Illinois

U.S. DEPARTMENT OF ENERGY | Energy Efficiency & Renewable Energy

DISCLAIMER

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INTRODUCTION

Membrane technology offers an energy efficient alternative to traditional industrial separation process steps and has now become the standard for numerous manufacturing applications. The successful use of membranes is the result of several decades of research and development; even so, a number of promising manufacturing applications for membranes remain. New membrane materials, developed at laboratory scale, offer significant benefits over currently available commercial membranes. However, manufacturing defects and high module costs at full production scale are preventing widespread adoption in applications where membranes hold the greatest promise to reduce energy consumption and manufacturing costs. Progress in membrane manufacturing now depends on adopting a more holistic approach to new membrane material development and is critical for improving many remaining industrial separation process applications.

The U.S. Department of Energy, Advanced Manufacturing Office (AMO) partners with industry, small business, universities, and other stakeholders to identify and invest in emerging technologies with the potential to create high-quality domestic manufacturing jobs and enhance U.S. competitiveness. To catalyze public-private collaboration and further explore the area of membrane technology, AMO hosted a workshop on July 24, 2012 in Rosemont, Illinois. Input from industry and academia stakeholders was gathered on the current state of membrane research, industry trends and emerging applications; the barriers to research, development and implementation of membrane technology at commercial scale; and potential actions needed to advance the use of membrane technology.

The meeting began with an introduction to AMO, a presentation summarizing results from prior workshops focusing on membranes, and a panel discussion with presentations from industry and academia. After the general session, participants were divided into two separate breakout sessions for facilitated discussions to address the following questions:

- What have been the successes in membrane technology? What are characteristics of success?
- What are high value current and emerging applications for membranes?
- What are the barriers to application and increased adoption of membranes for the opportunities identified?
- What are the potential actions to overcome the barriers identified?

The workshop discussions are summarized in this document. AMO would like to thank all the participants for their valuable contributions to the workshop. I would also like to thank SRA support staff Bryan Pai, Marci DuPraw, and Lee-Ann Tracy; as well as AAAS Fellows, Kelly Visconti, Lynn Daniels, and Marina Sofos who helped make this workshop possible.

Sincerely,

Dr. Robert Gemmer
Advanced Manufacturing Office

1 PAST SUCCESSES IN MEMBRANE TECHNOLOGY

Significant time and funds have been invested in membrane technology development but industrial implementations remain somewhat limited. Workshop participants provided both commercial membrane successes and key membrane technology developments including their rationale for the development successes. Table 1 and 2 present the successes and developments provided by the participants. Key themes in past membrane successes that emerged from the discussions include: (a) durability, (b) scalability, (c) reliability, (d) no viable alternatives, (e) regulations as incentives for innovation, (f) taking a systems view, (g) process economics; (h) cost-effective manufacturing, (i) manufacturing control of properties, (j) multiple approaches, (k) end user involvement, and (l) modeling and realistic testing.

TABLE 1: COMMERCIAL MEMBRANE SUCCESSES

#	Success	Reasons for Success
1	Reverse osmosis (RO)	• Significant R&D in polyamides (able to control pore structure) • Lower production cost than default replacement • High quality process control for RO module fabrication • Use of robotics was key • Achieved widespread application: low drop-in cost and outstanding performance
2	Gas separations: • Nitrogen enrichment of air for commercial blanketing and engine applications • Hydrogen recovery from ammonia purge • Low CO_2 level biogas and natural gas separation • Monomer recovery from storage vessels, capturing and recycling	• Benefited from materials being standard and the phase inversion processes were well known for liquids and could be easily transferred to gas separations (modified for gas – along the "evolution" of membrane development) • Development of cross-linked polyamides
3	Separators for lithium ion batteries (e.g., Nafion separators)	• No better alternatives
4	Synthesis of energetic chemicals	• Ability to produce on-site
5	120 °C polymer electrolyte membranes for fuel cells with high proton conductivity	• Multiple, coordinated work groups trying different approaches • Development of thin, high performance membranes for fuel cells and other electro-chemical reactors, especially composites • Achieved long-term durability while limiting water management and resistance issues
6	Carbonate conducting electro-chemical membrane for fuel cells	• Cost and productivity • DOE partnership
7	Hollow fiber artificial kidneys and other medical applications	• Low cost and effective • Met a key market need
8	Protein purification for pharmaceuticals	• Development of high flux and low membranes fouling (ceramic/titanium can be used for protein purification) • Applications in major markets (e.g., food and beverage industry, packaged water plant treatment)

#	Success	Reasons for Success
9	Hollow fiber membranes used in membrane bio-reactors for treating waste	• Time invested in waste pre-treatment • Collaboration between end users and developers • Consideration of whole system design by developers • Access to field test sites • Manufacturability, reliability, cost
10	Separation of liquids from natural gas	• Cost • Enabler for other essential things for which there were no alternatives • Simple yet robust
11	Nitrogen separation membranes	• Simplicity of design and modularity provided a favorable business case to replace existing technology pressure swing adsorption systems (PSAs)
12	Consumer products (e.g., silicon adhesives, contact lenses, Gore-Tex®)	• Provided a material with the right properties and processed into the right form factor • High gas permeability and fouling resistant to meet the performance need of the product
13	Development of low-permeability materials for packaging	• Met a major need
14	Ultrafiltration/microfiltration membranes	• Regulations that stopped dumping served as an incentive to develop alternatives • Better manufacturing control • Biopharmaceutical processing (gentler on sensitive chemicals)
15	Hydrochloric acid process	• Enabled by electrochemical-acceptable membrane performance
16	Materials and process integration	• Advancements in manufacturing techniques to turn materials into useful products (formability): use of hollow fiber and flat sheet, and development of the Spinneret technique for commercial production
17	Leveraging existing infrastructure and processes from other industries to develop commercial products	• Use of wet laid materials (e.g., paper, adhesives, etc.) from existing manufacturing systems at volume
18	PRISM® membrane technology	• Provided a hollow fiber material and filled in defects – resulting in development of an improved process technique to enable use in gas separations • Foundational to many other gas separation successes
19	Micro/ultra/nanofiltration membranes for drinking water	• Cost and reliability improvements led to more widespread adoption: >1-2 years life expectancy
20	Ceramic tube supported zeolite membranes and ceramic supported single/multichannel tubes	• Enabled alcohol/water separation and pervaporation, capable of withstanding high temperatures and corrosive environments
21	Ceramic honeycomb filtration membranes	• Use in water filtration • Manufacturing process innovation • More forward looking business models
22	Natural gas sweetening	• Collaboration for joint field test (shared risk and resources; a long-term development/demonstration activity)
23	Glassy polymer membranes	• Effective separations (not as permeable) • Application in reverse osmosis • Overcame challenges by using hollow fiber arrays

#	Success	Reasons for Success
24	Thin film composites	- No reasons provided
25	Dairy industry protein separators	
26	Coupling of membrane with distillation to remove volatile organic compounds	
27	Pervaporation for azeotope breaking	
28	Desalination membranes	
29	Oxygen separation membrane for IGCC and oxygen fuel combustion	
30	Fuel cell membranes	

TABLE 2: KEY MEMBRANE TECHNOLOGY DEVELOPMENTS (PILOT OR LAB SCALE)

#	Success	Reasons for Success
1	Phase inversion processes for polymer membranes (lab scale process)	- Enabled advancement in polymer membranes - Adapted roll to roll processing for larger scale
2	Roll to roll processing	- Enabled cost reduction and process improvements (continuous processes vs. batch)
3	Thin zeolite membranes <300nm thickness (lab scale success)	- Provided thermally and chemically robust materials - Improved performance and increased surface area (though module and material cost are still high for commercial applications - $\$1000/m^2$ vs. $\$10/m^2$)
4	Air separation membranes for automotive applications (pilot success)	- Achieved technical success using membranes for engine air intake - Reduced nitrogen oxide (NO_x) emissions with the use of air separation membranes - Provided an alternative to exhaust gas recirculation (EGR) but not commercially successful yet (i.e., there is no current supplier of these types of membranes)
5	Forward osmosis	- Advanced polymer development of cellulose triacetate (CTA) instead of polyamide provided much higher fluxes at pilot scale for water treatment - Emerging commercially for military and personal hydration applications
6	O_2 separation with perskovites (lab scale)	- High temperature compatibility of material

2 EMERGING OPPORTUNITIES

Workshop participants identified emerging opportunities for membrane technologies during the two breakout sessions. These opportunities are presented in Table 3. Certain benefits of novel membrane technology and applications framed the discussions and included energy savings potential, process intensification, contribution to U.S. competitiveness, broad applicability, and ability to perform a difficult separation. Only one breakout group identified opportunities by category as presented in Table 3. Overlapping opportunities between the two breakout groups have been combined in the table below; opportunities without categories from the other breakout group are presented last in Table 3. Items in italics are further analyzed in Section 3.

TABLE 3: EMERGING OPPORTUNITIES FOR MEMBRANE TECHNOLOGIES AND APPLICATIONS

#	Opportunity	Category
1	*Reactive separation (e.g., membrane reactors) for chemical and refining applications (e.g. fermentation process, natural gas separation, etc.)*	*Liquid/Liquid* (including water systems and organic systems)
2	*Separation of hydrocarbons with similar boiling points (e.g., olefin/paraffin)*	
3	Low pressure reverse osmosis (to replace existing RO)	
4	Membrane system for separating high temperature waters	
5	Membranes for cost-effective water treatment, particularly hard-to-treat waters (e.g., mining, hydraulic fracturing, tailing ponds) requiring fouling resistant membranes with high solids – specific to these feed streams	
6	High temperature liquid streams (e.g., catalyst recovery)	
7	Organic solvent resistant nanofiltration	
8	Azeotope breaking	
9	Hydrocarbon recovery/re-use from fuel	
10	Air separation for internal combustion engines (e.g., intake, combustion equipment, pre-treatment)	*Gas/Gas*
11	Nitrogen separation from natural gas	
12	Carbon separation	
13	Hydrogen sulfide separation	
14	Carbon capture	
15	Hydrogen separation from refinery gas streams and coal gas	
16	High temperature gas streams (e.g., water-gas shift)	
17	Next generation air separation membranes (oxygen/nitrogen) with better selectivity	
18	Advance membranes for electro-chemical systems: • Improve selectivity and durability of Nafion for flow batteries • Increase mechanical strength and temperature resistance of membranes for lithium ion batteries to improve safety • Stop dendrite growth of lithium batteries with membrane • Prevent ion cross-over	*Electrochemical Systems*
19	Cesium exchange membranes (large opportunity for battery use and waste separation)	
20	Ion selective membranes and artificial channels, including nano inorganic/proton transport polymer composite membranes (for flow batteries, water electrolyzers, and hydrogen or methanol fuel cells)	
21	Hydrogen stream purification using hydrogen electro-chemical pumping	
22	Application of successful membranes to realistic streams	*Cross-Cutting*

#	Opportunity	Category
23	Drying and dehumidification of industrial gas streams	Gas/ Liquid
24	Heat recovery from low pressure steam and hot process condensate treatment (90 °C temperature limit with polymers) – wide application including tire processing and food processing (large energy savings potential)	
25	Membranes for fermentation processes (for organic species) and bioreactors for wastewater treatment (build upon microstructure for water treatment, large systems for wastewater treatment and to recover co-products in chemicals or food processing plants with high biochemical oxygen demand systems)	Membranes Coupled to Bio-Systems
26	Membrane improvements (e.g., structure, materials) for biopharmaceutical processing and monoclonal antibody purification	
27	*New and improve existing materials (i.e., composite, polymeric, ceramic, and nano-materials), focusing on hydrophobicity, modularity, tuning, reduced fouling, improved flux, higher sensitivity, and surface modification*	No Category Provided
28	*Bio-refinery opportunities:* • *Deconstructing biomass into fuel, C5/C6 sugar separations using low or no solvents, low cost with high surface area for abrasive environment* • *High throughput (>1000GPM) to concentrate microbial solids 1% to 10% for algae strategies* • *Hydrocarbon recovery, as move to alcohol fuels using fermentation and catalytic processes to recover large amounts in the C8-C28 (gas and diesel) range* • *Dilute systems, fractionation of colloidal type species in biomass applications*	
29	*High surface area, low cost ceramic-based membranes for filtration includes produced water and algae harvesting and filtration for biological process streams (with low fouling)*	
30	*Technology for heating, ventilation, and air conditioning (HVAC) applications to enable high surface area, contacting modules that are inexpensively manufactured and combined (e.g., heat sealing or rapid formation approaches); also applicable to membrane distillation*	
31	Integrate available technology from other industries in current membrane technology and processes (e.g., overcome long term investment needed to address logarithmic scale-up required in some petrochemical applications)	
32	Improve material property data	
33	Improve non-destructive evaluation (NDE) or characterization (to predict failure in advance, address risk aversion in application of membranes, and reduce potential for failed membrane and potential impact to customer process)	
34	Membrane contactors, particularly to address petroleum and hydrocarbon distillation (distillation replacement is a large opportunity; need to improve the form and packaging of membranes, and integrate the membrane into the full system)	
35	High surface area, low cost zeolite membranes for gas separation, biofuel and hydrocarbon separation (also potential for membrane reactors to combine reaction and separation in-situ)	

#	Opportunity	Category
36	Anti-fouling advancements to increase fouling resistance for all membrane types: • Evaluate boundary layer control and intrinsic properties • Characterize organic content of the fouling waters, and try to negate charge on the membrane systems (enable better matching of the membrane material to the application) • Improve fouling without sacrificing flux: surface hydrophilic modification, nanocomposite coatings, weak brush type copolymers	No Category Provided
37	Forward osmosis (to treat brackish water, recoverable water and for desalination)	
38	Supportive systems development for membranes (e.g., improving pre-treatment reliability; improving efficiency of gas compressors to reduce costs)	
39	Mix polymers and inorganics by optimizing costs for each system	
40	Membranes for diagnostics, personal, water chemistry analysis, bio-specimen analysis and disease detection (may be some issues with scaling "down")	
41	Membrane improvements for methanol separation (to obtain higher methanol concentrations)	
42	Membranes for stationary fuel cells with high temperature organics via optimizing thinner films, better definition, onsite reforming, and lower operating temperatures (large opportunity for CHP because of the increased availability of natural gas)	
43	Hydrogen separation for portable power/backup power (i.e.,cell phone towers and building rooftops in cities; long-term durability testing needed)	
44	Natural gas liquid separation and recovery, separation of C2+ hydrocarbon vapors or liquids from natural gas (particularly relevant to shale gas operations)	
45	Heat recovery from thermoelectric power plants, where 60-70% of energy is typically lost to atmosphere in cooling towers (address high cost, low surface area by developing new product designs, membrane manufacturing processes and long-term field demonstrations of prototypes)	

3 Barriers and Potential Actions

With limited time available, workshop participants selected a subset of the identified opportunities to build on by listing barriers to the opportunities and possible actions to overcome the barriers. The "foundational" opportunities that were selected were considered to be transformative, pervasive, globally competitive, and significant in the clean energy industry. One breakout group focused on barriers and actions associated with membrane opportunity categories listed in Table 3, while the other breakout group discussed barriers and actions for specific membrane opportunities. The results of these discussions are presented in Sections 3.1 and 3.2.

3.1 Category Opportunities

Barriers affecting generalized categories of membrane uses are listed in Tables 4 through 7.

In addition to the barrier-specific actions listed in Table 4 for liquid/liquid separations for organic systems, actions that could affect multiple barriers to liquid/liquid separations include: (1) providing incentives to users and producers; (2) developing materials and manufacturing processes; and (3) developing multi-scale modeling approaches for module development, coupled with testing and validation.

TABLE 4: CATEGORY OPPORTUNITY - MEMBRANES FOR LIQUID/LIQUID SEPARATIONS (ORGANICS)

Barriers	Possible Actions to Overcome Barriers
Lack validated separation systems (membranes and associated hardware)	• Field testing of systems
Lack efficient module design for pervaporation systems	• Develop new module designs that are scalable and more cost-efficient
Lack ability to adequately address fouling systems	• Pulsatile flow and vibrating membranes
Lack membranes for hard-to-treat waters (e.g., mining, fracking, tailing ponds, waters with high solvents or salts, or with a wide temperature range)	• Conduct active research into these systems (need is large)
Lack properly selective membranes that can handle temperatures between 50 and 100 degrees Celsius	• No actions provided
Lack solvent resistance in both material and module; membrane swelling	
Lack ability to separate oil and water with sufficient flux	
Existing installed capital base	
Handling high viscosity (e.g., 10-200 cP)	
Gas in system (high vapor pressure components)	

Table 5 depicts barriers and actions to address gas/gas separations, in particular, membrane processes for nitrogen, oxygen, and hydrogen.

TABLE 5: CATEGORY OPPORTUNITY – MEMBRANES FOR GAS/GAS SEPARATIONS

Barriers	Possible Actions to Overcome Barriers
Selectivity and permeability/flux • Selectivity/permeability relationship is good for pure systems, but not field conditions • Idea that needed improvements are huge, while actually small changes in this area could be very meaningful	• New chemistry to improve selectivity/permeability (e.g., cross-link, vary current chemistry, graft new chemistries) • Develop economical manufacturing process for new materials to improve selectivity/permeability • Develop better design modules for system integration (smaller, sub-pilot scale with users) • Improve understand of industry specifications and needs with respect to flux and selectivity requirements
Contamination in gas stream	• Design material to withstand contaminants, using combinatorial approach
Module design and packaging	• Create cross-cutting teams focusing on advancing scalability, manufacturability, reliability, and cost-effectiveness (e.g., better/new module designs to mitigate parasitic pressure drops that hurt separation performance, especially for new membranes having very high flux, selectivity, or both)
Lack sufficient real field data for selection and use	• Work with industry to set targets and suggest protocols for unified testing • Involve and incentivize users to provide test sites and test new technology (requires users to provide financial support)
Thermal performance of system	• Undertake R&D regarding thermal performance
Limited understanding of durability/ reliability failure modes	• Undertake effective accelerated testing • Undertake material screening for mixed gas streams • Evaluate better techniques to make membranes
Binary and multi-component systems for separation	• No actions provided
High cost at scale (20% improvement needed)	
Limitations for membranes' pressure capability	

In addition to the barrier-specific actions listed in Table 6 for electro-chemical systems, actions that could affect multiple barriers for electro-chemical systems include: (1) development of asymmetric membranes; and (2) establishment of a contractual vehicle to support teaming between developers, producers, users, and systems experts.

TABLE 6: CATEGORY OPPORTUNITY – MEMBRANES FOR ELECTRO-CHEMICAL SYSTEMS

Barriers	Possible Actions to Overcome Barriers
Cost	• Develop alternative polymers
Selectivity	• Better design rules to control and optimize selectivity
Stability of proton conducting material (hydrogen electro-chemical pumping)	• Use computational chemistry approach to develop stable proton-conductors
Impurity tolerance (hydrogen electro-chemical pumping)	• Use computational chemistry approach to develop stable proton-conductors
Thin membranes with structural stability and resistance to chemical attacks	• Develop very thin membranes (e.g., 5-10 microns) • Better design rules to control and optimize selectivity • Improve mechanical stability (to access currently available 50-micron membranes) • Develop chemistry to support stability • Evaluate use of composites
Dimensional stability	• Develop composites and supported systems
Pore size control to deliver drinking water from seawater (desalinization)	• No actions provided
Avoiding salts, acids, and bases	
Ion control (ability to block some ions and not others) and transfer	
Durability	
Lithium batteries: • Mechanical stability • Avoid dendrite growth from moving across membrane (e.g., glass limits but has connectivity issues, is not a good ion barrier, is too fragile and costly; polymers also work but puncture easily) • Limited knowledge about cation selectivity • High cost of Nafion polymer precursor	

In addition to the barrier-specific actions listed in Table 7 for cross-cutting applications, actions that could affect multiple barriers include: (1) facilitating collaboration between end users with common needs, possibly in pre-competitive core technologies; (2) establishing a clearinghouse of product developers and producers to connect partners; (3) establishing application-driven performance targets (e.g., energy, operating costs) for membrane process systems as a whole that are applicable across an industry; (4) identifying new applications in membrane technology; and (5) providing consistent strategic funding for existing industry-university collaborative centers with either a primary or secondary focus on membranes and separations technology.

TABLE 7: CATEGORY OPPORTUNITY - MEMBRANES FOR CROSS-CUTTING APPLICATIONS

Barriers	Possible Actions to Overcome Barriers
Lack analytical methods to measure membrane and module performance	• Develop high throughput screening/combinatorial approaches • Develop accelerated testing and aging tests
Field trial tests assessing membrane performance in real environment required by end users	• Establish pilot scale and real world test facility • Conduct tests with extended on-stream time (e.g., >100 hours) in the field to demonstrate performance robustness (needed before end users will typically even consider new membrane technology)
Lack large sized membranes	• Establish R&D program for module design and reliability
Scale-up capability for modules; reliable seals	• Establish R&D program for module design and reliability
Lack quality control and assurance for manufacturing to ensure reproducibility	• Develop manufacturing control diagnostics (manufacturing QA/QC can be especially critical for ultra-thin or highly selective membranes)
Lack modeling tools for membrane module design and validation	• Develop multi-scale tools for membrane module design and expert systems with validation and appropriate experimental inputs (e.g., computational fluid dynamics)
Lack rapid synthesis techniques and processes	• Directed synthesis for control of membrane properties
Credibility of process economics (cost of energy in U.S. a key driver)	• No actions provided
Tube sheet material (temperature and chemical compatibility)	
Capital to produce the installed systems at scale	

3.2 Specific Opportunities

Barriers affecting specific membrane opportunities are listed in Tables 8 through 13.

Table 8 depicts barriers and actions to address reactive separations, particularly for chemical and refining applications such as fermentation processes and natural gas separation. A breakout session participant noted that there is a difference in the application for gas and liquid separations, with higher potential for liquid separations.

TABLE 8: SPECIFIC OPPORTUNITY - REACTIVE SEPARATIONS (#1)

Barriers	Possible Actions to Overcome Barriers
Membranes and reactors seldom/never operate at the same optimal conditions	• Find membranes that work under the reaction conditions • Integrate membrane with the catalyst (like fuel cells) • Develop an integrated team approach with catalyst and membrane expertise • Determine potential for gas separations (e.g., dehydrogenation reaction)
Lack ability to rapidly screen	• Develop rapid screening techniques (e.g., conduct lab work, review approaches, take the best of, and standardize a pilot system to allow for fast screening) • Standardize the types of instruments with characterization methodologies for membrane materials (e.g., porosity)
Lack understanding of how the reactive membrane breaks down	• R&D for understanding the breakdown at scale for integrated devices
Adaptive process control for HVAC, constantly changing conditions	• Integrate with the controls systems
Product pricing for existing materials is based on use in high value applications, making it difficult to obtain more attractive pricing for use in lower value systems	• Convince manufacturers to meet the lower grade requirements from the same materials • Develop an alternative platform for manufacturing (e.g., using processes such as paper manufacturing processes or galvanizing/metallurgical processes) • Apply knowledge from traditional industries (e.g., textiles, metallurgy, and aluminum foil production) to new industries

Table 9 depicts barriers and actions to address separation of hydrocarbons with similar boiling points, in particular olefin/paraffin separation.

TABLE 9: SPECIFIC OPPORTUNITY - OLEFIN/PARAFFIN SEPARATION (#2)

Barriers	Possible Actions to Overcome Barriers
Contaminants have not been addressed (lost 20 years of development time for facilitated transport)	• Evaluate real streams early on to find out, do side stream testing
Intrinsic selectivity, polymers are not adequate for debottlenecking	• Evaluate alternate materials (polymers/inorganic hybrids or carbon molecular sieves)
Enormous scale up (higher cost at large size for certain materials)	• Fully evaluate the required process for those materials that can be scaled to 1000 m^2
Physical scale up	• Develop high surface to volume materials to make them more compact • Consider using membranes as a contactor rather than as a selective process
Lack consistent life-cycle analysis (LCA) on process approaches (to understand if system is as energy efficient as expected)	• Develop and make available more consistent LCA information for membranes and processes
Low tolerance to risk for petrochemical industry adoption	• Long term demonstration of performance under actual conditions • Focus on debottlenecking rather than replacement as a first step • Use membranes as a contactor rather than as a selective process • Education and evaluate possibility of reducing operating temperature (or increase temperature for C2 separations) • Evaluate new designs and integrated systems
Membrane contactors/reactors require pre-treatment	• Develop a membrane without pre-treatment or improve filters and pre-treatment

Table 10 depicts barriers and actions for new and improved materials, including composite, polymeric, ceramic, and nano materials. Efforts may address hydrophobicity, modularity, tuning, reduced fouling, improved flux, higher sensitivity, and surface modification.

TABLE 10: SPECIFIC OPPORTUNITY - NEW AND IMPROVED MATERIALS (#27)

Barriers	Possible Actions to Overcome Barriers
High cost of high surface area materials	• Quick down-select evaluation of low cost options, develop cost model for scale up • Publish failures and lessons learned • Invest in R&D for manufacturing technology
Limited understanding of some fundamental science challenges necessary for manufacturing (e.g., need ultrathin skin with zeolites at 100 meters/minute)	• Invest in R&D for manufacturing technology
Limited raw materials availability for necessary non-membrane materials (e.g., support/backing materials, adhesives, and solvents)	• Pilot scale R&D facility and investment for scale up and production of membrane material • Co-develop other materials and pieces that make up the full membrane module
Lack holistic thinking across many scales (from small to process integration)	• Improve forward thinking and strategic planning, to help with down selecting and placing resources on those materials that are most likely to have commercial/large scale application • Ensure differentiation between fundamental understanding vs. applied/scale up R&D programs and funding • Expand partnerships
Lack strong design concepts for practical membrane products	• Develop innovative membrane fabrication processes
Lack testing and information in real world process conditions	• Conduct long term field demonstration for prototypes • Develop advanced process control systems for membrane systems
Limited material volumes and supply chain issues (e.g., not large enough market for membrane material manufacturers to make "exquisite formulations" for specialty chemical producers)	• Develop new ways to incentivize suppliers to get into making and supplying these materials • Use existing materials
Lack collaboration and global optimization	• Government facilitation of coordinated activities for membrane development like SEMATECH accomplished for the semiconductor industry • Collaboration between manufacturers and end users, including pilot scale funding and integration of the full process
Fouling as a result of materials with higher flux	• Develop innovative approaches to overcome fouling • R&D to understand fouling mechanisms of "real world" feed streams

Table 11 depicts barriers and actions to address bio-refinery opportunities, in particular C5/C6 sugar separations using low or no solvents.

TABLE 11: SPECIFIC OPPORTUNITY - BIOREFINERY C5/C6 SUGAR SEPARATIONS (#28)

Barriers	Possible Actions to Overcome Barriers
Scale up factors, reliability and breakdown are issues	• No actions provided
Lack knowledge about competing technologies and the techno-economic value proposition	
Separation of knowledge and understanding across the supply chain (end user info and value is different and kept separate from developers)	

Table 12 depicts barriers and actions to address high surface area, low cost ceramic-based membranes for filtration applications.

TABLE 12: SPECIFIC OPPORTUNITY - CERAMIC MEMBRANES (#29)

Barriers	Possible Actions to Overcome Barriers
Cost and low manufacturing speed	• Develop better, more well-defined techniques with improved manufacturing time (e.g., follow lead of the semiconductor industry in finding new methods) • Increase speed of development • Put zeolites on polymers to produce high volumes

Table 13 depicts barriers and actions to address technology for HVAC applications. A breakout session participant estimated the opportunity for air dehumidification and air exchange as well as humidification at approximately $20 billion/year.

TABLE 13: SPECIFIC OPPORTUNITY - HVAC APPLICATIONS (#30)

Barriers	Possible Actions to Overcome Barriers
High membrane cost (e.g., engineered micro-porous, polyvinylidene fluoride, and expanded polytetrafluoroethylene are twice acceptable cost)	• Lower membrane cost with same function via material science (e.g., polymeric under zeolite membrane) • Improve configuration of the module for the application
Challenge in designing modules to have high gas flow rate and low pressure drop	• Develop higher flux membranes • Improve configuration of the module for the application
Contractors that pay for and install the systems do not benefit from the energy savings	• Develop retrofit capability for these modules
Constantly changing conditions necessitate adaptive process control	• Integrate with control systems
Product pricing for existing materials is based on use in high value applications, making it difficult to obtain more attractive pricing for use in lower value systems	• Convince manufacturers to meet the lower grade requirements from the same materials • Develop an alternative platform for manufacturing (e.g., using processes such as paper manufacturing processes or galvanizing/metallurgical processes) • Apply knowledge from traditional industries (e.g., textiles, metallurgy, and aluminum foil production) to new industries

APPENDIX A: WORKSHOP AGENDA

8:00a.m.-9:00a.m.	**Registration and Breakfast**	
9:00a.m.-9:15a.m.	**Welcome and Introductory Remarks**	**Dr. Robert Gemmer, AMO**
9:15a.m.-9:30a.m.	**Review of Historical Membrane Workshop Results**	**Dr. Sharon Robinson, ORNL**
9:30a.m.-11:00a.m.	**Where are we today? *Industry and Academic Perspectives*** *10-minute overview presentations, followed by 10 mins of Q&A* **Mr. Shawn Feist** - The Dow Chemical Company **Dr. Zissis Dardas** - United Technologies Research Center **Mr. Charles Page** - Air Products **Mr. Shekar Balagopal** – Ceramatec **Dr. Jun Liu -** Pacific Northwest National Laboratory **Dr. William Koros** - Georgia Institute of Technology	**Expert Panel**
11:00a.m.-11:15a.m.	**Break**	
11:15a.m.-12:00p.m.	**Breakout Session: Past Successes** Facilitated by Lee-Ann Tracy and Marci DuPraw, SRA International ▪ Review facilitation ground rules and identify 2 reporters for each group. ▪ What have been the successes in membrane technology? ▪ What are characteristics of successes or "lessons learned"?	**Two concurrent sessions**
12:00p.m.-12:45p.m.	**Lunch and Networking Session**	
12:45p.m.-1:30p.m.	**Breakout Session: Emerging Opportunities** ▪ What are high value current and emerging applications for membranes? ▪ List the opportunities. *Characteristics to consider: energy savings potential, process intensification, contribution to US competitiveness, broad applicability, ability to perform a difficult separation, etc.*	**Two concurrent sessions**
1:30p.m.-2:30p.m.	**Breakout Session: Barriers** ▪ What are the barriers to application and increased adoption of membranes for the opportunities identified? ▪ List the barriers. *Types of barriers to consider: Materials characteristics (selectivity, flux, durability), manufacturing challenges, field testing, modeling or analytical capabilities, etc.*	**Two concurrent sessions**
2:30p.m.-2:45p.m.	**Break**	
2:45p.m.-3:45p.m.	**Breakout Session: Actions** ▪ What are the actions to overcome the barriers identified? ▪ List the actions.	**Two concurrent sessions**
3:45p.m.-4:00p.m.	**Break**	
4:00p.m.-4:30p.m.	**Breakout Session Reports & Closing Remarks**	**Rapporteurs and Dr. Gemmer**
4:30p.m.	**Adjourn**	

APPENDIX B: WORKSHOP PARTICIPANTS

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APPENDIX C: ACRONYMS

AAAS	American Association for the Advancement of Science
AMO	Advanced Manufacturing Office
CHP	combined heat and power
CO_2	Carbon dioxide
CTA	cellulose triacetate
DOE	Department of Energy
EGR	exhaust gas recirculation
GPM	gallons per minute
HVAC	heating, ventilation, and air conditioning
IGCC	integrated gasification combined cycle
LCA	life-cycle analysis
NDE	non-destructive evaluation
NO_x	nitrogen oxides
PSA	pressure swing adsorption
QA/QC	quality assurance/quality control
R&D	research and development
RO	reverse osmosis

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