

POSTER SESSION**Monday, May 13, 7:00 pm - 10:00 pm | Ballrooms 1 & 2****Poster Session Chairs**Prity Bengani-Lutz (Repligen Corp) plutz@repligen.comRamesh R Bhawe (Oak Ridge National Lab) bhaverr@ornl.govYuexiao Shen (Uni of California Berkeley) syxbach@gmail.com

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SESSION A - Innovation in Bio-Inspired and Bio-Applied Membranes**A1 High-Capacity Multimodal Anion-Exchange Membranes for Purification of Biologics,**

Joshua Osuofa (Clemson University)*; Scott Husson (Clemson University)

Multimodal membranes are a novel class of chromatography media that bind proteins and bioprocess impurities through combinations of Coulombic interactions, hydrophobic interactions and hydrogen bonding. Because of the multiple modes of binding, these membranes can operate over a wider range of conditions than conventional membranes, enabling their use in chromatographic purification steps with minimal or no pretreatment of the feed. In this study, we are evaluating the performance of Purilogics' multimodal anion exchange membrane in bind-and-elute mode under a variety of industrial relevant conditions. In this presentation, we will present performance data from dynamic binding capacity (DBC) measurements for bovine serum albumin (BSA), human immunoglobulin G (hIgG), and salmon sperm DNA (ssDNA) for a range of conductivities (0 -30 mS/cm) and pH values (5-9). We will show that these novel membranes have high capacities at short residence times even under conditions of high ionic conductivity. Dynamic binding capacities for BSA, IgG and ssDNA varied with pH and ionic conductivity. The isoelectric point of the protein determined the trend of DBC with pH. DBC also varied with ionic conductivity, often showing a maximum at 5.7 mS/cm (50 mM NaCl). Based on comparisons to commercial membrane products, these high-capacity membranes can be an alternative for purifying large bioprocess volumes using short residence times without dilution or desalting of the feed.

A2 High throughput screening of ultra-filtration membranes with mixed dextrans in 96 well plate,

Masha Khazan (Pall Corporation)*; James Hathcock (Pall Corporation); Jian Qiu (Pall Corporation)

High Throughput Screening (HTS) of ultra-filtration (UF) membranes was developed to eliminate membrane testing bottleneck and to allow assessment of membrane uniformity on a small scale. Using custom-made infrastructure to quickly assemble up to 24 various UF membranes into 96 well plates, we utilized commercially available automated liquid handling system to verify 96 well plate's integrity and to perform dextran challenge. Membrane dextran selectivity was assessed based on HPLC analysis of permeates performed directly from the 96 well collection plate. Dextran challenge conditions for 96 well plate were optimized to achieve Molecular Weight Cut Off (MWCO) correlation with stirred cells. Dyes were used to quantify volumetric water and dextran flux in 96 well plate test. During assay validation phase, we demonstrated uniformity of dextran selectivity within and between plates as well as ability to differentiate "good" vs. "bad" media on the same plate. Implementation of this HTS test for preliminary screening of UF membranes allows to evaluate fine scale membrane uniformity, speed up membrane performance testing, and free up operator time.

A3 Impacts of Bio-inspired Zwitterionic Membranes for Health Care Applications,

Yung Chang (R&D Center for Membrane Technology, CYCU)*

Bio-inspired zwitterionic materials are the latest generation of biomaterials for nonfouling interfaces and membranes in health care applications. This talk summarizes our fundamental developments in R&D Center for Membrane Technology (Taiwan) related to the functionalization of interfaces and membranes using zwitterionic materials. Our molecular designs of zwitterionic polymers and copolymers, sulfobetaine-based, carboxybetaine-based, or phosphobetaine-based, will be reviewed. Then, the strategies used to functionalize surfaces/membranes by coating, grafting onto, grafting from, or in situ modification will be introduced, and the important part of this talk will be the focus to key medical applications of zwitterionic membranes. Finally, some potential future directions for molecular designs, functionalization processes, and applications will be summarized. This work was supported by Ministry of Science and Technology in Taiwan. (MOST 108-2923-E-033 -001) References [1] C. C. Lien, L. C. Yeh, A. Venault, S. C. Tsai, C. H. Hsu, G. V.

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A4 Enhanced Membranes for Biogas Upgrading, Ning Shangguan (Compact Membrane Systems)*; Sudip Majumdar (Compact Membrane Systems); Kenneth Pennisi (Compact Membrane Systems)

Every year over 1 billion tons of fresh animal manure is produced in US and it can be a pollution source if not handled properly. "Anaerobic digestion" is an environmental friendly and energy efficient way to dispose animal manure. Biogas is a mixture of 60% methane, 40% carbon dioxide and trace amounts of other contaminant gasses such as hydrogen sulfide. Considered to be highly corrosive and toxic, biogas is often burned immediately as a low grade fuel and there is no storage. If the non-methane components can be removed from biogas, biogas will be chemically identical to natural gas and can be put into many advanced uses, which will increase the economic value of the anaerobic digestion. A low cost solution to upgrade raw biogas (remove CO₂, H₂S and H₂O) is much needed to improve the economics of this conversion from animal manure to bioenergy. Compact Membrane Systems is proposing a membrane separation technology which can efficiently upgrade biogas (remove CO₂, H₂S and H₂O). We have developed membranes with very high CO₂ flux and high CO₂/CH₄, H₂S/CH₄ and H₂O/CH₄ selectivity. These highly fluorinated membranes have shown excellent long term resistance to high concentration H₂S biogas. Economic analysis shows a significant cost saving compared with conventional CO₂ gas membrane separation used in biogas upgrading. We scaled up the biogas membranes, made membrane modules and are designing /building pilot membrane systems. Field test will be conducted on real biogas streams in farms. We expect this technology will promote the use of anaerobic digestion to treat animal manure for biogas production. This will result in less water pollution from animal manure, less greenhouse gas emission from animal manure degradation, more renewable energy from biogas production and more jobs in rural areas.

A5 Monitoring of Membrane Fouling by the Zeta Potential, Thomas Luxbacher (Anton Paar GmbH)*; Hermina Buksek (University of Maribor); Irena Petrinic (University of Maribor); Elisa Innocenti (GSK Vaccines S.r.l.); Krzysztof Trzaskus (Aquaporin A/S); Maria Salud Camilleri-Rumbai (Aquaporin A/S)

The tendency of a membrane towards fouling is influenced by the properties of the membrane, the composition of the feed solution, and the filtration conditions. Among the properties of a membrane, parameters which describe the interaction of membranes with their environment are of major importance for studies of membrane fouling. The membrane zeta potential gives direct information on electrostatic interactions between the membrane surface and compounds in the feed solution, which contribute to membrane fouling. The surface charge of a membrane can also be tuned to favor or suppress certain interactions with components in the feed solution. Surface charge analysis can also be used to optimize membrane cleaning by evaluating the effects of different cleaning agents on the membrane surface. We report on the zeta potential analysis of the inner surface of Aquaporin Inside® hollow fiber forward osmosis (HFFO) membranes, which were employed for the up-concentration of fermentation broths from vaccine production processes. Aquaporin Inside® HFFO fibers assembled in a lab-scale filtration module offers ideal conditions for the surface zeta potential analysis by the streaming potential method. The isoelectric points (IEPs) of pristine and fouled HFFO membranes were assessed by a pH scan of the zeta potential and compared with the IEP of fouled HFFO membranes after rinsing with deionized (DI) water. The preliminary zeta potential results suggest a temporary deposition of a fouling layer by organics in the fermentation broth that is successfully removed after rinsing. The efficient removal of HFFO membrane fouling is confirmed by the same flux of DI water determined before and after filtration and rinsing. The streaming potential technique is a unique method for the non-destructive analysis of the inner surface of hollow fiber membranes. It allows monitoring of fouling layer deposition on the membrane surface and supports quantification of the cleaning efficiency.

A6 Tangential flow microfluidics for the capture and release of nanoparticles and extracellular vesicles on conventional and ultrathin membranes, Mehdi Dehghani (Rochester Institute of Technology)*; Kilean Lucas (University of Rochester); James McGrath (University of Rochester); Thomas Gaborski (Rochester Institute of Technology)

Extracellular vesicles (EVs) contain nucleic acids and protein cargo of their cells of origin and accumulate in body fluids. The role of EVs in intercellular communication has received increased attention for diagnostic and therapeutic applications and the development of many alternative purification techniques. While membrane based separations have been widely used in the biomedical area due to their robustness and simplicity, these are not commonly used for EV purification. Here, we develop a method for the capture and release of nanoparticles and EVs in a novel microfluidic device and flow scheme. We term our novel purification strategy Tangential Flow for Analyte Capture (TFAC). In this approach, the sample is pushed tangentially through the channel of the microfluid device, particles are captured by the pores of the membrane surface due to a controlled rate of ultrafiltration. We show that that these particles can be visualized, counted and later released by simply reversing the transmembrane flow. We compare the capture and release of fluorescent

nanoparticles using conventional thick (10 μm) polymeric track-etched (TE) membranes to ultrathin (100nm) silicon nitride nanomembranes. We show that silicon nitride nanomembranes exhibit better capture and release and less irreversible pore clogging compared to TE membranes under the same flow conditions. This result suggests that TFAC on silicon nitride nanomembranes is a viable new method for the isolation and purification of EVs from small fluid volumes.

- A7 Low-cost ultrathin porous polymeric membranes with precise control over pore size and thickness gradient for investigation of leukocyte transmigration through barrier models**, Shayan Gholizadeh (Rochester Institute of Technology)*; Alec Salminen (University of Rochester); Zahra Allahyari (Rochester Institute of Technology); Robert Carter (Rochester Institute of Technology); Henry Chung (Rochester Institute of Technology); Marcela Mireles (University of Rochester); Thomas Gaborski (Rochester Institute of Technology)

Ultrathin porous membranes are currently used for a variety of biomedical applications, ranging from co-culture systems to tissue barrier models. In human barrier models, the intimate proximity between cell-types plays a significant role in cell-cell communication and transmigration across the barrier which cannot be physiologically modeled with conventional co-culture systems typically separating cell types by more than 10 μm . Importantly, regulated leukocyte transmigration across endothelial barriers can play a significant regulatory role in health and disease, but the physical constraints regulating this immune function are not fully understood. Here, we developed physiologically-inspired Parylene co-culture membranes with precise thickness gradients (from 200 nm to 1.5 μm) and highly controllable pore sizes on a single silicon wafer using a single patterned mask (obtaining pores ranging from 0.8 μm to 1.7 μm), which can result in porous free-standing membranes with a relatively wide range of pore sizes and thicknesses on a single silicon wafer. The process starts with coating water-soluble sacrificial layer on a 6" silicon wafer, followed by Parylene chemical vapor deposition on the physically confined silicon substrate. Using optical photolithography, distinct regions of the wafer is exposed with various user-defined exposure regimes, which would result in various pores with highly controllable pore sizes after RIE dry etching with a combination of Ar, SF₆, and O₂, and vigorous residual resist removal. These membranes enable leukocyte transmigration studies through defined pore sizes and thicknesses to identify critical dimensions. Moreover, the membranes can be used to understand the underlying mechanisms for leukocyte transmigration across barrier models including the blood brain barrier in neurodegenerative disorders.

- A8 Application of Novel Multimodal Anion-exchange Membrane Chromatography Columns in a Two-step mAb Purification Scheme—Aggregates and HCP Removal**, Daniel Henn (Purilogics, LLC)*; Anna Forsyth (Purilogics, LLC); Graham Temples (Purilogics, LLC); Jinxiang Zhou (Purilogics, LLC); Scott Husson (Clemson University)

Protein aggregation is a growing problem in the manufacturing of biologics due to increasing solution titers. Antibody aggregates and other impurities often are removed in a three or four-step process involving a bind-and-elute cation-exchange chromatography step and additional hydrophobic interaction chromatography (HIC) columns after an initial Protein A capture step. We present case studies in which aggregates and host cell proteins (HCP) are removed in a simplified two-step monoclonal antibody (mAb) purification scheme. In this scheme, the mAb is isolated from supernatant using a Protein A chromatography step followed by a polishing step purification using Purilogics' multimodal anion-exchange membrane chromatography columns (MMM-AEX) operating in flow-through mode. In this study, a variety of mAbs were purified using the two-step purification strategy. Different buffer types (e.g. Tris base, phosphate buffers) and buffer conductivities (1–15 mS/cm) were explored. HCP level and fractions of monomer, dimer and aggregates were compared before and after the polishing step. The results were compared with studies using two other leading commercial membrane products. Additionally, we will demonstrate the scalability and reusability of the novel MMM-AEX column.

- A9 Effect of Nanomembrane Orientation and Flow Modality on Benchtop Urea Clearance**, Sam Walker (The State University of New York at Buffalo)*; Kayli Hill (University of Rochester); Alec Salminen (University of Rochester); Dean G Johnson (University of Rochester)

Our lab has developed highly efficient nanomembranes (75 nm thick) that aim to replace center-based dialysis filters through the creation of a wearable hemodialysis device. Nanomembranes, formed from a thin-film stack on 5.4 mm by 5.4 mm chips, are exposed from the backside via a trench (2 mm by 0.7 mm) created in an etch process. Chips can be formed with either one trench or two giving two different membrane areas for dialysis. The different etching processes used on each side of the nanomembranes result in distinct surface characteristics and potential for anisotropic filtering. Benchtop single-pass hemodialysis experiments were designed to investigate whether membrane orientation affected urea clearance. Additionally, studies aimed to determine the effect of analyte to dialysate flow rate ratios on urea clearance were performed. Findings for the membrane orientation show that it is clear that neither chip configuration offers significantly better urea clearance than its counterpart under these experimental conditions. However, the analyte-trench combination is effective when clearing urea and should be implemented in future devices and experiments concerning blood analytes. Future studies will utilize blood samples to confirm this result. Results indicate a significant improvement in urea clearance when the flow rate ratio of analyte to dialysate is 1:2. The 2 $\mu\text{L}/\text{min}$: 4 $\mu\text{L}/\text{min}$ flow rate combination offered significantly better urea clearance

compared to that of 3 $\mu\text{L}/\text{min}$: 4 $\mu\text{L}/\text{min}$ and 4 $\mu\text{L}/\text{min}$: 4 $\mu\text{L}/\text{min}$ combinations. This is important to note as doubling membrane area offers considerably more than twice the urea clearance, under these experimental conditions. When compared to the previous results, the 2 $\mu\text{L}/\text{min}$ (analyte) and 4 $\mu\text{L}/\text{min}$ (dialysate) flow rate combination provided significantly better urea clearance. It is believed that faster analyte flow rates effectively decrease the volume of fluid near the membrane where diffusion has the potential to occur.

A10 Feed Spacer Modification for Listeria Control in Dairy Processing, Mainara Costa Teixeira (The University of Alabama)*; Preston Richier (The University of Alabama); Jake Colburn (The University of Alabama); Shelby Brooks (The University of Alabama); Will Baker (The University of Alabama); Thomas Hendrich (The University of Alabama); Ryan Summers (The University of Alabama); Stephen Ritchie (The University of Alabama)

Listeria monocytogenes (LM) is a serious foodborne pathogen that may be present in industrial dairy processes. Pasteurization is effective against the bacteria, but does not address downstream recontamination. Quaternary ammonium (QA) compounds are common antimicrobial agents. They can be immobilized on the feed spacer material that is used in spiral wound elements. Bacteria are adsorbed on the mesh surface due to electrostatic interaction between the positively charged QA head and negatively charged bacterial cell membrane. Permeation of the QA side chains then causes leakage of cytoplasmic material. Bacteria adsorption also reduces downstream concentrations. A modified feed spacer mesh material was produced to control bacteria growth. Vinylbenzyl chloride was reacted with octadecylamine to produce an aminated monomer. The resultant product was polymerized by photo-polymerization. We determined the anti-bacterial effectiveness of the polymer through biotesting with a surrogate for LM, *Lactobacillus plantarum*. Further testing showed that presoaking the material in water had a significant impact in delaying and reducing the growth of the gram-positive bacteria. Scanning electron microscope images before and after the biotest showed a high adsorption of bacteria to the surface. Preliminary results will also be presented on the functionalized polypropylene feed spacer and tests with LM.

A11 Critical Flux of Ultrathin Silicon Membranes in Tangential Flow Filtration of Protein Solutions, Danial Ahmad (University of Rochester)*; Kilean Lucas (University of Rochester); Mehdi (Aslan) Dehghani (Rochester Institute of Technology); Thomas Gaborski (Rochester Institute of Technology); James McGrath (University of Rochester)

Dead-end filtration of protein-rich fluids through ultrathin nanomembranes (<100nm thick freestanding) leads to rapid surface fouling due to their high permeability and lack of internal structure. By contrast, tangential flow operations with ultrathin membranes and complex biofluids (such as hemodialysis) have been found to proceed for days without a loss of membrane permeability, even in the presence of some ultrafiltration. Inspired by these observations, here we systematically test the hypothesis that ultrathin nanoporous membranes exhibit a higher 'critical flux' in tangential flow filtration (TFF) than conventionally thick membranes. After removing protein aggregates by centrifugation, we show that solutions of bovine serum albumin (BSA) as concentrated as 10 mg/ml achieve a critical flux of 1157 $\text{l}/\text{m}^2 \text{ h}$ in a microfluidic device featuring 18.8% porosity nanoporous silicon nitride (NPN) membranes. This critical flux is approximately five times higher than literature values achieved for TFF microfiltration, where a flux of 220 $\text{l}/\text{m}^2 \text{ h}$ was acquired with 0.2 μm track-etched (TE) membranes using 1 mg/mL BSA. Repeating our studies with 10 μm thick TE membranes with the same size (~50 nm diameter) and number (~5 x 10⁷) of pores as NPN confirms our hypothesis that membrane thinness leads to a higher critical flux. Based on the fact that transmembrane pressures (TMP) in these studies are higher for TE vs. NPN with the same ultrafiltration rate we posit a mechanism for critical flux enhancement: the inherent thinness of NPN mitigates the formation of a stagnant protein 'cake layer' on the membrane surface and instead promotes a 'flowing protein cake'. More specifically, a lower TMP limits the fouling experienced by NPN versus TE membranes and this confers long term viability and performance.

A12 Grafting Zwitterionic Polymer and Poly (amino acid) on Polyamide Membranes: "Defending and Attacking" Strategies for Biofouling Control, Wen Ma (Concordia University)*; Liuqing Yang (Concordia University); Saifur Rahaman (Concordia University)

In this study, dual functions block copolymers with fouling resistant and antimicrobial properties were grafted on polyamide membranes by utilizing graphene oxide (GO) as modification media to control biofouling. The block copolymer consisted of bacteria-"defending" and -"attacking" moieties formed by zwitterionic polymer (poly(sulfobetaine methacrylate), PSBMA) and poly (amino acid) (poly methacryloyl-L-Lysine, PLysMA), respectively. To controllably grow the copolymer on membranes with desired architecture, the activators regenerated by electron transfer-atom transfer radical polymerization (ARGET-ATRP) technique was utilized. The successful polymerization of copolymers on membrane was examined by FTIR and SEM. The grafting density and thickness of polymer brush was optimized by controlling the polymerization condition. Both PSBMA and PLysMA grafting significantly increased the hydrophilicity of the membrane and reduced its surface roughness and charge density. Combined PSBMA and PLysMA reducing the biofouling caused by gram positive (G+) bacteria, *B. Subtilis*, via bacterial-"defending" and -"attacking" synergistic effect. However, in case of biofouling caused by gram negative bacteria (G-), *E.coli*, "defending" functions played the predominant role. When the "defending"-PSBMA was grafted on the top and directly exposed to bacteria-containing suspensions, the membrane exhibited the lowest bacterial attachment and maintained a high water-permeation-flux along with biofilm growth. With a strong water affinity and fouling-resistance, the M-PLysMA-b-PSBMA membrane exhibited less flux

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A13 Monitoring of biological fluids with extraction membranes, Pinar Cay-Durgun (Arizona State University); Tianmiao Lai (Arizona State University); Nai-Yuan Liu (Arizona State University); Mark Sprowls (Arizona State University); Stewart Mann (Arizona State University); Leslie Thomas (Mayo Clinic in Arizona); Erica Forzani (Arizona State University); Mary Laura Lind (Arizona State University)*

Diagnosis and management of kidney and liver disorders could benefit from a point of care device for measurement of small molecules in biological fluids. Example conditions include ones which may alter systemic acid/base homeostasis, metabolic conditions, and other diseases of the kidney and liver. Practical and technical limitations of small molecule measurement have impeded the use of these molecules as a routinely employed biomarkers in medicine. We are developing membranes for selective extraction of small molecules from biological fluids for colorimetric detection. We will present our results on novel membranes for these separations.

A14 Fine-Tuned Biohybrid Polymeric Particles Mimicking Biological Compartmentalization Prepared by Membrane Emulsification, Emma Piacentini (National Research Council of Italy, Institute on Membrane Technology, CNR-ITM); Lidieta Giorno (National Research Council of Italy - Institute on Membrane Technology)*

Biomacromolecules such as enzymes have a considerable role at the heart of biotechnological processes. However, significant improvements in their formulation are required to broaden their application, in particular for the synthesis of pharmaceutical, food and cosmetic products. Enzyme immobilization might improve biocatalyst properties because substrate specificity might be enhanced and the effect of inhibitors might be reduced. However, many methods of immobilization and entrapment cause important structural deformation of the enzyme, leading to reduction in activity. The optimization of the immobilization method is therefore required to reach biocatalyst resistance to leaking, retention of enzyme activity over long-term storage, operational stability under adverse environmental conditions, accessibility to substrates, fast catalysis, and, in general, proper enzyme immobilization density with adequate orientation. Membrane emulsification (ME) is emerging as a very promising formulation method to produce monodisperse particles by using microporous membranes in mild operative conditions and low energy consumption. The use of ME for simultaneous preparation of polymeric microspheres and phase transfer biocatalyst immobilization will be described. Lipase is used as a model interfacial biomacromolecule to demonstrate the powerful of the use of ME mechanism in the production of carriers with tailored properties for amphiphilic molecule immobilization. Enzyme entrapment during particle formation permitted to orient the enzyme without affecting its intrinsic biocatalytic activity. Furthermore, it permitted an enzyme confinement with a good balance between molecular flexibility and rigidity. ME can potentially extend the development of bio-functionalized micro-nanostructured devices with improved functions, sensitivity, and stability for applications in biocatalysis, biosensors and biomolecule-responsive drug delivery systems.

A15 Bio-inspired immobilization of casein-coated silver nanoparticles on cellulose acetate ultrafiltration membranes: from laboratory to scale-up, Xiaobo Dong (University of Kentucky); Halle Shannon (University of Kentucky)*; Tequila Harris (Georgia Institute of Technology); Isabel Escobar (University of Kentucky)

Casein-coated silver nanoparticles (casein-AgNP) had been previously loaded on cellulose acetate (CA) ultrafiltration membranes for biofouling control[1]. However, when physically added to the membrane casting solution, AgNPs tend to leach off the membranes. Therefore, there is strong interest in developing methods to chemically bind the AgNPs to the membranes without losing their activity, and in making these methods scalable. Inspired by the affinity of silver to the thiol groups of cysteine proteins in bacteria, CA membranes were cast and imbedded with AgNPs via attachment with functionalized thiol groups using polymerized glycidyl methacrylate (GMA) and cysteamine. However, the chemical reactions required three steps after casting the membranes, and each step needs a large amount of solution bath. To minimize the materials and energy needed in the chemical attachment process and maximize the reaction efficiency, this study integrated all the chemical reactions in the stage of preparing dope solutions. The recipe and procedures changed due to the difference of dope solution and membranes. Membranes immobilized with AgNPs were successfully cast for laboratory-scale studies as well as for scale up studies. This method successfully prevented leaching of AgNPs during cross-flow and dead-end studies. *Pseudomonas fluorescens* Migula in brackish water was used for biofouling test and the membranes displayed a significant reduction in the accumulation of bacterial cells. This method provided a promising approach of casting CA membranes immobilized with AgNPs. 1.

A16 Surface-Specific Thermo-responsive Coating of Membranes, Marcela Mireles (University of Rochester)*; Cody Soule (Rochester Institute of Technology); Luis Delgadillo (University of Rochester); Thomas Gaborski (Rochester Institute of Technology)

Label-free biological separations such as filtration hold great potential for the isolation and recovery of viable biological material such as circulating tumor cells (CTCs) or extracellular vesicles. However, recovery can be limited by non-specific adsorption of the targeted species onto the membrane surface and over the pores. Thermo-responsive coatings, such as poly(N-isopropyl acrylamide) (PNIPAM) which undergoes a conformational transition from extended to collapsed, could be used to increase collection efficiency by releasing the trapped targeted species. However, conformal PNIPAM coatings of a membrane lead to potentially undesirable changes in pore size and a reduction in the initial flux values due to coating of the pore walls. In this work, nanospheres were placed on a SiO₂ film and coated with Au:Cu followed by Al. A porous pattern on the metallic layer is revealed upon nanosphere removal and transferred through dry etching into the SiO₂. The remaining Al is etched to expose the Au:Cu and the samples are placed in an ethanolic solution containing acetic acid for PNIPAM grafting. This coating is limited to take place at the membrane surface only due to metal-sulfur interaction of the thiol-terminated PNIPAM, hence not coating the pore walls. Chemical characterization validates the presence of PNIPAM and environmental atomic force microscopy showed its response to temperature which was evidenced by a change in polymer coating stiffness. Our approach preserves the specific pore size and characteristics of the membrane, while promoting release of adsorbed and captured species over the pores.

A17 Pervaporation Separation of n-Butanol from Aqueous Solutions Using PDMS/Lignin Mixed Matrix Membranes, Ali Zamani (University of Ottawa); Handan Tezel (University of Ottawa)*; Jules Thibault (University of Ottawa)

The scarcity and rising prices of fossil fuels, coupled with environmental challenges, lead researchers to find out a microbial alternative. Biofuel has emerged as an attractive solution which can be effectively used in the current scenario. Among them, biobutanol is an important renewable biofuel. Butanol is produced via acetone-butanol-ethanol (ABE) fermentation from renewable resources such as agricultural by-products. The most important challenge to produce this alcohol as an economically viable biofuel, is improving fermentation performance. To improve the productivity, the in-situ removal of the fermentation products, especially butanol as the most toxic one, from fermentation broth is essential. In this study, pervaporation, a membrane-based process was studied for in-situ separation of butanol. The primary objective of this study was to improve the performance of the Polydimethylsiloxane (PDMS) membrane for the pervaporation separation and the recovery of butanol by adding fillers into its matrix. Lignin, a natural polymer resin, was used as the filler. Different lignin percentages and membrane thicknesses were used and compared to the neat PDMS. Different characteristics of lignin and its impact on the performance of the host membrane were discussed. Results showed that increasing filler particles up to 10 wt% will improve MMM performance by 280% and 60% in flux and selectivity, respectively. This enhancement was reasonable due to the presence of lignin, which enlarged the free volume within the PDMS matrix and provided more permeation pathways for penetrants. On the other hand, by increasing the filler particles to 15 wt%, flux was improved by 40% but selectivity was reduced dramatically by 70%. The lignin agglomeration and low filler-polymer bonds at excessive loadings should be responsible for the water molecules (with smaller kinetic diameter than butanol) to more easily bypass the hydrophobic lignin particles and make the membrane less selective.

A18 Rapid and Selective Water Permeation Across Biomimetic Membranes Through Artificial Water Channel Aggregates, Woonchul Song (Penn State University)*; Ratul Chowdhury (Penn State University); Himanshu Joshi (University of Illinois at Urbana-Champaign); Joseph S. Najem (The University of Tennessee); Yue-xiao Shen (UC Berkeley); Chao Lang (Penn State University); Stephen Sarles (University of Tennessee); Jun-li Hou (Fudan University); Aleksei Aksimentiev (University of Illinois at Urbana-Champaign); Manish Kumar (Penn State University)

Achieving high permselectivity of desalination membranes is of great interest in membrane research, due to ever increasing global demands on safe water supply and reliance on membrane-based desalination technologies. However, overcoming desalination membranes' water/salt permeability and selectivity tradeoffs has not been quite successful compared to overall advances in water purification technology during last few decades. As next generation materials, biomimetic membranes have rapidly emerged as a promising desalination membrane development platform, because they can accommodate specialized pore structures, water channels. Here, we present new synthetic molecular architectures as a novel class of artificial water channels. These channels self-aggregate inside biomimetic membranes and provide cooperatively enhanced water permeation paths. Molecular transport studies reveal that these channels have intrinsic water/salt permselectivities that exceed current polymeric desalination membranes by orders of magnitudes, highlighting their potential in future desalination membrane development.

A19 Can porous membranes be engineered to induce physiologically relevant cell-substrate interactions?, Zahra Allahyari (Rochester Institute of Technology)*; Stephanie Casillo (Rochester Institute of Technology); Shayan Gholizadeh (Rochester Institute of Technology); Henry Chung (Rochester Institute of Technology); Thomas Gaborski (Rochester Institute of Technology)

Despite the increasing use of porous membranes in co-culture systems and barrier models, and their well-known contribution in cell-cell communication and multi-tissue interfaces, their role in controlling cell behavior including cell adhesion, cell migration and extracellular matrix (ECM) formation, and their enabling mechanisms are not fully understood. In the present work, we have developed ultrathin (300nm) SiO₂ porous membranes with micron and submicron features and we investigated how these membranes regulate cell-substrate interaction and affect different cellular behaviors including cell spreading, ECM formation, and cell migration. We demonstrated that porous membranes weakened cell-substrate interaction similarly to soft substrates and biomimetic barrier models, and subsequently reduced focal adhesion formation and endothelial fibronectin fibrillogenesis, and increased cell motility and cell-cell interaction. We further investigated the underlying mechanism of cellular response to these substrates by developing non-fouling micropatterned poly polyethylene glycol (PEG) islands to resemble pores in our porous membrane but without pore edges in order to decouple the role of surface disruption and cell gripping to the pore edges. Similarly to the porous membranes, cells showed reduced fibronectin fibrillogenesis on PEG islands and they exhibit a similar trend of changes in migration speed and directionality on both substrates, which confirms the role of surface disruption in cell-substrate interaction. On the other hand, we found reduced cell spreading and lower magnitude of migration speed on these patterned substrates as compared to porous membranes, suggesting "cell gripping to the pore edges" as a deterministic mechanism for cell-substrates interaction on a porous membrane. These finding can be further employed to modulate cellular responses and mimic tissue and barrier formation by optimizing the design of porous membranes.

A20 High Productivity Harvest - Intensify Harvest and Displace Depth Filtration in Fed-Batch Cell Culture, Shashi Kudugunti (Repligen Corporation)*, Jyoti Amatya (Repligen Corporation), Jamie Peyser (Repligen Corporation)

A conventional production fed-batch process involves a multi-stage seed expansion and elaborate clarification steps to isolate the protein of interest from other process impurities. The current clarification technology utilizes centrifugation and depth filtration trains that are complex and limited in their ability to operate in a sterile or low bioburden manner. With an increase in demand for production of protein therapeutics, it is essential to simplify the traditional fed-batch processes to result in better yield, shorter time and smaller footprint. Repligen developed a simplified & scalable single-step clarification method: High Productivity Harvest (HPH) using the XCell™ ATF system. HPH helps maximize the yield of a fed-batch bioreactor in a sterile manner while eliminating centrifugation, depth, and sterile filtration steps. The current project explores the benefits of combining the HPH method with a perfusion enabled (n-1) seed train bioreactor. The case study focuses on performing (n-1) bioreactor in a perfusion mode that enabled to inoculate production fed-batch bioreactor at 10e6 cells/mL, 20x higher compared to traditional seeding density. Increased seed density facilitates reducing the fed-batch culture duration by half. Implementing the HPH clarification process using XCell ATF system resulted in an enriched environment with a 150% boost in the overall yield in half the fed-batch culture time. The HPH process is performed as a single step in a sterile manner with a 0.2µm clarified product as the output. The product is readily available for either batch or continuous chromatography without additional processing.

A21 Membrane Filtration of Flexible Particles: Rejection of Single Stranded DNA, Hossein Nouri Alavijeh (Clarkson University)*; Ruth E. Baltus (Clarkson University)

In recent decades, DNA purification has generated interest in studying the feasibility of implementing membrane filtration for these flexible particles in pharmaceutical processes. The ability of flexible particles to adopt conformations and enter into membrane pores influences their filterability. In this study, the effects of flexibility and transmembrane pressure (TMP) on the rejection coefficient of single-stranded DNA (ssDNA) were investigated. To characterize flexibility of DNA, Fluorescence Recovery After Photobleaching was integrated with Worm Like Chain polymer model to determine the persistence length. Persistence length is an important parameter that shows the degree of flexibility; it is ionic strength dependent. The results demonstrate that increasing salt concentration results in increasing DNA flexibility. The rejection coefficients of ssDNA with 30 bases in different solution ionic strength were measured using the track-etched polycarbonate ultrafiltration membrane. In addition, The effects of TMP on the rejection coefficients were studied experimentally. In fact, DNA deformability necessitates studying how transmembrane pressure affects DNA transportations through the membrane pores. Results generated from this study will be important for the optimal design of micro- and ultrafiltration systems for water and wastewater treatment and in biotechnological and pharmaceutical sectors.

SESSION B - Innovation in Membrane Materials, Synthesis, and Characterization: Gases

B1 Covalently modified graphene oxide incorporated in PIM-1 mixed matrix thin film composite membranes for gas separation, Elvin Aliyev (Helmholtz-Zentrum Geesthacht)*; Volkan Filiz (Helmholtz-Zentrum Geesthacht); Sergey Shishatskiy (Helmholtz-Zentrum Geesthacht)

PIM-1 has received great attention since its discovery and the gas transport performances of the membranes based on PIM-1 have been studied for extensively, exhibiting the moderate ideal gas selectivities (α) for gas pairs, e.g. α (CO₂/N₂) \approx 20 and α (CO₂/CH₄) \approx 13. Graphene oxide (GO), being a two-dimensional material, has also attracted enormous attention in membrane science due to oxygen functional groups distributed on the graphene layers and their possibility for chemical modification. In this study, mixed matrix membranes (MMM) consisting of graphene oxide (GO) and functionalized graphene oxide (FGO) incorporated in a polymer of intrinsic microporosity (PIM-1) serving as a polymer matrix have been fabricated by dip-coating method. Their single gas transport properties were investigated. The pristine GO acts as an effective barrier material for single gas transport through the PIM-1/GO selective layer with both permeance and ideal selectivity decreasing with increase of the GO loading. The gas transport properties of GO embedded into the PIM-1 matrix are much different from properties of functionalized GO-AEDPPF and GO-DCIBAO. These show very good compatibility to the PIM-1 at 9 and even at 33 wt.% loading the MMMs show ideal selectivities overpassing those of the pure PIM-1 TFC membrane.

Acknowledgment The authors acknowledge financial support from the Helmholtz Association of German Research Centres through the Helmholtz Portfolio MEM-BRAIN and MOL-FIL Carbon nano-membrane project and German Academic Exchange Service (DAAD).

B2 Tunable Interlayer Channels in Graphene Oxide Membranes for Molecular Separations, Shaofei Wang (King Abdullah University of Science and Technology)*; Zhongyi Jiang (Tianjin University); Michael D Guiver (Tianjin University); Suzana Nunes (King Abdullah University of Science and Technology)

Two-dimensional (2D) lamellar membranes are highly advantageous in molecular separations. However, tuning the interlayer channel to realize high separation is challenging. In this presentation, we will show how the ions, molecules and nanoparticles work on channel-tuning to obtain high performance graphene oxide (GO) membranes for CO₂ separation and organic solvent nanofiltration. 1) By intercalating ion cross-linker, borate ions, GO membranes with favorable physical, chemical and water microenvironment for CO₂ molecules are created, rendering ordered size-selective nanochannels, plenty of fixed facilitated transport carriers and moderate water content to implement efficient CO₂ transport. 2) By intercalating molecular cross-linker, poly(ethylene glycol) diamines (PEGDA), we report GO membranes containing CO₂-philic and non-CO₂-philic nanodomains in the interlayer channels. Owing to the orderly stacking of nanochannels as well as the distributed nanodomains with moderate CO₂ affinity, high performance of CO₂ separation membrane in the dry state was reported. 3) By the in-situ intercalating and cross-linking of SiO₂ nanoparticles in the GO interlayers, we design dual-spacing channel GO membranes, that give high permeance, high rejection and high stability in organic solvent nanofiltration. The hydrophilic nanoparticles locally widen the interlayer channels to enhance the solvent permeance. In the alternating nanoparticle-free areas, the GO layers simultaneously bend and the π - π interactions keep the narrow and hydrophobic channel, promoting a high solute rejection.

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B3 Nanoporous two-dimensional nanosheets and their self-assembled gas-sieving membranes, Kumar Varoon Agrawal (École polytechnique fédérale de Lausanne)*; Mostapha Dakhchoune (École polytechnique fédérale de Lausanne); Luis Francisco Villalobos (École polytechnique fédérale de Lausanne)

An innovative route for the fabrication of the gas separation membrane is to synthesize nanoporous two-dimensional (N₂d) nanosheets hosting size-sieving nanopores [1]. Subsequently, N₂d can be self-assembled leading to thin yet permselective membranes, improving the scalability of nanoporous membranes. However, barring metal-organic frameworks nanosheets [2], this has not been demonstrated. In this presentation, I will report two examples of the top-down synthesis of N₂d materials (sodalite precursor RUB-15 [3] and polytriazine imide or PTI [4]) hosting crystalline nanoporous structures for sieving of H₂ from CO₂, N₂ and CH₄, as confirmed by our ab-initio molecular simulations. Highly crystalline layers were synthesized using optimized hydrothermal and solid-state synthesis routes for RUB-15 and PTI, respectively, leading to high-aspect-ratio layered plates. Exfoliation of these nanosheets into highly crystalline (as confirmed by high-resolution transmission electron microscopy) and predominantly single-layer nanosheets (as confirmed by atomic force microscopy) was achieved using swelling of the layers, melt compounding, and by the intercalation of solvents. Finally, packing of these nanosheets into compact films by self-assembly produced molecular-sieving membranes with attractive gas-sieving performances. For example, zeolite nanosheet membranes yielded H₂/CO₂, H₂/N₂ and H₂/CH₄ selectivities of 13, 93.7 and 116.6, respectively, while the PTI nanosheets membranes yielded H₂/CH₄ and H₂/N₂ selectivities of 41 and 93, respectively. Overall, the synthesis of molecular-sieving membranes by the colloidal self-assembly can address the scale-up issues related to the nanoporous membranes. References [1] Tsapatsis and coworkers, *Science* 2011, 334, 72. [2] Yang and coworkers, *Science* 2014, 346, 1356. [3] Gies and coworkers, *Angew. Chemie Int. Ed.* 1996, 35, 2869. [4] Schnick and coworkers, *Chem. - A Eur. J.* 2011, 17, 3213.

B4 Thermally Rearranged Semi-interpenetrating Polymer Networks (TR-SIPNs) for Olefin/Paraffin Separation Applications,

Won Hee Lee (Hanyang University)*; Young Moo Lee (Hanyang University); Jong Geun Seong (Hanyang University); Ho Hyun Wang (Hanyang University); Sun Ju Moon (Hanyang University)

In olefin/paraffin separation, there has been many reports on excellent separation using inorganic and organic membranes. However, there are some issues on large scale manufacturing and low separation performance far beyond the commercial level. Polymer membranes have exhibited potentials due to their good processabilities and economic benefits, and some of them have shown improved gas transport properties such as TR polymers¹ and their derivatives². However, further enhancements of gas separation performances have been still needed for polymer membranes to apply on practical hydrocarbon gas separation applications. Herein, we demonstrated TR-SIPNs incorporating network structures for olefin/paraffin separations. Free-standing films of TR-SIPNs were facilely fabricated via consecutive thermal treatments on polymer precursor solution mixture casted onto the glass plate. Hydroxyl polyimides and bismaleimide-based monomer building blocks in homogeneous casting solutions were used for linear and network polymers in TR-SIPNs, respectively. Chemical structures and chain configurations of TR-SIPNs were demonstrated by FT-IR, NMR, WAXD and SAXS. TR-SIPNs exhibited enhanced BET surface area and higher glassy transition temperature compared to reported TR polymers indicating microporous and rigid polymer structures. Pure gas transport behaviors of the resulting TR-SIPNs were explored for ethylene, ethane, propylene and propane gases. They showed far increased olefin permeability than linear TR polymers, resulting in pass the upper bound plots of ethylene/ethane and propylene/propane gas pairs. Moreover, TR-SIPNs showed reinforced plasticization resistances for all controlled hydrocarbon gases due to their rigid polymer frameworks. References 1. H.B. Park et al., Science 2007 318 (5848), 254-258 2. Y.S. Do and W.H. Lee et al., Chem. Commun., 2016 52 (93), 13556-13559

B5 Design of new polymeric materials for membrane gas-separation based on norbornenes bearing hydrocarbonic groups,

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Recently it has been shown that Si-containing polynorbornenes are promising materials for membrane separation of hydrocarbons or CO₂/N₂. Depending on the nature of Si-containing side substituent and the rigidity of polymer chain, it is possible to obtain high free volume polymers displaying extremely high gas permeability (like polyacetylenes or PIM's) or polymers exhibiting high C₄H₁₀/CH₄ and/or CO₂/N₂ selectivities. It is less known about gas-transport properties of polynorbornenes with hydrocarbon substituents. We have synthesized a group of such polymers and studied their gas-transport properties. The advantage of the considered polymers is their easy synthesis from dicyclopentadiene and α -olefins as well as the availability of the feed for their preparation. Desired homopolymers can be obtained with demanded molecular weights in high yields in the presence of common Pd-catalysts and appropriate cocatalysts. Addition polynorbornenes with side hydrocarbonic substituents are glassy and fully saturated, therefore, they exhibited good thermal stability. Being low free volume polymers, they are not prone to ageing. The obtained polynorbornenes displayed enhanced C₄/C₁ selectivity relative to Me₃Si-substituted counterparts and polydimethylsiloxane. The some reduced permeability is attributed to the formation of a more dense packing of polymer chains in comparison with Me₃Si-substituted addition polynorbornenes. This was supported by WAXD, fractional free volume and diffusion coefficients measurements. The combination of ease of preparation, good selectivity and moderate hydrocarbons permeability makes these polymers attractive materials for the following and detail studies. The work was supported by Russian Science Foundation, grant #17-19-01595.

B6 Cake layer characterization in Activated Sludge Membrane Bioreactor: Real-time analysis, Luca Fortunato (King Abdullah University of Science and Technology)*; TorOve Leiknes (King Abdullah University of Science and Technology)

Over the past two decades, the MBR technology that combines biological activated sludge process with membrane filtration has emerged as an innovative and alternative technology for tertiary wastewater treatment and reuse. Fouling represents one of the major drawback and disadvantages of the process. In this study, the suitability of real-time monitoring performed with Optical Coherence Tomography (OCT) to monitor fouling due to cake layer development in AS-MBR was evaluated. The in-situ observation was performed directly in the MBR reactor treating primary effluent to assess the online fouling development over a UF flat sheet membrane. Cake layer properties were evaluated using both 2D and 3D image analysis. The non-invasive nature of OCT imaging enabled monitoring fouling development over time, where an increase of thickness and a decrease of roughness was observed. The 3D OCT image analyses were also analysis was compared with the 3D CLSM image analyses performed at the end of the study. Results demonstrate that OCT imaging can be applied for on-line, real-time monitoring and analysis of fouling behavior in AS-MBR systems.

- B7 Facilitated Transport Membrane for CO₂ Capture from Flue Gas: Module Fabrication and Scale-Up**, Kai Chen (Ohio State University)*; Witopo Salim (Ohio State University); Yang Han (Ohio State University); Dongzhu Wu (Ohio State University); Winston Ho (Ohio State University)

In order to modularize a composite membrane with an ultrathin selective layer, it is a challenge to scale up the membrane fabrication procedure from lab to pilot scale. Herein, a knife-coating method was successfully integrated into a roll-to-roll fabrication machine, making a 165-nm thick facilitated transport membrane for CO₂ capture from flue gas with 14 inches in width and > 1200 feet in total length. The scale-up membranes were subsequently used to make spiral-wound (SW) elements and modules. To increase the membrane packing density in a single element, a detailed multi-leaf rolling procedure was developed to scale up the elements efficiently. Although the fabrication of a multi-leaf SW membrane module has been well recorded in the literature, the majority of the methods had all the membrane leaves directly attached to the central permeate tube, thus, the number of leaves was limited by the central tube surface area. In order to improve the fabrication, the glue lines were modified to allow an arrangement of a stack of staggered membrane leaves not attached to the central tube before rolling. Moreover, the spacer thickness was reduced to as low as 6 mil, which further increased the membrane area to 2.94 m² in the most recent modules. The modules also reproduced the transport performance of the flat-sheet membrane under various testing conditions. For instance, a CO₂ permeance of 1450 GPU and a CO₂/N₂ selectivity of 185 were showed with a simulated flue gas at 67°C. In addition, satisfactory pressure drops were also achieved. From the first successful SW element made in house to the most recent ones, a scale-up factor of >70 was achieved. A predictive model was developed to relate the operating conditions to the module separation performance, accounting for the limitations set by concentration polarization and pressure drop. The experience gained is helpful to design a full-sized element (40 inches in length and 8 inches in diameter) for industrial application.

- B8 Interfacial phenomenon-driven hierarchical structuring of hard templated asymmetric ultrathin carbon molecular sieves films**, Megha Sharma (Lehigh University)*; Mark Snyder (Lehigh University)

Inorganic membrane materials such as carbon molecular sieves (CMS) show promise in transforming gas and liquid separations, however, they struggle from the well-known trade-off between molecular selectivity and permeability. This motivates efforts to reduce defect-free membrane thickness while simultaneously tailoring membrane texture and function. In this talk, we present a versatile silica colloidal crystal based nanocasting approach that yields ultra-thin microporous polyimide-derived CMS self-supported on three-dimensionally ordered mesoporous (3DOM) carbon layers. We show how the large area associated with the template-replica interface in our 3DOM carbon films offers a previously unexploited handle for simultaneously tailoring microstructure of the replica phase. Specifically, we elucidate how temperature-tunable silanol surface chemistry of the template can be used to tailor the graphitic character (e.g., graphitic content relative to turbostratic carbon) of CMS replicas under mild carbonization conditions (600-900°C) and in the absence of specific metal catalysts. The interfacial origin of this effect is confirmed through studies showing a sensitivity of graphitic character to film thickness. Studies also show enhancement of graphitic character in thin carbon films as compared with untemplated carbon molecular sieves, with maximum sensitivity near the beginning of the carbonization process (around 600°C). We hypothesize that the interface-mediated tunability of the replica graphitic character derives from adsorption-induced orientation of pyromellitic dianhydride-co-4,4'-oxydianiline (PAA) precursors once the surface silanol density is reduced to the point of approximate registry (e.g., hydrogen-bonding) with PAA molecular dimensions. Taken together, this templating approach offers a strategy for multi-scale control over film structure, which can help in achieving high-flux, high selectivity separations.

- B9 Layer-by-Layer Assembled Metal Organic Framework Nanosheets with Polymer**, Christy Koerner (U.S. Department of Energy National Energy Technology Laboratory)*; Fangming Xiang (U.S. Department of Energy National Energy Technology Laboratory); Eric Popczun (U.S. Department of Energy National Energy Technology Laboratory); David Hopkinson (U.S. Department of Energy National Energy Technology Laboratory)

Metal-organic framework (MOF) nanosheets have been widely used in gas separation, sensing, and catalysis. They have been added as functional fillers into polymers due to their unique two-dimensional shape and tunable porous structure. However, the resultant composites usually showed limited improvement over the neat polymers that they were based on, due to misalignment and aggregation of MOF nanosheets. In this study, layer-by-layer (LbL) assembly was used to produce a polymer composite with exfoliated and highly aligned leaf-like zeolitic imidazolate nanosheets (ZIF67-L). Polyethylenimine (PEI) was used to replace the surface ligands on ZIF67-L through coordination bonding, due to its higher affinity with the cobalt ions in the MOF. This functionalization process was designed to add positively charged amine groups onto MOF nanosheets and enabled them to ionically bond with negatively charged carboxylate groups on poly(acrylic acid) (PAA). The successes of this functionalization strategy and the LbL assembly process were confirmed using Fourier-transform infrared spectroscopy (FTIR). The resultant polymer/MOF multilayer membrane featured exfoliated MOF nanosheets with parallel in-plane orientation, as evidenced by scanning electron microscope images as well as the preferential expression of {h00} peaks in the X-ray diffraction patterns. The method described here demonstrates for the first time how to produce polymer composite

membranes containing exfoliated and aligned MOF nanosheets, which could be of great interest to the polymer composites, gas separation, and MOF communities.

- B10 Highly oxygen-rich rubbery polymers for membrane CO₂/CH₄ separation**, Krysta Clark (The State University of New York at Buffalo)*; Junyi Liu (Air Liquide. Inc); Gengyi Zhang (The State University of New York at Buffalo); Haiqing Lin (The State University of New York at Buffalo)

Membrane materials with high CO₂/CH₄ selectivity and CO₂ permeability are in pursuit for the separation of CO₂ from natural gas. Glassy polymer-based membranes are one of the leading technologies for CO₂ capture from natural gas. These glassy polymers display high CO₂/CH₄ diffusivity selectivity, but the heavy hydrocarbons in natural gas decrease CO₂ permeability. To counter these issues of glassy polymers, rubbery solubility-selective polymers were synthesized. To maximize the ether/ester ratio cationic ring opening polymerization 1,3-dioxolane and 1,3,5-trioxane was used. The ether/ester groups allow the polymer to be CO₂-philic, leading to high CO₂/gas solubility selectivity. The macromonomer and polymers were characterized for physical properties and chemical structures using NMR, FTIR, MS, DSC, etc. The synthesized polymer with an O:C ratio of 0.71 (P71) exhibits a mixed-gas CO₂ permeability of 320 Barrers and CO₂/CH₄ selectivity of 21 at 50°C. These oxygen-rich polymers display robust CO₂/CH₄ separation properties that are better than conventional polyimides and cellulose acetate and are above the Robeson's upper bound.

- B11 Adsorptive and Destructive Mixed Matrix Membranes for Chemical Protection**, Yufeng Song (New Jersey Institute of Technology)*; John Chau (New Jersey Institute of Technology); Kamallesh K Sirkar (New Jersey Institute of Technology); Gregory Peterson (U.S. Army Edgewood Chemical Biological Center); Uwe Beuscher (W.L. Gore & Associates Inc.)

Flexible semi-permeable membrane filters which selectively allow moisture transport and block or destroy toxic gases/vapors are of significant interest for protective garments. Adsorptive and reactive nanostructured materials such as metal organic frameworks (MOFs) and metal oxides/hydroxides when incorporated in membranes can create a mixed matrix membrane (MMM) having those types of capabilities. We will report the results of our efforts to incorporate MOFs such as UiO-66-NH₂ in a polymeric membrane. We will also report results of barrier performance of such MMMs vis-a-vis toxic gases e.g., ammonia, chlorine from an environment along with our results of moisture vapor transmission rate through such a protection medium.

- B12 Maximizing Ether Oxygen Content in Polymers for Membrane CO₂ Removal from Natural Gas**, Junyi Liu (American Air Liquide. Inc)*; Gengyi Zhang (The State University of New York at Buffalo); Krysta Clark (The State University of New York at Buffalo); Haiqing Lin (The State University of New York at Buffalo)

Membrane materials for CO₂ removal from natural gas are based on glassy polymers with high CO₂/CH₄ diffusivity selectivity. However, these polymers suffer from a permeability/selectivity trade-off, competitive sorption by heavy hydrocarbons that decreases CO₂ permeability, and physical aging that reduces gas permeability with time. We circumvent these issues by designing rubbery, solubility-selective polymers with a ratio of ether/ester oxygen to carbon as high as 0.8 through the use of 1,3-dioxolane and 1,3,5-trioxane. The ether/ester oxygen groups interact favorably with CO₂ but do not interact with CH₄, leading to high CO₂/gas solubility selectivity that is unaffected by heavy hydrocarbons in the raw natural gas. These polar groups are incorporated in short branches to yield amorphous and rubbery nature, leading to high gas permeability that is stable over time. An exemplary polymer of P71 with an O:C ratio of 0.71 shows a mixed-gas CO₂ permeability of 320 Barrers, CO₂/CH₄ selectivity of 21, which is above upper bound and CO₂/C₂H₆ selectivity of 12 at 50°C. The long term stability is also studied in this presentation. The success of these highly oxygen-rich polymers may stimulate a pursuit of functional polymers with superior solubility selectivity for membrane gas separation.

- B13 Novel CO₂ gas separation membranes prepared by chemical modification of highly permeable polymers**, Eugenia Mariana Sandru (SINTEF AS); Arpenik Kroyan (Norwegian University of Science and Technology); Nebosja Simic (Norwegian University of Science and Technology); Jing Deng (Norwegian University of Science and Technology); Liyuan Deng (Norwegian University of Science and Technology); Marius Sandru (SINTEF AS)*

Most of the approaches of current gas separation membranes are based on increasing either the CO₂ solubility or CO₂ diffusivity over N₂ by using different methods to increase the free volume of polymers and their sieving capacity. An approach employed in the POLYMEM project is based on bulk modification with CO₂ reactive groups in a controlled manner and high CO₂ permeable but low selective polymers such as poly(trimethylsilylproyne) (PTMSP). This represents a new approach in gas separation membranes that mitigates the risks associated with use of polymer blends and addition of various CO₂ enhancement materials (nanoparticles, etc): incompatibility between materials, poor and limited dispersion of particles, reproducibility and difficulty in preparing membranes. In this paper, we will report membrane preparation by using bulk modification of poly(trimethylsilylproyne) (PTMSP) polymer using CO₂-philic groups (amines and carboxyl) and will discuss the influence of various parameters on membranes structure and their separation performances. The modified

polymers structure and their degree of modification is characterised by ¹HNMR, FTIR, DSC and TGA. The structural changes of polymers (PTMSP) were confirmed by ¹HNMR and FTIR and the amine content was estimated as well. The amine content of modified PTMSP was low, indicating that a small percentage of the monomer units in the polymer chains were modified. The membranes structure was characterized by SEM pictures and FT-IR and was correlated with the results from single and mixed gas permeation testing using a synthetic flue gas: 10% CO₂ in N₂, fully humidified. Depending on the polymer and modification method, significant CO₂/N₂ selectivity enhancement was documented. Acknowledgement This work is supported by the Research Council of Norway through CLIMIT program ("POLYMEM" project, No. 254791)

B14 Intrinsically Microporous Pentiptycene-based Polymers for Enhanced Gas Separation Performance and Physical Aging Resistance, Tanner Corrado (University of Notre Dame)*; Ruilan Guo (University of Notre Dame)

High-free-volume glassy polymers such as PIM-1 have shown exceptional promise for advancing current gas separation membrane technology. However, high-free-volume polymers are generally limited by drastic declines in permeability over time due to physical aging reducing their largely conformation-based free volume. Here, we present an innovative macromolecular design of ladder-like copolymers that exploit the unique molecular architecture of pentiptycene as building blocks for non-collapsible, configuration-based free volume with tunable microporosity. The structural hierarchy of the pentiptycene unit imbues intrinsic free volume into the polymer for increased size sieving while providing a versatile framework that allows tunable ultra-microporosity. Monomers utilizing different shapes of the pentiptycene framework (i.e., S- or C-shaped) were synthesized with tailorable substituent groups and incorporated into copolymers with PIM-1 to study the effect of configurational free volume on gas transport. Achieved copolymers have shown remarkable potential as gas separation membranes, surpassing the 2008 upper bound for several gas pairs. For example, incorporation of 33 mol % of the S-shaped pentiptycene unit provided exceptional combinations of permeability and selectivity for O₂/N₂, with an O₂ permeability of 2370 Barrer and an O₂/N₂ selectivity of 4.6. Additionally, a thin film integrated with only 17 mol % of the C-shaped pentiptycene unit had a hydrogen permeability of 5900 Barrer with upper bound selectivities for typical hydrogen-based separations (i.e., $\alpha(\text{H}_2/\text{CH}_4) = 4.9$; $\alpha(\text{H}_2/\text{N}_2) = 7.7$). A preliminary aging study showed that the 17 mol % C-shape polymer had 30% increases in permeability across all gases after aging 120 days, while maintaining selectivity. In this talk, synthesis and characterization of these new copolymers will be presented. Discussions will focus on elucidating the fundamental structure-property relationships within the series.

B15 Structural Designs of Cross-linked Polymer Network and Ionic Liquids for Ion Gel Gas Separation Membranes, Victor A Kusuma (U.S. Department of Energy National Energy Technology Laboratory)*; James S Baker (U.S. Department of Energy National Energy Technology Laboratory); Megan Macala (U.S. Department of Energy National Energy Technology Laboratory); Samir Budhathoki (U.S. Department of Energy National Energy Technology Laboratory); David Hopkinson (U.S. Department of Energy National Energy Technology Laboratory)

Certain ionic liquids were found to be excellent plasticizers for cross-linked poly(ethylene oxide) (PEO) polymers. 1,3-substituted imidazolium bis(trifluoromethylsulfonyl)imide ionic liquids can be compatibilized at high loadings to increase gas permeability of these polymers, and their low vapor pressure allows long term stability of the resulting ion gels. In this talk, we will discuss various strategies we have taken to improve the performance of these ion gels. We evaluated the effect of incorporating different functional groups on the imidazolium cation on gas permeability and found that the simplest alkyl substituents were more effective than having long alkyl, long alkoxy or a polar terminal group. While incorporating polar substituents resulted in better CO₂/N₂ selectivity, this was offset by the selectivity loss due to incorporation of the anion. One of the best ion gels we developed exhibited pure gas CO₂ permeability of 530 barrer coupled with CO₂/N₂ selectivity of 31 at 40°C. The second strategy we evaluated was modifying the cross-link density of the polymer network, either by changing the cross-linker or incorporating additional branching by introducing co-monomers. We found that increasing cross-link density reduces the amount of ionic liquids that can be incorporated and also reduces membrane performance. Molecular dynamics simulation of CO₂ in ionic liquid mixtures with low molecular weight PEO was employed to confirm that PEO-CO₂ interaction remained the dominant driving force for separation in these ion gels. We will also present preliminary results from our performance testing with high humidity CO₂/N₂ mixed gas.

B16 Scalable hydrogen-bonded polyimide/metal-organic framework hybrid membranes for ultra-fast separations of multiple gas pairs, Canghai Ma (Lawrence Berkeley National Laboratory)*; Jeffrey Urban (Lawrence Berkeley National Laboratory)

Membranes can effectively reduce the enormous amount of energy required for gas separations, compared to conventional separation processes, such as cryogenic distillation. Currently, polymers dominate gas separation membrane markets due to their appealing manufacturability and performance. However, polymeric membranes suffer from the productivity-selectivity tradeoff, i. e., the Robeson upper bound. To overcome this challenge, growing attention has been shifting towards hybrid materials synergistically utilizing advantages of each component in the hybrid membranes, i.e., easy processing of polymers and molecular sieving of fillers, such as metal-organic framework (MOFs). However, only a few MOF-based hybrid membranes perform above current Robeson upper bounds,

predominantly relying upon rigid Polymers of Intrinsic Microporosity or aggressive thermal annealing as high as 240 C, adding complications for scaling-up. Moreover, most hybrid membranes are specialized for a particular gas pair (e.g. CO₂/N₂), lacking a general approach to separating multi-component gas mixtures. This work demonstrates readily scalable polyimide/MOFs hybrid membranes residing above current Robeson upper bounds via a generalizable approach. The hydrophilic amino (-NH₂) groups in MOFs intensively interact with carboxylic moieties in a 6FDA-based polyimide via hydrogen bonds to foster a firm interphase adhesion. The polyimide/MOFs hybrid membranes demonstrate a CO₂ and H₂ permeability of over 2400 and 2900 Barrers, respectively, with a CO₂/CH₄, H₂/CH₄ and H₂/N₂ selectivity of over 29, 34, and 24 respectively, surpassing current Robeson upper bounds. The permeability was enhanced by record-high 14 times comparing with the neat polymer. With a processing temperature as low as 80 C and performance continuously exceeding the upper bounds for over 5300 h, the membrane is readily scalable and compatible with the state-of-the-art membrane manufacture processes.

B17 Performance Testing of Polyphosphazene-Based Membranes for Post-combustion Carbon Capture with Humidified Gas, Zi Tong (U.S. Department of Energy National Energy Technology Laboratory)*; David Hopkinson (U.S. Department of Energy National Energy Technology Laboratory); Victor A Kusuma (U.S. Department of Energy National Energy Technology Laboratory)

Polyphosphazene is a range of polymers with different side groups and a phosphorus-nitrogen backbone composition. This structure allows heteropolymers to be easily obtained at desired compositions, which makes polyphosphazene an excellent candidate membrane material to achieve high gas separation performance. However, in post-combustion carbon capture, the presence of moisture can significantly influence the membrane performance. Although the dry gas performance of polyphosphazene has been reported, there are few reports available using wet gas. In this work, the effect of humidity on polyphosphazene-based membrane CO₂/N₂ separation performance was investigated by testing under different humidity levels in our newly developed automated mixed gas permeation testing system. The designed humidification method allowed the system to be operated under a broad range of relative humidity, from dry to 95% relative humidity. Details of the humidified testing system are also shared in this report.

B18 Systematic Optimization of MOF-based Mixed-Matrix Membranes: Surface Functionalization, Particle Size, and Loading, Patrick Muldoon (Oak Ridge Institute for Science and Education)*

A number of promising examples of mixed-matrix membranes (MMMs) for gas separations have been published in which the incorporation of metal-organic frameworks (MOFs) enhances selectivity and/or permeability relative to pure polymer-based membranes. However, it is unclear the extent to which the interior pore chemistry and pore metrics of the MOFs is responsible for these changes when we consider the concurrent morphological changes to the polymer matrix that inevitably result from the incorporation of crystalline filler particles. Without understanding the nature of these competing effects, we cannot form a rational basis for the design of high-performance MMMs. In this study, three factors thought to affect integration of MOF and polymer are systematically tuned for MMMs comprised of UiO-66-NH₂ (University of Oslo) and PIM-1 (Polymers of intrinsic microporosity) -- namely, surface functionalization, particle size, and particle loading. Resulting MMMs are then evaluated for carbon capture applications.

B19 Membrane heat exchanger for novel heat recovery in post-combustion carbon capture, Shuaifei Zhao (Dalian Maritime University)*; Shuiping Yan (Huazhong Agricultural University); Qiufang Cui (Huazhong Agricultural University)

Post-combustion carbon capture using aqueous alkanolamine solvents is considered as one of the most mature methods to reduce CO₂ emissions. However, Post-combustion carbon capture still requires huge energy inputs for absorbent regeneration and CO₂ desorption. In this work, we demonstrate a commercial ceramic membrane heat exchanger (CMHE) with an average pore size of 4 nm for novel heat recovery in post-combustion carbon capture. The CMHE shows superior performance over a conventional stainless steel heat exchanger (SSHE) with the same dimensions in recovering heat from the stripped gas mixture (H₂O(g)/CO₂) on top of the stripper in a monoethanolamine-based rich-split carbon capture process. Due to the coupled mass and heat transfers of water vapor through the membrane, the CMHE has higher heat flux, heat recovery and overall heat transfer coefficient than the SSHE. Liquid water transfer dominates the mass transfer mechanism in the CMHE. Thermal conduction contributes to more than 80% of the total heat transfer, dominating the heat transfer through the membrane heat exchanger. Our study demonstrates that membrane heat exchangers can be excellent candidates for heat recovery in post-combustion carbon capture. In further research, more types of membranes with higher thermal conductivities (e.g., porous metal membranes with lower porosity and smaller thickness) should be fabricated and tested for further performance enhancement.

- B19 High temperature gas separation properties of sub-micron polybenzimidazole membranes**, Melanie M Merrick (The University of Texas at Austin)*, Benny Freeman (The University of Texas at Austin)

Polybenzimidazoles (PBIs) are a class of polymer materials that have the potential to improve and expand the applications of commercial gas separation membranes. While many commercial membranes can only perform gas separations up to 100°C, PBIs are both chemically and thermally stable at temperatures up to 400°C. A potential application of PBI membranes is the high temperature hydrogen-hydrocarbon separations proposed by the NSF Engineering Research Center for Innovative and Strategic Transformation of Alkane Resources (CISTAR). Two novel aspects of this work are the previously unstudied ethane and ethylene gas separation properties at elevated temperatures and the temperature dependence of gas transport in sub-micron films over an expansive temperature range. Hydrocarbon gas separation properties of Celazole® PBI membranes were characterized at temperatures up to 190°C. Gas permeabilities, gas selectivities, activation energies of permeation, and physical aging rates differed significantly between thin sub-micron and bulk 20-micron Celazole® films. In particular, the activation energies of permeation were 1.5 to 4 times higher in an aged 450-nm thin film than in a 27-micron bulk film, suggesting a denser membrane structure and greater size-sieving ability. The first known evidence of physical aging in PBIs showed an 80 percent decrease in methane permeability over a 1000-hour period at 190°C for a 450-nm Celazole® film. This study elucidates the effects of elevated operating temperature on thin films by encompassing a broader and higher temperature range than previous studies of flat, sub-micron polymer membranes.

- B20 CANAL Ladder Polymers for Membrane Gas Separation**, Holden W. H. Lai (Stanford University)*; Francesco Benedetti (University of Bologna); Zach Smith (MIT); Yan Xia (Stanford University)

Ladder polymers represents an interesting polymer architecture consisting of continuously fused rigid and contorted rings in the backbone, leading to inefficient chain packing and abundant microporosity. These unique features make ladder polymers promising materials for membrane gas separation, combining high permeability with moderate permselectivity. Despite their great potential, only two types of ladder backbones, benzodioxane and Troger's base, have been extensively investigated for their gas separation performance. Our lab recently developed the catalytic arene-norbornene annulation (CANAL) for the synthesis of a diverse array of nobornyl benzocyclobutene ladder polymers, which has enabled us to elucidate structure-property relationship of ladder polymers for important gas separation applications. The effect of chemical functionalities and chain conformation on solid-state packing and the transport of small molecules was investigated. The diffusion mechanism of gas molecules in these ladder polymers will also be discussed.

- B21 Fabrication of CO₂ selective miscible polyimide blend membranes for gas separation applications**, Chamaal Karunaweera (The University of Texas at Dallas)*; John Ferraris (The University of Texas at Dallas); Kenneth Balkus, Jr. (The University of Texas at Dallas); Inga Musselman (The University of Texas at Dallas); Samitha Panangala (The University of Texas at Dallas); Shahed Haghiri (The University of Texas at Dallas)

Synthesis of block-co-polyimides is widely used to obtain polymers with enhanced properties. However, complex syntheses procedures limit the applications of these polymers. Polyimide blends can be useful, low-cost alternatives for block-co-polyimides. Although, most polyimides are immiscible with each other, compatibilization can be utilized to enhance the properties of these immiscible blends. Herein we report how to convert an immiscible polyimide blend to a miscible blend using a small molecule additive. Scanning electron microscopy and differential scanning calorimetry were utilized to detect the miscibility of these blends. Enhanced CO₂ permeabilities and CO₂/CH₄ ideal selectivities were obtained for polymer blend membranes in comparison to membranes of the individual polymers.

- B22 On development of constant-volume permeation system for monitoring upstream pressure decay**, Haoyu Wu (University of Ottawa)*; Jules Thibault (University Ottawa); Boguslaw Kruczek (University of Ottawa)

Dynamic gas permeation experiments, which provide basis for the time-lag measurements, are a well-known method for the determination of permeability, diffusion and solubility coefficients of gases in polymer films. These dynamic permeation experiments are normally performed in a constant volume (CV) system, in which time-dependent gas permeation across the membrane is obtained from the rate of pressure increase in a receiving volume downstream from the membrane. In principle, one could monitor time-dependent gas permeation into the membrane based on the rate of pressure decay in a fixed upstream volume. However, since the resolution of an absolute pressure transducer is inversely related to the upper limit of the pressure transducer, the latter is not used in practical dynamic permeation experiments. On the other hand, there are potential advantages of dynamic permeation experiments relying on the upstream pressure decay. For example, when testing barrier films, it may take hours or even days before any gas molecules appear at the permeate side of the membrane. At the same time, the maximum rate of the upstream pressure decay exists right after initiation of a dynamic permeation experiment. Moreover, combining the capability of monitoring of the upstream pressure decay with monitoring of the downstream pressure-rise could provide invaluable information for the mechanism of gas transport in membranes. In this paper, we present the progress in the development of a constant-volume system capable of monitoring the rate of pressure decay. The latter is

measured based on a pressure difference between a working part of the upstream volume, in which the pressure decreases because of gas permeation into the membrane, and the reference volume in which the pressure is constant. This allows overcoming the resolution limit of high-pressure absolute pressure transducers. Examples of experimental results will be presented and the remaining challenges will be discussed.

B23 Two-dimensional-material mixed-matrix membranes for gas separation, Gongping Liu (Nanjing Technical University)*

Two-dimensional (2D) materials, with atomic thickness and micrometer lateral size, are emerging building blocks for separation membranes. Extraordinary molecular separation properties for purifying water and gases have been demonstrated by developing 2D-material membranes, which attract a huge surge of interest during last a few years. As a prominent characteristic of 2D-material membranes, inter-layer space has been proved to play a significantly important role in molecular transport. We introduced mixed-matrix approach to develop 2D-material membranes for gas separation, with particular focus on tailoring sub-nanosized interlayer spaces between nanosheets for fast and selective transport of gases. Two typical 2D-materials will be demonstrated in this presentation: graphene oxide (GO) and MXene. First, membranes with fast and selective CO₂ transport channels of GO laminates were proposed based on the construction of hydrogen bonding between GO nanosheets and PEBAX chain. Notably, incorporating only 0.1 wt% GO could double the CO₂ permeability and CO₂/N₂ selectivity of pristine PEBAX membrane, transcending the 2008 Robeson upper-bound. Our explorations (e.g., TEM, positron annihilation and sorption) found that molecular-sieving of the interlayer spaces and CO₂-philic pathways of the GO laminates play critical roles in the enhancement of gas transport properties. Second, borate and amine intercalated MXene membranes with ultra-thin skin layer (~20 nm) were fabricated by a facile spin-casting assisted assembly technique. With finely tuned interlayer spacing and introduced CO₂-falicitate transport groups, the intercalated MXene membranes show excellent CO₂ separation performance that overcomes the CO₂/CH₄ upper-bound. The transport mechanism was also understood by analyzing the coefficients of sorption and diffusion. Our results demonstrate that 2D-material mixed-matrix membranes offer exciting opportunities for efficient gas separation.

B24 Synthesis of crosslinked polyether-based membranes for gas separations, Malgorzata Chwatko (The University of Texas at Austin)*; Christina Rodriguez (The University of Texas at Austin); Caitlin Bentley (The University of Texas at Austin); Nathaniel Lynd (The University of Texas at Austin); Benny Freeman (The University of Texas at Austin)

Membrane technology is increasingly used to separate gases in industrial settings due to low footprint, efficient energy use and low capital expenditure.(1) In the area of CO₂ separations, state-of-the-art membranes are based on poly(ethylene oxide) (PEO). The performance of PEO is proposed to be derived from a specific interaction between the ether oxygens within the PEO repeat units and carbon dioxide.(2,3) However, while PEO is widely available, there are two potential drawbacks to using PEO as a membrane material: crystallinity and hydrophilicity. Crystallinity limits transport as crystalline domains are inaccessible to gases.(4) While, the hydrophilic nature of PEO could cause a reduction in selectivity due to plasticization by water vapor. Nonetheless, PEO is still a commonly used material due to its excellent performance relative to incumbents, but there are open possibilities for improvement. Polyethers based on terminal epoxides possess the same advantageous polyether backbone as PEO, but offer tunable properties via a pendant side group. The polyethers have not been studied in detail for gas separations due to limitations in synthetic methodology. In this study, we developed a new synthetic platform to overcome past synthetic challenges and create crosslinked polyether networks using monomers such as n-butyl glycidyl ether and 1,2-epoxydodecane. These crosslinked polyether-based membranes contain controllable degrees of hydrophobicity and crosslinking. The gas transport characteristics of the membranes was tested with the following gases nitrogen, oxygen, methane, hydrogen, and carbon dioxide. References: 1) Reijerkerk SR, et al. J Membrane Sci 2011, 367 (1-2), 33 2) Kalakkunnath S, et al. Macromolecules 2005, 38 (23), 9679 3) Lin H, Freeman BD. J Membrane Sci 2004, 239 (1), 105 4) Lin H et al. Macromolecules 2005, 38 (20), 8381

B25 Novel polyimides with bulky tert-butyl and fluorine-containing side groups: gas permeation parameters and free volume, Susanta Banerjee (Indian Institutes of Information Technology); Nikolay Belov (A.V. Topchiev Institute of Petrochemical Synthesis, Russian Academy of Sciences); Roman Nikiforov (A.V. Topchiev Institute of Petrochemical Synthesis, Russian Academy of Sciences); Mikhail Mazo (Institute of Chemical Physics, Russian Academy of Sciences); Ivan Strelnikov (Institute of Chemical Physics, Russian Academy of Sciences); Yury P Yampolskii (A.V. Topchiev Institute of Petrochemical Synthesis, Russian Academy of Sciences)*

Novel polyimides (PI) containing a diamine with bulky tert-butyl and CF₃ side groups and several common dianhydrides were prepared and studied. Gas permeation parameters (permeability (P), diffusion (D) and solubility coefficients) were estimated for a wide range of gases (He, H₂, O₂, N₂, CO₂, CH₄). Free volume in these polymers was investigated by means of Molecular Dynamics simulation. It was shown that the level of the P and D values of novel PIs is higher than those of majority of polymers prepared using the same dianhydrides apparently due to the presence of bulky tert-butyl and CF₃ groups in the structure of novel PIs. Size distribution of free volume elements in novel PIs was obtained using gas probes of different size from H₂ to Xe. Size distribution curves have a Gauss-type shape with extended tails and maxima of accessible cavity in the vicinity of 1.5-2 Å. It was shown that the average accessible volume fraction decreases with probe

(penetrant) radius r and its limiting value for zero r is about 40%. Comparison with the literature data indicates that similar values are observed in many glassy polymers and this apparently characterizes a general chain packing in glassy state. This work has been supported by Russian Science Foundation grant N18-19-00258 and Russian Foundation for Basic research grant N 17-58-45045 and Russian Foundation for Basic Research grant No 17-58-45045 .

B26 New mixed matrix composite membrane PEBA based membrane incorporated with metal organic framework for CO₂ separation, Tarik Eljaddi (Laboratoire Réactions et Génie des Procédés)*; Julien Bouillon (Normandie University); Laurent Lebrun (Normandie University)

The membrane technology presents only 10 % of the techniques used for carbon dioxide separation. For this reason, more investigations are needed to develop new membranes with high permeability and selectivity. Recently, several studies show promising results, when organic and inorganic materials were combined. In our work, new mixed matrix membranes (MMMs) were prepared by incorporating ZIF and HKUST metal organic frameworks into poly (ether-block-amide) as an active layer on the top surface of polymer porous support (PVDF). The membranes were prepared by solvent evaporation technique. The structure of the membranes was studied according to the thickness of the active layer, the quantity of fillers and the presence of additives. The membranes were characterized by TGA, FTIR, SEM and gas permeation measurements. The preliminary permeance tests revealed that incorporation of ZIF in PEBA matrix with dispersing additives increase the CO₂/N₂ selectivity.

B27 Dual-Layer MOF Composite Membranes with Tunable Gas Transport Properties for Post-combustion CO₂ Separation, Sameh K Elsaidi (U.S. Department of Energy National Energy Technology Laboratory)*; David Hopkinson (U.S. Department of Energy National Energy Technology Laboratory); Surendar Venna (U.S. Department of Energy National Energy Technology Laboratory); Mona Mohamed (University of Pittsburgh)

We present a novel concept for the fabrication of custom-designed dual-layer metal organic framework (MOF) membranes that show great promise in improving permeability and selectivity performance for CO₂/N₂ separation as compared with the individual constituent MOF materials. A highly selective thin MOF layer with narrow pore size (shell layer) was grown on the surface of a highly permeable MOF layer with large pore size (core layer). Most importantly, the interaction between the two layers was optimized through the chemical binding between the two MOF materials affording continuous, defect-free membranes. The two MOF@MOF membranes: SIFSIX-3-Ni@SIFSIX-1-Cu and SIFSIX-3-Ni@HKUST-1, represent the first examples of inorganic membranes constructed by dual-layer MOF composites. The CO₂/N₂ selectivities of the HKUST-1 and SIFSIX-1-Cu membranes were improved from 5.2 to 13 and 3.4 to 7.8, respectively, after the growth of a selective layer of SIFSIX-3-Ni. This work emphasizes the importance of the custom-design of the membrane material rather than the screening approach of dozens of materials.

B28 Performance of Pd-Based Membranes and Effects of Various Gas Mixtures on H₂ Permeation, Kourosh Kian (Worcester Polytechnic Institute)*

H₂ permeation and separation properties of two Pd-based composite membranes were evaluated and compared at 400°C and at a pressure range of 150 to 600 kPa. One membrane was characterized by approximately 8 μm-thick Pd-Au layer deposited on an asymmetric microporous SiO₂ substrate; the other membrane consisted of approximately 11 μm-thick pure Pd layer deposited on a YSZ support. At 400°C and with a trans-membrane pressure of 50 kPa, the membranes showed a H₂ permeance of $8.42 \times 10^{-4} \text{ mol/m}^2 \cdot \text{s} \cdot \text{Pa}^{0.5}$ and $2.54 \times 10^{-5} \text{ mol/m}^2 \cdot \text{s} \cdot \text{Pa}^{0.5}$ for Pd-Au and Pd membranes, respectively. Pd-Au membrane showed infinite ideal selectivity to H₂ with respect to He and Ar at 400°C and a trans-membrane pressure of 50 kPa, while the ideal selectivities for the Pd membrane under the same operating conditions were much lower. Furthermore, the permeation tests for ternary and quaternary mixtures of H₂, CO, CO₂, CH₄, and H₂O were conducted on the Pd/YSZ membrane. The H₂ permeating flux decreased at the conclusion of the permeation tests for all mixtures. This decline however, was not permanent, i.e., H₂ permeation was restored to its initial value after treating the membrane with H₂ for 7 hours. The effects of gas hourly space velocity (GHSV) and the steam-to-carbon (S/C) ratio on H₂ permeation were also investigated using simulated steam methane reforming mixtures. It was found that H₂ permeation is highest at the greatest GHSV, due to a decline in the concentration polarization effect. Variations in S/C ratio however, showed no significant effect on the H₂ permeation. The permeation characteristics for the Pd/YSZ membrane were also investigated at temperatures ranging from 350 to 400°C. The pre-exponential factor and apparent activation energy were found to be $5.66 \times 10^{-4} \text{ mol/m}^2 \cdot \text{s} \cdot \text{Pa}^{0.7}$ and 12.8 kJ/mol, respectively. SEM and XRD analyses were performed on both pristine and used membranes, and no strong evidence of the formation of Pd-O or any other undesirable phases was observed.

SESSION C - Innovation in Membrane Materials, Synthesis, and Characterization: Liquids

- C1 Layer-by-layer modification of aliphatic polyamide anion-exchange membranes to increase chloride/sulfate selectivity,** Muhammad Ahmad (University of Notre Dame)*; Chao Tang (University of Notre Dame); Liu Yang (University of Notre Dame); Andriy Yaroshchuk (Polytechnic University of Catalonia); Merlin Bruening (University of Notre Dame)

Anion-exchange membranes (AEMs) with high selectivities among anions may expand the applications of these materials in salt separations. We coated commercially available Fujifilm type-1 AEMs with 5.5 bilayers of poly(4-styrenesulfonate) (PSS) and protonated poly(allylamine) (PAH) to increase their Cl⁻/SO₄²⁻ selectivities and found that the increase in selectivity varies greatly with the source-phase salt concentrations. The selectivity of coated membranes increases dramatically from 5.3 to 140 in diffusion dialysis (DD) and from 7.4 to 70 in Electrodialysis (ED) when the source-phase NaCl and Na₂SO₄ concentrations increase from 0.01 M to 0.1 M. On the other hand, the selectivity of bare AEMs increases from 1.7 to 13 in DD and from 1.1 to 11 in ED for the same range of source-phase salt concentrations. In addition, much higher selectivities occur with AEMs coated only on the receiving side than those coated only on the source side. Partitioning experiments and modeling give evidence for potential mechanisms behind such remarkable selectivities. At higher source-phase salt concentrations, the partitioning experiments show an increased Cl⁻/SO₄²⁻ partitioning ratio. Additionally, modeling suggests that electromigration greatly decreases SO₄²⁻ flux in the AEM.

- C2 Development of electrically conductive hollow fiber membranes,** Melissa J Larocque (McMaster University)*, David R Latulippe (McMaster University), Charles-François de Lannoy (McMaster University)

Membrane fouling in municipal and industrial wastewater treatment applications incurs higher operational costs associated with lost productivity, membrane cleaning, and antifoulant usage. Recently, there has been considerable interest in the development of electrically conductive membranes due to their ability to mitigate fouling and biofilm development [1]. To date, all of the current research and development has been on the development of electrically conductive membranes in a flat-sheet format. However, hollow fiber (HF) membranes are the preferred geometry for large-scale treatment applications. In this work, we have developed the first-ever electrically conductive HF membranes by adhering a thin layer of carbon nanotubes (CNTs) onto the surface of commercially available HF membranes according to a protocol adapted from a seminal work on flat sheet membranes [2]. CNT suspensions were formed from functionalized single-wall CNTs, surfactants (e.g. sodium dodecyl sulfate) and chemical cross-linkers (e.g. polyvinyl alcohol, suberic acid) then pressure deposited onto the active side of different HF membranes. We then cured the cross-linked CNTs to adhere them to the membrane. This process formed porous electrically conductive coatings. We studied this technique on outside-in PVDF (SUEZ, 0.04 μm) and inside-out PES (Spectrum, 0.2 μm) HF membranes. We observed significant variations in 1) membrane permeance, 2) coating conductivity, and 3) coating stability on curved HF surfaces as a function of material and synthesis parameters. We quantified the impact of curing temperature, CNT concentration, chemical cross-linking density, and polymeric support on these performance metrics. [1] F. Ahmed, B. S. Lalia, V. Kochkodan, N. Hilal, and R. Hashaikh, *Desalination*, vol. 391, pp. 1-15, 2016. [2] C. F. de Lannoy, D. Jassby, D. D. Davis, and M. R. Wiesner, *J. Memb. Sci.*, vol. 415-416, pp. 718-724, 2012.

- C3 Structure Formation in Isoporous Hollow Fiber Membranes: An In Situ SAXS study,** Kirti Sankhala (Helmholtz-Zentrum Geesthacht)*; D. C. Florian Wieland (Helmholtz-Zentrum Geesthacht); Joachim Koll (Helmholtz-Zentrum Geesthacht); Maryam Radjabian (Helmholtz-Zentrum Geesthacht); Clarissa Abetz (Helmholtz-Zentrum Geesthacht); Volker Abetz (Helmholtz-Zentrum Geesthacht)

Isoporous block copolymer membranes hold the potential of providing energy-efficient separations.1 Self-assembly of block copolymers in combination with non-solvent induced phase separation (SNIPS) is required for the formation of mesoscopically porous flat sheet and hollow fiber membranes.2-5 The objective of this work is to understand the kinetics of evaporation-induced self-assembly of block copolymers and non-solvent induced phase separation (SNIPS) for fabrication of isoporous membranes, mainly isoporous hollow fiber membranes (HFM). Weakly and highly segregated polystyrene-block-poly(4-vinylpyridine) (PS-b-P4VP) diblock copolymer solutions as pristine and with additive magnesium acetate (MgAc₂), respectively are used to study the structure formation in HFM. The self-assembly of block copolymers during HF spinning is investigated by conducting in situ small-angle X-ray scattering (SAXS) experiments for different block copolymer solutions and the spinning parameters.6 The structural features obtained from in situ SAXS are correlated with the structure in the block copolymer solutions in the absence of shear and in the flat sheet and the HFM morphologies obtained by ex situ SEM.6 [1] V. Abetz. *Macromolecular Rapid Communication* 2015, 36:10. [2] K.-V. Peinemann, V. Abetz, P.F.W. Simon. *Nature Materials* 2007, 6:992. [3] M. Radjabian, J. Koll, K. Buhr, U. Vainio, C. Abetz, U.A. Handge, V. Abetz. *Polymer* 2014, 55:2986. [4] K. Sankhala, J. Koll, M. Radjabian, U. A. Handge, V. Abetz. *Advanced Materials Interfaces* 2017, 4:1600991. [5] K. Sankhala, J. Koll, V. Abetz. *ACS Macro Letters* 2018, 7:840. [6] K. Sankhala, D. C. F. Wieland, J. Koll, M. Radjabian, C. Abetz, V. Abetz. *Nanoscale* 2019, DOI: 10.1039/C8NR06892E

- C4 Microscopic membrane fouling characterization**, Nandini Debnath (University of Alberta); Aloke Kumar (Indian Institute of Science); Thoams Thundat (The State University of New York at Buffalo); Mohtada Sadrzadeh (University of Alberta)*

This work studies the microscopic fouling in a membrane mimic microfluidic device due to the complex interplay between hydrodynamic interactions and surface adsorption. Our microfluidic membrane mimic device consists of a staggered arrangement of pillars which enables real-time visualization and analysis at the pore scale. Different fouling scenarios are investigated by conducting constant-pressure and constant-flow rate experiments. Fouling experiments are performed with three different types of foulants: polystyrene particle solution (colloidal fouling), polyacrylamide polymer solution (organic fouling) and a mixture of these two solutions (combined fouling). Four major categories of microscopic fouling are observed: cake filtration (at upstream), pore blocking (inside the pores), colloidal aggregation (at downstream) and streamer fouling (at downstream). Experiments show that downstream colloidal aggregation and streamer formation have a significant effect on overall membrane fouling which was not studied before.

- C5 New Insights into the Impact of Nano-scale Surface Heterogeneity on the Wettability of Polymeric Membranes**, Md Farhad Ismail (University of Alberta); Behnam Khorshidi (University of Alberta); Mohtada Sadrzadeh (University of Alberta)*

Polymeric membrane surfaces often contain nanoscale heterogeneity. The role of this nanoscale heterogeneity on the membrane wettability, as well as surface tension, is still elusive. Conventional surface tension measurement includes quantifying the dispersive and polar components. Here, we showed that dispersive surface tension components may also alter due to the existence of nanoscale heterogeneity which in turn affects the overall solid-liquid interaction process. By analyzing five different commercial membranes with various non-polar probe liquids, we observed a linear dependency of the wettability on surface tension and consequently, and thus we could quantify the degree of heterogeneity. Further, the AFM and SEM results were used to validate this observation. This study provides valuable insight into tuning the membrane surface properties to obtain desired wettability and anti-fouling property.

- C6 A comparison of water and solute transport in ion exchange and desalination polymers**, Ryan Kingsbury (Membrion, Inc.); Jingbo Wang (UCLA); Mikayla D Armstrong (University of North Carolina at Chapel Hill)*; Orlando Coronell (University of North Carolina at Chapel Hill)

In electro-membrane processes, non-ideal water and salt transport across ion exchange membranes (IX) can severely compromise energy efficiency (Tedesco et al, 2017, J. Membr. Sci., 531, 172-182). However, a clear understanding of the factors underlying non-ideal transport is lacking. Accordingly, we measured the water and salt transport properties of 20 commercial IX membranes and evaluated their correlation to membrane physical and chemical properties. Results showed that water and salt transport in the membranes was governed primarily by the microstructure of the membranes, not the polymer type. This finding raised questions about how the transport characteristics of IX membranes compare to those of membrane polymers used in other applications such as desalination, and whether other polymers would be suitable for use as IX membranes or vice versa. Thus, we compared the water and salt transport properties of IX membranes with those of commercial desalination membranes and other desalination polymers. We used data collected in our laboratory and from literature. Results showed that the water and salt transport characteristics of IX membranes fall within similar ranges as those of desalination polymers. Further, IX membranes were found to have excellent water-salt partitioning selectivity, while polyamide active layers were found to have exceptional diffusion selectivity. On the basis of these findings, we propose a membrane architecture (i.e., polyamide coated with IX polymers) that combines the relative strengths of IX and desalination polymers to obtain superior water permeability selectivity compared to either polymer alone.

- C7 Water permeation through nanoporous particles in thin film nanocomposite membranes**, Pinar Cay-Durgun (Arizona State University)*; Mary Laura Lind (Arizona State University)

Most advanced reverse osmosis (RO) desalination membranes are composed of thin-film composite (TFC) membranes and nanoporous materials as fillers to form thin-film nanocomposite (TFN) membranes. The addition of the nanoporous fillers into the membranes can address the well-known permeability/selectivity trade-off by introducing molecular sieving transport mechanism in addition to the solution-diffusion transport governed by polymeric RO membranes. In literature, there are several TFN membrane studies with different particle types, sizes, and contents. Although these TFN membranes have enhanced water permeability compared to the corresponding TFC membranes, they exhibit inconsistent performance improvement trends with particle addition. Therefore, it would be useful to investigate the individual water transport contributions of the polymer, particle, and polymer/particle interface for the pressure-driven desalination to understand the behavior of TFN membranes. In this study, we investigated water permeation through single-crystal molecular sieve zeolite A particles in TFN membranes. First, we embedded different sizes of non-porous (pore-closed) and nanoporous (pore-opened) particles into conventionally polymerized TFN membranes. These membranes have some synthesis challenges such as particle aggregation and non-uniform particle dispersion in the membranes. To overcome the challenges, we developed a TFN-model membrane synthesis method that immobilizes the particles onto the support membranes surface before the polymerization reaction. Both

conventional TFN and TFN-model membranes have improved water permeability without significant change in salt rejection. Later, we analyzed the results using two different resistance models to quantify the possible water transport pathways in these membranes. Our analysis indicated that the nanoporous particles increase water permeability in TFN membranes primarily through increased water transport at the interface.

- C8 Printing Membranes: Enabling the Use of Both Conventional and Novel Polymers in High Performance Membranes,** Jeffrey R McCutcheon (University of Connecticut); Ayse Asatekin (Tufts University); Maqsd Chowdhury (University of Connecticut); Xin Qian (University of Connecticut); Tulasi Ravindran (University of Connecticut)*; Samuel Loudner (Tufts University)

Our recent work on printing polyamide membranes demonstrated the ability to make desalination membranes of exceptional smoothness and controllable thickness. The approach required the electrospray deposition of an amine monomer and an acid chloride crosslinker onto a substrate where they react to form an aromatic polyamide. The technique allows for exceptional control of the reaction and makes it advantageous over conventional interfacial polymerization. Conventional interfacial polymerization is a relatively uncontrollable process and has few options for independently tailoring selectivity and permeance. We can adapt this approach to making membranes of novel polymers as well, many of which cannot be formed easily into thin film or composite structures with high permeance and high selectivity. We demonstrate the use of the printing approach with several emergent polymer systems, including self-assembled materials, to demonstrate the value of this approach.

- C9 Functionalization of PVDF Membranes with Thiol Groups for Heavy-Metal Capture,** Ronald Vogler (University of Kentucky)*; Md. Saiful Islam (University of Kentucky); Evan Hatakeyama (Chevron Energy Technology Company); DB Bhattacharyya (University of Kentucky)

Heavy-metal ions, such as Hg^{2+} , pose a severe hazard to the environment and human health when present in water. Membranes are an emerging technology in the water-treatment field and can be functionalized with thiol groups for the capture of these ions from water. In this study, thiol-functionalized membranes were fabricated by first functionalizing the pores and surface of commercial polyvinylidene fluoride (PVDF) membranes with carboxyl groups via the in-situ polymerization of polyacrylic acid (PAA); the addition of PAA was confirmed by measuring the zeta potential of the surface of a PAA-functionalized membrane. Following functionalization with PAA, the membranes were functionalized with thiol groups using EDC/NHS coupling to bind cysteamine to their carboxyl groups. The convective-flow capture of Ag^+ was quantified for the resulting membrane and the focused-ion-beam technique along with energy-dispersive X-ray spectroscopy (EDS) were utilized to determine the location of this capture in the membrane. A shift in surface charge of a PVDF-PAA membrane near the pKa of PAA (~ 4.5) confirmed the presence of PAA on the surfaces of these membranes. After the successful incorporation of thiol groups into a membrane, its capture of Ag^+ was 71% of its estimated capacity during the convective flow of Ag^+ through the membrane. EDS performed on this thiol-functionalized membrane indicated that Ag^+ capture occurred all throughout the membrane pores (~170 μm deep). This capture of Ag^+ at all depths within the thiol-functionalized PVDF membrane indicated the potential of this membrane for the capture of Hg^{2+} at a high capacity. Future work with this type of membrane will involve an investigation of the impact that hardness and residence time have on its capture of Hg^{2+} from refinery water. This research was supported by NIEHS-SRP, NSF-EPSCoR, and Chevron Corporation.

- C10 Pure and mixed fluid sorption and transport in Celazole® polybenzimidazole: the effect of plasticization,** Kelly P. Bye (University of Oklahoma); Michele Galizia (University of Oklahoma)*

The vast majority of industrial chemical synthesis occurs in organic solution. Solute concentration and solvent recovery consume approximately 50% of the energy required to produce chemicals and pose problems that are as relevant as the synthesis process itself. Novel, energy-efficient technologies based on polymer membranes are emerging as a viable alternative to distillation. Despite organic solvent nanofiltration (OSN) could revolutionize the chemical industry, its development is still in its infancy for two reasons: i) the instability of traditional polymer materials in chemically challenging environments, and ii) the lack of fundamental knowledge of elemental transport phenomena in OSN membranes. Most of available transport data refer to composite membranes, where the presence of a fabric backing makes it difficult to provide a fundamental description of solvent and solute sorption and transport in the active layer. The lack of fundamental information has hampered the development of rational methods to design better materials for OSN application. Tough polymers are often reported as ideal membrane materials for separations in harsh environments. This study focuses on the solubility of pure and mixed organic liquids in Celazole®, a commercial polybenzimidazole. Methanol was selected as a model penetrant to run sorption and diffusion experiments in Celazole® in the activity range 0-1. The role of polymer-penetrant interactions, membrane degree of swelling and penetrant clustering on small molecule sorption and transport in Celazole® was discussed and several structure-property correlations were identified. Remarkably, methanol produces a severe matrix plasticization, which helps explain the mixed methanol/PEG400 sorption behavior. Finally, the effect of solvent sorption on Celazole® mechanical properties was investigated.

C11 Enhanced Water Interaction and Antifouling Compatible Zwitterion-PVDF Membrane Designs, Mahboobeh Maghami (University of Saskatchewan); Amira Abdelrasoul (University of Saskatchewan)*

The most common form of water toxicity occurring in Western Canada is sulfate toxicity. Elevated sulfate levels in water have become a major challenge because of the excessively high amounts of various sulphate salts present in water. The major goal of this study is to perform a systematic study on novel zwitterions into Poly(vinylidene fluoride) (PVDF) membrane to enhance hydrophilicity and salt rejection. The Zwitterionic-PVDF (ZW-PVDF) membranes have drawn much attention because of the promising performance of Zwitterionic polymer with respect to pH responsive, reducing metal ion adsorption, and significantly enhancing membrane hydrophilicity and membrane fouling resistance. In this study, density-functional theory (DFT) was used to simulate several modification designs of PVDF with compatible Zwitterionic polymer for enhanced water interactions and minimized sulfate interactions. Furthermore, fragment molecular orbital (FMO) and the Pair Interaction Energy Decomposition Analysis (PIEDA) were carefully interrogated. The mechanism of water transport inside these ZW-PVDF membranes were extensively investigated. These types of analyses included the inter fragment interaction energy (IFIE), like the electrostatic (ES), exchange repulsion (EX), and charge-transfer and mixing term (CT+mix). Furthermore, FMO and PIEDA results showed enhanced water transport through hydrogen bonding and interactions between water molecules and ZW function groups at different alignments. The influence of Zwitterionic on reducing fouling in nanofiltration of sulfate wastewater will be discussed.

C12 Novel strategy to develop a composite membrane for desalination by membrane distillation, Tarik Eljaddi (Laboratoire Réactions et Génie des Procédés - UMR 7274)*; Deisy Mejia Mendez (Laboratoire Réactions et Génie des Procédés - UMR 7274); Eric Favre (Laboratoire Réactions et Génie des Procédés - UMR 7274); Denis Roizard (Laboratoire Réactions et Génie des Procédés - UMR 7274)

Membrane distillation (MD) is a promising technology to get freshwater. However, MD is still confined at lab scale up to now. Indeed, MD can be easily coupled with RO to treat high concentrated brines with relatively low energy consumption. However, as a main drawback, permeability of conventional porous membranes is not stable with time because the pores will face the wetting issue. Thus, the separation efficiency by vaporization will rapidly decrease. Whereas most of current strategies to develop MD membranes are based on the chemical modification of membrane surface to generate hydrophobic properties, our group has studied a distinct approach. This strategy intends to use a thin, dense coating to fully prevent wetting hazard of the membrane pores. Hence, conversely to the usual approach focusing on membrane hydrophobicity, this approach is very different from the theoretical point because the intention is to protect the mouth of the pore from wetting by dense layer coating. In literature, pioneering trials in that direction concluded that this approach was not valid because the added transport resistance would preclude the application. Indeed, the permeance of a given membrane varies with two parameters: intrinsic permeability and layer thickness. Considering the wide scope of existing materials, in particular super glassy polymers, it can be simulated that with some materials, dense thin layers would have the same transfer resistance than porous membranes. With these membranes, the mechanism changes from vaporization into the pores to thermopervaporation with vaporization at the downstream side of the dense layer. But this modification does not affect energy needed for the water transport. But interestingly, the salts cannot anymore enter into the pore and only pure water is recovered. In the second part of our work we successfully prepared and tested such composite membranes as proof of concept. Even under harsh conditions of wetting, 100% salt rejection was reached.

C13 One-Step Tailoring Surface Roughness and Surface Energy to Prepared Superhydrophobic Polyvinylidene Fluoride (PVDF) Membranes for Enhanced Membrane Distillation Performances, Weihua Qing (The University of Hong Kong)*; Xiaonan Shi (New Jersey Institute of Technology); Chuyang Tang (University of New South Wales)

Superhydrophobic polyvinylidene fluoride (PVDF) membrane is a promising material for membrane distillation. Existing approaches for preparing superhydrophobic PVDF membrane often involve separate manipulation of surface roughness and surface energy. Here we report a one-step approach to simultaneously manipulate both the surface roughness and surface energy of PVDF nanofibrous membranes for enhanced direct-contact membrane distillation (DCMD) performances. The manipulation was realized in a unique solvent-thermal treatment process, during which a treatment solution containing alcohols was involved. We demonstrate that by using different chain-length alcohols in the treatment solvent, surface roughness can be promoted by creating nanofin structures on the PVDF nanofibers using an alcohol which has moderate affinity with the PVDF material. Meanwhile, surface energy can be tuned by adjusting the fraction distribution of crystal phases (mainly nonpolar α phase and polar β phase) in the membrane using different alcohols. PVDF membranes with different surface wettabilities were used to evaluate the effects of surface roughness and surface energy on the DCMD performances. Combining both low surface energy and multi-scale surface roughness, pentanol-treated PVDF membrane achieved best anti-water property (water contact angle of 164.1° and sliding angle of 8.1°), and exhibited superior water flux and enhanced anti-wetting ability to low-surface-tension feed in the DCMD application.

C14 High-Performance Thin Film Composite (TFC) Membranes: Design Consideration Underneath the Polyamide Thin Film,

Wangxi Fang (Suzhou Institute of Nano-Tech and Nano-Bionics, Chinese Academy of Sciences)*; Jian Jin (Suzhou Institute of Nano-Tech and Nano-Bionics, Chinese Academy of Sciences); Rong Wang (Singapore Membrane Technology Centre, Nanyang Technological University)

Despite the commercial success of thin-film composite (TFC) technique for reverse osmosis (RO) and nanofiltration (NF) membrane production, overcoming the longstanding "trade-off" relationship between permeability and selectivity of TFC membranes remains a global challenge. Extensive research efforts have been put on altering the layer formation chemistry or intrinsic nanostructure to simultaneously improve its permeability and selectivity, but the critical role of the underlying porous substrate on the membrane separation performance was often overlooked. In this study, we firstly demonstrated the relationship between the substrate surface pore profile and the TFC membrane separation behavior. Manipulating the substrate surface pore profile i.e. surface porosity, pore number density, etc. for water flow path improvement was proved efficient in enhancing the TFC membrane water permeability. Afterwards, we extended the idea of flow path improvement from conventional polymeric substrates to nanomaterial-based membrane structure. Although the involvement of nanomaterials has been proved to significantly improve the TFC membrane permeability and selectivity, the role of the nanomaterial in such improvement is still under debate. Via controlling the lateral position of the incorporated amphiphilic ABA copolymer-based hollow nanospheres within the TFC membrane, we found that the water permeability enhancement only occurred when the nanoparticles were positioned underneath the polyamide layer. Therefore, other than reducing the water permeation resistance inside the polyamide layer, the role of the nanoparticle is more towards improving the water flow path from the polyamide layer to the underlying substrate. This study clarifies longstanding misunderstandings concerning the effects of the underlying porous substrate as well as the nanomaterial incorporation on TFC membrane performance, and provides insight into designing highly permeable and selective TFC membranes.

C15 Wafer-Scale, Vertically-Aligned SWCNT Composite Membranes for Nanofiltration, Melinda L Jue (Lawrence Livermore National Laboratory)*; Chiatai Chen (Cornell University); Steven Buchsbaum (Lawrence Livermore National Laboratory); Eric Meshot (Lawrence Livermore National Laboratory); Sei Jin Park (Lawrence Livermore National Laboratory); Kuang Jen Wu (Lawrence Livermore National Laboratory); Francesco Fornasiero (Lawrence Livermore National Laboratory)

Carbon nanotubes (CNT) have attracted significant interest as nanopores for separation applications due to their ability to sustain ultra-fast fluid transport rates that exceed those of other similarly-sized porous materials. When formed into oriented composites with high nanotube density, the well-defined pore size allows for both superior flux and selectivity for nanofiltration applications. Unfortunately, achieving large-area CNT membranes with a high density of conductive channels remains challenging. Here we demonstrate the synthesis of ultra-high density, vertically-aligned single-walled carbon nanotubes (SWCNT) to create high flux nanofiltration membranes with large areas up to 4-in in diameter. Chemically resistant parylene-N is used to form the SWCN composite, which remains stable even in the presence of aggressive cleaning agents. These membranes exhibit exceptionally high water flux while completely rejecting nanometer-sized particles and dyes. In addition, the membranes preferentially sieve out multivalent ions, thus showing potential for water softening. To our knowledge, this work represents the best co-optimization of SWCNT diameter, density, and membrane area demonstrated so far in the literature.

C16 Vapor Phase Infiltration of Metal Oxides into Microporous Polymers for Solvent Stable Nanofiltration Membranes, Fengyi Zhang (Georgia Institute of Technology)*; Emily McGuinness (Georgia Institute of Technology); Yao Ma (Georgia Institute of Technology); Mark Losego (Georgia Institute of Technology); Ryan Lively (Georgia Institute of Technology)

Linear microporous polymers (e.g., PIM-1) possess microporosity and solution processability, which positions them as promising candidate materials for challenging molecular separations. However, these membranes are susceptible to swelling and plasticization in the presence of various organic liquids. This solvent-induced mobility of the polymer structure impairs the organic solvent separation performance of PIM materials. Pyrolytic carbonization and crosslinking are two prominent post-fabrication methods for polymer stabilization; however, it requires a near-complete transformation of the precursor in the former case and chemical/thermal treatments in the latter case. Here, we develop a straightforward vapor-phase post-fabrication modification technique to stabilize microporous polymers. Two cycles of vapor phase infiltration of metal-organic precursors and water into the PIM-1 polymer network create interpenetrating atomic-scale networks of metal oxide and PIM-1, which retain the microstructure and macroscale form factors and exhibit excellent solvent resistance to strong solvents for PIM-1 (chloroform, dichloromethane, and tetrahydrofuran). Pristine PIM-1 membranes ineffectively reject polystyrene oligomers (i.e. molecular weight cutoffs in excess of 1200 g/mol are observed) from solvents such as ethanol. However, the AlO_x/PIM-1 membranes exhibit consistent molecular weight cutoff below 204 g/mol in various solvents (e.g., ethanol, n-heptane, toluene, tetrahydrofuran, etc.). Moreover, the hybrid membranes are capable of solvent-solvent separations (e.g., alcohol mixtures, aromatic mixtures), which position these materials as good candidates for organic solvent reverse osmosis separations. Importantly, the vapor phase infiltration process can be directly applied to state-of-the-art hollow fiber membrane modules or

spiral-wound membrane modules, which suggests that this approach has the potential to be useful for large-scale manufacturing of advanced membranes.

C17 Understanding the Interlayer-spacing and Mass Transport Nexus of Graphene Oxide Membrane for Organic Solvent Nanofiltration, Sunxiang Zheng (UC Berkeley)*; Baoxia Mi (UC Berkeley)

Ultrathin membranes formed by stacking two-dimensional (2D) graphene oxide (GO) hold great promises for improved permeability and separation capability in organic solvent nanofiltration (OSN). However, analogous to the scenarios in aqueous phase, the separation capability of a layer-stacked GO membrane for OSN can be significantly limited by its natural tendency to swell, that is, absorb organic solvents into the GO channel and form an enlarged interlayer spacing (d-spacing). In this study, the d-spacing of a layer-stacked GO membrane was experimentally characterized by liquid-phase ellipsometry, which allows precise quantification of the d-spacing when the membrane is soaking in its working environment. We found that solvents with high dipole moments (e.g., dimethylformamide, n-methyl-2-pyrrolidone) tends to cause significant swelling of GO with d-spacing increasing up to 2.74 nm, while non-polar solvents such as hexane and toluene only cause subtle swelling. To understand such unique swelling behavior, the solubility parameter of GO was experimentally determined to mathematically describe the affinity between GO and the testing solvents, which is believed to be strongly related to the swelling degree. Separation performance of the GO membrane in different organic solvents were tested to understand the mass transport in confined GO nanochannel. The layer-stacked GO membrane could achieve > 90% rejection of small organic dye molecules (e.g., rhodamine B and methylene blue) in ethanol and acetone without crosslinking due to insignificant swelling. Additionally, it was found that solvents with different polarity shows distinct transport resistance, which was further investigated by molecular simulation.

C18 Organic-inorganic hybrid separation membrane having high chemical tolerance, Koichi Takada (TORAY Industries, Inc.)*; Takahiro Tokuyama (TORAY Industries, Inc.); Hiroki Minehara (TORAY Industries, Inc.); Takafumi Ogawa (TORAY Industries, Inc.); Masahiro Kimura (TORAY Industries, Inc.)

In late years, water problems, such as occurrence of the extraordinary drought by the global climate change, are actualized in addition to shortage of water and water pollution due to a rapid increase of the world population and industrial development. The expectation to a membrane technology increases as a water treatment technique to secure safe and stable enough water resources. Conventional reverse osmosis (RO) membrane consists of cross-linked aromatic polyamide or cellulose acetate (CA). Cross-linked aromatic polyamide membrane has especially high property (flux and rejection), on the other hand, CA membrane has high chlorine tolerance. The purpose of this research is creating a membrane which has both features of cross-linked aromatic polyamide membrane and CA membrane. In this research we report membrane property and the result of chlorine tolerance test of organic-inorganic hybrid membrane. On conventional support layer, a thin separation functional layer (≈ 200 nm) based on organic-inorganic hybrid material is prepared by in situ polymerization and cross-linking. The hybrid membrane has high flux ($1.0 \text{ m}^3/\text{m}^2/\text{day}$ @0.75 MPa, NaCl 500ppm) and high NaCl rejection (more than 90%). The chlorine tolerance test shows that the hybrid membrane has much higher stability of flux than CA RO membranes.

C19 Magnetron Sputtering-based Synthesis of Pd film on UF membrane support for environmental catalysis, Michael J Detisch (University of Kentucky)*; DB Bhattacharyya (University of Kentucky); John Balk (University of Kentucky)

Composite membranes with metallic films as top layers were synthesized for applications in separations and catalysis. Commercial ultrafiltration membranes are used as a base for the production of nanostructured thin films to generate these composite membranes. Magnetron sputtering is used to deposit thin films of tantalum and MgPd alloy on top of polysulfone (PSf) membranes 100 nm thick. A dealloying step in water removes the Mg component of the film creating a nanoporous (np) film of Pd. This generates a sponge-like structure of interconnected nanowires with characteristic size of 5 - 10 nm. These nanostructures are imaged with high resolution SEM combined with FIB cross-sectioning. Surface chemistry is analyzed using x-ray photoelectron spectroscopy. The np palladium is used with H_2 gas for the degradation of chloro-organics from water. PCB's were dechlorinated while permeated in a water solution under pressurization with 5% H_2 gas (remainder Argon). Over 60% of PCB-1 was degraded in solution with a single pass through the composite membrane at 40 LMH. Np metals may be fabricated from a variety of precursor systems. Depending on the reaction desired, various metals may be incorporated into the membrane system with minimal difficulty. These membranes can also be tuned for selective separations in both water and solvent media. The membrane showed improved rejection properties and a corresponding drop in flux with the addition of metallic top layers. Flux dropped from 180 LMH/bar for the base UF PSf compared to 3 LMH/bar for the composite system. The molecular weight cutoff (MWCO) of the UF PSf was found to be above 70 kDa while for the composite membrane the MWCO dropped to below 10 kDa. This illustrates an extensive modification of membrane properties through the addition of a thin (100 nm) film. This research is supported by the NIH-NIEHS-SRC (Award no.: P42ES007380), and by NSF KY EPSCoR grant (Award no: 1355438).

C20 Influences of polymeric additives in different solvent systems on membrane performance and fouling resistance, Catharina Kahrs (Leibniz University Hannover)*; Jan Schwellenbach (Sartorius Stedim Biotech GmbH)

Phase separation of polymer solutions is a commonly applied technique for the production of porous membranes. One mechanism to induce the demixing of these solutions is the non-solvent induced phase separation (NIPS). By applying this technique it is possible to fabricate membranes with a broad range of different characteristics. A crucial variable during the NIPS process is the composition of the casting solution as it has an important impact on the features of the resulting membrane. Apart from the membrane-forming polymer, a number of different solvents, non-solvents, and additives are available which can be varied in order to affect the kinetic and thermodynamic parameters during membrane formation. Consequently, the improvement of the control of resulting membrane characteristics requires an enhanced understanding of the NIPS process and its influencing factors. In order to gain a better insight into the underlying mechanisms of polyethersulfone membrane preparation by NIPS, the effect of the additives polyvinylpyrrolidone (PVP) and polyethylene glycol (PEG) was studied in four different solvent systems. Apart from comparing the influence of the respective solvent features, another aim was to investigate the impact of concentration and molecular weight variations in dependence of the applied solvents. Therefore, membranes with varying concentrations and molecular weights of PVP and PEG were produced for each of the four solvents. Subsequently the membranes were characterized in respect of structure, performance and fouling resistance by scanning electron microscopy, permeability and protein retention measurements, as well as by fouling evaluation through static protein binding and dynamic filtration experiments. The results which were found indicate that both, solvents and additives, can significantly impact membrane performance, fouling resistance and structure which can be attributed to an alteration of the kinetics during the membrane formation process.

C21 Porous membranes with synergic solvent and thermal resistance from polyoxindole derivatives, Bruno Pulido Ponce de Leon (King Abdullah University of Science and Technology)*; Suzana Nunes (King Abdullah University of Science and Technology)

The expansion of membrane technology into new applications drives a constant demand for novel materials. Particularly, organic solvent ultra- and nanofiltration (OSN), has been a rapidly growing research field that aims for more efficient chemical separations. Polyoxindole derivatives constitute a new family of polymers and are promising candidates as material for polymeric membranes with solvent and thermal resistance. These high-performance polymers are synthesized by superacid polycondensation, an efficient one-step, one-pot, metal-free, room-temperature method. We have synthesized functionalized polyoxindoles and manufactured them into porous membranes by non-solvent induced phase separation (NIPS). The prepared membranes were crosslinked mainly using two different strategies: (1) by reacting with dibromides or (2) by incorporating a propargyl pending group, followed by a heat-induced reaction in hot glycerol. More recently, we've explored membranes prepared of poly(oxindole-2,2'-biphenol), which is made from the monomers isatin and 2,2'-biphenol. The material is insoluble in many common organic solvents, but it can be made into porous membranes from solutions in polar aprotic solvents. Additionally, this polymer has a high density of hydroxyl groups that make the polymer very attractive for further functionalization. Moreover, these polymer membranes undergo a thermal-rearrangement at 300 °C which leads to membranes with increased solvent and thermal resistance. The MWCO for these membranes ranges from 1 kg/mol to 20 kg/mol and can be tuned by casting conditions, with dimethylformamide permeation of 68 L m⁻² h⁻¹ bar⁻¹ at 120 °C. The thermal rearranged membranes preserve their morphology and filtration performance. After treatment, all membranes have high solvent resistance, with minimum swelling and degradation temperature up to 400 °C, allowing them to be used in demanding organic solvent filtration processes.

C22 Functionalized random zwitterionic copolymers as chlorine- and fouling-resistant nanofiltration membranes, Samuel J Louder (Tufts University)*; Ayse Asatekin (Tufts University)

The purification of water is vital for many chemical separation processes. However, feedstocks containing foulants and/or chlorine represent harsh conditions in which many membranes are unable to operate. Accordingly, the development of membranes that can function effectively in such conditions is an important research endeavor. A zwitterion is defined as a molecule that contains an equal number of positive and negative charges. Random zwitterionic copolymers (RaZCs) are linear copolymers comprised of randomly distributed zwitterionic repeat units and non-zwitterionic repeat units. RaZCs self-organize to form a network of zwitterionic nanochannels that are surrounded by the non-zwitterionic repeat unit of the RaZC. The zwitterionic channels act as the effective ≈ 1 nm pores. Previous work shows that thin film composite membranes featuring these RaZCs as their selective layer exhibit high flux, exceptional fouling resistance, and size-based small molecule selectivity along with low salt rejection. However, for many applications, improved charged solute and divalent salt rejection would be beneficial. In this work, we show that RaZCs that combine zwitterionic, charged, and hydrophobic repeat units are versatile materials for the fabrication of robust membranes that exhibit high flux, divalent ion rejection, fouling resistance, and remain stable upon exposure to chlorine. Furthermore, the pore chemistry of these membranes can be tuned by a simple approach, thus rationally tuning membrane selectivity for desired applications. This approach represents a unique pathway to fabricating industrially relevant membranes with tunable separation properties.

- C23 Deterioration of nanofiltration polyamide membrane by strong acid and its mechanism**, Byung-Moon Jun (University of South Carolina); Hyung Kae Lee (Ulsan National Institute of Science and Technology); Young-Nam Kwon (Ulsan National Institute of Science and Technology)*

In this study, the effect of strong acids such as sulfuric acid and hydrogen halides (hydrochloric acid, hydrobromic acid, and hydroiodic acid) on polyamide NF membrane was systematically investigated using various analytical tools. The membrane exposed to sulfuric acid did not show noticeable difference in Scanning Electron Microscopy (SEM), Attenuated Total Reflectance-Fourier Transform Infrared spectroscopy (ATR-FTIR), X-ray photoelectron spectroscopy (XPS), contact angle, and zeta potential analysis compared to the virgin membrane. However, the performance changed after exposure to sulfuric acid, and the water flux and salt rejection of the membranes degraded at pH 0 and 1 were different. This was likely due to the distortion of hydrogen bonding or formation of tetrahedral structure caused by O- or N-protonation. On the other hand, the membrane exposed to hydrogen halides showed change of various physical and chemical properties along with permeability change after exposure to the acid. The degree of changes was in order of HCl, HBr, and HI. This was due to the halogenation of the polyamide membrane.

- C24 Opening new doors: Epoxides as novel chemistry for interfacial polymerization**, Rhea Verbeke (Katholieke Universiteit Leuven)*; Marijn Seynaeve (Katholieke Universiteit Leuven); Wouter Arts (Katholieke Universiteit Leuven); Elke Dom (Katholieke Universiteit Leuven); Ivo Vankelecom (Katholieke Universiteit Leuven)

TFC-membranes dominate the current nanofiltration (NF) and reverse osmosis market for water treatment and desalination. However, their applicability in more aggressive feeds (extreme pH, hypochlorite, solvents) is limited due to their limited chemical robustness. Provided the enormous growth potential of membrane technology in these industries, there is an ongoing quest to obtain solvent-, pH- and chlorine-stable (TFC) membranes, which are additionally performing well in terms of rejection and permeance. To comply with this demand, we successfully converted the well-known monophasic bulk epoxide polymerization (commonly used in e.g. the automotive and coating industry), into the synthesis of thin, yet cross-linked top-layers via interfacial polymerisation. Nanofiltration membranes with >90% Rose Bengal and 70% Methyl Orange rejection with water permeances above 2 L/m²hbar were achieved in the proof-of-concept study. Optimization studies already resulted in permeances of 25 L/m²hbar without compromising RB rejection. Additionally, the occurring reaction, a homopolymerisation of the epoxy monomer, results in a network of chemically stable polyether chains. As a consequence, unchanged membrane performance after immersion in oxidizing (500 ppm NaOCl, pH 4, 2.5 h) and acidic (pH 1, 48 h) environments was achieved. The correlations between IR, PALS, SEM and performance results further demonstrate the feasibility and reproducibility of this innovative membrane synthesis technique. The plethora of available epoxy monomers, reaction initiators and catalysts, as well as the use of other membrane supports, ensures high tunability in terms of final membrane performance, morphology and synthesis time. We therefore believe that this novel interfacial polymerisation chemistry may lay the foundation for a new generation of exceptionally stable (solvent resistant) NF TFC-membranes, opening immense possibilities with respect to chemical cleaning and novel membrane applications.

- C25 Solution-diffusion with ion association: a non-mean-field model that successfully describes NF of multi-ion mixtures**, Viatcheslav Freger (Technion - Israel Institute of Technology)*

Despite wide use of nanofiltration (NF), modeling NF separations and ion selectivity still presets a challenge, especially, for multi-ion solutions. Mean-field models of charged nanopores (e.g., Donnan or Poisson-Boltzmann) have been the standard for last two decades, yet they fail to reproduce correctly trends even for some single salts, which may be traced back to inherent flaws of mean-field theories in charged low-dielectric media. On the other hand, simple phenomenological models with adjustable ionic permeabilities work well, but require ad hoc composition-dependence and the physics behind this dependence remains obscure. Here we abandon the standard mean-field nanopore picture and introduce a simple solution-diffusion model of a homogeneous NF membrane that treats the strong departures from mean-field by adding ion association effects in a manner of classical Bjerrum theory. The model consistently explains our recent elaborate NF data for NaCl+CaCl₂ mixtures [1] and other published data. In particular, where existing models fail, the new model readily explains why (a) ion permeabilities rank Na⁺ > Cl⁻ > Ca²⁺, (b) NaCl permeability increases with concentration while that of CaCl₂ does the opposite; (c) addition of a small fraction of Ca²⁺ sharply increases NaCl permeability, (d) effective membrane charge is much lower than independent estimates etc. The results emphasize the importance of non-mean-field effects in general and ion association in particular for correct modeling of ion separations in osmotic membranes, for which the new model offers a simple yet physically sound and transparent way to treat the problem. [1] N Fridman-Bishop, KA Tankus, V Freger, Permeation mechanism and interplay between ions in nanofiltration, J. Membr. Sci., 2018, 548, 449-458

C26 Relative permittivity properties of hydrated polymer membranes for desalination applications, Kevin Chang (University of Virginia)*; Hongxi Luo (University of Virginia); Geoffrey M Geise (University of Virginia)

Polymers are widely used in membrane-based desalination to address global water shortages. To be effective, these polymers must act as a selective barrier and prevent ion passage. One approach to engineering effective desalination membranes is to prepare membranes that suppress ion sorption, because low ion sorption can lead to favorable salt rejection and efficient desalination. Thus, it is important to understand how to engineer polymer chemistry that suppresses ion sorption and maximizes membrane desalination performance. Movement of an ion from solution into the membrane phase is associated with a change in free energy, which is sensitive to both solution and membrane properties. Describing this free energy change requires knowledge of the relative permittivity properties of the hydrated polymer. Few studies report this information for desalination membranes, so relative permittivity is often estimated using a linear relationship between polymer water content and relative permittivity. This relationship, which is based on a small data set (primarily Nafion® 117 data), may not be universally applicable to all hydrated polymers. We evaluated the functional relationship between permittivity properties and water content for a series of cross-linked poly(glycidyl methacrylate) (XL-pGMA) polymers. At equivalent water content, XL-pGMA has a lower relative permittivity compared to Nafion® 117. This result supports the view that polymer water content alone may be insufficient for estimating the relative permittivity properties of hydrated polymers. Since lower relative permittivity correlates with higher ion rejection, relative permittivity measurements provide important insight into ion sorption properties that can be used to inform molecular level polymer design. Thus, understanding the structure/property relationships between polymer chemistry and ion sorption, via membrane dielectric measurements, is critical to guide the design of advanced desalination membranes.

C27 Multi-solute transport behavior of aqueous mixtures through polyether-based membranes, Jung Min Kim (Auburn University)*; Bryan S Beckingham (Auburn University)

Molecular transport in polymer membranes is important for a wide variety of applications from traditional separations to innovative new energy devices including electrochemical cells such as direct methanol fuel cells and solar fuel devices for the photoelectrochemical (PEC) reduction of CO₂. In these applications, understanding and controlling the selective transport of ions and molecules is crucial. For instance, one of the major challenges in PEC cells for CO₂ reduction to liquid products is to understand and manage product crossover through the ion exchange membrane. While there have been numerous studies investigating single ion or molecular transport through hydrated dense membranes, there have been relatively few studies focused on concurrent multi-solute transport in these materials. Polyethers are promising materials for membrane applications due to their wide range of potential chemical functionalities and ease of membrane fabrication through UV-photopolymerization through diacrylate and acrylate end groups. Membranes prepared from poly(ethylene glycol) diacrylate (PEGDA) have been used as a model system for investigating fundamental aspects of ion and molecular transport where water permeability and selectivity over a solute were impacted by varying the PEGDA to water ratio of the pre-polymerization mixture due to variation in crosslink density. In previous work, our group utilized custom diffusion cells with in-situ ATR-FTIR spectroscopy for monitoring the simultaneous transport of multiple solutes through ion exchange membranes. Here, we leverage this methodology to examine this solution-diffusion transport of single and multicomponent alcohol mixtures through PEGDA membranes and PEGDA-based membranes incorporating various mono-acrylate units within the structure. Permeability values extracted from diffusion cell measurements are complemented by solute solubilities from absorption-desorption experiments in order to fully describe the transport behavior.

C28 Comparative analysis of novel covalent organic framework nanofiltration membranes synthesis, composition, thickness and substrate dependence, Gabrielle Levato (University of Illinois at Urbana-Champaign)*; David Burke (Northwestern University); Zhiwei Jiang (Imperial College London); Daniel Mosiman (University of Illinois at Urbana-Champaign); William Dichtel (Northwestern University); Andrew Livingston (Imperial College London); Benito Marinas (University of Illinois at Urbana-Champaign)

It is essential to start emphasizing sustainable and efficient water treatment technologies due to increased water scarcity and lack of safe drinking water. Pressure driven membrane systems can be used effectively to recycle seawater, wastewater effluent or industrial water to potable quality. Commercial membrane systems can remove a wide range of water contaminants with low use of chemical additives and no thermal input, but the relatively limited polymeric surface chemistry currently available restricts the range of water permeability and solute selectivity achieved. An alternative to conventional polymeric membranes is covalent organic frameworks (COFs). COFs have a crystalline structure created by strong covalent bonds made through synthetic reactions of organic building units. The structure provides a well-organized layer with pore size control based on chosen building units. Thin film composite nanofiltration membranes with a COF active layer have been developed via interfacial polymerization and exfoliation techniques, allowing active layer thickness, comparative synthesis feasibility and reproducibility, and COF-substrate interaction to be analyzed. This work begins to assess the composition of COF TFC membranes on ultrafiltration solvent-resistant polyacrylonitrile (PAN) supports of varying pore sizes, and specifically how COF active layer thickness and synthesis method influence permeation and rejection capabilities of organic and salt solutions. Advanced physicochemical characterization of the COF membranes using techniques including grazing-incidence wide-angle x-

ray scattering (GI-WAXS), Rutherford backscattering spectrometry (RBS), atomic force microscopy (AFM), scanning electron spectroscopy (SEM), and transmission electron spectroscopy (TEM) provide valuable insight into COF membrane surface composition and support interaction. Combined, the two analyses of COF membranes elucidate clear pathways forward for further studies in this field.

C29 Copper-MOF Functionalized Nanofiltration Membranes for Enhanced Dye Removal: Effects of Dip-Coating and In-Situ Modification Techniques, Mostafa Dadashi Firouzjaei (University of Alabama); Zane Joseph Parkerson (University of Alabama); Milad Rabbani Esfahani (University of Alabama)*

Dyes are current threats to human and environmental health and pose a risk to the safety of groundwater and surface water. The main adverse properties of dyes are high toxicity, bioaccumulation, persistence in the environment, and are known to be endocrine disruptors and carcinogens. Presence of dyes in water decreases the gas solubility which consequently kills living species in water and also has a mutagenic effect on humans. Effluent treatment and water-recycling can play a significant role in reducing discharge pollution and providing reusable process water. In this study, we developed a surface modified-polyamide nanofiltration (NF) membrane by coating polydopamine layer incorporated with the copper-based metal-organic framework (MOF). Two different methods, (1) dip-coating and (2) In-situ filtration processes applied for surface modification of polyamide nanofiltration membranes. The membranes and fabricated Cu-MOF nanoparticle structure characterized by scanning electron microscopy (SEM), transmission electron microscopy (TEM), Fourier-transform infrared spectroscopy (FTIR), X-ray powder diffraction (XRD), X-ray photoelectron spectroscopy (XPS), Atomic Force Microscope (AFM), Ultraviolet-visible spectroscopy (UV-Vis), and Zeta potential. A cross-flow filtration unit employed for dye removal, antifouling and permeation examination of the modified membranes. The flux-rejection trade-off was highlighted based on the fabrication techniques. However, the addition of hydrophilic Cu-MOF nanoparticles increased the water flux where the dip-coated membranes showed higher (up to 90% rejection compared to pristine polyamide NF membrane) dye rejection due to the thicker active layer.

C30 Advancing Conductivity-Permselectivity Tradeoff of Ion-Exchange Membranes with Sulfonated CNT Nanocomposites, Hanqing Fan (Columbia University)*; Yuxuan Huang (Columbia University); Ngai Yin Yip (Columbia University)

Ion exchange membranes (IEMs) are widely applied in energy and water technologies, such as reverse electro dialysis for sustainable power generation and electro dialysis for desalination. An IEM with lower ionic resistance and better selectivity for counterions can reduce the energy demand and raise the efficiency of IEM-based processes. However, an empirically-observed tradeoff between conductivity and permselectivity always constrains the performance of IEMs. The incorporation of rationally functionalized 1-dimensional nanomaterials as filler into the polymer matrix offers opportunities to depart from this tradeoff. When highly dispersed, the 1-D nanomaterials with large aspect ratio can form a percolating network to facilitate ion transport. In this study, we developed nanocomposite cation exchange membranes (CEMs) by incorporating sulfonic acid-functionalized carbon nanotubes (sCNTs) in sulfonated poly(2,6-dimethyl-1,4-phenyleneoxide), sPPO, polymer matrix. The fabricated nanocomposite IEMs exhibit improved conductivity while maintaining permselectivity. Intrinsic resistivity, the reciprocal of conductivity, is lowered with greater blending of sCNTs filler into the sPPO matrix, decreasing by approximately 25% with 20 w/w% incorporation of sCNTs. The variation of permselectivity is within 3% across the different degrees of sCNT incorporation. Therefore, compared with pristine membranes, the conductivity-permselectivity tradeoff line of the fabricated nanocomposite membranes are advantageously advanced, improving overall performance. Enhancement in conductivity is more pronounced for membranes with lower swelling degree. We posit that the interconnected network of sCNT reduces the tortuosity of the ion diffusion path, thereby increasing effective ionic conductivity. This study demonstrates the potential of rational utilization of nanomaterials to advance the conductivity-permselectivity tradeoff governing conventional IEMs.

C31 Ceramic-supported thin film composite membrane for organic solvent reverse osmosis, Mi Zhang (University of Connecticut)*; Lingling Xia (University of Connecticut); Jeffrey R McCutcheon (University of Connecticut); Marcus Weyd (Fraunhofer-Institut für Keramische Technologien und Systeme)

Membrane separations has often been sought as a replacement for thermal separations processes due to the potential 10X reduction in energy consumption. Reductions of this magnitude were realized when reverse osmosis replaced thermal distillation for desalination applications. It is widely believed that such benefits would translate to solvent separations as well. Organic solvent reverse osmosis (OSRO) is an emergent area of membrane separations that offers a membrane-mediated separation between miscible solvent mixtures. We use a recently developed polyamide thin film composite (TFC) platform to evaluate OSRO. These TFC membranes were made by forming the polyamide selective layer via interfacial polymerization onto a ceramic tubular ultrafiltration membrane. The TFC membrane was then tested in the mixtures of methanol (32.04 g/mol) with 1 w/w% decane (142.29 g/mol), and hexane (86.18 g/mol). These membranes exhibited decane and hexane rejections of 85% and 42%, respectively.

C32 Dynamic FO tests of commercial low pressure RO TFC membrane, Du Bai (University of Ottawa); Farhad Asempour (University of Ottawa); Boguslaw Kruczek (University of Ottawa)*

Reverse osmosis (RO) is already a mature membrane separation technology, which has dominated seawater and brackish water desalination industries. Nevertheless, the quest to improve the properties of thin film composite (TFC) and thin film nanocomposite (TFN) membranes for RO, forward osmosis (FO) and nanofiltration (NF) applications continues to be an important research topic. In turn, this requires appropriate testing tools to assess the effect of modifications of TFC/TFN membranes on their structure and performance. We have designed and built a novel testing system that allows characterization TFC/TFN membranes in a dynamic test, similar to the time-lag method commonly used to characterize gas separation membranes. The dynamic experiment in the new system is initiated by a step change in the draw solution concentration, which leads to a step change in the osmotic pressure across the membrane. Since the dynamic experiments are carried under zero hydraulic pressure gradient, they are referred as dynamic FO experiments. The capability of the new testing system and the dynamic FO experiments is demonstrated by characterizing commercial, low pressure TFC RO membranes (Toray Industries Inc.). In this presentation we will discuss the effect of membrane orientation (active layer facing draw solution vs active layer facing feed solution) on the dynamic behaviour and the steady-state water and reverse salt fluxes. The effect of magnitude of the step change in draw solution concentration will also be discussed.

C33 New generation recycled polystyrene membranes for industrial water purification using membrane distillation, Machawe M Motsa (University of South Africa)*; Bhekile Mamba (University of South Africa)

Polystyrene is widely used as a packaging material this is poorly disposed after use. This material possesses several properties that could be ideal for membrane distillation membranes such as light weight, hydrophobicity, poor thermal conductivity and poor resistance to air permeance. Membrane filtration is not a common practise in most Southern African countries due to its heavy reliance on energy. Therefore, this work sought to develop membrane materials that will address both pollution by polystyrene and the costs incurred during buying commercial membranes. This was achieved by preparing new generation basic hydrophobic membranes from non-traditional polymers consisting of unique structural configurations for efficient mass transfer, thermal stability and good mechanical strength. Membrane characterization with scanning electron (SEM) and atomic force microscopy (AFM) revealed an asymmetric cross-sectional structure preceded by a thin top layer followed by a loosely arranged mesoporous layer largely characterised by microvoids. The membrane surface was found to be rough ($SA(nm) = 297 \pm 8.21$) which enhanced its hydrophobicity. It also exhibited an average weak positive charge brought about by the modification with hydrophobic surfactants. Measured water contact angles and subsequent interfacial free energy confirmed the extreme hydrophobicity of the surface ($CA > 117^\circ$). The membranes' separation properties were tested using a solar driven contact membrane distillation system for the purification of power generation cooling towers water with a total dissolved solute content of 1203 ppm. The recorded ion rejection was 97% at a temperature gradient of 50°C . The membrane exhibited good anti-scaling properties and permeate flux was stable over the 120 h experiment duration. The membranes presented a promising alternative to the treatment of industrial wastewater besides reverse osmosis and could be further optimised by various surface modifications.

C34 Advanced supported ionic liquid (SIL) membranes for Pi electron cloud mediated separation of aromatics, Mahmood Jebur (University of Arkansas); Arijit Sengupta (University of Arkansas); Ranil Wickramasinghe (University of Arkansas)*

Development of membranes for highly specific separations is challenging and will depend on specific surface interaction. Here we have investigated the feasibility of using Pi electron cloud interactions. Imidazolium-based ionic liquids were synthesized using vinyl imidazole and three different alkyl halides (chlorobutane, bromohexane, and allyl bromide). A 0.45 micron pore size PTFE membrane was used as the support structure. The imidazolium-based ionic liquids were pumped into the membrane pores using a stirred cell at a pressure of 2 bar producing a supported ionic liquid membrane. The supported ionic liquid membrane could be used for specific Pi electron cloud-mediated separation of solutes. Here the separation of styrene, divinyl benzene and toluene in hexane (non-aqueous medium) and Ramazol brilliant blue R (RBBR), Congo red (CR) and Eichrome black T (EBT) from aqueous medium have been investigated. The specificity for separation of aromatics was found to be related to the affinity of the ionic liquid towards the Pi electron cloud density and extent of conjugation in the solute. The separation efficiency for all SIL membranes was observed to be divinyl benzene > styrene > toluene, while in case of dyes the complicated electronic configuration led to Congo red (CR) having the highest selectivity. It was also shown that the SIL membranes displayed antibacterial activity. The antibacterial activity was investigated using two-gram positive bacteria (*Pseudomonas aeruginosa* and *Staphylococcus aureus*). SIL membranes with longer carbon side chains on the imidazolium ring showed greater antibacterial activity (bromohexane > chlorobutane > allyl bromide). The results obtained here indicate that membranes for highly specific separations could be developed based on Pi electron cloud interactions.

C35 Graphene Oxide Membranes for Selective Molecular Separation of Lignin Model Compounds, Ashish Aher (University of Kentucky)*; DB Bhattacharyya (University of Kentucky)

In the quest for selective separation of value lignin monomers, the performance of Graphene Oxide-based (GO) membranes was investigated with model lignin monomeric compounds. GO membranes were fabricated on a commercially available polyvinylidene fluoride support (PVDF) by casting aqueous GO dispersion using wire wound rod. The degree of reduction of GO was controlled to tune the performance of GO membranes towards selective separation. GO membranes were thoroughly characterized to establish the chemical state of GO and to establish membrane performance parameters. Efficacy of these membranes towards rejection and separation of value lignin model compounds (dimers and trimers) was verified. Impressive performance with the rejection of over 70% for the model compound BMP (trimer-2,6-Bis[(2-hydroxy-5-methyl phenyl)methyl]-4-methylphenol) was achieved compared to only 20% rejection for GGE (dimer-Guaiacylglycerol- β -guaiacyl ether) with isopropanol-water (90%-10% by volume) mixture as solvent. This corresponds to an encouraging selective separation with selective permeation of GGE (dimer) 3.5 times compared to BMP (trimer). We hypothesize that the steric hindrance effect plays the most important role in the excellent molecular rejection and separation performance of our membranes. Moreover, the controlled reduction of GO membranes by varying thermal incubation time was achieved. A decline in the rejection rate with increasing extent of reduction was observed which was explained based on the higher partitioning of lignin-derived molecules on the more hydrophobic domain. The present contribution identifies the impressive performance of GO membranes for selective separation of value lignin monomers in polar organic solvent media.

C36 High Flux and Anti-fouling Electrospun Nylon 6 Ultrafiltration Membrane Coated with GO/N-carboxyethylchitosan (NCECS) Functionalized Polyvinyl Alcohol Hydrogel, Liuqing Yang (Concordia University)*; Tiantian Chen (Concordia University); Zhibin Ye (Concordia University); Benoit Barbeau (Polytechnique Montreal); Saifur Rahaman (Concordia University)

Highly hydrophilic polymers have been widely used to improve flux and anti-fouling properties of ultrafiltration (UF) membranes. In this study, a new nylon 6 UF membrane was fabricated by using electrospinning technique, coated with GO/N-carboxyethylchitosan (NCECS) functionalized polyvinyl alcohol (PVA) hydrogel. N-carboxyethylchitosan (NCECS) was used for the first time for the fabrication of UF membranes due to its high hydrophilicity. Electrospun Nylon 6 membranes coated with PVA containing different NCECS were fabricated and characterized via SEM, Raman spectroscopy, and contact angle measurements. Results showed that uniform pore size distribution and increased hydrophilicity were achieved. The flux and anti-fouling properties of fabricated membranes were investigated by comparing with the pristine UF membrane. The increased flux and anti-fouling performance exhibit the potential of using N-carboxyethylchitosan (NCECS) for the fabrication of UF membranes used in wastewater treatment.

C37 Development and Characterization of nZVI/TiO₂ Supported Membranes for Photocatalytic Treatment of 1,4-Dioxane in Water, Larissa L. S. Silva (Federal University of Rio de Janeiro)*; Wael Abdelraheem (University of Cincinnati); Minghao Kon (University of Cincinnati); Mallikarjuna Nadagouda (Wright State University); Ana Maria Rocco (Federal University of Rio de Janeiro); Cristiano Borges (Federal University of Rio de Janeiro); Fabiana Fonseca (Federal University of Rio de Janeiro); Dionysios Dionysiou (University of Cincinnati)

Using nano-zero-valent iron (nZVI) as a catalyst in Fenton processes for water treatment has recently gained much attention due to its environmentally friendly properties and excellent catalytic performance. However, the problem of aggregation of nZVI particles in aqueous solution limits its practical application in water treatment. It's believed that immobilization of nZVI on membrane followed by impregnating TiO₂ nanoparticles on top of them could improve the stability of nZVI in aqueous solution. Moreover, due to the photocatalytic properties of TiO₂, the overall degradation power of TiO₂/nZVI system will be enhanced. 1,4-Dioxane (DXN) is an emerging contaminant that is found in various water distribution systems at relatively high concentrations of 0.07-9.1 $\mu\text{g/L}$. Owing to its deleterious health implications, DXN has raised an urgent need for its removal from water systems. Thus, this work aims at applying an innovative photocatalytic treatment technology based on UV/TiO₂/nZVI/membrane for the treatment of the DXN in water. Hydrophilic membranes were synthesized and utilized as a support for nZVI and TiO₂ nanoparticles. Various methods of impregnation of TiO₂ onto the nZVI/membranes were also investigated. The modified membranes were characterized by Scanning Electron Microscope (SEM), Fourier-transform Infrared Spectroscopy (FTIR), X-ray Powder Diffraction (XRD), Energy Dispersive X-ray (EDX), mass gain and total iron lost. DXN was successfully degraded by the current hybrid photocatalytic system. Results revealed DXN degradation by TiO₂/nZVI/membrane was higher than that achieved by nZVI/membrane and TiO₂/membrane systems. Furthermore, the membrane's stability during the degradation process was enhanced due to the presence of TiO₂. The current study provides important mechanism information on the degradation of DXN by the suggested system and justifies the improved photocatalytic properties of TiO₂/nZVI membranes based on AOPs.

C38 Oxone Mediated TEMPO-Oxidized Nanocellulose Form-I and Form-II: Materials, Membranes and Modeling, John P Moore (University of Arkansas)*

Nanotechnology in science has shown small materials can be used for novel and versatile applications. In the past few years, nanocellulose (and new derivatives thereof) has become a growing interest in nanomaterial research. Nanocellulose has shown to have excellent hydrophilic and tensile properties allowing for the tuning of membrane filtration performance. While, improvements using nanocellulose materials has seen success in the membrane field, more work is needed to lead the advance of natural fiber-based nanomaterials. The focus of this publication is to identify the parameters of interest to characterize the performance enhancing effect and antifouling capabilities of novel nanocellulose material derivatives (Oxone mediated TEMPO-oxidized nanocellulose form I and form II) on ultrafiltration membranes. Membranes are characterized by means of separation performance, physical properties, and morphology. Modified membranes displayed increased hydrophilicity, increased tensile capacity, decreased membrane resistance, and decreased fouling at the surface due to adsorption/concentration polarization.

C39 Facile Fabrication of Amphiphobic Nanocomposite Membranes for Application in Membrane Distillation, Tiantian Chen (Concordia University); Liuqing Yang (Concordia University); Saifur Rahaman (Concordia University)*

Two superhydrophobic and amphiphobic membranes, which can repel both water and low surface tension liquids (oil), are fabricated via electrospinning technique and subsequent surface modifications. Highly hydrophobic nanofiber mats are first prepared by electrospinning a mixture of poly(vinylidene fluoride-co-hexafluoropropylene) and reduced graphene oxide. Surface superhydrophobicity and amphiphobicity are implemented by grafting fluoroalkylsilane of low surface energy or hydrophobic silica nanoparticles. SEM, XPS, liquid entry pressure, and contact angle measurements are applied to investigate the effects of the surface modification on the morphology and structure of the membranes. The analyses reveal changes in the surface roughness, elemental composition, and hydrophobicity of the electrospun nanofibers. Both membranes show excellent superhydrophobicity and amphiphobicity, clearly demonstrated by their wetting resistance with water and low surface tension organic solvents. These promising membranes are tested to desalinate water from 35 g/L sodium chloride solution in the presence of a surfactant (sodium dodecyl sulfate) through a direct contact membrane distillation (DCMD) process. Our membranes exhibit enhanced stability and durability of MD performance with high permeation flux (~42 kg/m²h) and 99.99% salt rejection

C40 Graphene Oxide Nanoplatelets Embedded Polyamide Thin Films for Water Desalination, Mahsa Abbaszadeh (Mississippi State University)*; Santanu Kundu (Mississippi State University)

Polyamide thin film membranes are used in water desalination applications. Incorporation of graphene oxide nanoplatelets in the polyamide layer can alter the surface characteristic, enhance the anti-chlorination properties, and can improve the permeability and selectivity of the membranes. However, a standard and reproducible fabrication strategy to incorporate nanoplatelets/nanoparticles in the polyamide membranes is yet to be developed. In this study, a layer-by-layer synthesis technique has been used for embedding graphene oxide nanoplatelets (GONPs) in the polyamide layer. Polyamide layers with GONPs were constructed as alternating layers of GONPs and polyamide, and GONPs on top of the polyamide layer. Incorporation of GO resulted in an increase of surface hydrophilicity, as captured by the change of contact angle. The presence of GONPs in the synthesized membranes has been confirmed by XPS, SEM, TEM, and AFM. Water flux and salt rejection properties of synthesized membranes in chlorine and non-chlorine conditions have been investigated by using a dead-end cell. The GONPs containing membranes display significant improvement in the chlorine resistance properties in comparison to the pristine polyamide membrane. In addition, a small enhancement in the salt rejection properties has been observed for the GONP containing membranes.

C41 Development of Isoporous 0.2 Micron Nanoslit Silicon Nitride Membranes for Sterile Filtration of Biological Therapeutics, Evan Wright (McMaster University), Joshua Miller (Simpore), Andrew Gosselin (Simpore), Jared Carter (Simpore), James McGrath (University of Rochester), David Latulippe (McMaster University), James Roussie (Simpore)*

Current Good Manufacturing Practice (cGMP) standards for the production of biological therapeutics rely on sterile filtration processes using microporous polymeric membranes to remove microbial contaminants and product aggregates in order to ensure the safety of the final formulation. Existing polymeric sterile filters are not ideal for larger biological therapeutics such as antibody-particle conjugates, oncolytic viruses, or extracellular vesicles, as these often become entrapped within the high internal surface area of such polymer membranes. The resulting yield loss increases production costs of these therapeutics, and therefore, new process technologies are required to optimize the production of large-sized biological therapeutics. Here, we report on the development of nanoslit silicon nitride (NSN) membranes with isoporous sub-0.2 μm rectangular prism "pores" for addressing the need for improved biological therapeutic sterile filtration. We demonstrate fabrication processes that yield NSN membranes that are ultrathin (200 nm thick), exhibit high permeability (~33% porosity), and precision-patterned slit openings (0.19 μm X 10 μm). We characterized these newly developed

membranes for their gas and hydraulic permeability, differential pressure tolerance, and model solute retention and transmission. Most importantly, we challenged these membranes with 10^7 B. diminuta per cm^2 of NSN membrane and obtained complete retention of bacteria, demonstrating similar bioburden reduction properties to those of commercially available $0.22 \mu\text{m}$ sterile filters. Given these results, we anticipate that NSN membranes will enable sterile filtration of emerging large-sized biological therapeutics, resulting in improved yield during cGMP manufacturing.

SESSION D - Innovation in Membranes for Energy Applications

- D1 A membrane to separate light olefins and paraffins; an update on pilot trials, module design and C4 separations**, Ken Loprete (Compact Membrane Systems)*; Bill Charlton (Compact Membrane Systems); Hannah Murnen (Compact Membrane Systems); Kenneth Pennisi (Compact Membrane Systems); Sudip Majumdar (Compact Membrane Systems)

The separation of light olefins from paraffins is one of the most energy intensive separations in the chemical processing industries. The state of the art separation method is distillation, a technology that has remained unchanged over decades. Membranes hold the promise of a more modular, energy efficient and capital efficient method for separation. However, they have historically been hampered by low performance and stability. Compact Membrane Systems has developed a novel membrane material using a silver embedded fluoropolymer material to transport olefins across the membrane. This material has demonstrated over 2 years of longevity in laboratory operation and has shown high selectivity and permeance under realistic operating conditions. During the past year, CMS has been operating a pilot utilizing this membrane material in a spiral wound element at the Delaware City Refining Company. We will share the latest results from that pilot operation as well as the update on the scale-up of our membrane modules. The Delaware City pilot is operating on a low concentration olefin stream (i.e., ~10-15% propylene balance propane in the feed) with the goal of achieving an HD5 quality propane product and an enriched propylene stream. We will discuss the improvements we have made to module design that have enabled high performance at realistic field conditions. In addition, we will demonstrate stability for over 60 days in the field. CMS will also discuss initial results on laboratory testing of C4 streams. This includes mixed gas separation of n-butane and 1-butene with permeances between 200-500 GPU and selectivities greater than 20. We will share results for a number of operating conditions and will highlight several exciting C4 separation applications including those with isomer streams. In addition, longevity results for >30 days of C4 operation will be shared demonstrating the stability of the membrane in realistic streams.

- D2 Cross-linked Polyethyleneimine (XLPEI) with superior H₂/CO₂ separation properties**, Sankhajit Pal (The State University of New York at Buffalo)*; Weiguang Jia (The State University of New York at Buffalo); Haiqing Lin (The State University of New York at Buffalo)

Membranes with superior H₂/CO₂ separation properties are needed for H₂ purification and CO₂ capture from the syngas derived from coal. Polyethyleneimine (PEI) has been widely studied for CO₂ sorption, due to the strong interaction of amines with CO₂. This study demonstrates that the strong interactions between the CO₂ and PEI decrease the CO₂ diffusivity in the polymer, thus increasing H₂/CO₂ permeability selectivity. Specifically, PEIs were cross-linked with various amounts of hexamethylene diisocyanate (HMDI) to form free-standing films. The effect of cross-linking density on the properties (including gel content, density and glass transition temperature) is systematically investigated. As the HMDI content increases from 0 to 35 wt% in the film, the T_g increases from -52 to -4.8 °C. At a weight ratio of 65:35 for PEI: HMDI, the resulting film exhibits a H₂ permeability of 1.0 Barrers and H₂/CO₂ selectivity of 30 at 150 psig and 35 °C. Such selectivity is the highest reported for polymers for H₂/CO₂ separation. These results contradict the conventional wisdom that adding amine groups in polymers can increase CO₂ permeability.

- D3 Self-Cleaning Nanocomposite Membranes with Phosphorene-Based Pore Fillers for Water Treatment**, Joyner Eke (University of Kentucky)*; Isabel Escobar (University of Kentucky)

Photocatalytic membrane processes generate oxygen-reactive radicals under irradiation by light that could degrade pollutants in feed solutions. Phosphorene is a two-dimensional material made by exfoliating black phosphorus, a monotypic van der Waals crystal. Unlike other common two-dimensional materials, under light irradiation, phosphorene can generate reactive oxygen species (singlet oxygen, hydroxyl radicals and superoxide radicals). In this study, we exfoliated black phosphorus to synthesize phosphorene. Then immobilized the phosphorene nanomaterial into the membrane (sulfonated poly ether ether ketone and polysulfone blend). Studies were done under ultraviolet light irradiation. The dye, methylene blue was used as feed solution. Membranes were comprehensively characterized before and after modification. Results obtained showed enhanced flux recovery for the phosphorene modified membranes. Fluorescent studies also revealed lower coverage of methylene blue on these membranes as compared to the unmodified membranes. Mechanism of photocatalysis will be investigated and reaction equations proposed.

- D4 Scale-up of A Catalytic Membrane Reactor for the Production of 5-Hydroxymethylfurfural from Lignocellulosic Biomass,** Tanmoy Patra (University of Arkansas); Robert Beitle (University of Arkansas); Richard J. Ciora, Jr. (Media and Process Technology, Inc.); Ranil Wickramasinghe (University of Arkansas); Xianghong Qian (University of Arkansas)*

Significant efforts have been dedicated to developing economically viable processes for converting lignocellulosic biomass to biofuels, bio-based products and intermediates. 5-hydroxymethylfurfural (HMF) is a versatile platform chemical that can be produced from lignocellulosic biomass. The commercial viability for the production of HMF lies in its cost-effective production and separation from the reaction stream. This work explores the potential for development of a prototype catalytic membrane reactor for the production and separation of HMF using agricultural residues such as wheat and rice straws, as well as cornstover biomass. Our previous results have demonstrated the feasibility of producing HMF at the 0.01-0.1 L scale with over 70% yield from cellulose and pre-treated cornstover substrates in ionic liquid (IL), IL/gamma-valerolactone (GVL) and IL/H₂O mixed solvents. Our designed polymeric solid acid catalysts were immobilized on porous membrane substrates to increase the surface area and enable product separation. These catalysts consist of two adjacent polymer nanostructures, one sulfonic acid chain for catalyzing the biomass substrate, one poly (ionic liquid) chain for solubilizing cellulose and enhancing the catalytic activity. Here a semi-batch catalytic membrane reactor was designed and tested for the production and separation of HMF simultaneously in IL/H₂O mixed solvents at mild temperature of 110-140°C. Over 50% of HMF yield from cornstover biomass has been achieved.

- D5 Thin-Film Composite Hollow Fiber Membrane for Post-Combustion Carbon Capture,** Shouliang Yi (U.S. Department of Energy National Energy Technology Laboratory)*; James S Baker (U.S. Department of Energy National Energy Technology Laboratory); Ali Sekizkardes (Battelle/U.S. Department of Energy National Energy Technology Laboratory); Surendar Venna (U.S. Department of Energy National Energy Technology Laboratory); Victor A Kusuma (U.S. Department of Energy National Energy Technology Laboratory); Fangming Xiang (U.S. Department of Energy National Energy Technology Laboratory); Lingxiang Zhu (U.S. Department of Energy National Energy Technology Laboratory); Hyuk Kwon (U.S. Department of Energy National Energy Technology Laboratory); David Hopkinson (U.S. Department of Energy National Energy Technology Laboratory); Kevin Resnik (U.S. Department of Energy National Energy Technology Laboratory)

The National Energy Technology Laboratory (NETL) is developing the next generation of advanced CO₂ capture concepts. Post-combustion carbon capture from flue gas involves the separation of CO₂ (~10-16%) from nitrogen, the primary constituent of flue gas. Membrane and membrane-based processes have been considered as one of the most promising technologies for post-combustion carbon capture due to numerous advantages. Specifically, polymeric membranes have the additional benefits of being inexpensive and easy to manufacture. For industrial applications, asymmetric and/or composite membranes with a thin skin layer are typically used to achieve a high permeation flux. Among the various designs of membrane modules, hollow fiber membranes are preferred due to high packing density and self-supporting characteristics. In this presentation, Torlon, a commercial polyimide-amide polymer, was used to fabricate the highly porous substrate to develop high performance thin-film composite (TFC) hollow fiber membranes due to its exceptional mechanical, thermal and chemical resistant properties. Several advanced polymer materials including polymers of intrinsic microporosity (PIMs) and ultra-high molecular weight polyvinylamine were employed as a selective layer. The effects of dope compositions, spinning parameters, and dip-coating procedures were investigated in detail. The results showed that the CO₂ permeance of PIM-based TFC hollow fibers was 1500-2000 GPU with a CO₂/N₂ selectivity of 15-18 as measured using dry gas. The ultra-high molecular weight polyvinylamine-based TFC hollow fiber membranes demonstrated a CO₂ permeance of 50-60 GPU with CO₂/N₂ selectivity of ~50 under mixed gas with a composition of 14%CO₂/86%N₂ at 22 °C with humidity. We will review the effect of fabrication procedures for these composite hollow fiber membranes on the gas transport performance properties, mechanical properties, membrane morphology, durability, and applicability to future scale-up.

- D6 Salinity gradient heat engine: optimising reverse electrodialysis for thermal-to-electric,** Anna Hulme (Cranfield University)*

The Nano Membrane Toilet is a decentralised on-site sanitation system which requires an off-grid power supply to treat wastewater. Combustion of faeces within the system provides a reliable source of heat energy. However existing thermal-to-electric technologies are expensive and inefficient for conversion of heat below 100 °C. A salinity gradient heat engine consisting of a reverse electrodialysis (RED) stack and a thermal separation stage could offer improved efficiencies. RED utilises the Gibbs free energy of mixing solutions with a concentration gradient across ion exchange membranes to generate a voltage. Membrane distillation is a thermally-driven separation process which restores the concentration gradient of the RED feeds using low-grade heat to close the loop. Research on RED has focussed on large-scale power production using seawater and river water. For a small-scale heat engine, power output from a finite volume of feed solution must be maximised. The use of natural feeds with relatively low salinity gradients limits potential power densities. By contrast, use of artificial saline solutions enables optimal conditions for thermal-to-electric to be selected. A laboratory-scale five cell pair reverse electrodialysis stack was used to investigate the effect of process conditions on power density and energy efficiency in single pass and recycle. The effect of feed concentration, flow rate, temperature and current density on water and salt

transport within the stack was quantified. Increasing residence time within the stack increased energy efficiency. Recycling feeds led to the highest energy efficiency. Despite increased water transport, high salinity gradients recovered the most work per volume of solution. This demonstrates the suitability of increased salinity gradients in reverse electro dialysis for thermal-to-electric applications. Selection of current density is critical to maximise energy efficiency and manage water transport.

- D7 Use of desalination brine for low-energy concentration of orange juice via forward osmosis**, Haley D White (Tennessee Technological University)*; Leif Templeton (Tennessee Technological University); Shelby Jones (Tennessee Technological University); Laura H Arias Chavez (Tennessee Technological University)

Membrane technology has the potential to enhance sustainability at the food-energy-water nexus by reclaiming both energy and materials from 'waste' streams. Forward osmosis (FO) is a selective separation process that could facilitate such reclamation. It requires minimal energy when draw solution regeneration is avoided. To do so, concentrated waste streams can be used as single-use draw solutions in certain applications. We investigated a possible implementation of this strategy: concentrating liquid commodities using seawater desalination brine as a draw solution. Seawater desalination produces ~50 million m³/day of brine worldwide, representing 53 GWh/day in wasted chemical potential energy. Harnessing this energy for osmotic concentration can displace the use of prime energy for thermal concentration. Orange juice was selected as a model commodity due to the proximity of citrus production to seawater desalination in Florida. Juice concentration was conducted in a bench-scale FO system using commercial thin-film composite membranes and NaCl draw solutions simulating 50% or 60% recovered seawater desalination brine. Juice recovery reached 55% with water flux maintained at 5 to 8 L m⁻² h⁻¹. Fouling was reversible, with up to 98% of initial water flux regained after physical cleaning. Juice concentrates met quality standards for recoveries of up to 32%. At higher recoveries, sugar levels declined, likely due to fermentation during long experiment times in the bench-scale system. Transport of both draw solutes and juice components through the membrane increased over time, perhaps due to stretching or tearing of the membranes, which were not supported by spacers. From our data, we predict that modest fluxes can be maintained up to the juice industry requirement of 80% recovery, with desalination brine as the only significant source of energy. Despite bench-scale limitations, this study shows the potential of 'waste' streams to power relevant separations.

- D8 High-performance SSZ-13 membranes for CO₂ and N₂ removals from natural gas**, Rongfei Zhou (Nanjing Technical University)*; Xinping Li (Nanjing Technical University); Bin Wang (Nanjing Technical University)

Removal of the undesirable impurities such as CO₂ and N₂ from natural gas is a significant processing because that the impurity gases decrease the energy content of the gas and CO₂ can corrode pipelines in the presence of humidity. Zeolite membranes possess superior permeances and chemical, thermal and high-pressure stabilities. A SSZ-13 zeolite (CHA) with a pore size of 3.80 Å × 3.80 Å is a promising membrane candidate for separating CO₂ (3.30 Å) and N₂ (3.64 Å) from slightly larger molecule CH₄ (3.80 Å) due to its molecular sieving ability when it is made in membrane. High quality SSZ-13 membranes with improved separation performance were prepared on the asymmetric α -alumina tubes by a single hydrothermal secondary step. Some modifications were made for membrane synthesis in this current study. The SiO₂/Al₂O₃ ratio in the membrane gel were improved from 40 in our previous study (J. Membr. Sci., 475, 303-310, 2015) to 200 in order to improve the hydrophobic performance against the humidity. Ball-milled SSZ-13 seeds were used in this study to improve the induction ability of seed layer. Moreover, membrane calcination in pure oxygen at lower temperature was carried out for the current membrane instead of in air at higher temperature for our previous SSZ-13 membrane. The current SSZ-13 membrane had a CO₂ permeance of 1.20×10^{-6} mol/(m² s Pa) (equal to 3600 GPU) with CO₂/CH₄ selectivity of 300 and a N₂ permeance of 1.10×10^{-7} mol/(m² s Pa) (equal to 330 GPU) with N₂/CH₄ selectivity of 13 at 298 K and 0.2 MPa for equimolar CO₂/CH₄ and N₂/CH₄ mixture, respectively. Such separation performances of the membrane were beyond those of most of the membranes. Membrane stabilities for a long-term test and in the wet mixture were also investigated. The current high-silica SSZ-13 membrane has excellent potentials for CO₂ and N₂ removal in natural gas purification as a facile separation process.

- D9 Highly efficient CO₂ capture by mixed matrix membranes containing three-dimensional covalent organic framework fillers**, Youdong Cheng (National University of Singapore)*; Dan Zhao (National University of Singapore)

Mixed matrix membranes (MMMs) have long been considered as promising membrane types for industrial energy-intensive gas separation processes. Current MMMs are still facing grand challenges of poor filler dispersion and poor polymer-filler interfacial compatibility. The present study demonstrates that these challenges can be addressed by fabricating MMMs containing three-dimensional (3D) covalent organic framework (COF) fillers with ultrasmall size-selective pores. Two different polymer matrixes, including glassy 6FDA-DAM and rubbery Pebax, are explored to validate the effectiveness of 3D COF fillers in improving the membrane separation performance. The pure organic nature of COFs confers them with high affinity with pure organic polymer matrixes, leading to good interfacial compatibility in the resultant MMMs. These porous COF-300 fillers can increase the membrane fractional free volume that enhances the membrane gas permeability. Besides, the ultrasmall pores of COF-300 fillers and the rigidified polymer chains at the filler

surface can enhance the size discriminative processes, resulting in increased membrane gas pair selectivity. Moreover, the separation performance of COF-300 can be further improved by functionalizing it with polyethylenimine (PEI), enabling the design of advanced membranes suitable for industrial applications.

D10 – Industrially relevant membrane testing and novel mixed-matrix membranes for a brighter membrane future, Raymond Thür (Katholieke Universiteit Leuven)*

In an attempt to pass the Robeson upperbound, mixed-matrix membranes have been designed to combine the good separation potential of inorganic nanoparticles (e.g. MOFs) with cheap, well-processable polymers. Zirconium-based MOF are considered to be among the most promising materials for MMM synthesis, regarding their low cost, very good stability, easy synthesis in green conditions and functionalization. Two new Zr MOFs were investigated in their potential for use in MMMs: (a) Bipyridine-based UiO-67 was used as filler Matrimid MMMs. The combination of bipyridine UiO-67 with Matrimid led to doubled CO_2/CH_4 mixed gas selectivity (from 38 to 75) while CO_2 permeability was enhanced by 63%. Characterization of fillers and membranes showed that the MOFs affinity for CO_2 was increased by incorporating bipyridine linkers and that these Lewis-basic sites function as CO_2 carriers. Gas permeation experiments suggested a facilitated transport mechanism causing these high selectivities. (b) A relatively new, extremely stable Zr MOF (MOF-808), which can be tuned for enhanced CO_2 affinity was tested in 6FDA-based polymer membranes. It was noticed that controlling the colloidal stability of the MOF-polymer-solvent system via various strategies is key to obtain successful MMMs. Even though the perspectives for membrane technology are promising, there currently exists a discrepancy between academic and industrial testing of membranes. Testing of membranes under industrially more relevant conditions is therefore of high importance. Our group developed a second generation high-throughput gas permeation set-up, which allows simultaneous testing of 8 membranes for CO_2 separation at pressures up to 34.5 bar and for olefin/paraffin separation up to 25 bar, also in presence of water vapour. In this way, industrial streams like flue gas, natural or bio gas and olefin/paraffin mixtures can be mimicked to gain better insight in the real separation performance of the membranes.

D11 Torlon® Hollow Fiber Membranes for Organic Solvent Reverse Osmosis separation of Complex Aromatic Hydrocarbon Mixtures, Hye Youn Y Jang (Georgia Institute of Technology)*; Ryan Lively (Georgia Institute of Technology); JR Johnson (ExxonMobil); Dhaval Bhandari (ExxonMobil)

In this work, defect-free polyamide-imide (Torlon®) hollow fiber membranes were fabricated with the aim of investigating the potential for polymer-based organic solvent reverse osmosis (OSRO) separations of complex aromatic hydrocarbon mixtures. The quality of the synthesized membrane was probed using gas permeation experiments. The membranes were found to have He/N_2 permselectivities of ~200, whereas the dense film permselectivities are known to be ~310, suggesting that these membranes are nearly defect-free. These membranes were found to be stable in various hydrocarbon liquids, and did not experience significant swelling upon exposure to these liquids. Considering the high quality of the membrane and the stability of the polymer, these membranes were utilized in OSRO separation without any post-treatment procedures. The membranes were challenged with a mixture of aromatic hydrocarbons that are typically found in light fractions of crude oil. These multi-component separation experiments revealed a MWCO of 160-200 Da. To clearly demonstrate the OSRO separation modality, we also challenged the membrane modules with more concentrated mixtures such as a 90/10 (mol %) mixture of toluene and 1, 3, 5-triisopropyl benzene. The osmotic pressure for this system is estimated to be 25bar. At an upstream pressure of 70-80 bar, we find that the solvent concentration in the permeate is 99.4-99.6 mole %, and that the TIPB rejection coefficient is approximately 94.6-95.7%. The solvent permeance in these membrane modules is low (0.01 $\text{L}/\text{m}^2\text{-h-bar}$). Nevertheless, the ability to reject solutes as small as 160-200 Da using commercial polymers and commercially-inspired spinning techniques suggests that these membranes have the potential to enable challenging solvent-solute or even solvent-solvent separations found in the hydrocarbon processing industry. This work provides a benchmark for OSRO separation of complex hydrocarbon mixture using polymeric hollow fiber membranes.

D12 Performance Investigation of Polymer Derived Ceramic Composite Membrane in Microbial Fuel Cell (MFC), Vignesh Ahilan (University of Bremen)*; Camila Cabral de Barros (University of Bremen); Gourav Dhar Bhowmick (Indian Institute of Technology); Makarand M Ghangrekar (Indian Institute of Technology); Michaela Wilhelm (University of Bremen); Kurosch Rezwani (University of Bremen)

Polymer derived ceramic (PDC) membranes were developed as a Proton conducting membrane material for Microbial Fuel Cell (MFC). The chemical composition was altered by incorporating graphitic filler materials such as Graphene oxide and Carbon nanotube in the polysiloxane precursor. These distinct compositions were converted at 600°C and 1100°C to ceramic membranes. Physical characteristics of the synthesized membranes such as porosity, hydrophilicity, mechanical stability, ion exchange capacity, and oxygen mass transfer coefficient were determined to investigate the best membrane material for further testing in MFCs. The open porosity of samples ranged from 30 % to 40 %, and the pore size was attained in the range between 0.1-1 μm . The membrane ion exchange capacity was significantly improved after adding 0.5 wt. % of GO. It increased drastically corresponding to an increment of 78.6 % with respect to that

of the ceramic membrane without GO, while the oxygen mass transfer coefficient of the membrane decreased by 52.6 %. The performance of synthesized membranes was assessed in dual chamber MFC system in terms of power density generated, normalized energy recovery, Coloumbic efficiency and chemical oxygen demand (COD) removal efficiency. The maximum volumetric power density and COD removal efficiency of MFC with filler materials incorporated ceramic separator were 7.23W/m³ and 89 %, respectively. The power generation is 1.5 times higher than for a MFC conducted with a Nafion 117 membrane tested under similar condition. This study reveals the feasibility of using PDC membrane as energy efficient membrane material for the application in MFC.

- D13 PIM-1 based polymeric blend membranes for gas separation applications**, Ashley Miles (Oak Ridge Associated Universities/U.S. Department of Energy National Energy Technology Laboratory)*; Ali Sekizkardes (Battelle/U.S. Department of Energy National Energy Technology Laboratory); Janice Steckel (U.S. Department of Energy National Energy Technology Laboratory); David Hopkinson (U.S. Department of Energy National Energy Technology Laboratory)

Polymers of intrinsic microporosity (PIMs) have been widely studied as membranes for gas separation research. PIMs are known for high permeability, high free surface volume, and processability with aprotic solvents. However, PIM-casted membranes show poor mechanical properties, as they suffer from highly brittle film formation and low selectivity due to pore size (~1 nm). Here, we functionalize PIM-based polymers and blend them with compatible rubbery polymers to obtain superior membranes. In our process, we create binding sites that improve gas permeability and miscibility properties for the blended polymers. The resulting membranes show improved film formation, high CO₂ permeability (2500 Barrer) and high CO₂/N₂ selectivity (28). A description of the fabrication and characterization of these blend membranes will be presented. In addition, gas transport properties of blended membranes were studied for potential use in post-combustion flue gas separation applications.

- D14 The dynamic fate of Organic micro-pollutants in MBR and their accumulation in fish tissue**, Gal Dagan (Ben-Gurion University of the Negev)*; Inbal Zaibel (Ben-Gurion University of the Negev); Dina Zilberg (Ben-Gurion University of the Negev); Moshe Herzberg (Ben-Gurion University of the Negev)

Despite the extensive application of municipal recycled water for irrigation (in Israel 85% of the municipal wastewater), currently such use is not permitted for aquaculture. Previous studies on the bioaccumulation of organic compounds in fish cultured in municipal recycled water have demonstrated that heavy metals and organic contaminant levels in tissue were below the FDA limits. Organic micro-pollutants (OMPs) impact on fish is a key factor in determining the potential of using treated wastewater for aquaculture. The fate of OMPs strongly depends on processes including adsorption and biodegradation and the related operational parameters. Hence, there is a great potential in using recycled municipal wastewater from membrane bioreactors (MBR) effluents, for aquaculture. MBR is a wastewater treatment process that combines conventional biological treatment with membrane filtration for biomass retention. MBR allows sewage treatment at high mixed liquor suspended solids (MLSS) concentration, fixed sludge retention time (SRT) and hydraulic retention time (HRT), decoupled from one another. Our objectives were to evaluate the dynamic fate of two model OMPs, carbamazepine (CBZ) and diclofenac (DFC), in the MBR effluents and their related accumulation in fish tissues grown in MBR effluents. Intriguingly, the transient retention of CBZ and DFC in the MBR was mainly due to adsorption to the sludge and the membrane: CBZ has shown greater adsorption capacity to the sludge, whereas, DFC showed higher adsorption to the membrane. Currently, we quantify effects of these adsorption processes on the dynamic appearance of CBZ and DFC in the MBR effluents. In addition, accumulation of heavy metals and 21 OMPs compounds of interest in tissues of fish that were cultured in MBR effluents for 2 months, were below the maximum concentration allowed by the FDA. This study provides a premise of possibilities for aquaculture using MBR effluents under proper restricted conditions.

- D15 Improving H₂ Utilization of Solid Oxide Fuel Cell Using CO₂-Selective Membrane**, Kai Chen (Ohio State University)*; Witopo Salim (Ohio State University); Yang Han (Ohio State University); Mike Gasda (Bloom Energy Corporation); Winston Ho (Ohio State University)

Polymeric membranes with a high CO₂/H₂ selectivity are desired to recover H₂ from the anode exhaust of a high-temperature solid oxide fuel cell (SOFC) system for H₂ utilization. At a high temperature of 120°C, it is very challenging to maintain the high CO₂/H₂ selectivity. The membrane reported here contained a polyelectrolyte with quaternary ammonium ions as the cations bound to the polymer backbone. Fluoride was chosen as the counterion, which catalyzed the reaction between CO₂ and water. The composition also included a boric acid to further catalyze the reaction and a hydroxide-based mobile carrier for the facilitated transport of CO₂. The membrane showed a CO₂ permeance of 100 GPU and a CO₂/H₂ selectivity of 116 at 120°C, making the membrane suitable for the abovementioned application. Hydration of the membrane was also found to be important as water is involved in the facilitated transport of CO₂. Next, a high-level techno-economic analysis was conducted for the integration of the membrane process into the SOFC system. Parameters studied were the membrane transport performances, H₂ recovery, and feed to sweep flow ratio. The CO₂ removal cost using the membrane with a CO₂ permeance of 100 GPU and a CO₂/H₂ selectivity of 116 was calculated to be \$62.8/tonne. Furthermore, in order to improve the process, a vacuum was proposed to be pulled on the permeate side so that the removed CO₂ could be captured.

D16 Adapting a Blood CO₂ Removal Device for CO₂ Removal from Flue Gas, Katherine Hornbostel (University of Pittsburgh)*

The purpose of this project is to investigate the use of hollow fiber membrane contactors (HFMC) currently used for CO₂ removal in medical applications for CO₂ separation from flue gas. HFMC's are hybrid devices that combine the advantages of membranes (high surface area, gas permeability) with the advantages of solvents (CO₂/N₂ selectivity, high CO₂ absorption rate). HFMC's can be used with nearly any low-viscosity CO₂ solvent, ranging from water to amines. Because of the intrinsically high surface area of HFMC's, cheap/abundant solvents (e.g. water, carbonate solution) can be used in lieu of traditional solvents (e.g. amines). This proposal couples the unique expertise of two professors at the University of Pittsburgh: Prof. Katherine Hornbostel (MEMS) and Prof. William Federspiel (BIOE, McGowan Institute for Regenerative Medicine). Hornbostel brings experience with modeling CO₂ separation using encapsulated solvents, while Federspiel brings experience with experimental HFMC research for blood oxygenation and CO₂ removal. The ultimate application for this technology would be CO₂ separation from coal or natural gas power plants. Initial CO₂ separation experiments have been performed on a wearable artificial lung device that is commonly used to remove CO₂ from the blood of COPD patients. In these experiments at room temperature and pressure, simulated flue gas was flowed through the hollow fibers, and water or Instant Ocean flowed on the other side. The results demonstrated up to 50% CO₂ removal, with best performance occurring at high liquid flow-rates with water and a larger device. Future tests will be done using NaOH and Na₂CO₃ solutions as the sweep fluid, which should significantly boost CO₂ mass transfer rates. Future experiments will also study the impact of carbonic anhydrase coating, mechanical agitation, and higher temperature for raising CO₂ removal rates from simulated flue gas.

D17 Experimental study of dehumidification potential of PDMS hollow fiber membrane for HVAC applications, Michelle K Croal (Oakland University); Jonathan Maisonneuve (Oakland University)*

Energy consumption in buildings constitutes approximately 40 % of primary energy use in the USA, with heating, cooling and ventilation being sizable portions thereof. Furthermore, in hot and humid climates, latent cooling loads (i.e. dehumidification) can be almost equal to sensible cooling loads, if not greater. While desiccant systems allow for separating latent and sensible cooling loads, they still require thermal energy input to regenerate the saturated desiccant. Membrane dehumidification systems require minimal energy input, as they utilize humidity gradients to remove water vapor. In this study, a polydimethylsiloxane (PDMS) hollow fiber membrane module is tested under various isothermal flow conditions, with varying feed and sweep relative humidity. Latent energy removal varied widely, but was found at maximum to be 97% of psychrometric limit, presenting significant potential for energy savings in building applications. Net dehumidification efficiency ranged between 35 - 85%. Sensible heat transfer is also studied by considering fresh air intake at 35°C and exhaust sweep air at 20°C for additional energy recovery.

D18 The Perfluoropolymer Upper Bound, Albert Wu (MIT)*; James Drayton (MIT); Zach Smith (MIT)

Perfluoropolymers have fundamentally distinct thermodynamic partitioning characteristics compared to their hydrocarbon counterparts. The original upper bound theory for polymer gas separations assumes hydrocarbon solubility behavior for all polymers. In this study, the difference in solubility behavior for perfluoropolymers is explicitly considered to create a new level of design and predictability to transport performance in polymer membranes with diverse chemical characteristics. New theoretical perfluoropolymer upper bounds are established, showing a positive shift of the upper bound front as a result of improved solubility selectivity for certain gas pairs. Comparisons are made with current separation performance data. Using the framework of the solution-diffusion model, a deconvolution of transport and partitioning characteristics is evaluated. A new correlation is presented that relates penetrant properties and an adjustable parameter used in upper bound theory to predict the current upper bound position for a variety of gas pairs, including those not previously considered. Promising future applications for perfluoropolymers are discussed.

D19 Synthesis and characterization of catalytic PtNa-PdAu membranes for hydrogen production, Ana M Tarditi (Instituto de Investigaciones en Catálisis y Petroquímica)*; Laura Cornaglia (Instituto de Investigaciones en Catálisis y Petroquímica); Yohana Martínez Galeano (Instituto de Investigaciones en Catálisis y Petroquímica)

Hydrogen is one of the most promising energy carriers because of being a zero-emission fuel and presents high efficiency. In this actual scenario, Pd-based membranes play an important role in hydrogen production and purification due to their excellent permeability and selectivity. Zeolites have been widely applied in catalysis, due to their small pore size capable of carrying out selective catalysis. We have reported the use of PtNaA zeolite as an efficient catalyst for the water gas shift reaction [1]. Considering that, the aim of this work was to develop catalytic PtNaA-PdAu membranes for hydrogen production. PdAu alloys were deposited by means of sequential electroless plating. The PtNaA zeolite was deposited on top of the PdAu alloys employing the encapsulated method reported in a previous publication [1]. Different synthesis variables were considered: surface modification with APTES and the number of the hydrothermal synthesis. The samples were characterized by SEM-EDS, XRD, and XPS and evaluated in streams containing H₂, CO, and H₂O. A compact and homogeneous zeolite coverage was successfully obtained by previous functionalization of the PdAu surface with APTES. XRD diffraction

patterns of the PtNaA-zeolite deposited on the PdAu layer showed the characteristic reflections associated with the NaA zeolite phase. Upon exposure to CO, the membrane showed a reduction in the H₂ permeance, although the recovery was almost 100% after H₂ exposure at the same evaluated temperature. Likewise, no nitrogen permeation flux was detected, indicating that the PdAu membrane continues to be H₂ selective. Uniform and homogeneous PtNaA-PdAu membranes were obtained employing an optimized synthesis protocol. The membranes showed good stability and resistance to streams with contaminant gases and present themselves as promising materials for H₂ production. [1] Martínez Galeano, Y., Negri, F., Moreno, M.S., Múnera, J., Cornaglia, L., Tarditi, A.M., Appl. Catal., A 572 (2019) 176-184.

D20 Hybrid facilitated transport membranes containing 2D GO-based nanoplatelets and scaffolds for CO₂ separation, Saravanan Janakiram (Norwegian University of Science and Technology)*; Juan Luis Martín Espejo (Norwegian University of Science and Technology); Zhongde Dai (Norwegian University of Science and Technology); Luca Ansaloni (SINTEF Industry); Liyuan Deng (Norwegian University of Science and Technology)

Amine-based fixed-site carrier membranes transport CO₂ through reactional pathway in addition to solution diffusion under humid conditions. Incorporation of tailored fillers in facilitated transport membranes leads to enhanced separation performance and superior mechanical strength in the hybrid matrix. Anisotropically shaped thin nanosheets triggers nanoscopic changes in polymer chain packing, resulting in enhanced permeation performance at very low loading when compared to conventional fillers like Zeolites, MOFs. Additionally, incorporation of 2D nanofillers like graphene oxide have been found to improve both selectivity and permeability due to the molecular sieving effect while reducing CO₂ plasticisation. As a novel approach, the current study aims at resulting in a mechanically stable thin composite membrane with superior separation performance. GO-based nanofillers were successfully incorporated in facilitated transport sterically hindered polyallyl amine membranes to obtain novel membranes for CO₂ separation. Defect-free ultrathin selective layers with thicknesses less than 300 nm were successfully coated on porous polymeric supports. Good compatibility of GO-based fillers favoured uniform coating with no visible voids or interfacial defects. CO₂ permeance in hybrids increased as high as 610 GPU with a CO₂/N₂ selectivity of 37. Structural changes and chemical functionalization of GO nanosheets are also made to study the effect of filler modifications on the permeation performance. Furthermore, as a step closer to industrial realization, fabrication and testing of hollow fibers modules with high packing density are under investigation.

D21 Current Efforts in Harvesting Algae At-Scale For Biofuels to Meet the Dual Energy Challenge, Mark A Deimund (ExxonMobil Research and Engineering)*

Recently, ExxonMobil announced continuation of its partnership with Synthetic Genomics, Inc. (SGI) to begin a new phase of their joint algae biofuel research program, where the two companies will work to develop the technical ability to produce algae biofuels at large-scale. This endeavor will require innovation and scale-up efforts for many technologies across orders of magnitude in water purification/treatment, algae growth and harvesting, and lipid extraction to convert algae products to fuels. To date, larger-scale growth and harvesting pilot work has been primarily conducted at SGI's growth site in Calipatria, CA, known as the "California Advanced Algae Facility" (CAAF). Algae harvesting requires separation from dilute growth media (~1 g algae/L water) to allow water recycle and lipid extraction with minimal energy usage; thus, membranes are a natural choice for initial dewatering. A summary of ExxonMobil's test results for harvesting algae with membrane systems will be presented, as well as some key learnings from this larger biofuels scale-up effort. Membrane-based separation systems have been demonstrated to be very effective at algae separation during ExxonMobil pilot tests, providing nearly-pure permeate and a concentrated algae slurry. This slurry can then be sent for further processing and lipid extraction, with greatly reduced pumping capacity requirements and more efficient downstream handling. Additionally, the resulting permeate is virtually free of any potential contaminants, such as extracellular material or other undesirable species, enabling recycle of large amounts of growth media with minimal treatment. While parameters such as membrane fouling, cleaning protocols, and membrane lifetime are key considerations, membranes show promise as an initial dewatering step in the large-scale production of biofuels.

D22 Atomically-Ordered Intermetallic Hydrogen Separation Membranes, Casey O'Brien (University of Notre Dame)*

Palladium-alloy membranes are attractive for a wide range of hydrogen separation applications due to their rare combination of high permeability and high-selectivity for hydrogen separation from mixed gas streams. However, other reactive gases that are common to hydrogen-containing gas streams, such as CO, propylene, and H₂S, can severely inhibit hydrogen permeation by blocking hydrogen adsorption, or reacting with the membrane to form compounds with low permeability. Nearly all studies of Pd-based membranes have focused on substitutionally disordered alloys, where the non-Pd elements occupy lattice positions that are normally occupied by Pd. In this talk, I will discuss a new approach--intermetallic membranes--for creating high performance hydrogen separation membranes. In contrast to substitutionally disordered alloys, intermetallic compounds are solids composed of at least two metals that form an atomically-ordered crystal structure where the different elements occupy definite positions with the lattice. The ordered crystal structure of intermetallics

results in some unique properties that have been exploited in several fields, including hydrogen storage, and catalysis. Although intermetallic membranes have received minimal attention, they are very promising as hydrogen separation membranes. Our work with intermetallic PdCu suggests that intermetallic membranes perform better than disordered alloys. Intermetallic PdCu has higher permeability than all disordered PdCu alloys, including Pd. Intermetallic PdCu resists corrosion from H₂S under conditions that result in severe corrosion of disordered PdCu alloys. Intermetallic PdCu is also more resistant to poisoning from CO due to the isolation of active sites on the membrane surface. In this talk, I will also discuss a new operando spectroscopy tool that we developed to monitor the interactions of reactive gases with intermetallic membrane surfaces in-situ under realistic permeation conditions.

D23 Molten Hydroxide Dual-Phase Membranes for Intermediate-temperature Fuel Cells, Vedasri Vedharathinam (Lawrence Livermore National Laboratory)*; Anna Ivanovskaya (Lawrence Livermore National Laboratory); Maira Ceron Hernandez (Lawrence Livermore National Laboratory); Patrick Campbell (Lawrence Livermore National Laboratory)

Anion-exchange membrane (AEM) fuel cells are sought after because they enable non-precious metals as electrocatalysts and enhanced reaction kinetics. Typical polymer membranes contain quaternary ammonium or phosphonium groups that conduct OH⁻ ions at temperatures below 90°C, limiting their applications at elevated temperatures. Operation at elevated temperature allows for improved electrode kinetics, system efficiency, and simplified heat management. Hence, there is a need to develop hydroxide ion-conducting membranes that are chemically and mechanically stable and can operate at intermediate temperature ranges (150–400°C) without compromising ionic conductivity. Here we report a novel hydroxide-ceramic dual-phase (HCDP) membrane technology that utilizes molten alkaline hydroxides (e.g. sodium, potassium, and lithium) impregnated into a porous zirconia matrix. In typical alkaline electrolytes, hydroxide ions react with CO₂ from air to form carbonate, leading to performance degradation of the fuel cell due to loss of OH⁻ ionic conductivity. The CO₂ poisoning effects are rapid and severe, necessitating the use of pure oxygen instead of air as cathode feed. Our proposed technology overcomes the CO₂ poisoning issue when using air as the oxidant by shifting the chemical equilibrium of the undesired carbonate ions toward hydroxide and CO₂ in the presence of water at elevated temperatures, thus releasing CO₂ from the electrolyte in situ during fuel cell operation and preventing performance degradation. This contribution will highlight our recent developments in this area.

D24 High-Yield Recovery of Dissolved Methane Using Omniphobic Membranes, Xuesong Li (University of British Columbia); Abhishek Dutta (University of British Columbia); Qirong Dong (Fibrecast); Sasha Rollings-Scattergood (Anaergia); Jongho Lee (University of British Columbia)*

Efficient recovery of dissolved methane from anaerobic effluents is crucial to renewable energy production via anaerobic wastewater treatment processes. In this study, we present a novel membrane process (solvent-based membrane contactor or SMC) for recovering dissolved methane through the normal range of domestic wastewater temperatures (15°C - 35°C) by utilizing an omniphobic (non-wetting) microporous membrane that traps air within its pores when submerged in liquids. Driven by solubility-gradient, dissolved methane is extracted from a methane-rich aqueous solution (feed), transported across the omniphobic membrane, and absorbed into a non-polar organic solvent (draw) that has an order of magnitude higher methane solubility than does water. We fabricated the omniphobic membrane by coating a microporous polymeric membrane with silica nanoparticles, followed by a surface fluorination with low surface energy materials. The omniphobic membrane exhibited excellent wetting resistance against both water and low-surface tension organic liquids (e.g. dodecane and ethanol). Using the omniphobic membrane and dodecane as the draw solution in the SMC process, we demonstrate nearly 90% or above recovery rates of dissolved methane from methane-saturated feed water at 15°C, 25°C and 35°C, simulating anaerobic effluents produced in the psychrophilic to mesophilic temperature range, while a negligible transport of water is observed due to the low water solubility in the draw. A comparative energy analysis suggests that this novel membrane process for methane recovery can enable a net energy production, with a higher value at a lower temperature (up to 0.46 MJ per m³ of methane-saturated feed at 15°C), which outperforms other dissolved methane recovery techniques.

D25 Aging minimization of CMSMs from the incorporation of copper pillars derived from metal organic polyhedra-18, Whitney Cosey (University of Texas at Dallas)*; Inga Musselman (University of Texas at Dallas); John Ferraris (University of Texas at Dallas); Kenneth Balkus (University of Texas at Dallas)

Membrane-based gas separations have made strides within the last two decades due to their lower operating cost and ease of manufacturing. While polymeric membranes are currently used commercially, they are limited by an inherent trade-off between selectivity and permeability. However, carbon molecular sieve membranes (CMSMs) are not bound by this trade-off and thus surpass polymeric membranes in terms of permeability and selectivity due to the presence of micropores (0.7-2.0 nm) and ultramicropores (<0.7 nm), which provide high flux and high selectivity. While several researchers focus on tailoring the pore aperture to improve performance, improving the stability of the CMSMs by reducing physical aging (collapsing of pores) has yet to be addressed. Highly soluble metal organic polyhedra-18 (MOP-18) was introduced into Matrimid® 5218 with a loading of 40 wt% to form a mixed matrix membrane

(MMM). Pyrolysis of the MMM at 550°C allowed for copper oxide to be reduced by carbon to copper metal nanoparticles. The nanoparticles act as pillars for the graphene sheets within the CMSMs, preventing the collapse of the micropores and thus minimizing the aging of the CMSM. Gas permeation at 35°C and 2 atm showed the membrane's permeability for CO₂ was 725 Barrer and was 39 Barrer for CH₄. After a period of 20 days, only a 2% decrease in CO₂ permeability and a 15% decrease in CH₄ permeability was observed, with retention of CO₂/CH₄ selectivity.

D26 (Cross-linked Poly(ionic liquid)-Ionic Liquid-Zeolite) Mixed-Matrix Membranes for CO₂/CH₄ Gas Separations Based on Curable Ionic Liquid Prepolymers, Collin A Dunn (University of Colorado Boulder)*; Zhangxing Shi (University of Colorado Boulder); Rongfei Zhou (Nanjing Technical University); Douglas Gin (University of Colorado Boulder); Richard Noble (University of Colorado Boulder)

A three-component, (cross-linked poly(ionic liquid) (PIL) - ionic liquid (IL) - zeolite) mixed-matrix membrane (MMM) platform based on curable IL prepolymers of controlled length has been developed for separating CO₂ from CH₄. Solutions of these curable prepolymers demonstrate increased resistance to support penetration compared to comparable solutions of analogous cross-linkable IL monomers. By adjusting the curable IL prepolymer chain length, it is possible to manipulate polymer susceptibility to support penetration, polymer solution gelation time, and gas separation performance in MMMs based on these materials. When a 50 wt% solution of the curable IL prepolymer with a degree of polymerization of 87 was cast on an ultrafiltration support membrane, only 3.7 wt% of the polymer penetrated into the support. As the degree of polymerization of the curable IL prepolymer increases, the CO₂/CH₄ gas separation performance of the resulting MMM performance also improves. An MMM synthesized using 64 wt% curable IL prepolymer, 16 wt% [EMIM][Tf₂N], and 20 wt% SAPO-34 zeolite demonstrates a CO₂/CH₄ selectivity of 42±5, and CO₂ permeability of 47±1 barrers. This CO₂/CH₄ separation performance is comparable to the previous generation of MMMs based on curable small-molecule IL monomers with the same IL and zeolite. However, this new MMM system also exhibits faster curing gelation times and the ability to be solution-cast onto a porous support for formation of thin-film composite membranes without significant selective layer soak-in.

D27 Integral hollow fiber membrane with chemical cross-linking for pressure retarded osmosis operated in the orientation of active layer facing feed solution, Ye Li (Nanyang Technological University)*; Rong Wang (Nanyang Technological University)

Pressure retarded osmosis (PRO) is one of the promising techniques for harvesting salinity gradient energy. However, the performance of PRO is exacerbated by the severe membrane fouling occurring within the porous support. Changing the membrane orientation from active layer facing draw solution (AL-DS) to active layer facing feed solution (AL-FS) is a potential alternative for sustainable power harvesting due to its low membrane fouling propensity. In this work, a novel integral PRO hollow fiber membrane was fabricated using the phase inversion method followed by a facile cross-linking post-treatment. The structure and properties of the resultant membrane were systematically investigated using a series of characterization protocols. The PRO performance of the membrane was evaluated under various hydraulic pressures at the AL-FS orientation. The results reveal that the substrate with sponge-like structure and relatively dense inner surface can better withstand high pressure in PRO process. Two steps of cross-linking endowed the membrane with a smaller pore size on the outer surface that exhibits high rejection against various inorganic salts. The newly developed membrane can achieve a stable power density output around 4.3 W·m⁻² at a pressure of 12 ~ 13 bar, using a real wastewater reverse osmosis (RO) retentate as the feed and a synthetic seawater brine (1.0 M NaCl) as the draw solution. This result demonstrates that the PRO operation in the AL-FS orientation offers a significant advantage over the AL-DS orientation by eliminating the pretreatment of the feed water or/and other measures associated with membrane fouling control in the AL-DS orientation. To implement the PRO operation with the AL-FS orientation, developing a robust membrane with an integral structure is critical. The newly developed integral hollow fiber membrane via chemical cross-linking presents potential for PRO operation in the AL-FS orientation.

D28 GHG separation membrane application in KOGAS LNG regasification facilities, Kyung Taek Woo (Korea Gas Corporation)*; Hyun Seok You (Korea Gas Corporation); Jong Tae Chung (Korea Gas Corporation); Jae Dong Kim (Korea Gas Corporation)

The Green House Gases (GHG) such as carbon dioxide (CO₂) and methane (CH₄) have been critical issue in terms of global climate change. The majority of GHG is emitted by combustion of fossil fuel to generate electric power. In order to overcome the issue, Carbon Capture, Utilization and Storage (CCUS) has been introduced one of the technologies to reduce GHG. The majority of GHG emission in KOGAS is generated in Submerged Combustion Vaporizer (SCV) one of the gasification facilities of LNG using combustion thermal of natural gas to boil up the water bath containing LNG pipelines. The flue gas from the SCV facilities is composed of CO₂ (7~8%), H₂O (13~15%), O₂ (3~6%), CO (<100ppm), NO (<50ppm), and N₂ (balance). KOGAS has been considered the CO₂ separation technologies to SCV facilities in terms of the application site limitation and capture cost. Membrane gas separation process could be the solution to reduce CO₂ emission in KOGAS process. Therefore, the fundamental study of membrane gas separation process has been carried out to set basic operation conditions. KOGAS is emitted GHG not only CO₂ but also CH₄ from boil off gas (BOG) which is mainly generated in summer season. The BOG is treated by combustion process. As a result, CO₂ is generated by the combustion of BOG and it should be captured as well.

D29 High performance electrochemical structures for power generation and oxygen separation, Ralph A Bauer (Global Research and Development Inc.)*

Traditional inorganic ion conducting layer approaches to fuel cell power generation have hampered the solid oxide fuel cell's development and practicality in numerous applications. It has long been understood that thinning these layers is critical to overcoming the technical hurdles facing the technology. Recent work at Global Research and Development Inc. and the Ohio State University has developed a readily scalable fabrication methodology, that allows economic and reproducible formation of <200nm thick layers of metallic and oxide layers. Fabricated nano-layered solid oxide fuel cells have shown high power densities, long operational lifetimes while operating at <600C. Further a similar nano-layered electrochemical cell has been designed for the pumping of oxygen and has shown output ~100X above the state of the art electrochemical oxygen pumps.

D30 Techno-economic comparison of RO and MD for small-scale brackish water desalination, Haamid S Usman (Concordia University)*; Khaled Touati (Concordia University); Saifur Rahaman (Concordia University)

Membrane Distillations (MD) is a promising separation technology that can contribute to reduce the world-wide water-energy stress that our globe is facing. Its ability to use low-grade thermal energy is a potential advantage that attract the interest of research and makes of it one of the emerging technologies that may reduce the energy consumption of water desalination. Reverse osmosis (RO) is still considered as the best energy-efficient seawater desalination technique. However, for low scalability, RO is also criticized in term of cost-effectiveness. In the current work, we aim to compare the cost-effectiveness of MD and RO during brackish water desalination for a small-scale plant. For that, a techno-economic analysis was performed for both technologies to determine the cost of desalinated water using a desalination plant capacity of 100 m³/hr. It was assumed that MD is integrated with photovoltaic solar power technology, which provides an alternative source of energy to fossil sources. Capital cost (CapEX) and operation cost (OpEX) were calculated for each sub-system (i.e., intake, pre-treatment, RO separator, post treatment, and outfall) under real operational conditions. The cost breakdown results conclude that, even though the cost of water using RO system is still cheaper, MD can compete with RO for desalination plant with low capacity, if more technological improvements in membrane and heat recovery efficiency are brought to the system.

D31 Tailor-made amphiphilic copolymer membranes for efficient gas and water vapor transport, Faheem Hassan Akhtar (King Abdullah University of Science and Technology)*; Klaus-Viktor Peinemann (King Abdullah University of Science and Technology)

Membrane-based dehumidification is a critical, energy intensive and crucial process for several industries, e.g., air conditioning and flue gas dehydration. Various PEG-based membranes have been shown to have excellent water vapor/N₂ selectivity, but these membranes suffer from low permeabilities and mechanical strength. Herein, we demonstrate high-performance membranes for water vapor and CO₂ separation based on novel amphiphilic copolymers. We have synthesized ternary amphiphilic copolymers comprising PAN, PEGMA and PDMAEMA segments via an economical and facile free radical polymerization. These membranes are mechanically-robust, and water vapor permeability and selectivity are enhanced by the chain-length and content of PEGMA segments. In all the varying concentrations of PEGMA segments, a substantive improvement in water vapor permeability is observed with very high vapor/N₂ selectivities. Optimized PEGMA segments yield very high CO₂/N₂ and CO₂/CH₄ selectivities with an enhanced CO₂ permeability. The reason for this superior gas and water vapor separation performance will be discussed in detail during my presentation.

D32 High-Temperature and High-Pressure Permeability-Selectivity Upper Bounds for Gas Separation Membranes Prepared From High Performance Polymers, Edson V Perez (The University of Texas at Dallas)*; Kenneth Balkus, Jr. (The University of Texas at Dallas); John Ferraris (University of Texas at Dallas); Inga Musselman (The University of Texas at Dallas)

The performance of polymer membranes for gas separations is currently measured in terms of their ability to surpass the permeability-selectivity upper bound (Robeson plot). The current Robeson plot (L.M. Robeson, J. Membr. Sci. 2008, 320 (1-2), 390-400) uses data from membranes tested at 35°C and <5 atm and is, therefore, limited to membranes tested under these conditions of temperature and pressure. There is, however, the need to measure the performance of membranes for gas separations at higher temperatures and higher pressures, conditions at which there is not an available upper bound due to limited published data. In this project, several membranes from high performance polymers (e.g., VTECTM, Matrimid® 5218, polybenzimidazole, 6FDA-DAM) were cast, annealed at 300°C, and tested for H₂, CO₂, and N₂ gas permeation at temperatures of 35, 100, 200, and 300°C and at pressures of 5 and 30 atm. The high-temperature permeability-selectivity upper bounds for H₂/CO₂, defined from these data, are located above the 35°C bound (L.M. Robeson, J. Membr. Sci. 2008, 320 (1-2), 390-400). The bounds, with constant slope, show an increasing upward shift with increasing temperature. Increasing the feed pressure does not significantly affect the position or slope of the bounds. The results of the study suggest that higher temperatures increase membrane performance, and that there is marginal impact from a change in feed pressure. At the limits of the new bounds lie polybenzimidazole with the highest selectivity and smallest permeability and 6FDA-DAM with the smallest selectivity and highest permeability.

- D33 Synthesis and Characterization of Anion Exchange Membranes based on Semi-Crystalline Poly(Ethylene-block-Styrene-block-Ethylene) Triblock Copolymer**, Carrie Trant (Rensselaer Polytechnic Institute)*; Chulsung Bae (Rensselaer Polytechnic Institute); Sangwoo Lee (Rensselaer Polytechnic Institute)

The ability of polymer-based ion exchange membranes to efficiently transport ions is important in a wide range of electrochemical energy applications including fuel cells, batteries, and electrolyzers. To better understand the impacts of microstructured morphology on water uptake and the formation of hydrated ion conducting channels to aid ion conductivity, we investigated the effects of polydispersity and ion exchange capacity (IEC) on the microscopic and macroscopic structures and the performance of the semi-crystalline poly(ethylene-b-quaternized styrene-b-ethylene) (ESE) triblock copolymer-based alkaline anion exchange membranes (AAEMs). The quaternary ammonium group functionalization of the styrene middle block was quantitatively controlled by acid-catalyzed Friedel-Crafts bromoalkylation reaction followed by amination with trimethylamine to synthesize membrane materials with a range of IECs of 0.64 to 1.89 meq/g. Our results suggest that strongly-segregated microdomains without a long-range order are desirable for membrane processing and performance compared to the other membranes with anisotropic lamellar morphology.

- D34 Effect of Polyvinylamine Content on the CO₂ Separation Performance of Facilitated Transport Membranes**, James S Baker (U.S. Department of Energy National Energy Technology Laboratory)*; Victor A Kusuma (U.S. Department of Energy National Energy Technology Laboratory); David Hopkinson (U.S. Department of Energy National Energy Technology Laboratory)

Polyvinylamine (PVAm) is one of the most commonly studied facilitated transport polymers for CO₂ separation membranes due to its high-density of amine groups (carriers) and excellent film forming properties. The most common route to prepare PVAm is to first synthesize poly(N-vinylformamide) (PNVf), followed by acid or base hydrolysis to yield PVAm. The hydrolysis is typically not conducted to full conversion; therefore, the product polymer is a random copolymer of PVAm and PNVf repeat units. Since PVAm is a more effective CO₂ carrier than PNVf, it would seem logical to maximize conversion to PVAm to maximize the density of carrier sites within the polymer. However, several researchers have suggested that high degrees of conversion to PVAm can result in a decrease in CO₂ permeability, possibly due to formation of crystalline domains within the polymer film. To date there have been no systematic studies in the open literature confirming this trend. We are conducting a rigorous examination of the effect of PVAm content in the copolymer upon the CO₂ permeability and CO₂/N₂ selectivity for the polymer films. PNVf from a single batch of polymer was hydrolyzed to varying degrees of PVAm content, deprotonated to pH 11, and free-standing films of 20-30 microns dry thickness were cast for gas permeation and mechanical property testing. Gas permeability of the films was tested with humidified (95% RH), mixed feed gas (1.38 bar, 14: 86 CO₂: N₂) at 60°C. Moderate levels of PVAm content yielded the highest CO₂ permeability and selectivity, with 52 mole % PVAm films having a mean CO₂ permeability of 386 barrer and a CO₂/N₂ selectivity of 89. Polymers containing 0, 20, 42, and 76 mole % PVAm had CO₂ permeabilities of 161, 279, 349, and 249 barrer and selectivities of 36, 48, 79, and 49, respectively. We are using X-ray diffraction (XRD) of the polymer films to determine if there is a correlation between polymer composition and degree of crystallinity.

- D35 Effect of organic ballast properties on the energy efficiency of a concentration gradient flow battery**, Fei Liu (University of North Carolina at Chapel Hill)*; Ryan Kingsbury (Membrion, Inc.); Jeromy Rech (University of North Carolina at Chapel Hill); Wei You (University of North Carolina at Chapel Hill); Orlando Coronell (University of North Carolina at Chapel Hill)

A concentration gradient flow battery is a membrane-based system for storing clean energy (Kingsbury 2016, van Egmond, 2016). The concentration battery operates through a combination of an electrodialysis (ED) stage where energy generated from renewable resources is used to produce highly concentrated brine and dilute solution, and a reverse electrodialysis (RED) stage where the brine and dilute solutions are mixed to generate power. However, the non-ideal transport of water through the membrane by osmosis has a substantial negative impact on the power density and faradaic efficiency of the battery. A promising approach to mitigate osmosis is to use uncharged osmotic ballasts in the dilute solution to balance the osmotic pressure and significantly reduce faradaic energy losses. The objective of this study is to investigate the effect of ballast size, orientation (linear vs cyclic), and end group on the energy efficiency of a concentration battery. To accomplish this objective, we tested 7 sugars and 5 glycol-based compounds as osmotic ballasts in a closed-loop ED/RED cell. Our results show that the ballasts with higher molecular weight generally resulted in higher efficiency and lower water transport. We also observed that the glycol-based ballasts with asymmetric end groups had lower water transport compared to those with symmetric end-group. We also found that glycol-based ballasts resulted in lower open circuit voltage and water transport than sugar ballasts. Overall, the best performing ballast was triethylene glycol monomethyl ether, reducing osmosis by 128% at a faradaic energy efficiency of 53%. These findings contribute to the fundamental understanding of the effect of ballast physical and chemical properties on the performance of salinity gradient batteries and provide useful guidelines for optimizing osmotic ballasts. Our findings may also benefit other closed-loop energy processes such as RED systems for waste heat recovery and redox flow batteries.

SESSION D - Innovation in Membranes for Energy Applications

E1 Feasibility of long-term treatment of malting wastewater in a submerged anaerobic membrane bioreactor (SAnMBR) at psychrophilic temperature conditions, Esmat Maleki (Lakehead University)*; Baoqiang Liao (Lakehead University)

Malting wastewater that is discharged from the steeping step of malting plants has a low temperature ranging between 14°C and 18°C in Canada. Currently, most malting plants discharge their wastewater to the municipal water treatment plant and pay high discharge fees. Aerobic treatment of this wastewater doesn't recover its resources content. Malting wastewater is rich in nutrients and has high soluble COD content. Hence, it is a good candidate for the anaerobic treatment that converts the COD of wastewater to biogas. Anaerobic membrane bioreactor (AnMBR) technology is capable of recovering both energy and nutrients resources from this waste stream. However, operation of anaerobic bioreactors in low temperature slows down the biomass growth rate and hinders the hydrolysis reactions. Hence, most industrial plants consume energy to warm up their wastewater and operate their AnMBRs at mesophilic conditions which is costly. Operating the AnMBR at low temperatures could save energy and reduce the operational costs. It is necessary to evaluate performance of AnMBR technology at psychrophilic temperatures before its industrial scale implementation. Therefore, this study investigated the feasibility of long-term operation (376 days) of a submerged anaerobic membrane bioreactor for treating malting wastewater at psychrophilic conditions (21-16°C) and resource recovery in the form of biogas and nutrients. High COD removal efficiency of 92.58±1.44% was achieved, and the average biogas yield was 0.25±0.05 L at STP/g CODremoved. Moreover, the permeability of the fouled membrane was recovered up to 56.9% after physical cleaning, 80.0% after basic-chemical cleaning, and 89.8% after acidic-chemical cleaning. The results of this study proved the feasibility of treating malting wastewater at psychrophilic conditions in a submerged anaerobic membrane bioreactor.

E2 Biofouling in ultrafiltration process for drinking water treatment and its control by chlorinated-water and pure water backwashing, Shao Senlin (The University of Hong Kong)*

We investigated biofouling in ultrafiltration (UF) for drinking water treatment and its control by backwashing with chlorinated-water or pure water. By using sodium azide to suppress biological growth, the relative contribution of biofouling to total fouling was estimated, and its value (5.3-56.0%) varied with the feed water, and increased with the increases of filtration time and membrane flux. The biofouling layer could partially remove biodegradable organic matter and ammonia (32.9-74.2%). Backwashing using chlorinated-water partly inactivated the microorganisms (23.8%) but increased the content of extracellular polymeric substances (7.7%) in the biofouling layer. In contrast, backwashing using pure water led to a looser and more porous fouling layer according to optical coherence tomography observation. Consequently, the latter was more effective in reducing fouling resistance (33.41% reduction) compared to backwashing by chlorinated-water (8.6%). These findings reveal the critical roles of biofouling in pollutants removal in addition to membrane permeability, which has important implications for addressing seasonal ammonia pollution.

E3 Membrane Distillation of High Salinity Water by Induction Heated Thermally Conducting Membranes, Avner Ronen (Temple University)*; Arezou Anvari (Temple University)

Membrane Distillation (MD) has been gaining interest in the recent decade as a method for providing desalinated water from several water sources including high salinity water and produced water. The method has gained popularity due to the low required pressure, especially when the osmotic pressure makes membrane desalination such as RO uneconomic. MD is a thermally driven process in which the vapor pressure gradient over the porous hydrophobic membrane leads to the transport of water vapor. To ensure an efficient driving force, the feed solution is continuously heated, leading to a substantial energy requirement as most of the heat is not directly used due to a limited surface area and mass transport limitations. We suggest a novel approach which heats only the membrane-water interface through inductive heating (IH). Thus, significantly decreasing the required energy and increasing the permeate flux while mitigating inorganic scaling and the influence of high salinity such as found in produced water. Carbon nanotubes coated iron nanoparticles (CNT-Fe) membrane with high thermal conductivity are fabricated through spraying on a PTFE base support and the heating is done by exposing the CNT-Fe membranes with an iron loading of about 45 Wt.% to a high-frequency magnetic field. Preliminary results show the ability of heating water directly on the surface of the membrane to a boiling temperature in a matter of seconds by exposing the CNT-Fe membrane to an electromagnetic field at a fixed frequency (283 kHz). The heating ability was found to be related to the loading of CNT-Fe on the base support and the feed flow rate. In addition, permeate flux from the IH-MD system was found to be significantly higher than conventional MD systems and the flux increased with increasing feed salinity. Inorganic fouling (e.g. CaSO₄), which typically leads to a flux decline in MD systems had almost no impact on the IH-MD system flux.

E4 Bromide Removal from Drinking Water Source Impacted by Energy Wastewater Discharge Using Electrically Conductive Membranes, Avner Ronen (Temple University)*; Mei Sun (University of North Carolina at Charlotte); Kartikeya Kekre (Temple University)

In recent years, wastewater discharges from the energy industry, including coal-fired power plants equipped with wet flue-gas desulfurization units and from shale gas extraction, have been identified as contributors to elevated bromide concentrations in several watersheds across the United States. Bromide reacts with drinking water disinfectants and dissolved organic matter to form DBPs in downstream drinking water system. Elevated bromide levels have been one important cause of compliance violation of DBP regulations across the US. In this research, we developed and evaluated a membrane-based electrooxidation process to remove bromide from impacted drinking water sources. The electrooxidation takes place on carbon nanotubes-based electrically conductive membranes (ECM) and uses an external potential applied on the membrane surface to oxidize bromide during filtration. We initially tested the oxidation using cyclic (CV) and linear voltammetry (LV) which allowed us to detect bromide oxidation at an anodic potential of 1-1.1V against a silver/silver chloride reference electrode. As these reactions occur when the contaminated solution is in contact with an electrode, which has a limited surface area and limited mass transport, bromide removal rates were relatively low. The anodic potential at that range did not impact membrane electrical conductivity which remained stable following 24 hours of applied potential. Next, a similar approach was evaluated using the membrane in a cross-flow filtration cell. As there is no diffusion limitation due to the convective transport in filtration, removal rates were very fast following a contact time of 1-3 seconds flow through the membranes. Applying a whole cell potential of 2.5V with the ECM serving as the anode allowed continues removal of about 60% of the bromide from the permeate stream in a single pass while additional removal was detected at the concentrate stream.

E5 A surface modification of forward osmosis (FO) membranes to enhance dye retention and fouling resistance for the treatment of textile wastewater, Sara Azari (Sterlitech)*; Mohammad Karimi (Amirkabir University of Technology)

Dye containing wastewaters are generated in large volumes in the textile industry and due to their toxicity to all forms of life, they are a major environmental challenge if not treated properly. Due to their high solubility in water and non- biodegradability, conventional treatment methods are unable to effectively remove or degrade the dye molecules. Membrane processes are alternative technologies that are commonly applied for tertiary treatment of dyeing wastewater. In this project forward osmosis membrane process was studied for treating/concentrating dye containing wastewaters. CTA and TFC FO membranes from HTI Water were tested in bench top FO test cells. Our initial results showed 10-15% and 12-20% flux decline due to fouling for CTA and TFC FO membranes, respectively. Moreover, diffusion of dye molecules into the membrane polymer structure and its penetration to the draw solution was noted. These observations may affect long term stability and efficiency of FO membranes to produce colorless permeates. Here we present a facile surface modification using L-Dopa to increase dye retention and to reduce membrane fouling. Membranes were coated on the active side using L-DOPA. Contact angle and zeta potential measurements showed higher hydrophilicity and higher negative surface charge of the modified membranes. While the membrane flux remained almost intact, surface modified membranes showed better antifouling properties, as indicated by flux decline with operating time. An improvement in dye retention by modified membranes was also observed. Such an improvement in the performance, can be explained by more hydrophilic nature of the modified membrane and electrostatic repulsion between charged molecules of the dye and the membrane surface. This surface modification can be performed in situ, i.e. in the original module assembly post-manufacturing process, making this approach very interesting from point of view of practicality in larger scale systems.

E6 Evaluation of surface, bulk and electrochemical properties of $Ti_3C_2T_x$ membranes used for selective ion removal from brine., Yousuf Z Bootwala (Georgia Institute of Technology)*; Wahiduz Zaman (Vanderbilt University); Kelsey Hatzell (Vanderbilt University); Marta Hatzell (Georgia Institute of Technology)

Transition metal carbides, carbonitrides, and nitrides or MXenes represent a large family of 2D materials derived from a class of ternary ceramic materials known as MAX described by the general formula $Mn+1AX_n$ where $n=1,2,$ or 3 and M represents an early transition metal, A is a group A element, X is carbon and/or nitrogen. MAX phase materials are layered hexagonal materials with $P6_3/mmc$ symmetry and are composed of metal carbide and/or nitride layers ($Mn+1X_n$) twinned with respect to each other and separated by an A-layer (Naguib et al). There are approximately 70 known MAX phases that have been experimentally produced and have numerous potential applications. More recently, they have attracted interest for both gas and aqueous phase separations due to their high stability in aqueous environment, flexibility, high surface area and conductivity (Ren et al). This includes organic contaminant removal from water, energy storage and gas separation (Ren et al). The layered structure of MXene allows the inter-layered spacing to be tuned to allow rejection of selective ions based on their size and charge. When compared to graphene oxide membranes, MXene membranes have higher water flux due to 2-3 layers of water molecules in the spacing between the layers (Ren et al). Here, we will explore the surface and bulk properties of pristine $Ti_3C_2T_x$ membranes, and $Ti_3C_2T_x$ membranes with ion based intercalants (K^+ , Li^+). In situ surface science (ambient pressure XPS and FTIR) will be presented in various relevant conditions (e.g. temperature, relative humidity). In addition, the electrochemical properties of the membranes (conductivity, resistance, capacitance) will be presented. Finally, experimental insight into salt base separations will be

presented. 1. Naguib, M. et al. 25th Anniversary Article: MXenes: A New Family of Two-Dimensional Materials. *Adv. Mater.* 26, 992-1005 (2014). 2. Ren, C. E. et al. Charge- and Size-Selective Ion Sieving Through $Ti_3C_2T_x$ MXene Membranes. *J. Phys. Chem. Lett.* 6, 4026-4031 (2015).

E7 Microwave-enhanced Membrane Filtration for Water Treatment, Wanyi Fu (New Jersey Institute of Technology)*; Wen Zhang (New Jersey Institute of Technology)

Sustaining high flux (permeability) and diversified pollutant rejection (selectivity) are two crucial benchmarks for membrane filtration processes. Here, we report a microwave-enhanced membrane filtration process that uses microwave (MW) irradiated and catalyst-coated ceramic membranes to achieve efficient removal of pollutants (i.e., 1,4-dioxane) and significant mitigation of fouling. MW irradiation was selectively absorbed by catalysts and hydrogen peroxide to produce "hotspots" on membrane surface that promoted generation of radicals and nanobubbles. These active species enhanced pollutant degradation and further prevented membrane fouling. In contrast to ultrasound and ultraviolet radiations, MW could efficiently penetrate membrane housing materials and selectively dissipate energy to membrane-impregnated catalyst nanoparticles. Our study of MW-assisted membrane filtration processes may open new avenues toward next-generation antifouling and high-efficiency separation techniques.

E8 Application of Nanofiltration (NF) Membranes for Perfluoroalkyl and Polyfluoroalkyl substances (PFAS) Removal, Daniel G Kulas (Michigan Technological University)*; Andre da Costa (Michigan Technological University); Ananya Ananya (Michigan Technological University); Sam Jacobs (Michigan Technological University)

Perfluoroalkyl and Polyfluoroalkyl substances (PFAS) are an emerging and extremely pervasive contaminant with a potentially high health risk. They are currently being found throughout the United States in ground and surface waters. At least one city's drinking water, Parchment MI, was found to contain PFAS above the EPA's limit of 70 ppt, forcing them to switch to an alternative water source. In all likelihood more cities will soon find themselves in the situation of having unsafe drinking water due to PFAS as testing increases. It is thus essential for sustainable solutions to be developed for the safe removal of PFAS from water. We will present an evaluation of membranes as a sustainable solution for the removal of PFAS from water in a drinking water treatment process. Past research has shown that nanofiltration (NF) membranes are capable of removing PFAS from pure water, however no study has looked at removing PFAS from a real water source. We are testing several commercial NF membranes in a range of MWCO from 200-1000 Daltons with sample water from Parchment MI containing a PFAS concentration of 30,000 ppt. All experiments are being performed in a stirred cell dead-end filtration system. We are also investigating the effect of contact angle and surface energy on PFAS rejection. The water's hardness is being varied to determine its effect on PFAS rejection was also tested in the presence of hardness and chlorine to determine potential placement points within the water treatment process. Results will be presented on both the PFAS rejection and flux of commercial NF membranes.

E9 Development of membrane synthesis and novel draw materials for forward osmosis process, Yusak Hartanto (Katholieke Universiteit Leuven)*

Thin-film composite forward osmosis (TFC-FO) membrane prepared by interfacial polymerization utilizes organic solvents which often have serious environmental and human health impacts. Furthermore, highly volatile nature of these solvents also increases membrane manufacturing cost due to significant solvent evaporation. Ionic liquid (IL) is proposed as organic phase to replace hexane in interfacial polymerization of polyamide layer. The resultant TFC-FO membrane prepared using IL has similar performance in terms of its water flux and reverse salt flux. This innovative method represents a step towards greener and more sustainable membrane preparation process. Another important aspect of forward osmosis (FO) technology is draw materials development. Thermo-responsive hydrogels are semi-solid FO draw materials which have potential to solve the problems of inorganic salts when used as draw solute materials. These hydrogels are often copolymerized with ionic comonomers to improve their water drawing ability. However, the water release ability of these hydrogels is hampered by the presence of ionic moieties within the hydrogel networks. Non-ionic copolymer microgels are recently proposed as novel FO draw materials which are able to overcome the ionic contribution of ionic thermo-responsive copolymer hydrogels/microgels

E10 3D Printed Self-Assembled Zwitterionic Copolymer Membranes, Xin Qian (University of Connecticut)*; Samuel J Louder (Tufts University); Ayse Asatekin (Tufts University); Jeffrey R McCutcheon (University of Connecticut)

Zwitterionic copolymer self-assembled membranes have been shown to have impressive selectivity for nanofiltration applications. Conventional approaches used to fabricate these asymmetric membranes, however, typically result in thick selective layers being formed that can limit permeance. In this work, we evaluate the use of electrospray to print thin layers of amphiphilic zwitterionic selective layers onto UF membrane substrates. Dyes with different sizes are used to probe the selectivity of these membranes while their thickness is reduced by orders of magnitude compared to casting methods. As thickness is decreased, water permeance was found to proportionally

increase while dye selectivity was maintained. While it was found that a threshold minimum thickness was required to maintain selectivity, we also found that the intrinsic permeability of the polymer films was changed as a function of thickness. Annealing the membranes was found to increase permeance as well without a significant loss of selectivity. Notably, one of our annealed ultra-thin TFC membranes was found to exhibit a water permeance value of 205LMH/bar and a Chlorophyllin rejection at 99.67%. Interestingly, this permeance is indistinguishable from the supporting UF membrane permeance, suggesting that even higher permeance without selectivity loss is possible.

E11 Antifouling and Antiwetting Janus Membrane for Treating Hypersaline Oily Wastewater by Membrane Distillation, Chenxi Li (University of British Columbia); Xuesong Li (University of British Columbia); Xuewei Du (Colorado State University); Tiezheng Tong (Colorado State University); Tzahi Cath (Colorado School of Mines); Jongho Lee (University of British Columbia)*

We present a novel approach to fabricate a robust Janus membrane with excellent wetting and fouling resistances for treating highly saline oily wastewater through membrane distillation (MD). An omniphobic membrane was first fabricated by grafting silica nanoparticles (SiNPs) on the nanofibers of a quartz-fiber mat, creating multi-level re-entrant structures, followed by surface fluorination to reduce the surface energy. The Janus membrane was then fabricated by grafting a zwitterionic polymer brush layer via surface-initiated atom-transfer radical-polymerization (ATRP) on the omniphobic substrate. Membrane characterization, including fluorescence microscopy, Fourier-transform infrared spectroscopy, and contact angle measurement, confirms that the surface hydrophilicity can be precisely controlled by tuning the ATRP reaction duration. The brush layer was confined on the top surface of Janus membrane, rendering the surface hydrophilic. Still, the rest part of the membrane remained omniphobic, resisting the wicking of low-surface-tension liquids including ethanol and hexane. A static oil fouling test using a crude oil showed that oil droplets were readily adsorbed on the omniphobic membrane surface in water. In contrast, oil droplets that were placed on the Janus membrane came off from the membrane surface when it was immersed in water, proving the effective oil fouling resistance. Finally, we performed direct-contact MD experiments using a surfactant-stabilized crude oil-in-saline water (1M NaCl) emulsion as a feed solution, which mimics industrial hypersaline oily wastewater. The results show that the Janus membrane exhibits superior wetting and fouling resistances compared to the omniphobic membrane, maintaining a stable water flux and nearly perfect salt rejection over a 12-hour MD test. Our work highlights the great potential of MD using antiwetting and antifouling Janus membranes for water reclamation from hypersaline industrial wastewaters.

E12 Treating Hydraulic Fracturing Produced Waters by Membrane Distillation, Ranil Wickramasinghe (University of Arkansas)*

Membrane distillation is an emerging technology for treating hydraulic fracturing flow back and produced waters (PW). These wastewaters are highly impaired often containing over 100,000 ppm dissolved salts as well as polar and non-polar organic compound and low surface tension compounds. Membrane stability is often limited for these highly fouling feeds. Typically, hydrophobic membranes are used. However, adsorption of organic compounds and low surface tension compounds must be minimized in order to minimize flux decline and breakthrough of the water. We have investigated the feasibility of using direct contact membrane distillation (DCMD) to treat real PW using commercially available polypropylene, polyvinylidene fluoride, and poly(ethylene chlorotrifluoroethylene) membranes. Two approaches have been used to improve membrane stability; pretreatment of the feed and modification of the membrane surface. Feed streams were pretreated using electrocoagulation. Electrocoagulation reduced the total suspended solids (TSS), total organic carbon (TOC) and turbidity by ~84, ~75 and ~89% respectively. This resulted in lower membrane fouling and consequently, lower flux decline during DCMD. Long-term experiments were conducted, concentrating the feed water, containing 135 g L⁻¹ TDS, up to 265 g L⁻¹. Development of fouling-resistant membrane surfaces is essential to minimize pretreatment costs and suppress the breakthrough of water. However, the development of economically viable membrane surface modification protocols will be essential. Here we have modified base membranes by grafting a variety of polymers (hydroxyethylmethacrylate, acrylic acid, polyionic liquids, zwitterionic groups) using UV initiated polymerization. In addition, surface oxidation of the membrane has been conducted using KMnO₄ and NaOH. Our results indicate that by modification of the membrane surface the overall fouling resistance can be enhanced leading to lower electrocoagulation requirements.

E13 Synthesis of Polystyrene-b-poly(solketal methacrylate) (PS-b-PSMA) Polystyrene-b-poly(glycerol methacrylate) (PS-b-PGMA) Block Copolymers for Isoporous Membranes, Sarah Saleem (Helmholtz-Zentrum Geesthacht); Sofia Rangou (Helmholtz-Zentrum Geesthacht); Clarissa Abetz (Helmholtz-Zentrum Geesthacht); Brigitte Lademann (Helmholtz-Zentrum Geesthacht); Volkan Filiz (Helmholtz-Zentrum Geesthacht)*; Volker Abetz (Helmholtz-Zentrum Geesthacht)

Block copolymers are well known for the formation of many microphase separated morphologies depending on the architecture of the block copolymer(s) involved, molecular weight, composition and thermodynamic properties. Anionic living polymerization provides a way to the creation of well-defined block copolymers by the sequential addition of monomers. It is mostly used to synthesize block copolymers with controlled compositional and structural parameters such as molecular weight, narrow molecular weight distribution, copolymer composition, branching, and other architectural parameters. In this work; we compare double hydrophobic polystyrene-b-poly(solketal

methacrylate) (PS-b-PSMA) and amphiphilic polystyrene-b-poly(glyceryl methacrylate) (PS-b-PGMA) diblock copolymer membranes which are prepared by combining the block copolymer self-assembly in solution with a non-solvent induced phase separation (SNIPS)¹. Diblock copolymers (i.e., PS-b-PSMA) were synthesized by sequential living anionic polymerization, whereas polystyrene-b-poly(glyceryl methacrylate) (PS-b-PGMA) were obtained by acid hydrolysis of the acetonide groups of the polysolketal methacrylate (PSMA) blocks into dihydroxyl groups (PGMA). Membrane structures and bulk morphologies were characterized by scanning electron microscopy (SEM) and transmission electron microscopy (TEM); respectively. The resulting PS-b-PGMA diblock copolymers produce an ordered hexagonal cylindrical pore structure during the SNIPS process, while membranes fabricated from the double hydrophobic (PS-b-PSMA) do not under similar experimental conditions. Membrane performance was evaluated by water flux and contact angle measurements.

E14 Uranium isolation and concentration using reactive membranes for nuclear forensics applications, Abenazer W Darge (Clemson University); Timothy DeVol (Clemson University); Scott Husson (Clemson University)*

This presentation describes the development of reactive membranes for the isolation and concentration of uranium from circumneutral pH solutions by ultrafiltration (UF). Polyethersulfone (PES) UF membranes were modified by grafting uranium-selective polymer films from surface of the membrane via UV-initiated polymerization. The resulting uranium-selective membranes (USMs) were used as a substrate for direct alpha spectrometric analysis of bound uranium isotopes. To guide membrane synthesis, we studied growth kinetics of the selective polymer film by measuring thickness as a function of UV-irradiation time using ellipsometry with a model PES substrate that simulates the surface of USMs. Alpha spectroscopy pulse height spectra were analyzed to determine the optimal selective layer thickness that would result in the highest uranium uptake without sacrificing energy resolution. Batch uptake experiments were conducted to determine uranium binding capacity of USMs at different concentrations. Flow through uptake experiments were conducted to identify the residence time for optimum detection efficiency at selected pH values. Results from this work are being used to develop a detection method for the rapid analysis of radionuclides in water using a field portable device, which would be a powerful nuclear forensics tool.

E15 Development of Nano-enabled Membrane Technology for Water Reuse in Agriculture, Xingmao Ma (Texas A&M University); Yinghao Wen (Texas A&M University)*; Jieming Yuan (Texas A&M University)

Due to water contamination and increased water demand for clean fresh water, conventional water supply is insufficient to meet all societal needs. Alternative sources such as treated effluents from wastewater treatment plants, brackish groundwater must be explored to augment current water supply. The need for alternative sources is particularly strong for the agricultural sector due to its vast water needs. Desalination can be a powerful technology to treat polluted water for water reuse in agriculture. Challenges in water reuse for agriculture include adequate removal of pollutants to ensure food safety, but not to over-treat the source water to remove essential nutrients. The technology for such purpose also needs to be cost effective and is suitable for large scale use. Therefore, there is a critical need for the membrane community to develop both highly permeable and selective membranes for water desalination. We investigated the effectiveness of nanoparticles enhanced ultrafiltration for water reuse in agriculture and compared the effectiveness of the newly synthesized membrane with several conventional ultrafiltration and nanofiltration membranes, using a synthetic wastewater effluent as our source water. The results demonstrate strong potential for the applications of membrane desalination in water reuse for agriculture.

E16 Detection of Electrically Conductive Membrane Fouling by Impedance Spectroscopy, Nan Zhang (McMaster University)*; Charles-François de Lannoy (McMaster University)

Monitoring membrane fouling is critical for the onset of fouling detection and effective fouling removal in ultrafiltration process. This work investigates the use of electrochemical impedance spectroscopy (EIS) on the surface of electrically conductive membranes to precisely measure the onset of surface fouling. An electrochemical cell was developed in which an electrically conductive membranes acted as a working electrode and a graphite electrode acted as the counter electrode. Conductive membranes were fabricated by coating single-walled/double-walled carbon nanotubes (SW/DWCNT) on polyethersulfone (PES) supporting membranes. Membrane fouling was simulated by pressure depositing different amounts of latex beads onto the surface of the membrane in a dead-end filtration cell. Changes in membrane permeance were measured to correlated fouling amount. Clean membranes had a permeance of 392 LMH/bar. Reduction to membrane permeance of 9.1%, 9.2%, 17.1% and 20.6% were observed for membranes covered with 0.028mg/m², 0.28 mg/m², 1.40 mg/m² and 2.80 mg/m² (approximately equivalent to 1/10, 1, 5, and 10 latex layers on the membranes), respectively. These small changes were statistically resolvable in Nyquist plots. It was observed that the higher frequency (103 ~ 106 Hz) diameter of the semicircle in Nyquist plots increased with greater fouling, while the impedance in the diffusion region (1 ~ 103 Hz) decreased with increased latex fouling. These observations were hypothesized to correspond to exposure area of conductive layer decline and negative-charged fouling particles accumulation at the interface. The interpretation for fouling layer formation was proposed by fitting EIS results with a proper equivalent circuit. Morphology of fouled membranes, surface conductivity, surface hydrophilicity, and pore size were measured by SEM, four-point probe conductivity analysis, contact angle measurements, and MWCO experiments, respectively.

E17 Stability of Polyamide Nanofiltration Membranes with Peracetic Acid/Hydrogen Peroxide Disinfection, Mohsen Ghafari (State University of New York at Buffalo)*; Boya Xiong (MIT); Ning Dai (State University of New York at Buffalo)

Chlorine is a conventional and effective disinfectant for biofouling control, but it reduces the lifetime of polyamide membranes. Peracetic acid/hydrogen peroxide (PAA/H₂O₂) mixture has been or proposed as a low-cost alternative disinfectant in wastewater treatment plants, but yet the impact on polyamide membranes has not been investigated at a mechanistic level. In this work, we compare the chemical mechanism of polyamide incubated with PAA/H₂O₂ mixture and chlorine. We demonstrate that PAA/H₂O₂ as a disinfectant with comparable anti-microbial activity to chlorine is capable of maintaining chemical properties and performance of polyamide membranes. The water flux and salt rejection of commercial flat sheet DOW NF90 membranes were monitored using a dead-end filtration cell after the exposure to PAA/H₂O₂ and NaOCl (100-24000 ppm-h) at pH=6.5. Results showed that PAA/H₂O₂ mixture was less detrimental to the membrane than chlorine. Water flux decreased by 18% after ~18000 ppm-h exposure to PAA/H₂O₂ mixture compared to 67% decrease after ~4000 ppm-h exposure to chlorine. In FTIR analysis, disappearance of the amide II and aromatic amide vibration peaks at 1541 and 1609 cm⁻¹, respectively, indicated the cleavage of amide cross-links in the membrane treated with chlorine. In contrast, no such change was observed for PAA/H₂O₂ treated membrane. Membrane treated with ~18000 ppm-h PAA/H₂O₂ increased surface hydrophilicity based on water contact angle measurements (62 to 46), while those treated with chlorine showed an initial increase and then a decrease in water contact angle, likely due to initial chlorination of -NH- and aromatic ring and subsequent degradation of amide groups to amine and carboxyl groups with continued chlorine exposure. Further characterizations including XPS, SEM, and AFM will be carried out to elucidate the mechanism. Findings will inform appropriate conditions to enable an effective biofouling control with maximized polyamide membrane lifetime.

E18 Fouling-Resistant Two-Dimensional (2D) Covalent Organic Framework Membranes for Industrial Water Reuse, Phuoc Duong (University of Wyoming); Valerie Kuehl (University of Wyoming); Mohammad Afroz (University of Wyoming); John Hoberg (University of Wyoming); Bruce Parkinson (University of Wyoming); Katie D Li-Oakey (University of Wyoming)*

Membranes with high permeability, selectivity, and fouling resistance provide significant advantages in water reuse and purification such as low consumption of energy, equipment and cleaning costs, and prolong membrane life span. In this study, a new highly porous two-dimensional (2D) covalent organic framework (COF) with carboxylic nanopores of approximately 2.8 nm was synthesized and used to form thin selective layers of composite membranes for shale gas produced water treatment. It is well-known that water transports predominantly through graphene oxide (GO) membranes via an interlayer spacing. In contrast, the high density of hydrophilic nanopores of the COF reported in this study allows for facile water transport primarily through the pores, resulting in a far superior water permeance of ~2260 L m⁻² h⁻¹ bar⁻¹, as compared to ~7.6 L m⁻² h⁻¹ bar⁻¹ for the GO membranes under the same conditions. The COF membrane exhibits excellent performance for treatment of shale gas produced water with an oil rejection of 100% and a total dissolved solid (TDS) removal rate of 25%. In addition, the COF membrane shows enhanced fouling resistance compared to commercially available polymeric membranes.

E19 Reduced-holey graphene oxide(r-HGO) membranes with enhanced water permeance for water purification, Xiaoyi Chen (The State University of New York at Buffalo)*; Liang Huang (The State University of New York at Buffalo); Zhihao Feng (The State University of New York at Buffalo); Janavi Gohil (The State University of New York at Buffalo); Haiqing Lin (The State University of New York at Buffalo)

Reduced-graphene oxide (r-GO) membranes have emerged as a potential candidate for next-generation nanofiltration (NF) applications. However, previously reported r-GO membranes have lower water permeance than polyamide-based NF membranes because of the small 2D channels required to achieve good size-sieving ability. We report here an effective approach in enhancing the water permeance by creating nano-pores on the r-GO nanosheets. Specifically, GO sheets are chemically etched using H₂O₂ to form holey GO sheets, which are then deposited on porous supports before being reduced by HI. The prepared membranes were thoroughly characterized using SEM, Raman Spectroscopy, FTIR, and XRD. The effect of the etching and reduction conditions on the membrane performance is systematically investigated. Increasing the etching time increases the water permeance with slight decrease in the salt rejection rate, while increasing the reduction degree decreases the water permeance and increases the salt rejection. For instance, increasing the etching time from 0 h to 4 h improves the water permeance from 0.4 L m⁻²·h⁻¹·bar⁻¹ to 6.6 L m⁻²·h⁻¹·bar⁻¹ by over 15 times, while the Na₂SO₄ rejection remains at 98.5%. The r-HGO membranes exhibit NF performance comparable with the commercial polyamide-based membranes. For instance, when r-HGO with 4 h etching and a reduction using 34 wt.% HI was fabricated into a 20 nm-thick membrane, it exhibits water permeance of 12 L m⁻²·h⁻¹·bar⁻¹ and Na₂SO₄ rejection of 91.4% at 4 bar and 22°C. We have also prepared multi-layer r-HGO membranes with various degrees of etching and evaluated for NF applications. We will also present the long-term stability test results of these membranes using a crossflow system.

E20 A Comparison of PolarClean, Gamma-Valerolactone and their Mixture as Bio-derived Solvents for Polysulfone Membrane Fabrication, Xiaobo Dong (University of Kentucky)*; Halle Shannon (University of Kentucky); Isabel Escobar (University of Kentucky)

Petroleum-derived solvents used for membrane fabrication through the nonsolvent induced phase separation (NIPS) process are known for their toxicity. One big challenge is that by 2020, some common solvents, N-Methyl-2-Pyrrolidone (NMP) and Dimethylacetamide (DMAc) will be banned by Registration, Evaluation, Authorisation and Restriction of Chemicals (REACH) in Europe[1]. Therefore, bio-derived and low-toxicity solvents are a focus of increasing investigations. Examples of bio-derived, low-toxicity solvents include methyl-5-(dimethylamino)-2-methyl-5-oxopentanoate (PolarClean) and gamma-valerolactone (GVL). PolarClean has been previously used to fabricate polysulfone (PSf) membranes but having membrane pores collapse during membrane cleaning. To address this issue, GVL was investigated as a sole solvent and a co-solvent with PolarClean to fabricate PSf membranes[2,3]. Membranes prepared using GVL as a sole solvent were observed to be gelatinous, hence not ideal for filtration[2]. GVL and PolarClean were used as co-solvents, viable membranes were cast with surface charge and hydrophilicity not being significantly different from membranes made using PolarClean alone. Specifically, the solvent mixture produced PSf membranes with zeta potential values of about -20mV and contact angles at around 65°. Furthermore, the average pore size of membranes decreased from 48nm to lower than 1nm as adding GVL in dope solutions. The membranes prepared using solvent mixtures showed pure water flux at 300-500 LMH and over 99% BSA rejection. Therefore, the use of PolarClean/GVL as co-solvents showed promise for the fabrication of PSf membranes. 1. <https://chemicalwatch.com/22940/reach-clp-hub-authorisation-vs-restriction> 2. Dong, X.; Shannon, H.D.; Escobar, I.C. Green polymer chemistry: New products, processes, and applications, American Chemical Society: 2018; Vol. 1310, pp 385-403. 3. Wang, H.H.; Jung, J.T.; Kim, J.F.; Kim, S.; Drioli, E.; Lee, Y.M. J. Membr. Sci. 2019, 574, 44-54.

E21 Filterability of crude oil emulsions stabilized by COREXIT 9500 dispersant, Seyma Kucuk (Michigan State University); Charifa Hejase (Michigan State University)*; Iryna Kolesnyk (National University of Kyiv-Mohyla Academy); Jia Wei Chew (Nanyang Technological University); Vlad Tarabara (Michigan State University)

During the 2010 Deepwater Horizon oil spill, nearly 800 million liters of oil were released into the Gulf of Mexico polluting the deep ocean and more than 1600 km of the Gulf's shoreline. A large amount (1.84 million US gallons) of dispersant, Corexit 9500A, was applied to the spill; as a result, the oil was emulsified into microdroplets that remained suspended in the water column. Even though small droplets facilitate biodegradation, they can pose significant environmental risks. Membrane filtration is one of the most cost-effective remediation technologies that can remove emulsified oil. Despite extensive studies, mechanisms of membrane separation of emulsified oil remain poorly understood. In the present work, we investigate the impact of salinity on the properties and filterability of crude oil-in-water emulsions stabilized by Corexit 9500A. To our knowledge, this is the first study on membrane filtration of Corexit-stabilized crude oil emulsions. Direct Observation Through the Membrane (DOTM) technique was employed to visualize the droplets in real time on the surface of a microfiltration membrane. Corexit altered both the emulsion stability and the wetting properties of the membranes. Corexit decreased the oleophobicity of the membrane in both DI water and seawater. Emulsion characterization and constant pressure filtration tests indicate that salinity affects the stability of emulsions and can enhance microfiltration performance. Almost complete rejection of oil was achieved, but was accompanied by a precipitous flux decline. The low values of the steady state permeate flux indicate that microfiltration is suitable as a polishing step that follows an extensive pretreatment by large throughput deoiling unit processes such as hydrocyclonic separation or flotation.

E22 Polyamide/CNT Thin Film Nanocomposite (TFN) Seawater RO Membranes with Improved Boron Rejection, Aysa Guvensoy (Istanbul Technical University); Süer Kurklu Kocaoglu (Istanbul Technical University); Cansu Yildirim (Istanbul Technical University); Sadiye Velioglu (Istanbul Technical University); S. Birgül Tantekin-Ersolmaz (Istanbul Technical University)*

Thin film nanocomposite (TFC) RO membranes have remarkably improved in terms of salt removal; however, removal of boron from seawater is an emerging problem. According to World Health Organization (WHO), boron concentration should not exceed 2.4 ppm for potable water and 0.5 ppm for irrigation water used for crops such as citrus fruits and nuts. Since boron is present in seawater as boric acid and its effective diameter is close to hydrogen bonded cluster of water molecules, conventional TFC membranes fail to achieve effective boron removal. Incorporating nanomaterials into TFC membranes has potential for improving selectivity as well as water flux and anti-fouling properties. However, this requires optimizing the conditions for loading, size, type, and functional groups of the nanomaterials as well as the interfacial polymerization and post-treatment protocols. In this study, we investigate the influence of embedding carbon nanotubes functionalized with carboxyl groups into polyamide RO membranes on their boron rejection performance. Deposition and alignment of SWCNTs on a commercial polysulfone UF membrane was carried out by vacuum filtration. The polyamide layer was prepared by interfacial polymerization using m-phenylene diamine (MPD) and tri-mesoyl chloride (TMC) as monomers. Membranes were characterized by SEM, FTIR, XPS, polarized Raman spectroscopy, and crossflow filtration tests. Results showed that concentration of CNT significantly affects dispersion and alignment of CNTs inside the polymeric matrix as well as homogeneity, thickness and crosslinking ratio of polyamide layer. TFN membranes exhibited increased salt and boron rejection relative to neat polyamide membranes. To the best

of our knowledge, this is the first assessment of the performance of TFN desalination membranes for more effectively removing boron from seawater. This work is supported by the Scientific and Technological Research Council of Turkey (TUBITAK) through Project No. 114Y165.

E23 New generation of patterned membranes for water treatment, Asad Asad (University of Alberta); Dan Sameoto (University of Alberta); Mohtada Sadrzadeh (University of Alberta)*

Surface patterning is a promising method to enhance membranes performance without the need to apply chemical approaches. The addition of patterns simply increases the effective surface area and thus increases the water permeate flux without sacrificing selectivity. It also generates local streamlines at the vicinity of the pattern which might help reducing the attachment of fouling materials. In this study, a novel method is developed to prepare patterned membranes based on hydrogel facilitated phase separation (HFPS). HFPS method relies on the high-water content in hydrogel, which initiate phase separation once in contact with polymer solution resulting in a dense skin layer at the patterned side of the membrane. This method offers a facile approach for direct fabrication of various patterns with different dimensions on the membrane surface. The filtration performance of the HFPS patterned and unpatterned membranes were examined using a cross-flow filtration system. Results showed that the pure water flux through HFPS patterned was doubled compared with the unpatterned one. Moreover, fouling test with Bovine Serum Albumin (BSA) solution showed 76% increment in the flux results for the patterned membrane with almost the same rejection after 90 minutes of filtration demonstrating the significant advantages of patterned membranes for water treatment.

E24 Enhancing boron rejection on electrically conducting reverse osmosis membranes through local electrochemical pH modification, Bongyeon Jung (UCLA)*; David Jassby (UCLA)

As a result of growing population, demand on seawater desalination as a source of drinking water and irrigation water is growing. Among various desalination technologies, reverse osmosis (RO) takes up a large portion of world's desalination capacity due to its high salt removal efficiency. However, RO membranes show relatively low rejection rate on molecules having small size and neutral charge. Boron is one of the examples. Boron is not particularly harmful to mammals but can be lethal to highly boron-sensitive crops such as citrus. Thus, boron concentration should be monitored and strictly limited when desalinated water is used for agricultural purposes. A common practice in RO plants to reduce boron concentration of produced water is to elevate pH using alkaline chemicals. This result in transformation of boron from non-charged to charged and fully hydrated form, which can be easily removed by RO membranes. Although this method can successfully produce water containing small amount of boron, its application is limited by scaling. Thus, typically a double-pass design is employed, which raises water production cost. In this study, electrically conducting RO membranes were exploited to eliminate alkaline dosing and the double-pass design while achieving high boron removal efficiency. When membrane acting as a cathode was connected with an external potential source, hydroxide ions were generated along the membrane surface by water electrolysis. Therefore, pH in the permeate stream was elevated as potential applied to the membrane increased. In addition, boron elimination efficiency was significantly improved compared to membrane with no voltage applied.

E25 Cellulose Triacetate Membrane Parameter Estimation Under Osmotic and Osmotic-Assisted Process Conditions, Jacob L Weidman (U.S. Department of Energy National Energy Technology Laboratory/Oak Ridge Institute for Science and Education)*; Sara Osipi (Federal University of Rio de Janeiro); Alexander V Dudchenko (Carnegie Mellon University); Meagan S Mauter (Carnegie Mellon University); Nicholas Siefert (U.S. Department of Energy National Energy Technology Laboratory)

Power plants and oil & gas wells that produce high salinity brines as effluent pose a technological challenge for implementing waste treatments to achieve zero liquid discharge (ZLD). While mechanical vapor compression is a commercially-available option, emerging membrane technologies have the potential to lower the capital cost and energy costs associated with ZLD. Commercially-available reverse osmosis (RO) membranes are limited by the maximum pressure they can withstand, and this restricts their use to concentrations < 90 g/L. To overcome these limitations, an osmotically-assisted reverse osmosis (OARO) process can be used to produce potable water by subsequently stepping down salt concentration through a series of cellulose triacetate membranes, a commonly-used membrane material for seawater desalination. In this study, cellulose triacetate membranes were tested with sodium chloride solutions in a lab-scale OARO configuration to determine critical transport parameters of the membrane, including water permeability (A), salt permeability (B), and the membrane structural parameter (S). Various conditions were tested, including a range of pressures and concentrations, as well as different configurations of RO, FO, PRO, and OARO. Analysis of the results provided baseline values for the membrane parameters and demonstrated an expected high rejection of sodium chloride ions. However, the data also suggests that the A and S parameters are dependent on operating conditions, as compression of the support layers and possible dehydration of the membrane impact performance. These lab scale results provide a promising baseline for potential OARO applications, necessitating consideration of scale-up effects that would impact performance on the power plant scale. Further studies on OARO membranes will focus on utilizing hollow fiber modules and designing novel membranes with optimal parameters for more effective performance.

- E26 Porous hydrophobic-hydrophilic composite flat and hollow fiber membranes for direct contact membrane distillation,** Aishwarya Puranik (New Jersey Institute of Technology); Lydia Rodrigues (New Jersey Institute of Technology); John Chau (New Jersey Institute of Technology); Lin Li (New Jersey Institute of Technology); Kamallesh K Sirkar (New Jersey Institute of Technology)*; Ashok Sharma (Applied Membrane Technology Inc); Stephen Conover (Applied Membrane Technology Inc); Adam Juelfs (Applied Membrane Technology Inc); Connor Colling (Applied Membrane Technology Inc); Saket Sharma (Applied Membrane Technology Inc)

Among a number of innovations taking place in direct contact membrane distillation (DCMD)-based desalination, composite membrane structures are of increasing interest. Specifically, in terms of membrane structure, an integral composite of a thin hydrophobic porous coating plasma polymerized over a porous hydrophilic layer or a stacked composite of a thin porous hydrophobic layer over a more conventional hydrophilic porous membrane are of interest. Integral composite membranes in flat form or hollow fiber form have been investigated for desalination by DCMD. A class of such membranes of both types yielding quite high water vapor fluxes have been characterized using a variety of characterization techniques: Contact angle, liquid entry pressure (LEP), bubble-point pressure, scanning electron microscopy (SEM), energy-dispersive X-ray spectroscopy (EDS), atomic force microscopy (AFM). Novel conditions created lead to very high water vapor fluxes compared to those from conventional hydrophobic membranes supported on a mesh support.

- E27 Polyamide-imide: a new platform for fabrication of oil/water separation membranes,** Nusrat Helali (University of Alberta); Masoud Rastgar (University of Alberta); Mohtada Sadrzadeh (University of Alberta)*

Hydrophilic membranes with underwater oleophobic property can potentially enhance both water permeability and antifouling properties for oily wastewater treatment. In this study, polyamide-imide (PAI) was used to make porous hydrophilic membranes via non-solvent induced phase inversion technique. To increase the hydrophilicity of membrane further, hydrophilic additives PEG (0.4 and 6.0 kDa) and PVP (10 and 360 kDa) were added to the polymer solution. Oil rejection experiments were conducted for three consecutive cycles at a very low transmembrane pressure i.e., 7 psi to evaluate the reusability of the synthesized membranes. Results showed that the use of additives resulted in a wide range of membrane morphology, porosity, pore size and surface chemical property, which influenced the water permeation and flux recovery. However, all prepared ultrafiltration membranes showed above 98% rejection. Membranes modified with PEG 0.4 and 6 kDa and PVP 10 kDa had underwater oil contact angle (OCA) above 155°, and showed lower flux decline and higher flux recovery (FRR) in all three cycles. In the case of additive PVP 360 kDa, a lower flux recovery observed due to decrease in oleophobicity (OCA=124°).

- E28 Monolayer Graphene transfer onto polyvinyl alcohol (PVA) microfiltration membrane for water desalination.,** Mansour Saberi (Clemson University)*

Fresh and clean water is a primary concern for all the people around the world. So far, seawater desalination has been mainly performed via multistage flash distillation and reverse osmosis. Reverse osmosis (RO) is of interest in brackish water desalination because of near-resistance-free extremely-fast transport of water molecules through a membrane while obstructing all ions. One of the most famous and recently studied candidates for use in RO membranes is graphene which has excellent thermal, chemical, and mechanical stability and it is the most prominent thinnest possible membrane with its one atom thickness acting as the membrane. A crucial stage in the fabrication of an efficient graphene RO membrane is a suitable substrate that can offer the essential support to its single atom thick layer while also allowing for rapid water transmission. This poster presentation will focus on poly (vinyl alcohol) that is cross-linked to make a hydrogel as a support for graphene sheet as a RO membrane. The graphene is transferred onto PVA support by a novel method to decrease the chance of defect formation. Experimental work combined with membrane characterization methods (FTIR, SEM, and TEM) and filtration studies using a home-made RO system to examine the graphene as a RO membrane will be presented. These results will be compared with the other synthesized membrane and different type of supports.

- E29 Membrane Distillation-Crystallization (MDC) for Maximum Water Recovery in Inland Desalination,** Evangelos Balis (University of Nevada, Reno); Sage Hiibel (University of Nevada, Reno)*

Alternative freshwater demand is increasing around the world, and many coastal regions rely on seawater desalination for potable water. For inland regions brackish ground waters are an alternative water source, and desalination can potentially provide potable water. Unfortunately, most desalination techniques developed for coastal regions cannot be directly translated to their full extent inland due to water chemistry differences between seawater and brackish waters. Concentrated brine disposal is also a challenge in inland areas as the ocean cannot serve as a repository for the brines. Thus, zero liquid discharge (ZLD) approaches that minimize the concentrated waste streams while maximizing water recovery are desired. This work couples membrane distillation (MD) and crystallization to effectively treat RO brine resulting from desalinating inland brackish waters with the ultimate goal of ZLD. MD is a non-pressure-driven process that uses a hydrophobic, microporous membrane. Compared to conventional distillation, MD requires small temperature differences and is well suited for coupling to other processes. Because the driving force of MD is the vapor pressure of the brackish water, which is

relatively independent of salt concentration, it is an ideal technology because it can treat brines to near saturation. When coupled with crystallization, the MDC system can remove salt as solid crystals away from the membrane surface to maximize membrane longevity. The MDC system was tested using a hyper saline feed solution (323 g/L NaCl). After 9 hours of operation, the MDC system was able to remove 2.5 times more water from the feed solution than MD alone. This was achieved by capturing 226 g of solid salt in the crystallizer. This work validates MDC as an effective method for reducing feed volumes beyond the threshold of the saturation limit, and also offers the potential of a value-added byproduct in the solid salt that can be sold to offset operational costs.

E30 Insights regarding thermomechanical bonding between porous membranes and thermoplastic polymers, Masoud Aghajani (MAST Center, University of Colorado Boulder)*; Adrienne Blevins (University of Colorado Boulder); Jason P. Killgore (National Institute of Standards and Technology); Ryan Sylvia (MilliporeSigma); Christina Carbrello (MilliporeSigma); Alan R. Greenberg (MAST Center, University of Colorado Boulder); Rong Long (MAST Center, University of Colorado Boulder); Yifu Ding (MAST Center, University of Colorado Boulder)

During filter device fabrication, a porous membrane needs to be intimately bonded with a thermoplastic polymer under controlled thermomechanical conditions. Under mechanical loading, the viscous polymer flows and infiltrates the membrane pores to create both mechanical interlock and interfacial adhesion. Failure to do so can result in product failure and thus increase the overall cost of manufacturing. Because of its practical importance, there is a need for greater understanding of the underlying mechanisms that drive bonding process. Fundamentally, the complexity of this bonding process rises from the interplay between polymer pore-flow and membrane densification, both of which are functions of temperature, pressure and time. In this study, we aim to understand the nature of this interplay so that successful bonding can be carried out in a predictive way. We systematically investigate the thermomechanical bonding between model membranes (with varying pore size and chemistry) and selected polymers. We utilize a suite of AFM-based nanomechanical measurements that enable us to precisely characterize not only the degree of infiltration but also local interfacial structures. In this presentation, we will discuss the relationships between thermomechanical bonding conditions, properties of both the polymers and the porous membranes, and the effectiveness of the bonding.

E31 Ion exchange polymer coatings enhance solute rejection of polyamide thin-film composite membranes, Mikayla D Armstrong (University of North Carolina at Chapel Hill)*; Ryan Kingsbury (Membrion, Inc.); Kasia Grzebyk (University of North Carolina at Chapel Hill); Orlando Coronell (University of North Carolina at Chapel Hill)

Significant research efforts to enhance the water permeability of desalination membranes has substantially improved their energy efficiency. However, a recent review made a strong case for the importance of improving water-solute selectivity (i.e., solute rejection) over water permeability (Werber et al, 2016, Environ. Sci. Technol. Lett., 3, 112-120). Our recent work shows that ion exchange (IX) polymers are better at excluding inorganic solutes from the membrane matrix than polyamide active layers of thin-film composite (TFC) membranes, while solutes are less mobile in polyamide than in IX polymers. Accordingly, to leverage the strengths of different polymers for enhanced water-solute selectivity, we coated polyamide TFCs with an IX polymer, yielding membranes with the high solute exclusion properties of IX polymers and low solute mobility properties of polyamide. The polyamide TFCs that were coated included three commercial membranes and membranes prepared in-house by interfacial polymerization of trimesoyl chloride with m-phenylenediamine (MPD) or piperazine (PIP). We evaluated solute rejection (i.e., NaCl, trivalent arsenic As(III) and boron (B)) and water permeability of uncoated and coated membranes in a dead-end filtration system with simulated groundwater. All coated membranes rejected solutes better than, or similar to, their uncoated controls, but displayed lower water permeability due to uncontrolled coating thicknesses. Notably, NF90 solute rejection increased from 89% to 91.7% for NaCl, 59.2% to 83.5% for As(III), and 66.0% to 87.8% for B. Solute rejection by the TFC-MPD membrane increased from 69.9% to 86.3% for As(III), and 63.6% to 74.7% for B, and remained unchanged at 95% for NaCl. Coating polyamide membranes with an IX polymer resulted in hybrid membranes with improved ability to reject solutes from simulated groundwater. Future work will focus on increasing water permeability by minimizing coating thickness.

E32 Mechanical behaviour of the porous support of TFC membranes and its influence on the overall resistance, Masoud Aghajani (University of Colorado Boulder)*; Alan R. Greenberg (University of Colorado Boulder); Yifu Ding (University of Colorado Boulder)

It is commonly believed that the overall resistance of thin film composite (TFC) membranes is dictated by the crosslinked, ultrathin polyamide barrier layer, while the porous supports merely serve as the mechanical support. However, this understanding is based on the "separate" rating of the resistance of the porous support under high trans-membrane pressure (TMP), which is distinctively different from the situation during high-pressure reverse osmosis (RO). In this study, we used two different methods to study the mechanical behavior of the porous support and how it affects the resistance of TFC membranes. For the first method, we used nanoimprint lithography to achieve precise compressive deformation in commercial TFC membranes. Based on DI water permeation measurements, the intrinsic membrane resistance showed negligible changes at strain levels lower than 30-40%, but increased exponentially at higher strain level of 40-60%. These results suggested substantial contribution of the porous support in the overall resistance at high strain values. Therefore, in our

second method the goal was to measure the true resistance of the porous support during high-pressure RO. To this purpose we developed a new measurement method that uses a series arrangement of a TFC membrane on top of a typical porous support. Our results show that, under high overall TMP (> 5 MPa), the plastic deformation of the additional porous support is as much as 3X larger than that of the same support subjected to identical TMP but without the TFC membrane on top. Moreover, DI water permeation experiments revealed as much as an order of magnitude increase in resistance for the deformed porous supports in comparison to the pristine (undeformed) ones. Most importantly, our analysis indicates that the resistance of a representative commercial porous support used to fabricate TFC membranes can account for up to 33% of the overall TFC membrane resistance during high pressure permeation (5.5-8.2 MPa).

E33 Development of Membrane Distillation through Tuning Membrane Surface Properties and Module Design, Siamak Nejati (University of Nebraska-Lincoln)*; Mahdi Mohammadi (University of Nebraska-Lincoln); Mona Bavarian (University of Nebraska-Lincoln)

Membranes with special wettability have a variety of applications. Our focus here is on the membrane distillation (MD) process. Designing membranes for the MD process is tightly bound to feed composition and properties. Because the MD process is accompanied by phase change, interfacial and surface properties of materials play a key role in determining the performance of the membranes. The other critical factor in MD operation is thermal management; this concept is the bottleneck of the MD process and better thermal management, even at the membrane level, can dramatically enhance membrane performance. Here we present the predicted performance of the MD membrane, using first principle multiphysics modeling; we will demystify the underlying phenomena governing the MD process for different membrane structures. We will design composite membranes based on the modeling results and fabricate them through a combined phase inversion, spray-on, and state-of-the-art vapor phase polymerization. The experimental result will be compared to our model prediction. A few examples of these membranes, e.g., Janus membranes and omniphobic membranes, will be demonstrated. Particularly, the omniphobic properties of the created surfaces will be highlighted. We will demonstrate that the omniphobic structure of the fabricated membranes hinders the wetting by large droplets, (ca. 1.5 mm in diameter), and how low surface energy liquids come into contact with the surface with an impact velocity of around 2 m/s. Additionally, we will demonstrate that through proper design, we can achieve permeate flux exceeding what has been reported in the literature for MD membranes. The fabricated membranes were challenged by complex feed compositions, and accelerated scaling and oil wetting tests were performed. Lastly, we demonstrate the integration of a wide-band IR absorber into the module design to realize the development of a solar desalination technology.

E34 Integration of Forward Osmosis in the Treatment of Sewage by *Chlorella vulgaris*: Comparison between External and Immersed Systems, Xue Jin (Oregon State University)*; Mathieu Larronde-Larretche (University of Glasgow)

Microalgae have attracted increasing attention due to their promising application in sustainable biofuel generation, wastewater remediation, carbon dioxide sequestration and pharmaceuticals production [1]. Despite the promise, one technical challenge remaining to be overcome is the high energy cost of algae harvesting and dewatering that accounts for 20-30% of the total operating cost [2]. In our previous study, the feasibility of microalgae dewatering using forward osmosis (FO) has been demonstrated. The key fouling mechanisms, involving the excretion of carbohydrate by the microalgae under stress conditions, have also been described [3-4]. In this study, we further developed the integration of FO dewatering with wastewater treatment by microalgae. An immersed and an external FO cell were compared based on nutrients recovery, biomass recovery, filtration performances, and long term efficiency. Our findings reveals that the wastewater treatment efficiency (nutrients removal), as well as the production of biomass were greater with the immersed FO system due to a greater microalgae growth. However, these may not be sustainable in a long term operation of the immersed system. The external FO system was found better in terms of salinity build-up and FO dewatering performances. Overall, an external FO dewatering is recommended due to its better flexibility and sustainability. Reference: [1] S.A. Razzak, et al., *Renew. Sust. Energ. Rev.* 27 (2013) 622-653. [2] C. Gudin, C. Thepenier, *Adv. Biotechnol. Process.* 6 (1986) 73-110. [3] M. Larronde-Larretche, X. Jin, *Algal Research*, 23 (2017). 12-19. [4] M. Larronde-Larretche, X. Jin, *Algal Research*, 15 (2016). 1-8.

E35 Nanoengineered condensation surfaces for air gap membrane distillation, Yashwant S. Yogi (Purdue University); Sina Nejati (Purdue University); Akshay K. Rao (Purdue University); Rishav Roy (Purdue University); Abhimanyu Das, Longnan Li (University of Illinois, Urbana-Champaign); Soumyadip Sett (University of Illinois, Urbana-Champaign); John Lienhard (MIT); Nenad Miljkovic (University of Illinois, Urbana-Champaign); Justin A. Weibel (Purdue University); Jaichander Swaminathan (Massachusetts Institute of Technology); David Warsinger (Purdue University)*

The thermal desalination technology air gap membrane distillation (AGMD) is an energy efficient configuration, being especially dominant at high salinity. However, the large mass transfer resistance of the air gap dramatically reduces permeate flux, impairing performance. Higher condensation performance can be achieved through smaller air gap size, but with normal condensate flow pattern (film type) the air gap gets flooded before reaching the optimal gap size (<1mm). It was found through system level numerical modeling and experimentation that condensing flow regimes like dropwise and jumping droplet achieved using hydrophobic and superhydrophobic condensing surfaces respectively were able to both improve the mass transfer coefficient in the airgap, and improve droplet shedding,

allowing for thinner gap sizes. This allowed increases of GOR (Energy efficiency) by 2.1x while avoiding flooding even at gap size of 0.2mm. More novel condensing surfaces like a combination of the superhydrophobic and superhydrophilic pattern created pathways for faster permeate removal producing more complex flow regimes.

- E36 Fouling of Anion Exchange Membranes in Ferric Chloride Solutions: mechanism and the role of ion exchange capacity, water content, and pore structure,** Michael J. McGrath (University of Colorado Boulder)*; Nicholas Patterson (UC San Diego); Bryce Manubay (University of Colorado Boulder); Hans Funke (University of Colorado); Samantha Hardy (University of Colorado Boulder); Andrew Basalla (University of Colorado Boulder); Xiujun Yue (UC San Diego); Ping Liu (UC San Diego); Douglas Gin (University of Colorado Boulder); Richard Noble (University of Colorado Boulder)

Anion exchange membranes (AEMs) have potential applications in redox flow batteries (RFBs) because of their potential to prevent electroactive metal ionic species crossover, and therefore prevent self-discharge. The all iron flow battery (AIFB) has been evaluated as a prime example thanks to the economical advantages stemming from the abundance of iron. However, fouling of AEMs has previously been observed in chloride-based AIFBs due to the presence of the ferric tetrachloride anionic complex and subsequent dehydration of the membrane. A phase-segregated AEM made from a polymerizable surfactant with positively charged discrete 1-nm pores was hypothesized to sieve iron species from the pores to prevent fouling. However, the membrane still rapidly fouled. Impedance measurements indicate the conductivity of AEMs drops rapidly upon exposure to ferric chloride solutions. Raman spectroscopy confirms iron tetrachloride is able to enter the membrane. SEM/EDX examines the distribution of iron across the membrane during the relevant time-scale of fouling. Iron tetrachloride is likely less hydrated compared to Cl⁻, supporting the observation that iron tetrachloride leads to dehydration of the pores. The fouling of the phase-segregated, polymerizable surfactant AEM is compared to that of three commercial homogeneous AEMs with different ion exchange capacities and water contents. We show that fouling occurs at different iron chloride concentrations for different AEM's, depending on their ion-exchange capacity and water content. Discrete pore modification of the phase-segregated AEM affects its fouling kinetics, demonstrating the importance of membrane structure and water domain environment on the fouling behavior of AEMs. Research of AEMs for AIFBs should recognize the need to prevent iron tetrachloride from entering the membrane to prevent fouling; suggestions for modification of AEMs to prevent fouling are made.

SESSION F - Innovation in Modeling of Membrane Fundamentals and Processes

- F1 Molecular Dynamics Processing Tool for Transmembrane Simulations,** Jia Lin Cheoh (Purdue University)*; Abhimanyu Das (Purdue University); David Warsinger (Purdue University)

Molecular dynamics has become a widely used simulation method to investigate the properties of membranes in advancing technologies for a variety of fields including but not limited to renewable energy, water processing, and smart health applications. Advancement in high-performance computing and molecular dynamics simulations make it possible to perform simulations that closely model real phenomenon on transmembrane channels. However, performing molecular dynamics simulations on transmembrane channels is both time-consuming and difficult to comprehend for non-trained scientists in this field. We develop a simplify molecular dynamics simulations tool that sets the only requirements for end users to be that they have the high-performance computing power and the relevant input files without having to perform all the intermediary molecular dynamics processing steps. Our research will present implications for future interdisciplinary research at the intersection of membrane separation methods and high-performance simulations techniques, and further advance the pace of membrane-related research with the explicit solvent simulation method.

- F2 Low energy-consumption pre-treatment system for integrated forward osmosis - reverse osmosis desalination process,** Yunchul Woo (Korea Institute of Civil Engineering and Building Technology)*; June-Seok Choi (Korea Institute of Civil Engineering and Building Technology); Kwang-Duk Park (Korea Institute of Civil Engineering and Building Technology)

Forward osmosis (FO) process has been attracting attention for its potential applications such as industrial wastewater treatment, wastewater reclamation, and seawater desalination. Particularly, in terms of fouling reversibility and operating energy consumption, the FO process is assumed to be more preferable to the RO process. Moreover, hybrid FO-RO membrane systems should have an economic advantage compared to currently available technology for desalination such as a standalone RO model, and comparable costs with wastewater treatment and recovery system. The objective of this study was to evaluate the best economical, viewpoint of operating energy consumption and fouling, pretreatment system for FO-RO hybrid desalination process. Various processes were used for FO pretreatment of real secondary wastewater effluent. SWRO was operated with a diluted draw solution, such as treated secondary wastewater effluent by FO system. With applying above fouling control strategies, FO and RO fouling tests were conducted for 12 to 48 h and then flux decline rates were compared based on the initial flux of each case. Energy consumption during each FO-RO with the

pretreatments was calculated by operating pressure and measured feed water flux. Our results suggest that membrane fouling can be effectively controlled by the pretreatment process. Moreover, the osmotic dilution process by the FO system is a non-pressurized membrane system and, thus, the energy consumption of the overall desalination system was the lower than standalone RO system. In addition, the structure of the fouling layer on the FO membrane is relatively weak and reversible enough to be disrupted by simply hydrodynamic washing. Therefore, the FO-RO process with low salinity feed water through a suitable pretreatment system is possible as a less energy consuming desalination system with efficient membrane fouling control.

F3 Arrested mobility effects on the spinodal decomposition of ternary polymer solutions for immersion precipitation, Jan Garcia (UC Santa Barbara)*; Douglas Tree (Brigham Young University); Kris Delaney (UC Santa Barbara); Glenn Fredrickson (UC Santa Barbara)

Many polymer membranes are made by immersion precipitation: a polymer solution film is immersed in a nonsolvent bath, inducing phase separation of the film into a polymer-rich phase that becomes the membrane matrix and a polymer-poor phase that becomes the membrane pores. Microstructure formation of these membranes is still not fully understood, given the interdependent nature of several physical processes: the mass transfer of solvent and nonsolvent through the film-bath interface, the ensuing phase separation of the film, the coarsening of domains, and finally the glass transition of the polymer-rich phase that arrests the membrane microstructure. In this work, we use phase-field models of the polymer-nonsolvent-solvent system to solve the coupled convection-diffusion and momentum equations that describe the immersion precipitation process. We model the glass transition using contrasts in the viscosity and mobility of the polymer-rich and polymer-poor phases. We report how the glassy dynamics changes the microstructures formed by bulk spinodal decomposition. We also study how the mass transfer kinetics between the bath and film are changed by the formation of a glassy interface.

F4 Hydro- and perfluoro-carbon sorption, diffusion and permeation modeling in poly(dimethylsiloxane) using a PC-SAFT Equation of State, Liang Liu (The University of Melbourne)*

The transport behavior of gases and vapors in poly(dimethylsiloxane) (PDMS) has been investigated extensively due to its easy processability and good separation performance. As a rubbery polymer, the membrane selectivity is mainly determined by penetrant solubility. The Flory-Huggins model is widely used to model this sorption behavior. Although this model works well for small gases such as N₂, CO₂ and CH₄, it lacks predictive ability for some other penetrants, for example, hydro- and perfluoro-carbons, as a concentration dependent interaction parameter must be used to achieve reasonable results. It is of great interest to develop a fundamental model to investigate the thermodynamic properties of these penetrant-polymer systems, so that they can be incorporated into an appropriate diffusion model to determine the transport properties of the membrane. In this work, the Perturbed Chain Statistical Associating Fluid Theory (PC-SAFT) equation of state was applied to investigate the sorption of small gases, hydrocarbons and perfluorocarbons in PDMS. All model results agreed well with experimental data and only one fixed interaction parameter over the entire experimental pressure range was used for each penetrant-polymer pair. The sorption behavior of gas mixtures in the polymer matrix was also investigated, without any adjustable parameter, indicating the versatility of the model. Moreover, permeation data could be fitted to a solution-diffusion model incorporating this approach. The diffusivities and concentration profiles of the penetrants across the membrane were also explored.

F5 The Potential of Low-Temperature Forward Osmosis for Water Recovery, Jeffrey Martin (University of Toronto); Georgios Kolliopoulos (University of Toronto); Vladimiro Papangelakis (University of Toronto)*

Industrial wastewater treatment poses significant challenges, for it is necessary to recover clean water for reuse while reducing the volume of the effluent. Compared to traditional water recovery technologies, forward osmosis (FO) is an attractive solution due to its low fouling potential and favourable energy consumption. Forward osmosis uses a concentrated draw solution to spontaneously pull water across a semipermeable membrane from an aqueous process stream, rejecting and concentrating solutes in the process water. There is significant potential for FO to recover water from low-temperature effluents such as mining activities in the winter in the north, yet the effects of temperature on the performance of FO have only been investigated in the literature for temperatures greater than 20°C. There is a lack of understanding of FO performance at temperatures between the solution freezing point and room temperature. To address this gap, we have experimentally studied the performance of a Sterlich forward osmosis membrane cell at low temperatures, by measuring the water flux and reverse draw solution flux for different draw solution concentrations. It was found that the water flux across the membrane can be reduced by 50% due to the lowering of the osmotic driving force, the decreasing draw solute diffusivity and increasing draw solution viscosity. However, this increased mass transfer resistance also inhibits the reverse draw solute flux, which provides a greater water flux selectivity at lower temperatures. Based on this work, the potential of FO for low-temperature applications can be optimized through a detailed understanding of its performance, elucidating the water flux selectivity and determining the optimal sub-room temperature operating window for the FO process.

- F6 Fouling mechanisms in constant flux crossflow ultrafiltration**, Alon Kirschner (The University of Texas at Austin)*; Yu-Heng Cheng (The University of Texas at Austin); Donald Paul (The University of Texas at Austin); Robert Field (University of Oxford); Benny Freeman (The University of Texas at Austin)

Four fouling models due to Hermia (complete pore blocking, intermediate pore blocking, cake filtration and standard pore blocking), have long been used to describe membrane filtration and fouling in constant transmembrane pressure operation of membranes. A few studies apply these models to constant flux dead-end filtration systems. However, these models have not been reported for constant flux crossflow filtration, despite the frequent use of this mode of membrane operation in practical applications. We report derivation of these models for constant flux crossflow filtration. Of the four models, complete pore blocking and standard pore blocking were deemed inapplicable due to contradicting assumptions and relevance, respectively. Constant flux crossflow fouling experiments of dilute latex bead suspensions and soybean oil emulsions were conducted on commercial poly (ether sulfone) flat sheet ultrafiltration membranes to explore the models' abilities to describe such data. A model combining intermediate pore blocking and cake filtration appeared to give the best agreement with the experimental data. Below the threshold flux, both the intermediate pore blocking model and the combined model fit the data well. As permeate flux approached and passed the threshold flux, the combined model was required for accurate fits. Based on this observation, a physical interpretation of the threshold flux is proposed: the threshold flux is the flux below which cake buildup is negligible and above which cake filtration becomes the dominant fouling mechanism.

- F7 Hitz zeolite membrane separation system (HDS) for liquid separation**, Akira Hamasaki (Hitachi Zosen Corporation)*

Hitachi Zosen Corporation (Hitz) has actively developed and commercialized our zeolite membrane separation systems for several kinds of industry use in liquid- and gas-separation. Hitz membrane elements are 16 mm in diameter and 1130 mm in length. The element is composed of a Al_2O_3 porous support tube with a closed end and a zeolite thin film deposited on outer surface of the tube by a hydrothermal synthesis process. The element constitution is only inorganic material, which enables the membrane to be used under high temperature and high-pressure conditions. We have developed six varieties of zeolite membranes (HZM-1 to HZM-6) with different composition, pore size and chemical affinity and the optimized zeolite membrane is selected depending on the separation use and the customer requirement. Regarding the liquid separation use, HZM-1 and HZM-2 membranes are used for several solvents dehydration and HZM-3 to HZM-5 membranes are used for the dehydration of the solvents with higher water content and/or acidity. The performance of the membrane elements has been tested in pervaporation (PV) and vapor permeation (VP) process. For example, the VP dehydration flux and separation factor of HZM-1 membrane element for the feed of ethanol (90 wt%)/water (10 wt%) at the temperature of 130 degree centigrade was $50 \text{ kg m}^{-2} \text{ h}^{-1}$ and several thousand or more, respectively. These performance is 6 times higher than that of the conventional zeolite membrane. Hitz dehydration system (HDS) was adopted for the first commercial bio-ethanol plant with the capacity of 50,000 L/d in Japan. The system has been operated successfully for about six and half years without any trouble and membrane replacement and it is found that the bio-ethanol product purity is 99.9 to 99.95 vol% at the capacity of 50,000 to 53,000 L/d.

- F8 Effect of short-term contact with C1-C4 alcohols on the water permeance and salt rejection of MPD-TMC thin-film composite reverse osmosis membranes**, Jaime A Idarraga-Mora (Clemson University)*; Michael Lemelin (Clemson University); Steven Weinman (Clemson University); Scott Husson (Clemson University)

This poster discusses the effect of C1-C4 alcohols on the transport properties of thin-film composite reverse osmosis membranes. Five commercial membranes were studied using direct-flow filtration to quantify the changes in water permeance and sodium chloride rejection before and after contact with five different C1-C4 alcohols. Membrane performance was correlated with active layer characteristics. Young's modulus measurements of the surface showed decreased stiffness of the active layer after contacting the membranes with alcohol, suggesting a plasticization effect. Water permeance generally increased without decreasing rejection after short-term alcohol contact. The extent of these changes depends on the membrane and alcohol used. Analysis of the data using a dual-sorption model found correlations between the change in water permeance after alcohol contact and both the initial water permeance of the membrane and the change in free energy of mixing of water and the alcohols. We suggest that the mixing of water with the alcohols facilitates penetration of the alcohols into the active layer, likely by disrupting inter-chain hydrogen bonds, thus increasing the free volume for water permeation. Our studies provide a modeling framework to estimate the changes in transport properties after short-term contact with C1-C4 alcohols.

- F9 Whey recovery using forward osmosis with hollow fiber configuration - Evaluating the factors limiting the flux performance**, YiNing Wang (Nanyang Technological University)*; Rong Wang (Nanyang Technological University)

The focus of whey processing has been changed from waste treatment to the production of valuable products owing to the advancement of membrane technology. Producing high quality whey products at low energy consumption entails novel techniques for whey concentration. This study proposes forward osmosis (FO) as a potential approach to concentrate whey protein solutions, which is superior

to the concentration via reverse osmosis (RO), mainly owing to the low hydraulic pressure during FO process. In particular, this work validated the feasibility of FO-based whey concentration using high-performance hollow fiber (HF) membranes that were fabricated in-house. The investigation focused on the effects of various operating conditions including different modes of physical cleaning on the concentration performance. The experimental results reveal that optimal concentration efficiency would be achieved by appropriately choosing the cross-flow velocity, draw solution concentration and the maximum attainable concentration of whey protein solution. It is worth noting that a rapid formation of a polarized or gel foulant layer at the membrane surface takes place (fouling accumulation with time is of minor importance in this case). This proposed mechanism is evidenced from the flux decline behaviour at different whey protein concentration. It is further supported by the results of physical cleaning with water, showing that the post-process cleaning after one concentration cycle was able to recover the membrane performance, whereas the intermediate cleaning during one concentration cycle had little impact on the concentration efficiency enhancement. This study has practical significance for the application of FO in the concentration of dairy streams and other streams with high solid content.

F10 Bimetallic Nanoparticles Incorporated Poly(methacrylic acid) Functionalized Membranes for Water Remediation:

Synthesis, Advanced Characterization and Reactive Properties, Hongyi (Derek) Wan (University of Kentucky)*; Md. Saiful Islam (University of Kentucky); Nicolas Briot (University of Kentucky); Anthony Saad (University of Kentucky); Lindell Ormsbee (University of Kentucky); DB Bhattacharyya (University of Kentucky)

The dechlorination of toxic chlorinated organics in groundwater has been reported using bimetallic (Fe/Pd) nanoparticle methods. However, the aggregation as well as the difficulties to recycle for the particles hinder the application in field. The integration of catalytic particles and functionalized commercial membranes was achieved (in both commercial flat-sheet membranes and spiral membrane modules) to solve these issues. The Fe/Pd nanoparticles were synthesized inside the pores of membrane through in situ reduction after ion-exchange with the carboxylate groups (methacrylic acid (MAA) was polymerized inside the pores). The functionalized MAA controlled the size of particles and recapture the Fe after dechlorination treatment. The reactive membranes were tested in the treatment of lab synergic polychlorinated biphenyls and field groundwater (from a Superfund site, which includes trichloroethylene, carbon tetrachloride, etc.). At 2.2 s residence time, 90% of chlorinated organic species (10-1000 ppb) in the groundwater were dechlorinated in the convective flow mode. The pilot studies with functionalized commercial spiral membrane modules are in progress. Advanced characterization methods, such as FIB, TEM, XPS were applied to understand the correlation between nanoparticle properties and depth inside membrane pores. The depth profile of functionalized membrane indicated that particle size was uniform inside membrane pores (24 ± 6 nm) but slightly smaller than those nanoparticles located on the surface (39 ± 9 nm). Furthermore, the use of TEM and XRD enables the calculation of Pd monolayer coverage on the Fe surface. The effects of Pd surface coverage and particle compositions on the H_2 production (Fe corrosion in water) and corresponding dechlorination rate were evaluated to find the optimal Pd content for the dechlorination. This research is supported by the NIEHS-SRP grant P42ES007380. Partial support is also provided by NSF KY EPSCoR grant (Grant no: 1355438).

F11 Membrane compaction in forward osmosis process, Daniel Yee Fan Ng (Nanyang Technological University); Yunfeng Chen (Nanyang Technological University); Rong Wang (Nanyang Technological University)*; Zhili Dong (Nanyang Technological University)

Membrane compaction is commonly observed in polymeric membranes when subjected to elevated hydraulic pressure. Such phenomena is thought to be the main cause of irreversible reduction in membrane permeability for most hydraulic pressure-driven membrane separation process. In forward osmosis (FO) process, it is commonly assumed that there were little hydraulic pressure exerted on the membrane, and therefore the highly porous membrane should experience negligible compaction. In the current investigation, three types of TFC membranes were fabricated from different hollow fiber substrates that possess different water permeability. The TFC membranes were continuously tested in FO experiments for 24 hours by using DI water as feed and NaCl solutions of different concentration as draw, and their performance were checked by with fresh feed solutions. At the end of FO experiments, the water flux of the TFC membrane with the most permeable support layer decreased by 9% and 21% , whereas the water flux of the TFC membrane with the less permeable support layer decreased by 32% and 52%, when 0.5 M NaCl and 2.0 M NaCl were used as draw solution, respectively. Furthermore, unexpected "plummeting" water flux pattern was also observed on the TFC membrane with the least permeable support layer when switching to higher draw concentration in the FO experiments. Visible changes in the cross-section morphology and surface topography of the TFC membranes were also observed under SEM and AFM after the FO experiments, suggesting that these signs of membrane compaction could be driven by "negative hydrostatic pressure" build-up within the support layer of the TFC membranes. The current study could shed light on the important considerations that should be taken into account during membrane fabrication and when establishing the testing protocols for characterization of forward osmosis membrane.

F12 Novel Isothermal Acid Sweep Membrane Distillation for Selective and Energy Efficient Removal and Recovery of Ammonia, Stephanie N McCartney (Columbia University)*; Natalie Williams (Columbia University); Chanhee Boo (Columbia University); Ngai Yin Yip (Columbia University)

In membrane distillation (MD), the permeation of volatile components is traditionally driven by a partial vapor pressure gradient set up by a transmembrane temperature differential. Conventional MD can be employed for the separation of volatile components, e.g., soluble gases such as ammonia, from aqueous feed streams and collected on the sweep side, but the process suffers from undesired simultaneous water permeation that dilutes the sweep stream and incurs large energy losses due to the enthalpy of vaporizing water. In this study we present a novel operation of MD, termed isothermal acid sweep membrane distillation (IASMD), for the separation and recovery of ammonia from aqueous solutions, while suppressing water transport. The innovative operating features of IASMD that distinguish it from conventional MD are: i) same temperature on both the feed and sweep sides and ii) acidic solution on the sweep side. High ammonia flux with minimal water permeation for isothermal membrane distillation was realized with 500 mM total ammonia nitrogen (TAN) to simulate urine as the feed, and either 100 mM acetic acid or deionized (DI) water as the sweep. Traditional MD operating at feed and sweep temperatures of 40 and 20°C, respectively, exhibited ammonia flux of 9.3 mol/m²h with water flux at 8.3 kg/m²h, while IASMD was enhanced ammonia flux to 13.9 mol/m²h, while diminishing water flux to 0.15 kg/m²h. Ammonia permeation in isothermal MD is enhanced 1.5-fold when acidic sweep solution is used compared to DI water. IASMD operation from 20 to 60 °C demonstrates that ammonia flux increases with increasing temperature, from 5.6 to 22.8 mol/m²h, while suppressing water flux to below 0.5 kg/m²h across all temperatures. Furthermore, IASMD is substantially more energy efficient than traditional MD, achieving energy savings of 92%. IASMD has promising potential for the selective and energy efficiency removal and recovery of volatile contaminants from aqueous waste-streams.

F13 In-situ micro-rheology of a foulant layer, Jose Agustin Epstein (Technion - Israel Institute of Technology); Guy Z Ramon (Technion - Israel Institute of Technology)*

Fouling remains a major problem in membrane-based water purification and desalination processes, leading to increased operational costs and necessitating extensive pre-treatment. In particular, characterization of organic matter deposits and bio-fouling, their resulting properties and the ways in which they conspire to determine process losses requires further physical insight, from which better control strategies may be developed. This research demonstrates an in-situ approach for foulant monitoring, aimed at measuring the mechanical properties of the foulant layer at their membrane surface, during the separation process. We employ fast confocal microscopy and particle tracking algorithms for the analysis, with alginate as a model foulant used to create a hydrogel deposit on a nano-filtration membrane (NF270). Fluorescent particles of 0.5 μm diameter are embedded in the deposit, and particle trajectories are utilized to calculate the storage (G') and loss (G'') modulus using the generalized Stokes-Einstein relation (GSER). Confocal microscopy enables the accurate monitoring of known positions within the layer, resolving depth variation of its structure and mechanical properties. Results demonstrate the ability to characterize the deposit mechanics and heterogeneity. Specifically, the alginate layer is shown to be a frequency/dependent viscoelastic material with mechanical depth variations. Notably, different permeate fluxes generate changes in the material response as our results show that the foulant-layer mechanical properties are dependent on the permeate flux, with responses varying from viscoelastic to elastic-solid-like. This research demonstrates a first analysis of this type of characterization, opening new avenues for studying foulant properties and response to operating conditions. Such physical insight can lead to better fouling control practices.

F14 Mixed-gas permeation in thermally rearranged poly(benzoxazole-co-imide) polymer membranes, Adele Brunetti (Institute on Membrane Technology of Italian National Research Council); Elena Tocci (Institute on Membrane Technology of Italian National Research Council); Jong Geun Seong (Hanyang University); Young Moo Lee (Hanyang University)*; Enrico Drioli (Institute on Membrane Technology of Italian National Research Council); Giuseppe Barbieri (Institute on Membrane Technology of Italian National Research Council)

The mutual influence of each component of a gas mixture on the other gas permeation was systematically investigated for mixtures including CO₂, N₂, CH₄, H₂, and CO. The mixed gas permeation was measured at 35°C at up to 5 bar of feed pressure in thermally rearranged poly(benzoxazole-co-imide) (TR-PBOI) membranes. How and how much CO₂ (the most soluble gas) and H₂ (the fastest diffusing gas among the gas species tested) affect each other permeation as well as the permeation of the other gases were specifically addressed by a discussion based on sorption and diffusion contributions. For quantifying the sorption contribution to the permeation, sorption isotherms of binary mixtures were calculated using the Grand Canonical Monte Carlo approach. CO₂ concentration in the polymeric matrix was not affected by other gases except for CH₄ because of its competitive sorption. CO₂ permeance measured feeding mixed gases was independent of the other gas in the mixture and did not deviate from its single gas value. However, CO₂ significantly affected the other gases permeation, reducing H₂, N₂, CO, and CH₄ permeance by 18, 14, 12, and 1.3%, respectively. H₂ permeance did not change in mixtures but H₂ influenced N₂, CO, and CH₄. Consequently, in all CO₂-containing mixtures the mixed gas selectivity was greater than the one based on single gases, whereas the opposite trend occurred in all H₂-containing mixtures. Both H₂ and N₂ gases in mixture showed

linear sorption isotherms, confirming a very low interaction between them and with the polymer. The permeance of CO₂ and H₂ remained unchanged, whereas the permeance of the other gases was reduced by the presence of CO₂ or increased by the presence of H₂.

- F15 Plug flow reactor IEMB - performance and modelling**, Shalom Fox (Ben-Gurion University of the Negev); Kristina Stadnik (Ben-Gurion Univ.); Amit Thakur (Ben-Gurion University of the Negev); Zeev Ronen (Ben-Gurion Univ.); Yoram Oren (Ben-Gurion University of the Negev); Jack Gilron (Ben-Gurion University of the Negev)*

Ion exchange membrane bioreactors have been used to remove oxyanions from process streams and contaminated groundwaters. The process involves Donnan dialysis to drive the contaminating ions from the water side to the bioside where bioreduction takes place. In the past most work has been done using reactors with high water recycling rates on the water side which caused them to operate at low fluxes since the membrane was exposed to the lowest exit concentration. This group has designed two forms of plug flow reactors, one plate and frame and one spiral wound to drastically increase the throughput possible. The reactors have been tested on perchlorate, nitrate, and mixed perchlorate and nitrate feeds at different flow rates. The design equation for the reactor incorporated the flux equation developed by Velizarov and coworkers, but modified it to reflect the ion adsorption isotherms obtained with different membranes for the same oxyanion. The results of the design equation are compared to the PFR results and future directions are suggested.

- F16 Isolation of Extracellular Vesicles from a Biofluid Using Ultrathin Microslit and Nanopore Silicon Membranes**, Jared Carter (SiMPore inc.)*; Cassandra Walinski (SiMPore Inc.); Akash Patel (SiMPore Inc.); Joshua Miller (SiMPore Inc.); Jon-Paul DesOrmeaux (SiMPore Inc.); James A Roussie (SiMPore Inc.)

Extracellular vesicles are emerging as a potentially powerful class of next-generation diagnostic analytes. In particular, Urinary extracellular vesicles (UEVs) are abundantly present in urine, carry protein and nucleic acid cargoes from their cells of origin, and derive from all cell types of the nephron and urinary tract. Because urine can be obtained non-invasively, UEV-based urinalysis liquid biopsies have received a great deal of attention. Isolating UEVs out of urine and away from matrix factors [e.g., urinary cells and Tamm-Horsfall protein (THP) filaments] remains a challenge especially for microfluidic-based approaches. Without integrated sample preparation capabilities, these microfluidic UEV detection systems may find little utility as next-generation research and diagnostic tools. Here, we report on the development of a new three-step UEV isolation procedure that has a total processing time of less than 1hr for 500 μ L human urine samples. The process relies on chip-format nanomembranes that can be integrated into microfluidics, including microslit silicon nitride (MSN) membranes for urine matrix factor removal and nanoporous silicon nitride (NPN) membranes for UEV capture. We demonstrate that MSN membranes with 0.5x50 μ m slit rectangular prism "pores" can yield a filtrate that is cell-free, protein-depleted (4X reduction), and \geq 95% of initial volume, in under 5-minutes at 900xG centrifugation. We further demonstrate that NPN membranes with 50 nm mean cylindrical pores can capture UEVs with nearly quantitative efficiency from the MSN membrane's filtrate in 20 minutes at 600xG centrifugation. We verify our results by multiple metrology and molecular biology techniques. Together, these results demonstrate ultrathin silicon nanomembranes offer unique capabilities for UEV sample preparation and may provide the sought-after solution for UEV isolation in microfluidic analysis platforms.

- F17 High-Pressure Reverse Osmosis for Energy-Efficient Desalination of High Salinity Brines**, Douglas M Davenport (Yale University)*; Akshay Deshmukh (Yale University); Jay Werber (Yale University); Yuhao Du (Yale University); Menachem Elimelech (Yale University)

Water scarcity, expected to become more widespread in the coming years, demands renewed attention to freshwater protection and management. Critical to this effort are the minimization of freshwater withdrawals and elimination of wastewater discharge, both of which can be achieved via zero liquid discharge (ZLD), an aggressive wastewater management approach. Reverse osmosis (RO) is widely accepted as the most energy-efficient desalination process for solutions with a concentration less than \sim 70,000 mg/L total dissolved solids. However, the high brine salinities encountered in ZLD necessitate the use of thermal desalination processes. Because of the high energetic cost of thermal desalination, ZLD is particularly challenging for high-salinity wastewaters. In this presentation, we highlight the potential of high-pressure reverse osmosis (HPRO) (i.e., reverse osmosis operated at a hydraulic pressure greater than \sim 100 bar) to efficiently desalinate hypersaline brines. We will first discuss the inherent energy efficiency of membrane processes compared to that of conventional thermal processes for brine desalination. We then present process-scale energetic modeling to showcase the opportunity of HPRO to reduce energy requirements for the desalination of key high-salinity industrial wastewaters. The current state of membrane materials and processes for hypersaline brine desalination is also presented, emphasizing several process design considerations unique to HPRO. The most pressing research needs for the development of HPRO are also discussed, notably the development of membranes and modules suitable for high pressures. Lastly, we will share recent insights into the nature of compaction and salt transport at pressures and salinities relevant to HPRO.

- F18 Computationally Efficient Methods of Simulating Membrane Spacers**, Jacob Johnston (Colorado School of Mines)*; Jincheng Lou (Colorado School of Mines); Nils Tilton (Colorado School of Mines)

Membrane spacers play an important role in fluid flow, concentration polarization, temperature polarization, and mineral scaling in membrane separation processes, including nanofiltration, reverse osmosis, and membrane distillation. To date, computational fluid dynamics studies of spacers have been limited by the fact that most commercial computational fluid dynamics software uses body-fitted grids to simulate spacer surfaces. Such grids are time consuming to build, and limit the number of spacer geometries that can be considered. Thus motivated, we leverage recent advances in immersed boundaries to develop a method of simulating spacers without body-fitted grids. Rather, the method uses simple Cartesian grids that nevertheless recover the same order of accuracy as traditional grids. We show that the method accurately simulates not only the no-slip condition for the fluid flow, but also the advection of heat and salts near the spacer surface interface, which are often tricky to simulate. Using our method, we simulate heat and mass transport in a direct-contact membrane distillation system with spacer elements in both the feed and distillate channel.

- F19 Dissipative Particle Dynamics Simulations of PES membrane via NIPS**, Eric Ledieu (University of Arkansas)*; Yuanhui Tang (University of Arkansas); Rosario Cervellere (University of Arkansas); Paul Millett (University of Arkansas); David Ford (University of Arkansas); Xianghong Qian (University of Arkansas)

Polymeric membranes produced by Non-solvent Induced Phase Separation (NIPS) have been widely used across a wide array of microfiltration and ultrafiltration processes. However, despite their wide use, current fabrication processes are largely determined by trial and error. Better insights on the factors affecting membrane morphology would be of great use. To that end, Dissipative Particle Dynamics (DPD), a mesoscale simulation technique, was used to simulate membrane formation process involving polymer (polyether sulfone, PES), solvent (methyl-2-pyrrolidinone, NMP) and nonsolvent (H₂O) with several million beads and over several microseconds. The interactions between these beads are determined according to Flory-Huggins thermodynamic theory and continuum transport equation. Two configurations of the periodic unit cell were set up: (1) symmetric unit cell with water on both sides of the polymer/solvent solution; (2) asymmetric unit cell with polymer solution surrounded by water on one side and a hard wall on the other side. Both synthetic models were found to form pores in the nanometer scale at the skin layer consistent with experimental data, although symmetric unit cell produced much larger inner pores resembling the finger-like structure found deeper within the membrane, which warrants further study.

- F20 Leveraging Surplus Energy from Nuclear Power Generation for Seawater Desalination: A Process Modelling Investigation**, J. Hunter Himes (Tennessee Tech University); Mary Adkisson (Tennessee Tech University); Laura H Arias Chavez (Tennessee Tech University)*

Nuclear power plants represent a significant, untapped supply of low-grade waste heat and intermittently available surplus electricity that could be used for seawater desalination. The majority of the thermal energy generated at these facilities is discharged to the environment as low-temperature heat; only one third is converted into electricity. In addition, nuclear power production in the United States cannot be ramped up or down to match the fluctuating demand for electricity, forcing generation facilities to sell electricity at a loss at times of low grid demand. If an appropriate partner process can be identified, this surplus energy can be used to desalinate seawater, enhancing coastal water supplies without significantly increasing energy demand while also improving the economics of nuclear power generation. To effectively leverage both surplus electricity and waste heat, a wide range of desalination technologies were investigated for stand-alone use or in combinations. These include reverse osmosis, membrane distillation, multi-pass nanofiltration, and others. Processes were ordered according to their unique advantages and disadvantages with respect to maximum achievable water recovery, energy utilization, tolerance of fluctuations in available energy, and susceptibility to scaling. Material and energy balances were used to model potential process combinations in MATLAB in order to predict the quantity and quality of water that could be produced from a given amount of energy. The feasibility of achieving zero liquid discharge in this unique energy use context was also investigated. Results were considered together with water-use data in southeastern Florida to estimate the cost and value of desalinating and supplying water alongside a hypothetical 300 MW (thermal) nuclear power plant at Turkey Point, Florida. These metrics were used to identify the most promising directions for future research into surplus-energy-powered seawater desalination.

- F21 Maxwell-Stefan characterization of surface diffusion flow through defect containing silicalite membranes.**, David Carter (University of Ottawa); Shaaima Al Akwaa (University of Ottawa); Boguslaw Kruczek (University of Ottawa); Handan Tezel (University of Ottawa)*

Although zeolite membranes can withstand temperatures in excess of 500°C and harsh chemical environments, their widespread industrial adoption for separating gas mixtures has been impeded by two main factors. These are firstly the ability to fabricate zeolite membranes containing as few defects as possible, and secondly, the means to evaluate the performance of novel membranes, and therefore design of membrane processes. Our group and others in the literature have investigated the former challenge. The present study

addresses the latter challenge of characterizing novel membranes and utilizes the Maxwell-Stefan (MS) model to determine characteristic diffusivities and exchange coefficients, which describe only the surface diffusion contribution to overall membrane permeance for defect containing membranes. Since surface diffusion flow is subject to synergistic adsorption and diffusion phenomena, these diffusivities and exchange coefficients can be used to relate the pure gas permeances of novel membranes with gas mixture separation performance predictions. To accomplish this goal, it is necessary to discount the defect contributions to overall membrane permeance, which has been accomplished by utilizing parameters determined using a simple model that is based on the results of in-situ pure gas permeation experiments. For two defect containing silicalite membranes, MS diffusivities of CO₂ (\bar{D}_{CO_2}) and N₂ (\bar{D}_{N_2}) of $7.26 - 8.33 \times 10^{-8} \text{ m}^2 \cdot \text{s}^{-1}$ and $1.17 - 1.95 \times 10^{-8} \text{ m}^2 \cdot \text{s}^{-1}$, respectively, were determined. The corresponding exchange coefficients \bar{D}_{N_2}/CO_2 and \bar{D}_{CO_2}/N_2 were also determined, and \bar{D}_{N_2}/CO_2 was found to be at least 1.38 times greater than \bar{D}_{CO_2}/N_2 for both membranes. These characteristics are similar for both membranes, and can be used to predict the CO₂/N₂ gas mixture separation performance of silicalite membranes at untested conditions.

F22 Self-Regulating FO-RO Hybrid Systems, Noah Ferguson (University of Connecticut)*; Nicole Beauregard (University of Connecticut); Jeffrey R McCutcheon (University of Connecticut)

Though reverse osmosis (RO) is an industrially mature and widespread desalination technology, its susceptibility to fouling makes it challenging to operate using more difficult feedwaters. Pretreatment is one approach to reducing fouling in RO membranes, and such systems often comprise a majority of a desalination plant's total footprint. Hybridization of forward osmosis (FO) with RO has been considered as an alternative configuration to more conventional pretreatment schemes, but the lack of understanding of how these systems might operate and the potential for complex control schemes to balance fluxes between the FO and RO systems create uncertainty. In this work, we demonstrate self-regulating behavior of FO-RO hybrid systems that can lead to drastically reduced complexity of these systems. We show this behavior using a module-scale test bed that can mimic the behavior of larger scale systems. In short, the system shows volumetric flux convergence between the FO and RO modules when perturbed by a change in RO module pressure and therefore does not need to have complex controllers in place to ensure even flows between the two processes.

F23 Estimating salt diffusion coefficients in polyamide active layers of reverse osmosis membranes using microscale continuum modeling, Riley Vickers (University of North Carolina at Chapel Hill)*; Jingbo Wang (UCLA); Timothy Weigand (University of North Carolina at Chapel Hill); Casey Miller (University of North Carolina at Chapel Hill); Orlando Coronell (University of North Carolina at Chapel Hill)

Analysis of water and solute transport through reverse osmosis (RO) membranes in the literature shows that water and solute permeability of RO membranes depend on geometric (thickness, pore structure, surface roughness) and intrinsic transport (partition and diffusion) properties of their polyamide (PA) active layers. Developments in characterization techniques through the past decade have yielded experimental methods to quantify almost all geometric properties and water and solute partition coefficients of PA active layers. However, there is no method to experimentally quantify diffusion coefficients of salts and other solutes of common interest in PA active layers. Atomistic modeling techniques are the primary method for estimating diffusion coefficients, but they do not account for the morphology and topology of PA active layers (Ding et al., 2014, *Desalination*, 343 48-53). Our previous work (Lin et al., 2018, *J. Membr. Sci.*, 564, 935-944) estimated water diffusion coefficients in RO membranes during permeation of pure water by using finite element microscale continuum modeling. In this study, we build upon that work to estimate both water and solute diffusion coefficients in RO membranes during permeation of salt solutions. To achieve this, we experimentally determine membrane water and salt permeability, water and salt partition coefficients, active layer thickness, pore sizes, and pore volume fraction. We then use this geometric characterization, water flux, and salt rejection data as model inputs to estimate water and salt diffusion coefficients. Using these salt diffusion coefficients, we evaluate which geometric or intrinsic transport properties have the strongest correlation to salt permeability. This modeling approach constitutes a tool for membrane scientists and developers to estimate the diffusion coefficient of solutes in PA active layers, and aids in targeting structural and intrinsic transport properties for optimization of membrane performance.

F24 Energy-efficient Biogas Upgrading Membrane Process, Chung-Seop Lee (Airrane Co. Ltd); Jinhyuk Lim (Airrane Co. Ltd); Sang Hoon Han (Airrane Co. Ltd)*; Sejong Kim (Airrane Co. Ltd); Seong Yong Ha (Airrane Co. Ltd); Won Seok Chang (Korea District Heating Corporation); Moon Sei Oh (Korea District Heating Corporation)

Biogas is a kind of gas mixture produced by the anaerobic digestion or fermentation of organic matters such as municipal solid waste, sewage sludge, feedstock waste or any other biodegradable waste. Biogas from the anaerobic digestion has been mostly combusted for heating and power generation; however, the purification of biogas is getting popular in that the cost of methane by biogas purification is more economic than the cost of power generation by the combustion. Biogas purification has been mostly performed using pressure swing adsorption (PSA) process with solid adsorbent, but more recently the application of gas separation membrane is enlarged due to its simple process, compact footprint, low maintenance, high energy saving and low operation expenses, etc. The dehydrated biogas is

consisted of mainly methane (60~70 vol%) and carbon dioxide (30~40 vol%) with few hydrogen, hydrogen sulfide, oxygen, nitrogen and siloxane, etc. Its low oxygen and nitrogen concentration enables the separation of methane from biogas more efficient than the separation from landfill gas; the state-of-the-art polymer membrane is the most economic process for biogas purification. Membrane-based biogas purification is performed in the order of dehydration, pretreatment, gas compression, heat exchange unit and membrane skid, etc. Pretreatment removes siloxane and acid gas which may reduce the long-term operation performance of membrane separation due to the sorption on the surface or corrosion of polymer membrane. The pretreated gas is compressed up to 10-20 barg. The multi-stage of membrane modules is tested with small membrane area at the lab-scale study, and the methane concentration of retentate stream was over 96-98 vol% enough to be put in the liquefied natural gas grid while the carbon dioxide enriched gas stream was permeated at the downstream.

F25 Multi-stage Membrane Process for CO₂ Separation from LNG flue gas, Chung-Seop Lee (Airrane Co. Ltd)*; Sejong Kim (Airrane Co. Ltd); Chung-Seop Lee (Airrane Co. Ltd); Won Seok Chang (Korea District Heating Corporation); Moon Sei Oh (Korea District Heating Corporation)

The enormous amount of greenhouse gas emission by the combustion of fossil fuels from 19th centuries causes the man-made global warming with the increase of atmospheric CO₂ concentration over 400 ppm. There are the six major greenhouse gases: carbon dioxide (CO₂); methane (CH₄); nitrous oxide (N₂O); hydrofluorocarbons (HFCs); perfluorocarbons (PFCs); and sulphur hexafluoride (SF₆). CO₂ has the lower greenhouse index, but the effect to the global warming is more than 50% due to the worldwide fossil fuel for power generation, automotive, and petrochemical processes, etc. One of the substantial alternatives against the global warming is carbon capture, utilization and storage (CCUS) technologies. CCUS can reduce the emission of greenhouse gases into the atmosphere and also create the additional beneficial products. Membrane-based gas separation process is one of the most feasible gas separation processes for CCUS competing with amine-based solvent-scrubbing and sorbent-based capture. We developed a bench-scale multi-stage CO₂ separation process inside a 3×6 m² of movable container box. The process is equipped in the order of flue gas blower, knockout drum, heat exchanger, gas compressor, gas dryer, multi-stage membrane cascade and three vacuum pumps connected to each membrane permeate flow. The membrane process was installed at Pangyo Division in Korea District Heating Corporation (KDHC) which operated the combined heat and power plant (CHP) and supplied both heat and electricity. The flue gas from CHP is composed of the lower CO₂ concentration than the one from the pulverized carbon (PC) power plant, cement and steel manufacturing plant. The parametric experiments were focused to increase the CO₂ concentration from the lower CO₂ feed stream to the level for the appropriate CO₂ utilization process.

F26 Cost Optimization of Pressure Retarded Osmosis, Alexandra N Newby (Carnegie Mellon University)*; Timothy V Bartholomew (Carnegie Mellon University); Meagan S Mauter (Carnegie Mellon University)

Pressure Retarded Osmosis (PRO) is a technology which mixes two water sources of different concentrations and generates electricity, and is a potential solution to the growing need for low carbon energy sources. Previous analyses on the PRO membrane show that electricity can be generated. However, these studies are limited by not considering the operation, inefficiencies, and cost of a full system needed for PRO, nor is the capacity factor for PRO considered to account for the total cost of this technology. This study identifies the cost optimal design and operation using a nonlinear programming model to minimize the levelized cost of electricity (LCOE) of an entire PRO system for a specified feed salinity and process and financial parameters. Our model includes a detailed finite difference module-scale model that explicitly considers the pressure drop along the module and non-constant solution properties, mass and heat transfer coefficients, and equipment inefficiencies. Additionally, the LCOE and capacity factor for PRO is compared to other low carbon energy sources to determine the competitiveness of this technology. Preliminary results show that PRO should not be pursued low carbon energy solution until after membrane technology and equipment efficiencies can be improved significantly.

F27 Tearing propagation of an airship envelope fabric based on FEM and X-FEM methods, Chen Yonglin (Shanghai Jiaotong University); Wang Fengxin (Shanghai Jiaotong University)*

This paper studied tearing properties of an airship envelop fabric by numerical analysis. The finite element method (FEM) and the extended finite element method (X-FEM) were carried out to simulate the crack tip propagation on such fabric. ANSYS and MATLAB were applied as FEM and X-FEM software, respectively. To simulate the discontinuity on the specimen, both of the Galerkin's and the Heaviside functions were introduced during calculating strengthening function in X-FEM. The strain contours and the stress fields were obtained by two methods. Meanwhile, the stress field propagation in membrane crack tip was contrasted between such two methods. Then, the stress intensity factor of the airship envelope was solved. It is found the stress distribution of such fabric was proved to be nonlinear. And the X-FEM is preferable to simulate crack propagation on membrane material.

F28 Modelling of the effect of current density and contact time in electro-coagulation on membrane fouling, In-Soung Chang (Hoseo University)*

Electro-coagulation process has been gained an attention recently because it could overcome the membrane fouling problems in MBR (membrane bio-reactor). Effect of the key operational parameters in electro-coagulation, current density (ρ_i) and contact time (t) on membrane fouling reduction was investigated in this study. A kinetic model for ρ_i and t required to reduce the membrane fouling was suggested under different MLSS concentration. Total 48 batch type experiments of electro-coagulations under different sets of current densities (2.5, 6, 12 and 24 A/m²), contact times (0, 2, 6 and 12 hr) and MLSS (mixed liquor suspended solids) concentration (4500, 6500 and 8500mg/L) were carried out respectively. After each electro-coagulation under different conditions, a series of membrane filtration was performed to get information on how much of membrane fouling was reduced. The membrane fouling decreased as the ρ_i and t increased but as MLSS decreased. Total fouling resistances, $R_t (=R_c+R_f)$ were calculated and compared to those of the controls (R_0), which were obtained from the experiments without electro-coagulation. A kinetic approach for the fouling reduction (R_t/R_0) rate was carried out and three equations under different MLSS concentration were suggested: $\rho_i^n * t = \text{constant}$. Those equations state that the product of ρ_i and t needed to reduce the fouling in certain amounts (in this study, 10% of fouling reduction) is always constant.

F29 Characterization and Molecular Dynamics Simulation of Poly(arylethersulfone) Ultrafiltration Hemodialysis Membrane, Arash Mollahosseini (University of Saskatchewan); Amira Abdelrasoul (University of Saskatchewan)*

A significant number of patients around the world with end-stage renal diseases (ESRD) are receiving hemodialysis treatment as an alternative therapy for kidney transplant. Polymeric membranes, as the main element of the hemodialysis systems, still lack an optimum biocompatibility profile. Consequently several research approaches are currently focusing on biocompatible polymeric membranes with low- or non-activation behaviour. This study aimed to assess the effects of blood on hemodialysis membrane. As part of the experiment, before and after assessments were conducted on blood contacted membranes. To increase the relevance of the study, poly (arylethersulfone-vinyl pyrrolidone) (PAES-PVP) hemodialysis membranes were chosen. Fourier transmission infrared (FTIR) spectroscopy and Raman spectroscopy were used to assess the initial chemical structure of the membrane along with the subsequent variations with the blood infections. Primary chemical interactions were discussed based on the variations in spectroscopy peaks. Scanning electron microscopy (SEM) and Transition electron microscopy (TEM) were implemented in order to assess the morphological patterns in the membrane's surface structure and cross section. The research helped visualize the structural membrane variation, as well as blood aggregations and blood clots on the membrane's surface. Molecular dynamics (MD) simulation was performed using material studio software to evaluate the interaction of PAES-PVP with major human blood proteins, specifically in terms of interaction energy. The macromolecules were chosen from plasma protein component since they are considered to be the main elements responsible for blood constituent fouling on hemodialysis membranes. This is the first time that an MD technique was applied for the analysis of blood-hemodialysis membrane interactions.

F30 Humidified gas permeabilities in polybenzimidazole gas separation membranes, Joshua D Moon (The University of Texas at Austin)*; Benny Freeman (The University of Texas at Austin); Donald Paul (The University of Texas at Austin)

Polybenzimidazoles (PBIs) have recently been investigated for use as gas separation membranes due to their thermal stability and good H₂/CO₂ separation performance at elevated temperatures. However, PBIs are hydrophilic, and effects of water vapor on PBI separation performance are generally unexplored. Recent studies have shown that water binds strongly to PBIs and that the high water uptake of PBIs (up to 25 wt%) causes significant swelling and changes in volumetric properties such as polymer fractional free volume. The effect of humidity on gas transport in both commercial PBI (Celazole®) and recently synthesized sulfone-containing PBIs has been examined using single gas humidified permeation measurements. Samples were pre-equilibrated with water at relative humidities ranging from 2 to 60% at 35°C prior to permeating a single gas species (e.g., H₂ or CO₂). Gas permeabilities decreased by up to an order of magnitude at low humidities, which is believed to be due primarily to competitive sorption. Gas permeabilities increased slightly at higher humidities where more significant swelling and plasticization occurred. Humidified gas permeabilities can be correlated with changes in fractional free volume that result from water uptake and swelling.

F31 Hollow Fiber Countercurrent Dialysis for Continuous Buffer Exchange of High Value Biotherapeutics, Christopher Yehl (Penn State University)*

There is growing interest in the development of continuous biomanufacturing processes for the production of high value biotherapeutics. These continuous processes have the potential to provide lower cost operation, greater manufacturing flexibility, and enhanced product quality. Buffer exchange, desalting, and formulation of high-value biotherapeutics are currently performed using batch diafiltration (DF); however, this type of tangential flow filtration process would be difficult to implement as part of a fully continuous biomanufacturing process. The objective of this study was to explore the potential of using countercurrent dialysis for continuous protein formulation and

buffer exchange. Experiments were performed using concentrated solutions of immunoglobulin G (IgG) with commercially available polysulfone hollow fiber dialyzers having 1.5 and 1.8 m² membrane surface area. More than 99.9% buffer exchange was obtained over a range of conditions, as determined from the removal of a model impurity (vitamin B12). The dialyzers were able to process more than 0.5 kg of IgG per day in an easily scalable low-cost process. In addition, buffer requirements were less than 0.02 L of buffer per gram IgG, which is several times less than that used in current batch DF processes. These results clearly demonstrate the potential of using low-cost hollow fiber dialyzers for buffer exchange and product formulation in continuous bioprocessing. Further studies will be performed to explore potential opportunities for using hollow dialyzers for simultaneous buffer exchange and product concentration by employing a transmembrane pressure to drive the ultrafiltration. Higher flux / permeability dialyzers are being generated in our laboratory by chemical modification of commercially-available dialyzers. This provides exciting new opportunities for the use of membrane systems in continuous downstream processing of high value biotherapeutics.

F32 Multiscale modeling of microporous polymer blends for CO₂ separation, Alec Kaija (U.S. Department of Energy National Energy Technology Laboratory)*; Ali Sekizkardes (Battelle/U.S. Department of Energy National Energy Technology Laboratory); Samir Budhathoki (U.S. Department of Energy National Energy Technology Laboratory); Janice Steckel (U.S. Department of Energy National Energy Technology Laboratory)

Polymers of intrinsic microporosity (e.g. PIM-1) are promising materials for gas separations - particularly in post-combustion CO₂ capture - due to their ultra-high permeability. Unfortunately, PIM-1 suffers from brittleness and low gas selectivity. Recently, the high permeability of PIM-1 has been leveraged by incorporating it into polymer blends for use in gas separation membranes. Several polyphosphazene polymers have been identified for blending with PIM-1 because they have better mechanical properties and higher CO₂/N₂ selectivity than PIM-1. Here we discuss approaches to modelling different PIM/polyphosphazene blends with the goal of predicting miscibility, phase separation, and gas permeation behavior. While atomistic simulations are effective for predicting certain chemical and physical properties (e.g. gas diffusivity) they do not lend themselves to the kinds of temporal and spatial scales necessary for evaluating miscibility. We discuss some of the challenges of modelling these particular systems as well as the development of a coarse-grained model for the consideration of chemical and physical properties not feasibly predicted by atomistic models alone.