Basic Information

1. **Title:** "Hollow fiber membrane air stripping for the removal of carbonate species in produced water from hydraulic fracturing"
2. **Focus categories:** Treatment, Water Quality, Wastewater
3. **Keywords:** hydraulic fracturing, water purification, membrane application, pretreatment
4. **Duration:** March 1, 2015 to February 28, 2016
5. **Federal funds requested: $5,000**
6. **Non-federal funds pledged: $10,000**
7. **Principle Investigator:** Dora Frances Sullivan-González, University of Texas at Austin, Department of Environmental and Water Resources Engineering, Master's student, dfsg@utexas.edu, (662) 832-3103, Dept. of Civil, Architectural and Environmental Engineering, 301 E. Dean Keeton St; Austin, TX 78712
8. **Co-Principal Investigators:**

    a. Dr. Lynn Katz, University of Texas at Austin, Dept. of Civil, Architectural and Environmental Engineering, Professor and Director of Center for Research in Water Resources, lynnkatz@mail.utexas.edu, (512) 471-4244, 301 E. Dean Keeton St.; Stop C1786; Austin, TX 78712
    b. Dr. Desmond F. Lawler, University of Texas at Austin, Nasser I. Al-Rashid Chair in Civil Engineering, Dept. of Civil, Architectural and Environmental Engineering; dlawler@mail.utexas.edu, (512) 471-4595, , 301 E. Dean Keeton St; Stop C1786; Austin, TX 78712
    c. Dr. Benny Freeman, University of Texas at Austin, McKetta Department of Chemical Engineering, Richard B. Curran Centennial Chair in Engineering, freeman@che.utexas.edu, (512) 232-2803, 200 E Dean Keaton St. Stop C0400, Austin, TX 78712-1589

9. **Congressional District:** TX-25
10. **Abstract:**

Approximately 5.66 million m^3 of wastewater per year is produced by hydraulic fracking; the "flowback" water constitutes about 10-30% of the water used in the fracking process. The ideal situation would be to treat and reuse the flowback water to reduce disposal costs and the demand for fresh water, but such treatment is difficult due to high saline content and presence of oils and other organics. In their pilot study, Miller et al. addressed the use of ultrafiltration (UF) and reverse osmosis (RO) membranes modified with a polydopamine coating to treat produced water from the Barnett shale gas basin in Texas. I propose the addition of a hollow fiber (HF) air stripping membrane unit for CO_2 removal as an intermediate step in this treatment train to improve the desalination performance of reserve osmosis. I will initially test the HF membrane using a variety of synthetic waters that contain varying concentrations of total dissolved solids under a range of parameters including transmembrane pressure and fluxes to achieve outlet concentrations <1ppm CO_2. Then, I will test a combined HF membrane unit and reverse osmosis train with synthetic waters before testing the system with water from the Maggie Spain Water Reclamation Facility.

11. Title of Proposal

Hollow fiber membrane air stripping for the removal of carbonate species in produced water from hydraulic fracturing

12. Statement of Critical Regional or State Water Problem

The popularity of hydraulic fracturing, or fracking, over the past decade has increased the production of natural gas in North America and, consequentially, the need for improved technologies to treat the accompanying flowback water.[1] Fracking requires large volumes of water, putting a strain on local freshwater demands and disposal practices. Approximately 5.66 million m^3 of wastewater per year is produced by fracking;[2]; this "flowback" water constitutes approximately 10-30% of the water used in the fracking process.[1]

Disposing of the produced water can cost up to $4 per barrel including costs for transportation and injection wells.[1] Therefore, it is ideal to reuse the flowback water to reduce disposal costs and the demand for fresh water. However, challenges to produced water treatment occur due to the high saline content and presence of oils and other organics. According to Thiel and co-workers, produced water samples from the Permian shale basin contained up to 183,000 mg/L of total dissolved solids (TDS), while Miller et al. reported produced water characteristics from the Barnett shale basin of up to 99,000 mg/L TDS.[2,1]

The rise of membrane technology for purification of flowback water is attributed to their small energy footprint, high efficiency, and ability to be moved from one drill site to the next.[1] Recent advances in membrane research for flowback water treatment include the use of microfiltration, ultrafiltration, nanofiltration, and reverse osmosis. Alzahrani and co-workers reviewed the different types of membrane technologies to conclude that current practices have "high potential" for meeting the needs of the petroleum industry while future goals can target a standard reference for produced water characterization, treatment of produced water at its source by integrated membrane technologies to aim for "zero liquid discharge," and the recovery of by-products from produced water.[3] The biggest drawback to membrane technologies is their tendency to foul due to the constituents in the water being treated.

In their pilot study, Miller and co-workers addressed the use of ultrafiltration (UF) and reverse osmosis (RO) membranes modified with a polydopamine coating to treat produced water from the Barnett shale gas basin in Texas.[1] The polydopamine coating was used as a surface modification for the membranes to reduce the effects of fouling. The polyacrylonite hollow fiber UF membranes were further modified by grafting poly(ethylene glycol) to the polydopamine coating. The UF membranes removed organic material, specifically emulsified oils, from the flowback water while RO membranes desalinated the UF permeate. The surface modifications successfully decreased the resistance to mass transport in the UF membranes. The polydopamine coating did not affect the water flux or the transmembrane pressure of the modified RO membrane compared with the unmodified RO membrane; the surface modification did, however, increase the salt rejection of the modified RO membrane. In that study, the TDS in the RO feed ranged from $2x10^{-4}$ to $6.5x10^{-4}$ mg/L, which represented the salt concentration of the waters.

13. Statement of Results or Benefits

To improve the desalination performance of reserve osmosis, different pretreatment options are available.[4] Jamaly and co-workers recommend the use of UF or NF as part of the pretreatment membrane train to extend the lifetime of RO membranes because the UF/NF membranes can handle a salinity range > 35,000 ppm.[4] However, the results of the pilot study in the Barnett shale gas region, suggest that an intermediate step between UF for organic removal and RO for desalination could be used to remove carbonate species from the produced water to prevent precipitation and scaling of the RO membrane.

Thiel and Lienhard reported that the carbonate species in the produced water were the most likely to scale membranes based on their saturation index.[2] Therefore it is worthwhile to examine the benefits of adding to the membrane treatment train by using hollow fiber air stripping as RO pretreatment to remove CO_2 from produced waters. Liqui-Cel® Membrane Contactor systems have been used for CO_2 removal from water prior to secondary treatment by RO or electrodeionization to decrease the scaling effect of carbonate species in several places including San Antonio, Texas and China[5,6]. However, the use of CO_2 for reuse or treatment of produced water from fracking operations has not been investigated previously.

The benefits of reducing scale formation in membrane processes are evident as fouling is typically the main cause of reductions in membrane performance as measured by membrane flux and water recovery. However, the development of a cost-effective membrane process for treating produced water from hydraulic fracking operations that will allow water reuse or provide safe disposal options is the major benefit of the proposed research; this is especially true in semi-arid regions such as Texas where the demands on our limited water resources are continually increasing. Despite the fact that surface water withdrawals of necessary volumes for hydraulic fracking generally represent only a minor part of total water consumption, the demand places significant burdens in local regions already under significant water stress. Recognition of the need for water conservation and reuse in the oil and gas industry led the Railroad Commission of Texas, which regulates the oil and gas industry, to adopt new rules in 2013 to encourage recycling. Under these rules, operators no longer need a permit to recycle water if they are on their own land leases[7]. Thus, the development of cost-effective options for reuse of water from fracking operations is necessary especially within Texas where the population is growing and water demands from other sectors compete with the oil and gas industry.

14. Nature, Scope, and Objectives of the Research

The objective of this project is to develop a cost-effective membrane treatment system for produced water treatment from hydraulic fracking operations. I propose the addition of a hollow fiber (HF) air stripping membrane unit for CO_2 removal as an intermediate step in a treatment train that includes ultrafiltration and reverse osmosis. I hypothesize the addition of this unit to the process will decrease the amount of carbonated species in the water and, therefore, reduce scaling and increase the water flux and recovery through the RO membrane. I will initially test the HF membrane using a variety of synthetic waters that contain varying concentrations of inorganic salts, carbonate concentrations, and background organics under various transmembrane pressure and fluxes. The membrane will be tested under both pressure using nitrogen and vacuum. Upon optimization of the conditions and elucidation of the controlling parameters, the system will be combined with ultrafiltration and reverse osmosis and tested with synthetic waters. Finally, the combined system will be tested using water from the Maggie Spain Water Reclamation Facility. For my experiments, the raw water will be treated with coagulation, sedimentation, and a polydopamine-modified UF membrane to remove suspended solids and organic material. Since the pH of the water for treatment will already have been reduced to approximately a pH of 5 before UF, hollow fiber membrane air stripping will be an efficient process for removing dissolved CO_2 from the water.

15. Methods, Procedures, and Facilities

I will use the 1.7 x 5.5 MiniModule® PP X50 membrane contactor system from Membrana Contactors. These Liqui-Cel membranes were originally designed for liquid-liquid extraction in the late 1980s. However, the original parallel flow microporous membranes, which resembled a shell and tube heat exchanger, displayed disappointing separation results when the membrane contactor was scaled up. The manufacturer company, Hoechst-Celanese at the time, worked in collaboration with UT Austin to determine what caused such poor results. Dr. Frank Seibert and his team from the Solutions Research Program at UT proved, in the early 1990s, that shell side fluid bypassing the membrane led to much shorter contact times than expected (Seibert, personal communication). At that time, Hoechst-Celanese also discovered that gas permeates out of the aqueous phase, which led to the primary current application of this membrane technology: degassing (or air-stripping) from water. After modifying the module design to prevent shell side short-circuiting, the process became much more attractive and was commercialized primarily for water degassing particularly in the microelectronics industry.

The membrane system to be used in this research can achieve outlet concentrations <1ppm CO_2 and can accommodate a maximum flowrate of 2.5L/min, appropriate to handle a laboratory scale water flowrate of 0.8L/min. The hollow fiber membrane in this unit is hydrophobic polypropylene appropriate for CO_2 removal in a countercurrent flow setup with water on the shell side and either a vacuum or sweep gas on the tube side to remove CO_2 from the system.

Initial experiments to be conducted in the first eight months of the project will utilize synthetic waters of varying composition (see Table 1; note that strontium will also be evaluated at up to concentrations of 6,400 mg/L even though it is not included in Table 1) and focus only on the HF membrane. A range of alkalinities will be tested from approximately 50 to 500 mg/L as $CaCO_3$ and the degree of potential oversaturation with respect to barium, strontium and calcium carbonates will be varied through changes in pH, alkalinity and alkaline earth metal ion concentrations. Operating parameters to be varied include liquid and gas flowrates and sweep gas pressure; parameters to be measured include pH, total carbonate species concentration in terms of ppm of CO_2, and water flux through the RO membrane. In the final four months of the project, the membrane will be tested in conjunction with the UF and RO system using 1) synthetic water and then 2) water from the Maggie Spain Water Reclamation Facility.to determine whether the results from the synthetic water are consistent with actual field waters and to assess the potential of the complete flow train.

Table 1. Composition ranges of Barnett and Marcellus flowback waters[1]

Parameter	**Barnett (5 locations)**		**Marcellus (19 locations)**	
	Range	**Median**	**Range**	**Median**
pH	6.6–8.0	7.1	5.8–7.2	6.6
Total dissolved solids (mg/L)	23,600–98,900	36,100	38,500–238,000	67,300
Alkalinity (mg/L $CaCO_3$)	238–1,630	610	48.8–327	138
Chloride (mg/L)	16,500–72,400	22,200	26,400–148,000	41,850
Bicarbonate (mg/L $CaCO_3$)	145–994	372	29.8–162	74
Sulfate (mg/L)	145–1,300	1080	<0.031–106	25.9
Calcium (mg/L)	454–6,680	1020	1440–23,500	4950
Barium (mg/L)	1.5–16.8	2.11	21.4–13,900	686
Iron (mg/L)	11.8–76.7	17.8	10.8–180	39
Sodium (mg/L)	7420–25,300	15,500	10,700–65,100	18,000
Magnesium (mg/L)	75.3–757	156	135–1550	559

The research will be conducted in the EWRE laboratories at the University of Texas. The research team has already purchased all necessary membranes, pumps and appurtenances required to build the membrane system.

16. Related Research

See Numbers 12-14 of the proposal for discussion of related research.

17. Training Potential

One Ph.D. student (Sullivan-González)

18. Investigators' Qualifications

Resumes for the graduate student and faculty investigators are attached.

Sources Cited:

1. Miller, Daniel J., Xiaofei Huang, Hua Li, Sirirat Kasemset, Albert Lee, Dileep Agnihotri, Thomas Hayes, Donald R. Paul, and Benny D. Freeman. "Fouling-resistant Membranes for the Treatment of Flowback Water from Hydraulic Shale Fracturing: A Pilot Study." *Journal of Membrane Science* 437 (2013): 265-75.

2. Thiel, Gregory P., and John H. Lienhard, V. "Treating Produced Water from Hydraulic Fracturing: Composition Effects on Scale Formation and Desalination System Selection." *Desalination* 346 (2014): 54-69. Print.

3. Alzahrani, Salem, and Abdul W. Mohammad. "Challenges and Trends in Membrane Technology Implementation for Produced Water Treatment: A Review." *Journal of Water Process Engineering* 4 (2014): 107-33. Print.

4. Jamaly, S., N. N. Darwish, I. Ahmed, and S. W. Hasan. "A Short Review on Reverse Osmosis Pretreatment Technologies." Desalination 354 (2014): 30-38. Print.

5. Liquicel Membrane Contactors, China Power Plant Installs Advanced Integrated Membrane System (IMS) to Reduce Capital Costs and Decrease Energy Use. Technical Brief, Charlotte: Membrana, 2007..

6. Liquicel Membrane Contactors, Ion Exchange: Using Membrane Contactors for CO_2 Removal to Extend Resin Bed Life. Technical Brief, San Antonio: Membrana, 2003.

7. Railroad Commission of Texas, Railroad Commission Today Adopts Amendments to Oil & Gas Well Construction Rules, http://www.rrc.state.tx.us/news/052413/ (accessed 12/11/2014).

Frances Sullivan-González
C: 662-832-3103
dfsg@utexas.edu

EDUCATION

University of Mississippi
B.S.Ch.E Chemical Engineering | B.A. Mathematics | GPA 3.74

- Sally McDonnell Barksdale Honors College
- Senior thesis: "Performance and Stability of Room Temperature Ionic Liquid Membranes for the Dehumidification of Methane"

Universidade Federal do Ceará – Fortaleza, Ceará, Brazil
Pontificia Universidade Católica do Rio de Janeiro – Rio de Janeiro, Brazil

HONORS AND AWARDS

- Endorsed by the University of Mississippi for the Marshall Scholarship
- Recipient of the W.R. Newman Award (University of Mississippi foundation scholarship for exceptional academic and leadership record)
- Recipient of National Merit Scholarship
- Recipient of LuckyDay Merit Scholarship
- Recipient of John Roger Moore III Scholarship 2011-2012
- U.S. – Brazil Consortium for Drinking Water Sustainability Grant

WORK HISTORY

Student Aid | National Sedimentation Laboratory **06/2014 to 07/2014**

- Performed phosphorus extractions on soils from Mississippi Delta

Undergraduate Researcher | University of Mississippi **10/2012 to 12/2013**

- "Performance and Stability of Room Temperature Ionic Liquid Membranes for the Dehumidification of Methane" article presented to the American Institute of Chemical Engineers national conference November 2013, San Francisco.

Teaching Assistant | University of Mississippi **08/2013 to 12/2013**

- ENGR 540: Environmental Organic Transport. Graded homework and assisted students with questions when the professor was unavailable.

Intern **06/2011 to 07/2011**
Huntsville Advanced Defense Technology Cluster Initiative – Huntsville, AL

- Coordinated summit for collaboration and cooperation of small businesses and research facilities of the North Alabama region.

ACTIVITIES

- Tau Beta Pi Engineering Honors Society (2011-2014)
- Phi Kappa Phi Honors Society (2011-2014)
- Phi Beta Kappa Liberal Arts Honors Society (2013-2014)
- American Institute of Chemical Engineers (2009-2014)

SKILLS

- PROII, LabView, Mathcad, Fortran, Mathematica, Microsoft Word, Excel, PowerPoint
- Spanish

Lynn E. Katz, Ph.D., P.E.
Bettie Margaret Smith Professor of Engineering
Director of the Center for Research in Water Resources
The University of Texas at Austin • 301 E. Dean Keeton St. Stop C1786 • Austin, Texas 78712

A. Professional Preparation

The Johns Hopkins University	Environmental Engineering	B.E.S	1980
The University of Michigan	Environmental Engineering	M.S.E	1984
The University of Michigan	Chemistry	M.S.	1990
The University of Michigan	Environmental Engineering	Ph.D.	1993

B. Academic and Professional Appointments

2013-Pres	Director, Center for Research in Water Resources, University of Texas at Austin
2007- Pres.	Professor, Bettie Margaret Smith Centennial Professor, Department of Civil, Architectural, and Environmental Engineering, The University of Texas at Austin
2001– 2007	Associate Professor, John A. Focht Centennial Teaching Fellow, Department of Civil, Architectural, and Environmental Engineering, The University of Texas at Austin
1998-2001	Assistant Professor, Civil, Architectural and Environmental Engineering, UT-Austin
Fall 1997	Visiting Scholar – Dept. of Plant and Soil Sciences, University of Delaware
1996-1998	Associate Professor of Environmental Engineering and Cooperating Associate Professor – Chemistry, University of Maine
1993-1996	Cooperating Assistant Professor – Chemistry, University of Maine
1991-1996	Assistant Professor, Department of Civil and Env. Engrg., University of Maine
1988-1991	Research Assistant, Department of Civil and Env. Engrg., University of Michigan
1984-1988	Laboratory Manager, Department of Civil and Env. Engrg., University of Michigan
1980-1982	Environmental Engineer, C.C. Johnson & Assoc., Inc, Silver Spring, MD

C. Synergistic Activities

2014-Pres.	Chair, Faculty Women's Organization
2014-Pres	Chair, AEESP Awards Commitee
2012-present	Member of University of Texas Gender Equity Council
2008-2012	Program Chair and Division Chair of Geochem. Div. of Amer. Chem. Society
2005-2008	Co-Founder and President of Assoc. of Environ. Engrg. & Science Professors Foundation

D. Selected Publications

1. Chambers, B. A., Afrooz, A. R. M. N., Bae, S., Aich, N., Katz, L., Saleh, N. B., Kirisits, M. J. (2014) "Effects of Chloride and Ionic Strength on Physical Morphology, Dissolution, and Bacterial Toxicity of Silver Nanoparticles"*Environ Sci Technol*, 48, 761-769.
2. Mangold, J. et al., (2014) Surface Complexation Modeling of Hg(II) Adsorption at the Goethite/Water Interface using the CD-MUSIC Model, *Journal of Colloid and Interface Science*, 418(15) 147–161.
3. Carter, E.C., Jackson, M.C., Katz, L.E., Speitel, G.E., (2013) "A coupled sensor-spectrophotometric device for continuous measurement of formaldehyde in indoor environments," Journal of Exposure Science and Environmental Epidemiology, doi:10.1038/jes.2013.61.
4. Ha, Y.; Liljestrand, H. M.; Katz, L. E., (2013) Effects of lipid composition on partitioning of fullerene between water and lipid membranes, *Water Sci. & Technol*,68(2), 290-295.
5. Kwon, S., Sullivan, E.J., Katz, L.E. Bowman, R.S. and Kinney, K.A. Laboratory and Field Evaluation of a Pretreatment System for Removing Organics from Produced Water, *Water Environment Research*, (2011), 83(9), 843-854.
6. Johnson, N. W., Katz, L.E. and Reible, D.D. (2010) Biogeochemical changes and mercury methylation beneath an in-situ sediment cap, *Environ. Sci. and Technol.*, 44(19):7280-6.
7. Kwon, J-H, Liljestrand, H. M., Katz, L. E., Yamamoto, H. (2007) "Partitioning Thermodynamics of Selected Endocrine Disruptors between Water and Synthetic Membrane Vesicles: Effects of Membrane Compositions," *Environ. Sci. Technol.*, 41(11), 4011-4018.

Desmond F. Lawler

Nasser I. Al Rashid Chair in Civil Engineering
University Distinguished Teaching Professor
Department of Civil, Architectural and Environmental Engineering
The University of Texas at Austin; C1786, Austin, Texas 78712

Education: Ph.D. Environmental Engineering, University of North Carolina at Chapel Hill, May 1980.
M.S. Environmental Engineering, University of North Carolina at Chapel Hill, August, 1975.
B.S. Civil Engineering, University of Notre Dame, June 1968. (*Magna Cum Laude*)

Academic and Professional Appointments

Nasser I. Al Rashid Chair in Civil Engineering	University of Texas at Austin	9/11-present
Bob R. Dorsey Professor of Engineering	University of Texas at Austin	9/07-8/10
University Distinguished Teaching Professor	University of Texas at Austin	3/97-present
W.A. Cunningham Professor of Engineering	University of Texas at Austin	9/92-8/07
Professor of Civil Engineering	University of Texas at Austin	9/91-9/92
Associate Professor	University of Texas at Austin	9/85-8/91
Assistant Professor	University of Texas at Austin	01/80-8/85
Guest Research Professor,	Universität Karlsruhe, Germany Institut für Siedlungswasserwirtschaft	Summers, 1982, '84, '87

Products Related to the Proposal

1. Benjamin, M.M., and Lawler, D.F., Water Quality Engineering: Physical-Chemical Treatment Processes, a graduate textbook *to be published* by John Wiley, spring 2013. (Any of the 15 chapters can be made available for review if desired.)
2. Lawler, D.F., and Nason, J.A., "Granular Media Filtration: Old Process, New Thoughts," *Water Science and Technology*, 53, 7, 1-7, 2006.
3. Kim, J., Nason, J.A., and Lawler, D.F., "Influence of Surface Charge Distributions and Particle Size Distributions on Particle Attachment in Granular Media Filtration," *Environmental Science and Technology*, 42(7): 2557-2562, April 2008.
4. Russell, C.G, Lawler, D.F., Speitel Jr., G.E., and Katz, L.E., "Effect of Softening Precipitate Composition and Surface Characteristics on Natural Organic Matter Adsorption, *Environmental Science and Technology*, 43, 20, 7837-7842, October 2009
5. Kim, J., and Lawler, D.F., "The Influence of Hydraulic Loads on Depth Filtration," *Water Research*, 46, 2, 433-441, February 2012
6. Lawler, D.F., "Hydraulic Characteristics of Water Treatment Reactors and Their Effects on Treatment Efficiency," Chapter Four in the 6th edition of *Water Quality and Treatment,* AWWA and McGraw-Hill, November, 2010.
7. Greenlee, L.F., Testa, F., Lawler, D.F., Freeman, B.D., and Moulin, P., "Effect of antiscalant degradation on salt precipitation and solid/liquid separation in RO concentrate," *Journal of Membrane Science,* (DOI 10.1016/j.memsci.2010.09.040), 366, 1-2, 48-61, January, 2011.
8. Kim, Y., and Lawler, D.F.; "Selectivity Coefficients of Cation-Exchange Membranes: Maximizing Consistency and Minimizing Error Amplification," *Separation and Purification Technology*, 81, 357-362, October, 2011Kim, Y., and Lawler, D.F., "Overlimiting current by interactive ionic transport between space charge region and lectric double layer near ion-exchange membranes," *Desalination*, 285, 245-262, January 2012.

BENNY D. FREEMAN

Professional Preparation

North Carolina State University	Chemical Engineering	B.S., 1983
University of California-Berkeley	Chemical Engineering	Ph.D., 1988
Ecole Supéreure de Physique et de Chimie Industrielles de la Ville de Paris	NSF/NATO Postdoctoral Fellow Area: Polymer Physics	1988-89

Appointments

2012 – present	Richard B. Curran Centennial Chair in Engineering, UT Austin
2007 – 2012	Paul D. and Betty Robertson Meek & American Petrofina Foundation Centennial Professor of Chemical Engineering, UT Austin
2005 – 2012	Kenneth A. Kobe Professor of Chemical Engineering, UT Austin
2002 – 2005	Matthew van Winkle Professor of Chemical Engineering, UT Austin
1989 – 2002	Assistant, Associate, and Full Professor of Chemical Engineering, NCSU

Products

Five Relevant Products (from a total of >350 research articles and 5 edited books)

1. Arena, J.T., S.S. Manickam, K.K. Reimund, B.D. Freeman, and J.R. McCutcheon, "Solute and Water Transport in Forward Osmosis Using Polydopamine Modified Thin Film Composite Membranes," *Desalination*, **343**, 8-16 (2014), DOI: 10.1016/j.desal.2014.01.009.
2. Greenlee, L.F., B.D. Freeman and D.F. Lawler, "Ozonation of Phosphonate Antiscalants Used for Reverse Osmosis Desalination: Parameter Effects on the Extent of Oxidation," *Chemical Engineering Journal*, **244**, 505-513 (2014), DOI: 10.1016/j.cej.2014.02.002.
3. Geise, G.M., D.R. Paul, and B.D. Freeman, "Fundamental Water and Salt Transport Properties in Polymeric Materials," *Progress in Polymer Science*, **39**, 1-42 (2014), DOI: 10.1016/j.progpolymsci.2013.07.001.
4. Greenlee, L.F., D.F. Lawler, B.D. Freeman, B. Marrot, and P. Moulin, "Reverse Osmosis Desalination: Water Sources, Technology and Today's Challenges," *Water Research,* **43(9),** 2317-2348 (2009), DOI: 10.1016/j.watres.2009.03.010.
5. McCloskey, B.D., H.B. Park, H. Ju, B.W. Rowe, D.J. Miller, B.J. Chun, K. Kin, and B.D. Freeman, "Influence of Polydopamine Deposition Conditions on Pure Water Flux and Foulant Adhesion Resistance of Reverse Osmosis, Ultrafiltration, and Microfiltration Membranes," *Polymer*, **51**, 3472-3485 (2010), doi:10.1016/j.polymer.2010.05.008.

Five Other Significant Products

1. Wang, H., J.K. Keum, A. Hiltner, E. Baer, B. Freeman, A. Rozanski, and A. Galeski, "Confined Crystallization of Polyethylene Oxide in Nanolayer Assemblies," *Science,* **323**, 757-760 (2009), doi:10.1126/science.1164601.
2. Park, H.B., B.D. Freeman, Z-B. Zhang, M. Sankir, and J.E. McGrath, and B.D. Freeman, "Highly Chlorine-Tolerant Polymers for Desalination," *Angewandte Chemie,* **120(32)**, 6108-6113 (2008), doi:10.1002/anie.200800454.
3. Park, H.B., C.H. Jung, Y.M. Lee, A.J. Hill, S.J. Pas, S.T. Mudie, E. van Wagner, B.D. Freeman, and D.J. Cookson, "Polymers with Cavities Tuned for Fast, Selective Transport of Small Molecules," *Science*, **318**, 254-258 (2007), doi:10.1126/science.1146744.
4. Lin, H., E. van Wagner, B.D. Freeman, L.G. Toy, and R.P. Gupta, "Plasticization-Enhanced H_2 Purification Using Polymeric Membranes," *Science,* **311(5761)**, 639-642 (2006), doi:10.1126/science.1118079.
5. T. C. Merkel, B. D. Freeman, R. J. Spontak, Z. He, I. Pinnau, P. Meakin, and A. J. Hill, "Ultrapermeable, Reverse-Selective Nanocomposite Membranes," *Science* **296**, 519-522 (2002), doi:10.1126/science.1069580.

Total Number of Graduate Students Advised: 59 (45 prior and 14 current).

Total Number of Postdoctoral Scholars Sponsored: 18 (16 prior and 2 current).

Budget Breakdown			
Start Date	03/01/15		
End Date	02/28/16		
Project Number	*to be completed by TWRI*		
Project Title	Hollow fiber membrane air stripping for the removal of carbonate species in produced water from hydraulic fracturing		
Principal Investigator(s)	Dora Frances Sullivan-Gonzale (UT PI supervisors: Lynn Katz, Desmond Lawler)		

Cost Category	Federal	Non-Federal	Total
1. Salaries and wages			
- Professional		$5,918	$5,918
- Graduate Student(s)	$2,100		$2,100
- Undergraduate Student(s)			$0
- Other			$0
Total Salaries and Wages	$2,100	$5,918	$8,018
2. Fringe benefits			
- Professional		$533	$533
- Graduate Student(s)	$630		$630
- Undergraduate Student(s)			$0
- Other			$0
Total Fringe benefits	$630	$533	$1,163
3. Tuition			
- Graduate Student(s)	$1,945		$1,945
- Undergraduate Student(s)			$0
Total Tuition	$1,945	$0	$1,945
4. Supplies	$325		$325
5. Equipment			$0
6. Services/Consultants			$0
7. Travel			$0
8. Other direct costs			$0
9. Total direct costs	$5,000	$6,451	$11,451
10. Indirect costs		*Input IDC on federal portion here*	
		$3,549	$3,549
11. Total estimated costs	$5,000	$10,000	$15,000

Budget Justification

1. Salaries and wages: Graduate student Sullivan-Gonzale will work 1.08 months on the grant at a base monthly rate of $1,950. Professor Katz will contribute effort equal to 0.20% of one month's salary ($3,073) and Professor Lawler will contribute effort equal to 0.15% of one month's salary ($2,846).

2. Fringe benefits: The fringe benefit rate for graduate student Sullivan-Gonzale is 30% of wages. The fringe benefit rates for both Professors Katz and Lawler is 9.0%.

3. Tuition: Graduate student Sullivan-Gonzale requests $1,945.00, equivalent to the cost of summer tuition.

4. Supplies: $325 for supplies are requested.

5. Equipment: No funds for equipment are requested.

6. Services/Consultants: No funds for services or consultants are requested.

7. Travel: No funds for travel are requested.

8. Other direct costs: None.

9. Total direct costs: $5,000 is the resulting total direct cost.

10. Indirect costs (to be applied to 2:1 match): The indirect cost rate is 55% of modified total direct costs.