Ultra Low Energy, Low Cost Industrial Nanomembrane Manufacturing for Desalination, Water Purification, and Remediation

DE-SC0013182
Covalent LLC
Project Period 2015-2017

PI: Martin Edelstein, Ph.D., Covalent, LLC
Presenter: Gayle Pergamit, Covalent, LLC

U.S. DOE Advanced Manufacturing Office
Program Review Meeting
Washington, D.C.
June 14-15, 2016

COVALENT LLC

Objectives

Program Objective:

Develop and demonstrate atomically precise nanomembranes and nanomembrane/substrate composites that will:

1. **Reduce energy requirements for Water Purification by up to 99% and Desalination by 66%**
2. **Reduce Water Purification and Desalination costs by >50%**
3. **Demonstrate scalability from Single User to Municipal Scale**

Project DE-SC00013182 Objective:

Demonstrate Scalable Manufacturing of atomically precise nanofilms and nanomembranes for use in Water Purification and Desalination

COVALENT LLC

Objectives

THE PROBLEMS	THE DIFFICULTIES	THE SOLUTION
▪ Scarcity of fresh, pure water • Aquifer depletion • Water pollution • Changing rainfall patterns, drought • Rising population, increased demand	• Expense and energy burden of removing salts and trace toxic impurities from water • Energy cost of water transport	• Atomically precise membranes to lower cost of removing impurities • One atomic-layer thin membranes. Gravity feed to lower energy cost of separations • Cost-effective distributed systems to lower energy used moving water

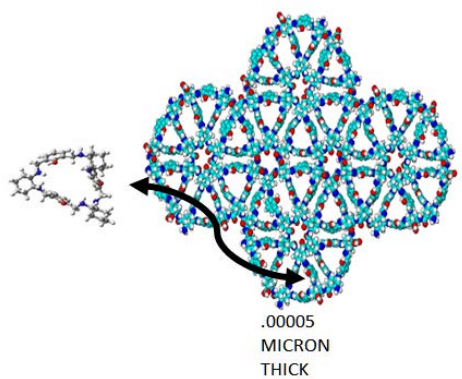
Technical Innovations

Standard Membranes

Low precision,
5-10 micron thick

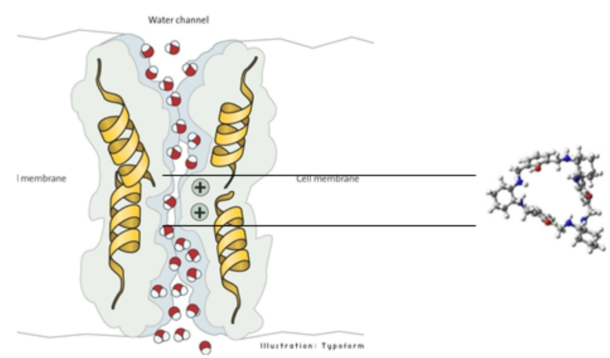
Covalent Nanomembranes

Atomically precise, .0005 micron thick membranes



Atomic Precision Enables Biomimicry

Mimic water transport in the cell



COVALENT LLC

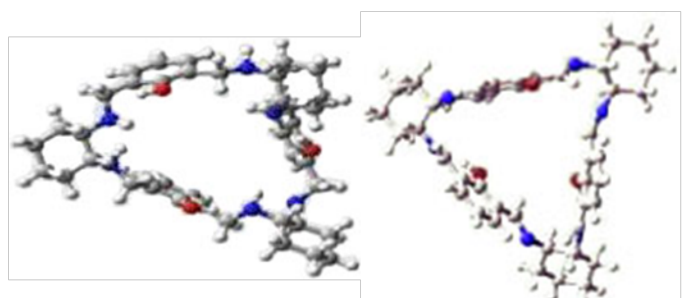
Technical Approach: Atomically Precise Materials Provide Unprecedented Filtration Specificity

	Computer Prediction		Actual Performance	Actual Performance
Solute	**Radius of Solute**	**Radius of solute w/ $H_2$0** (#'s in parentheses denote 2nd hydration shell)	***PORE 1*** **Radius = 3.9 Å**	***PORE 2*** **Radius = 3.3 Å**
Urea marker- Li^+	0.6	2.0 (5.6)	Yes	No
Sodium - Na^+	1.0	2.2	Yes	Yes
Potassium - K^+	1.3	2.7	Yes	Yes
Calcium - Ca^{2+}	1.0	2.7	Yes	Yes
Mg^{2+}	0.7	2.8 (5.5)	Yes	No
NH_4^+	1.9	2.9	Yes	Yes
Cs^+	1.7	3	Yes	Yes
$MeNH_3^+$	2	3	Yes	Yes
$EtNH_3^+$	2.6	3.6	Yes	No
NMe_4^+	2.6	3.6	Yes	No
Aminoguanidine	3.1	4.1	Yes	No
Choline	3.8	4.8	Yes	No
NEt_4^+	3.9	4.4	No	No
Glucosamine	4.2	5.2	No	No
NPr_4^+	-	-	No	-

Earth salts

Pore 2 was built for urea exclusion while allowing earth salt passage, and defeating larger contaminants.

Note precise cutoffs, not rejection ratios



Laboratory performance matches computer prediction

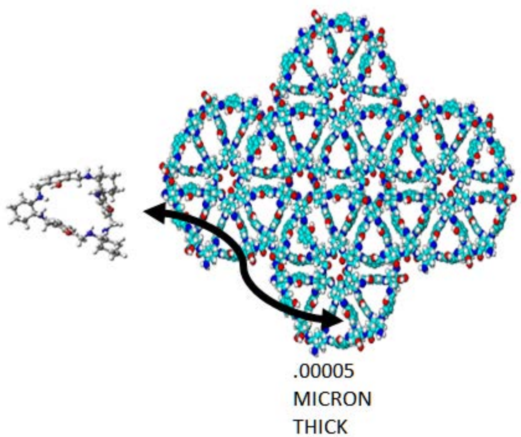
Pores have "personality" and membranes can be "tuned" by using pores that, for example, prefer one earth salt over another.

COVALENT LLC

Technical Approach

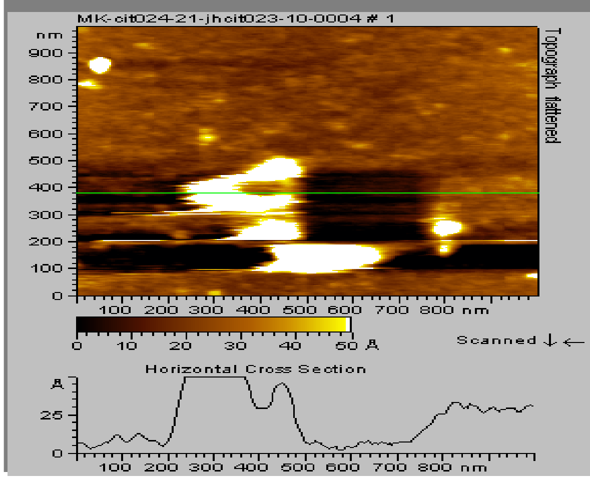
New Approach to Membranes

Chemical building blocks self-assemble into nanomembranes



Atomic Precision

Smooth **surfaces minimize fouling**



Cost Aspects

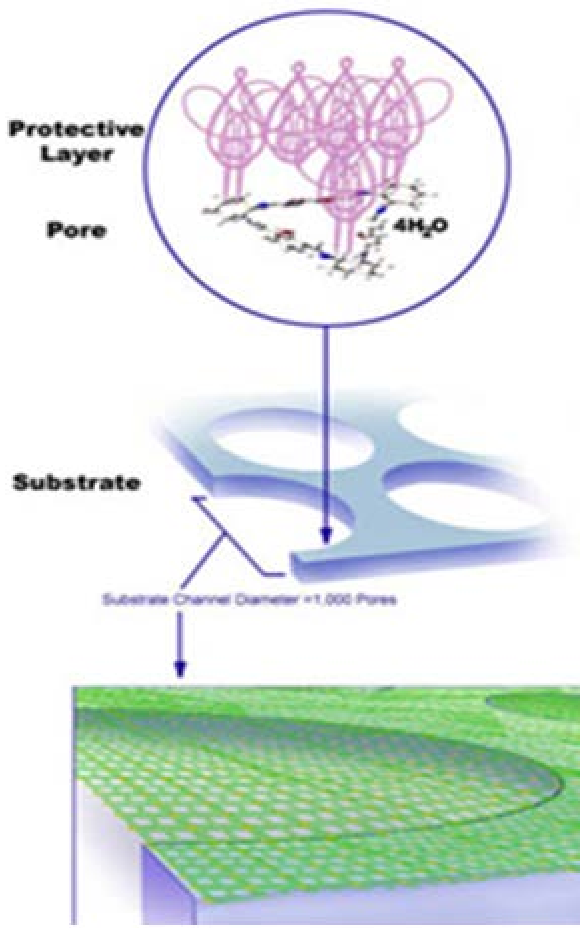
Standard, low pharmaceutical-like manufacturing costs

COVALENT LLC

Technical Approach

How to Build an Atomically-Precise Membrane

1. Synthesize precise, self-assembling building blocks
2. Self-assemble the building blocks into a nanofilm
3. Permanently attach the building blocks to each other to form a nanomembrane.
4. Attach the nanomembrane to a porous substrate.
5. Attach a protective layer to the nanomembrane surface
6. Move from manual fabrication to automated Manufacturing. Methodology proved at lab scale, DOE Phase 1



Participants

Covalent LLC –
Membrane Manufacturing

Agua Via Ltd –
End User Relationships, Marketing and Sales

COVALENT LLC

Technical Approach

DE-SC00013182 MANUFACTURING

1. **Synthesize Building Blocks (Completed)**
2. **Self-assemble Building Blocks (Completed)**
3. **Scale-up (DOE funding)**

COVALENT LLC

Technical Approach & Execution Attributes

TECHNICAL RISKS AND UNKNOWNS	EXECUTION ATTRIBUTES	
No apparent defects at micron resolution are observable. What if there are sub-micron defects? Mitigation: Methodology for curing sub-micron defects planned for Q2 2017	Former CEOs of 1st and 2nd largest US water companies, American Water and American States Water World's top desalination technical talent, Former Head of Thames R&D Former US Secretary of State George Shultz, who also built out Middle East desalination as Bechtel CEO Leading engineering/ installation team: Toshiba/UEM. International scope	Largest US water company on Advisory Board, American Water . Represented by VP, Chief Environmental Officer 1st customer: world's largest water bank. Providing same volume as $1B largest desalination plant in Western Hemisphere Customers in process: more California water districts, leading direct-to-consumer water sales partner with international presence US, Europe, India, China, South East Asia, Africa

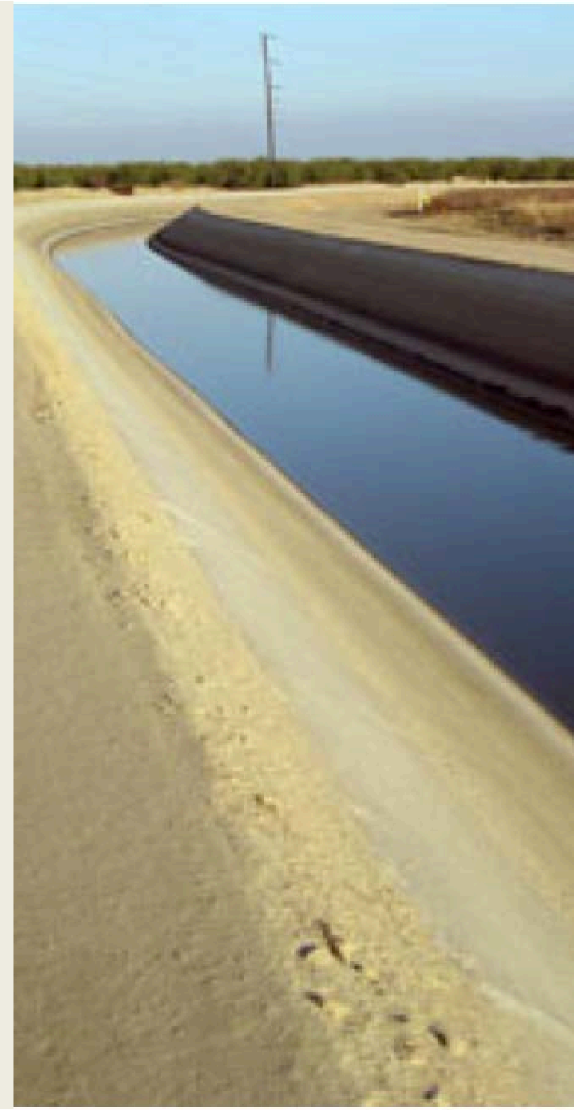
Transition and Deployment

COVALENT LLC

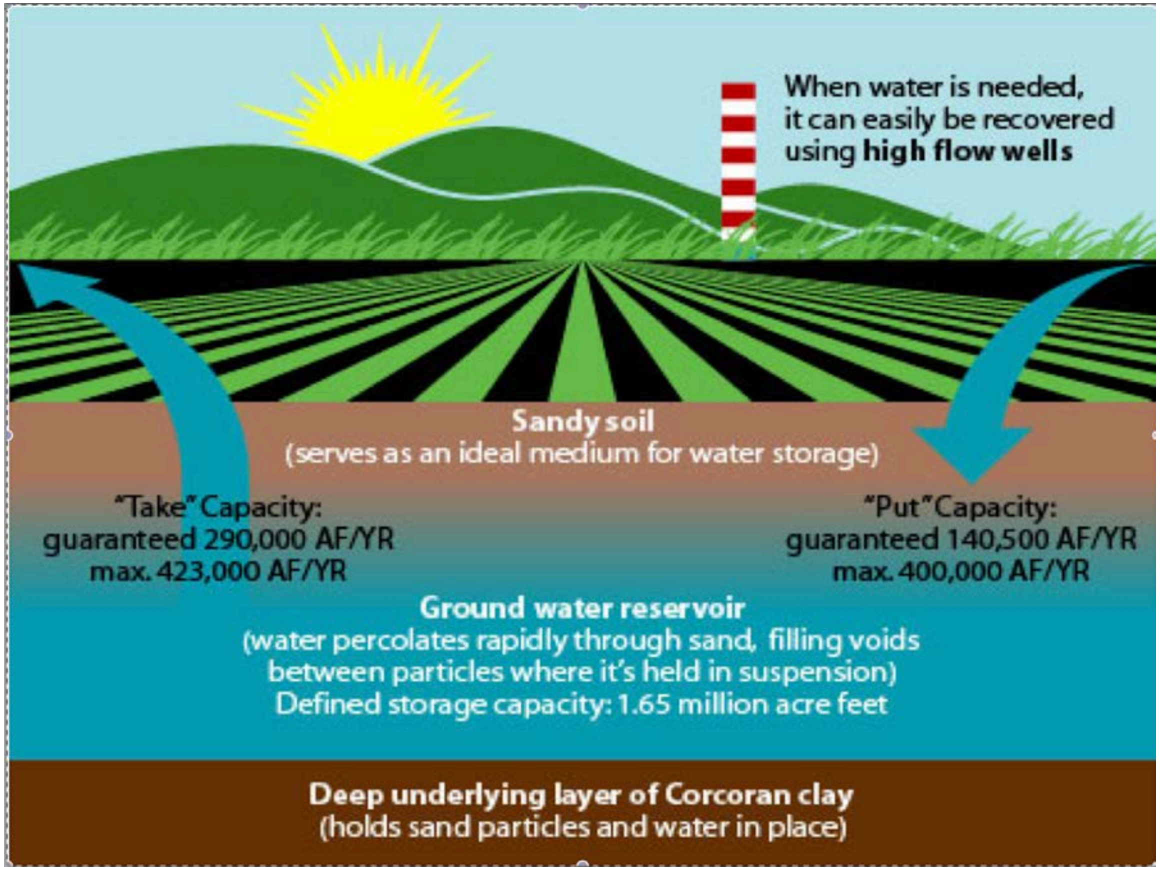
FIRST END USER CUSTOMER

- SEMITROPIC: world's largest water banking system
- CALIFORNIA CENTRAL VALLEY: drought, groundwater depletion.
- FIRST COMMITMENT: 40M Gallons per day from contaminated wells.
- DISTRIBUTED SYSTEMS: multiple wellhead installations (~20) Wells average 1.5 to 2Million Gallons Per Day.

- BENEFITS: Energy reduction. Highest purity water no matter how contaminated. Smallest footprint. Significantly increase California's agricultural water at low cost.
- WHEN: Wellhead deployment complete 36 months after financing
- WHAT: Producing Agricultural (Ag) water from high TDS feedstocks, e.g., chloride, arsenic, boron, nitrate



Water Banking at Semitropic

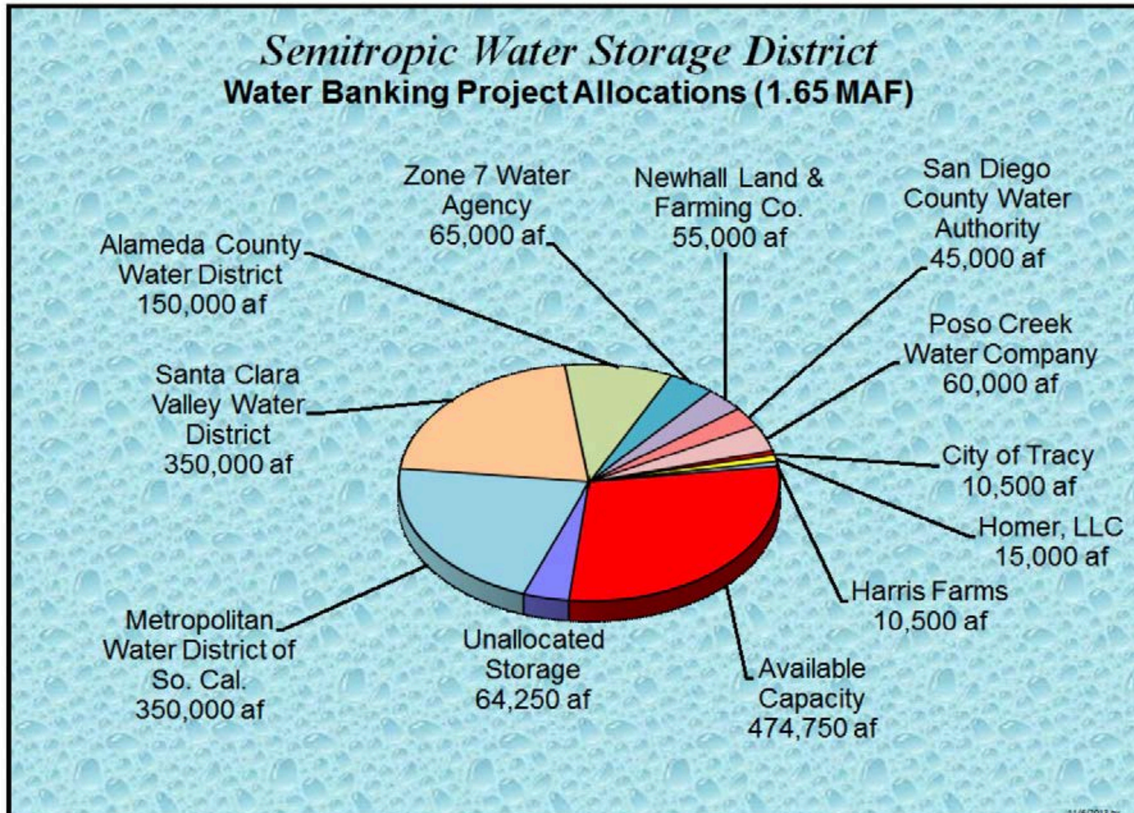


Source: Semitropic

Transition and Deployment

- Semitropic has critical role in California water supply, serving major Northern and Southern California water districts. Metropolitan (Los Angeles area), San Diego, Alameda County, Santa Clara Valley (Silicon Valley)
- Cutting edge water/energy practices
- Global model for best practices

Banking Partners and Allocation Of 1.65 Million Acre-Feet of Total Storage Capacity



Source: Semitropic

COVALENT LLC

Measures of Success: Water Delivery to Agriculture

- Lower energy for water purification
- Affordable water for agriculture

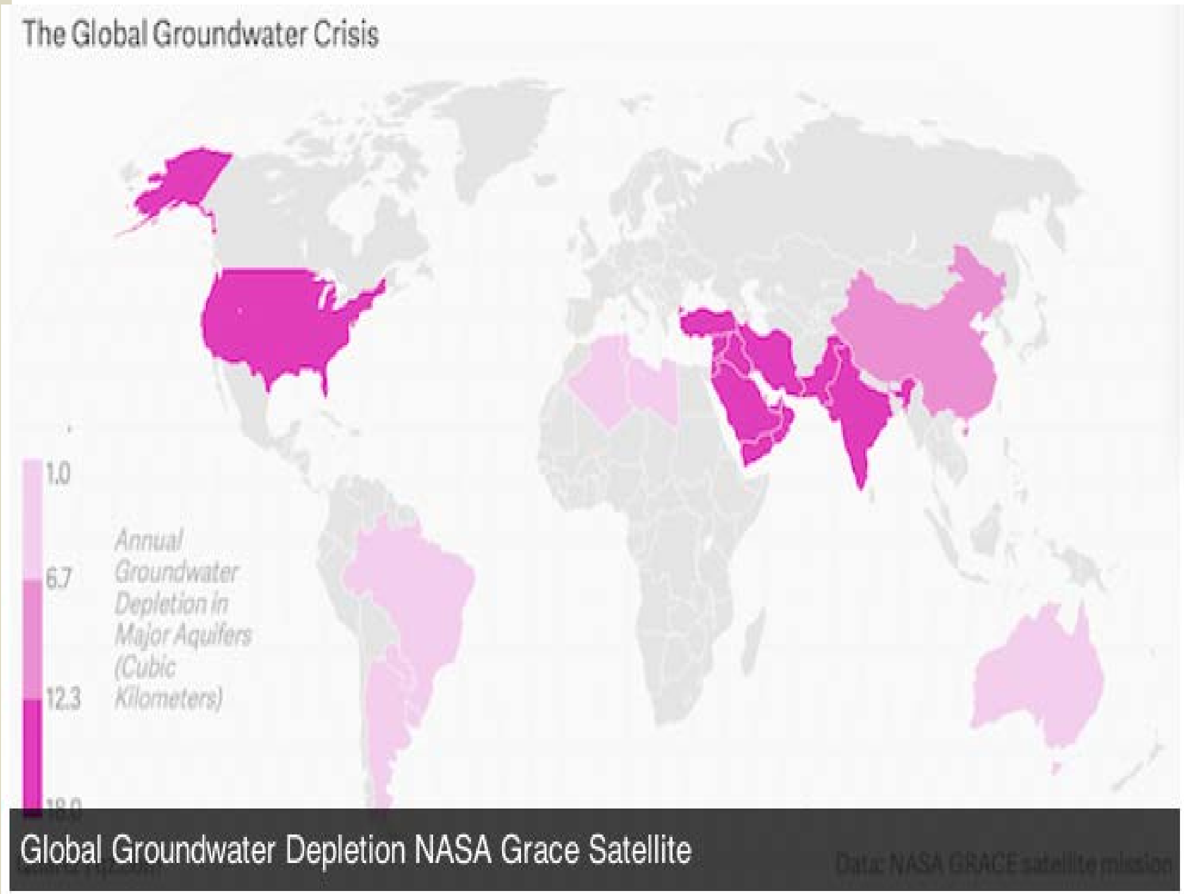
- Distributed systems mean lower energy use for water transport

- Increase in crop yield
- Less toxic substances in crops, e.g., arsenic

	Carlsbad	Orange County	Covalent at Semitropic
	Seawater	Brackish 1,000 TDS	Brackish 1-3,000 TDS
Gallons per day	50M	86M	40.18M
Gallons per year	18.3B	31.4B	14.67B
Acre feet per day	153.4	263.9	123.3
Acre feet per year	55,991	96,324	45,000

Transition and Deployment Roadmap

- Serve the problems and pain points caused by drought, groundwater crisis, high contaminant loads, tight economics
- First, California Central Valley water districts
- California agricultural (ag) water
- Use ag water wells to achieve California potable water certifications
- Next, potable water to high poverty, rural Central Valley, Calif.
- Then, international deployment to India



Source: data from NASA; map by qz.com Quartz

COVALENT LLC

Project Management and Budget

COVALENT LLC

PROJECT DURATION

Phase 1: 2/15-11/15

Phase 2: 4/16-4/18

PROJECT BUDGET

DOE Phase 1 (PH 1)	$100,000
DOE Phase 2 (PH 2)	$1,000,000
Total	$1,100,000

PROGRAM TASKS

Completed

1 - Designed porous building block

2 – Demonstrated building block solute specificity

3 – Demonstrated building block self assembly

4 – Demonstrated nanofilm formation with building blocks

5 – Demonstrated nanomembrane formation with building blocks

6 – Demonstrated composite building block/substrate compatibility

Work in progress - DOE support

7 - Demonstrate scalable manufacturing

8 – Lab demonstration of prototype membrane

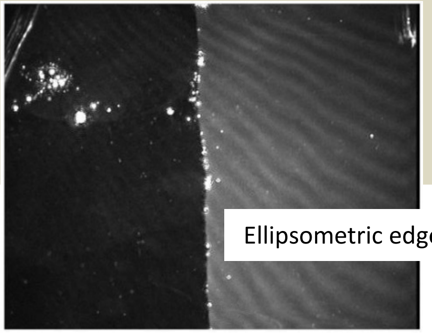
9 – Lab demonstration of prototype membrane cartridge

10 – Field demonstration of prototype cartridge

		Project Milestones
PH 1	√	Q2 Design nanofilm contact surface
	√	Q3 Build nanofilm contact surface
	√	Q4 Test nanofilm contact surface
PH 2		Q6-7 Design multiple nanofilm forming breadboard
		Q8-9 Build multiple nanofilm forming breadboard 0.1% scale
		Q10-11 Build multiple nanofilm forming breadboard 25% scale
		Q12-13 Build multiple nanofilm forming prototype 100% scale

Results and Accomplishments

COMPLETED BEFORE DOE PHASE 1	CHALLENGES	ACCOMPLISHMENTS
Membranes individually built	Novel manufacturing technique needed	Proof-of-manufacturing concept validated
Manual fabrication – time intensive, high level of skill required to control complex parameters, slow	Can control be achieved of surface chemistries, varied ambient conditions across a multi-nanomembrane manufacturing system?	Low cost, multi-nanomembrane manufacturing system built at small scale
But, reliable, reproducible, high quality product	Critics say a low cost manufacturing system is impossible and costs will be in the $Billions	Nanofilm/manufacturing materials shown to be compatible with full scale manufacturing



Ellipsometric edge study of manually fabricated nanomembrane

COVALENT LLC