Nanosystems Engineering Research Center for Nanotechnology-Enabled Water Treatment

An Overview

Qilin Li
Associate Director for Research
VISION

Enable access to treated water almost anywhere in the world, by developing transformative and off-grid modular treatment systems empowered by nanotechnology that protect human lives and support sustainable development.
Focus on Two Applications

• Off-grid humanitarian, emergency-response and rural **drinking water** treatment systems

• Industrial **wastewater reuse** in remote sites (e.g., oil and gas fields, offshore platforms)
Why Nano?

Leap-frogging opportunities to:

• Develop small, high-performance multifunctional materials & systems that are easy to deploy, can tap unconventional water sources, and reduce the cost of remote water treatment

• Transform predominantly chemical treatment processes into modular and more efficient catalytic and physical processes that exploit the solar spectrum and generate less waste
Operational Vision and Outcomes

Applications and Outcomes

- Simple operation, low cost, humanitarian water supply (higher efficiency, lower energy requirements)
- Emergency water supply for disaster recovery
- Tailored water treatment in O&G fields

Sustainability

- Global health through safer water
- Renewable energy for water treatment and desalination
- Revitalization of water infrastructure
- O&G recovery with lower environmental impacts

Education

- Globally competitive technology innovators and entrepreneurs
- Enhanced competitiveness of U.S. industries in the emerging markets of global health and water-energy nexus management and treatment

Basics Science and Discovery

Technological Innovation

Commercialization and Economic Development
Safe Use of Nanomaterials

Risk = Hazard X Exposure

Hazard
- Prioritize use of ENMs of benign, low-cost, and earth abundant compositions (GRAS); Green Chemistry and Green Engineering
- Experts panel to select ENMs before incorporation into products
- Interface with TSCA in the US and REACH in the EU

Exposure
- Immobilize ENMs to minimize release and exposure and enable reuse (no free NPs)
- Model & monitor treated water for leaching
- Foster safety in manufacturing by iterating with OSHA on best practices
- Independent certification for meeting health & safety stds.
• Three NAE members, two Clarke Prize laureates

• Pioneers in environmental nano and advanced water treatment
  – Photothermal nanoparticles
  – Fouling-resistant membranes
  – Solar-based nano-photocatalysts and upconversion
  – Superparamagnetic nano-sorbents; hypercatalysts; etc.
  – Fate, transport and potential environmental impact of ENMs
Domestic Partners

- Innovation across value chain (nanomaterial and equipment manufacturers, service providers, R&D and deployment partners, and users)
• Co-development and production of advanced multifunctional materials
• Globally-relevant research and education experiences for students
• Testbed sites for applications in fast-growing water markets
### Partners Across the Value Chain

<table>
<thead>
<tr>
<th>Category</th>
<th>Logos</th>
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<tr>
<td>Nanomaterial and advanced material manufacturers</td>
<td>EEC, Cabot, HTI, Purifics</td>
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<td>Equipment manufacturers</td>
<td>Ahlstrom, Amway, LifeSource Water Systems, Pall</td>
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<td>Research, development and deployment partners</td>
<td>NASA, NSF, Cadmus, GHP, UNESCO, Water Research Foundation, WetSus</td>
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<td>Service providers</td>
<td>American Water, Baker Hughes, CH2M Hill, GSI Environmental, Localized Water Solutions, Inc., SWRC, Veolia</td>
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<td>End users</td>
<td>CNPC, Consol Energy, Devon, Shell, SWN, Statoil</td>
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Modular Treatment Systems
Match treated water quality to intended use

- High Performance Modules
- Lower Chemical Consumption
- Lower Electrical Energy Requirements
- Less Waste Residuals
- Flexible and Adaptive to Varying Source Waters
The Energy Challenge

Theoretical minimum:
1.06 kWh/m³ (35 g/L, R = 50%)

Current Solar Desalination: Solar PV

Overall energy efficiency:

- Sunlight
  - Solar panel, 14 – 19%
- Electricity
  - High pressure pump, 60 – 90%
- Pressure
  - RO water recovery, 35– 50%
- Brine
  - Energy recovery, 80– 95%
  - Brine discharge, 5 – 20%
Solarthermal Energy

Efficiency = % of solar captured by collector

- Unglazed are best for -0 to 10°C above ambient
- Flat-plate are best for -10°C to 50°C above ambient
- Evacuated tubes are best for more than 50°C above ambient

Temperature above ambient (°C) vs. solar radiation (W/m²)

http://www.wbdg.org/resources/swheating.php
Enabling Technology
Desalination

Direct solar (membrane) distillation
– Uses nanophotonics
– Converts sunlight to heat efficiently

Multifunctional membranes
– Fouling-resistant
– High-flux
– Self-cleaning
Nano(photo)catalysts that use solar radiation to generate ROS that destroy resistant microbes and recalcitrant pollutants without generating harmful disinfection byproducts.
Enabling Technology
Electrosorption for Scaling Control

Nanocomposite electrodes to remove multivalent ions from brines, and generate smaller waste streams

Cathode

Anode
Enabling Technology
Multifunctional nanosorbents

Selective removal of target contaminants by functionalized nanoparticles supported in macroscale structures or subject to magnetic separation for enhanced removal kinetics and easier reuse.
What We Will See in 10 Years

Compact, solar-harvesting, high-performance, flexible water treatment systems that meet the growing industrial and societal needs for decentralized water supply and reuse
Welcome to Join NEWT

NEWT kickoff meeting

Oct. 21-22, 2015
Rice University
Houston TX
43 million Americans lack access to municipal water; 800 million worldwide lack access to safe water.

Global market for drinking water ~ $700 billion

Larger market for industrial wastewater reuse

- Public health
- Energy production
- Food security
- Economic development
Overarching Goals

1. Conduct high-risk/high-reward research that expands fundamental knowledge and the limits of water technologies

2. Deploy transformative, decentralized water treatment systems

3. Create centralized testbed and training facilities

4. Inspire and train the next-generation, diverse, globally-competitive workforce that enables sustainable development
Water Treatment Landmarks

144 B.C.
Rome builds its third aqueduct. Unlike other aqueducts built to carry water for bathing and flushing, this one was erected primarily to transport drinking water.

1804
Paisley, Scotland, becomes the world’s first municipality to provide drinking water filtration for its entire city, installing sand filters to produce potable water.

1854
John Snow’s investigation into a cholera outbreak in London links its spread to drinking water. This led to awareness that drinking water could carry disease, and in turn, to improvements in drinking and wastewater treatment systems.

1974
The Safe Drinking Water Act passes to protect public health by regulating the nation’s drinking water supply.

2009
The EPA updates the list of drinking water contaminants it regulates, bringing the number of monitored contaminants to 90.

2015
A collaborative effort involving universities, industry partners, and NSF begins to apply nanotechnology to develop decentralized water treatment systems that tap a broad range of source waters, are easy to deploy, and utilize solar processes for off-grid humanitarian water supply and industrial wastewater reuse.

2015 and Beyond
The Nanotechnology-Enabled Water Treatment Center (NEWT), now funded by industry with state plus municipal support, continues to produce transformative technologies and systems that improve global health and contribute to sustainable development.

Growing need for decentralized water treatment for humanitarian and remote supply, emergency response, and water reuse = market disconnect
Gaps with Current Water Treatment Systems

- Water infrastructure was rated D− by ASCE
- Lack adaptivity to changes in source water
  - New pollutants
  - Climate change
- Lack portability for emergency response or use in remote or constrained places due to large size
- Use large quantities of chemicals and electricity
- Do not utilize solar processes for treatment
- Need to improve kinetics, efficiency, capacity, and cost

http://www.sandiego.gov/cip/about/faq/index.shtml
Safe Use of ENMs

- Prioritize use of ENMs of benign, low-cost, and earth-abundant compositions (GRAS)
- Experts panel to select ENMs before incorporation into products
- Foster culture of safe manufacturing practice
- Immobilize ENMs to minimize release/exposure and enable reuse
- Model and monitor treated water for potential leaching
# Aspirational Impacts

<table>
<thead>
<tr>
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<th>5 years</th>
<th>10 years</th>
<th>Beyond</th>
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<tbody>
<tr>
<td><strong>Local</strong></td>
<td>Improved water treatment in rural communities (remove EDCs, POPs, resistant bacteria)</td>
<td>Broader access to affordable potable water for millions of off-grid people who lack it</td>
<td>Higher participation of underrepresented groups in STEM careers &amp; leadership</td>
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<tr>
<td><strong>State</strong></td>
<td>Distributed treatment systems lowering the water footprint of oil and gas production</td>
<td>Drought alleviation, enabled by tapping a broader range of source waters</td>
<td>Improved water treatment and industrial wastewater reuse infrastructure</td>
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<td><strong>National</strong></td>
<td>High-performance materials and mobile systems for disaster relief and emergency response</td>
<td>Energy production with less fresh water withdrawals and lower environmental impact</td>
<td>Globally-competitive, diverse innovators; more jobs to export novel technologies</td>
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<td><strong>Global</strong></td>
<td>Easy-to-deploy systems for disaster relief and humanitarian water supply</td>
<td>Affordable low-energy (solar) desalination, improved adaptation to climate change</td>
<td>Improved global health, food security, and sustainable development</td>
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Thrust 1: Multifunctional ENMs
- Selectivity
- Scalability
  • Superior nanosorbents with option for magnetic separation
  • Advanced, selective (photo)catalysts

Thrust 2: Solar-Thermal Processes
- Light penetration and heat transfer
- Nanoparticle immobilization without loss of efficiency
  • Low-energy desalination
  • High-flux, low-pressure RO membranes

Thrust 3: Scaling and Fouling Control
- Control of nucleation of scaling elements
- Membrane functionalization without adverse effects
  • Effective pre-treatment to prevent scaling and fouling
  • Multifunctional membranes
New Education Programs

Graduate
• Sustainable engineering in multidisciplinary and multicultural settings for global technology development

Undergraduate
• Project-based curriculum across NEWT institutions
• National model for inquiry-based learning

Pre-college education
• New professional development course (100 teachers reaching >15,000 students annually)
• Use NEWT’s compelling research as “hook” to inspire diverse K-12 students to pursue STEM careers
Organizational Structure

- Transparent, collaborative, experienced leadership
- Frequently scheduled work and advising sessions
- World-class advisory boards
- Supported by management tools and processes
Management Objectives

• Leadership built on shared vision, transparency, and effective communication with all stakeholders

• Open and collaborative approach

• Centralized management

• Team-driven projects

• Clearly delineated roles and responsibilities

• Quick identification and timely resolution of problems
Wong & Kim

**Thrust 1. Multifunctional ENMs**
1.1. Multifunctional ENM sorbents
1.2. Multifunctional magnetic-core ENMs
1.3. Multifunctional Photocatalytic ENMs

**Thrust 2. Solar Desalination Processes**
2.1. ENM-light Inacteration
2.2. Nanophotonics-enhanced solar MD
2.3 Mixed matrix NF/RO membrane

Halas & Lind

**Thrust 3. Scaling and Fouling Control**
3.1. Nanotemplate for mineral nucleation
3.2. ENM coatings for fouling/scaling control
3.3. Nanocomposite electrodes for electrosorption

Elimelech & Li

**Westerhoff, Alvarez & Li**

**Drinking Water/Industrial Wastewater Testbeds**

**INTERFERING SPECIES CONTROL**

- Thrust 1.1. Multifunctional ENM sorbents
- Thrust 1.2. Multifunctional magnetic-core ENMs
- Thrust 3.1. Nanotemplate for mineral nucleation
- Thrust 3.2. Fouling and scaling control
- Thrust 3.3. Nanocomposite electrodes for electrosorption

**PRIORITY CONTAMINANT REMOVAL AND/OR LOW-ENERGY DESALINATION**

- Thrust 1.3. Photocatalytic ENMs
- Thrust 2.1. ENM-light Interaction
- Thrust 2.2. Nanophotonics solar MD
- Thrust 2.3. Mixed matrix NF/RO

Contaminated Water

Drinking or Reclaimed Water
Top-Down Strategic Approach

- Off-grid humanitarian, rural, and emergency drinking water treatment trains
- Desalination and conditioning systems for industrial wastewater reuse
- Cost Complex O&M Reliability & robustness Access to materials Energy supply Interdisciplinary workforce for global emerging markets

SYSTEM INTEGRATION TESTBEDS

- TECHNOLOGY ELEMENTS
  - CALIBRATION & VALIDATION
  - SYSTEM REQUIREMENTS & SUSTAINABILITY ASSESSMENTS

- CALIBRATION VALIATION & SYSTEM REQUIREMENTS & SUSTAINABILITY ASSESSMENTS

- FUNDAMENTAL INSIGHT & GUIDE DATA ACQUISITION

- ENABLING TECHNOLOGIES
  - THRUST 1 MULTIFUNCTIONAL MATERIALS
    - Selective nanosorbents
    - Photocatalysts in active matrices
    - Magnetic NPs
  - THRUST 2 SOLAR- THERMAL PROCESSES
    - Nanophotonics model
    - Direct solar membrane distillation
    - Low pressure NF/RO membranes
  - THRUST 3 SCALING & FOU LING CONTROL
    - Selective electrosorption
    - Nanotemplate-assisted nucleating agents
    - Fouling-resistant membranes

- STAKEHOLDERS
  - Water Industry
  - Public Health Agencies
  - O & G Industry
  - Native Americans
  - Rural Areas Expanding Megacities

- REQUESTS & NEEDS
  - PRODUCTS & OUTCOMES

- FUNDAMENTAL KNOWLEDGE (Thrusts 1, 2 & 3)
  - ENM-contaminant interactions
  - Fate & transport of ENMs
  - Heterogeneous catalysis & interfacial sciences
  - Scale formation
  - Transport in ENM-polymer composite
  - Nanophotonics & solar processes

- BARRIERS
  - Safety
  - Efficiency
  - Selectivity
  - ENM immobilization
Culture of Inclusion

- NEWT will be a magnet to increase the number of underrepresented groups in STEM fields contributing to scientific progress, economic growth, and global health.

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<tr>
<th>Objective</th>
<th>Approach</th>
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<tr>
<td>Recruit and retain underrepresented UG STEM students (start at K-12)</td>
<td>Form partnerships with school districts and industry (internships)</td>
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<tr>
<td>Recruit and nourish diverse GR STEM students</td>
<td>Summer exchange programs and international opportunities</td>
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<td>Help students develop careers</td>
<td>Promote networking</td>
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<td>Increase diversity of STEM faculty</td>
<td>Targeted recruitment and placement of graduates</td>
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Innovation Ecosystem to Support Translational Research

• Foster entrepreneurship to accelerate commercialization and facilitate startup ventures
  – Mentoring and validation of business models
  – Market research
  – Legal assistance for IP
  – Incubator space
  – Network of experienced innovation partners and entrepreneurs

• Populate I.E. with partners that fill “missing links” across the value chain

Brad Burke, IE Director
Runs the Top Global University Business Incubator in the World, and top program in graduate entrepreneurship
What We Will See in 10 Years

- Affordable access to potable water almost anywhere using modular treatment units that tap unconventional sources (drought alleviation, disaster relief, emergency supply)
- Lower industrial water footprint (e.g., energy production with less fresh water and with lower environmental impact)
- Synergistic research support to/from other NSF investments
- A more diverse technical work force trained to translate basic research into innovative products
- More jobs and exports of innovative water technologies

“People don't know what they want until you show it to them” – Steve Jobs
BACKUP SLIDES
Crosscutting Research Thrusts and Testbeds

Thrust 1. Multifunctional ENMs
1.1. Multifunctional ENM sorbents
1.2. Multifunctional magnetic-core ENMs
1.3. Multifunctional Photocatalytic ENMs

Thrust 2. Solar-Thermal Processes
2.1. ENM-light Interactions
2.2. Nanophotonics-enhanced solar MD
2.3. Mixed matrix NF/RO membrane

Thrust 3. Scaling and Fouling Control
3.1. Nanotemplate for mineral nucleation
3.2. ENM coatings for fouling/scaling control
3.3. Nanocomposite electrodes for electrosorption

Drinking Water Testbeds
- Mobile NEWT
  - Hardness Control
  - HIX/H-GAC
  - Photocatalytic reduction
- Solar Decathlon
  - Carbon Block
  - Direct solar MD
  - Photo catalytic reduction
- NEWTskid
  - Photocatalytic oxidation
  - Magnetic ENM Si Removal
  - Antifouling coating

Industrial Wastewater Testbed
- NEWTskid
  - Photo catalytic oxidation
  - Magnetic ENM Si Removal
  - Nano composite membrane
  - CDI

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Research Components

Nano-Science

Modeling

Integrated Treatment Systems

Reactor Engineering

Cross-cutting Theme: Safety & Sustainability
<table>
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<tr>
<th>Research Thrust</th>
<th>Year 1</th>
<th>Year 2</th>
<th>Year 3</th>
<th>Year 4</th>
<th>Year 5</th>
<th>Year 6-10</th>
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<tr>
<td>Thrust 1. Multifunctional Nanomaterials</td>
<td>1.1. Multifunctional ENM sorbents</td>
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<td>1.2. Multifunctional magnetic-core ENMs</td>
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<td>1.3. Multifunctional Photocatalytic ENMs</td>
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<td>New Reactors</td>
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<td>Thrust 2. Solar-Thermal Processes</td>
<td>2.1. ENM-light &amp; polymercoveraction</td>
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<td></td>
<td>2.2. Nanophotonics-enhanced solar MD</td>
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<td>2.3 Mixed matrix RO membrane</td>
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<td>Thrust 3. Scaling and Fouling Control</td>
<td>3.1. Nanotemplating</td>
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<td>3.2. Nanocomposite electrodes</td>
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<td>3.3. Anti-fouling ENM coatings</td>
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<th>Testbeds</th>
<th>Research roadmap</th>
<th>Year 1</th>
<th>Year 2</th>
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<th>Year 5</th>
<th>Year 6-10</th>
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<tr>
<td>Testbed 1. Drinking Water (Mobile NEWT)</td>
<td>Hardness control</td>
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<td>Modular GW pilot systems</td>
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<td>Carbon block</td>
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<td>Photocatalytic oxidation</td>
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<td>Photocatalytic reduction</td>
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<td>Testbed 2. Solar Decathlon House</td>
<td>Research roadmap</td>
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<td>Testbed 3. Industrial O&amp;G Water (NEWTskid)</td>
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- Red circle: Fundamental research
- Red diamond: Development of enabling technologies
- Blue diamond: Research to support innovation in years 6-10
America’s water infrastructure is outdated, worn, and in some cases, failing. Most experts agree that it is inadequate to meet the demands of the 21st-century global economy.
Why We Need a National Research Center

• Attract the brightest minds/students to focus on water security

• Provide a platform and resources to synergize and engage industry and other partners to provide a road to deployment and commercialization

• Collaborate with other NSF centers, hubs, and related investments (sustainability, advanced materials, solar energy, water-energy-food nexus)
By the End of this Visit, You Will See

✓ Strong technical team and students
✓ Leading-edge research driven by societal and industrial needs
✓ Efficient and transparent use of resources
✓ Synergism with industrial and government partners across the value chain providing a path for financial sustainability beyond 10 years
✓ Award-winning entrepreneurship model for commercialization
✓ Education of next-generation, diverse workforce
“Whiskey is for Drinking; Water is for Fighting Over”

~Mark Twain