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Physical, Chemical, and Biochemical Technologies for Minimizing Biofouling on Water Treatment Membranes

Susan J. Altman, Ph. D.

Sandia National Laboratories

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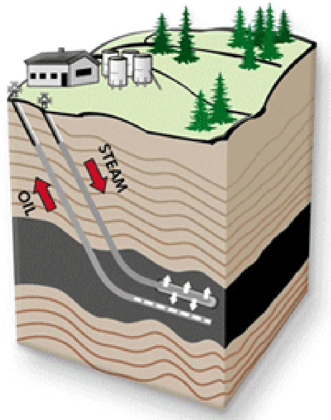
Many Industries Can Benefit From Biofouling Resistant Membranes

BIOFOULING OF WATER TREATMENT MEMBRANES

PETROLEUM PRODUCTION

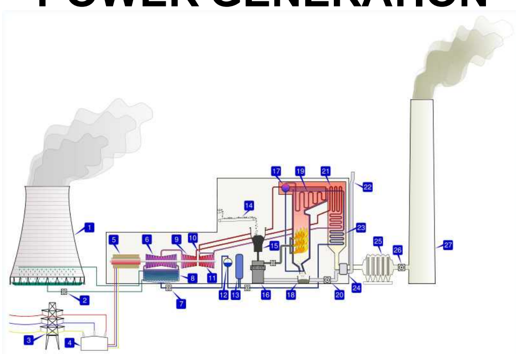


Steam generation for heavy oil extraction

WASTEWATER TREATMENT

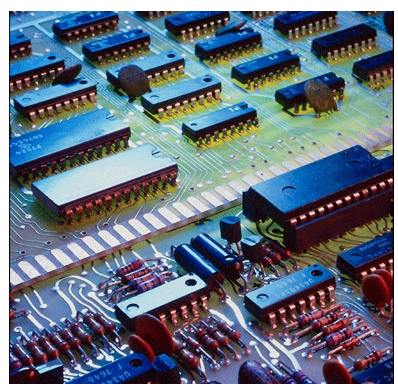
Water Reuse

POWER GENERATION



Cooling Tower Water Recycling

ULTRAPURE WATER PRODUCTION



Pharmaceuticals/Microchips/Electronics

BRACKISH WATER AND SALT WATER DESALINATION

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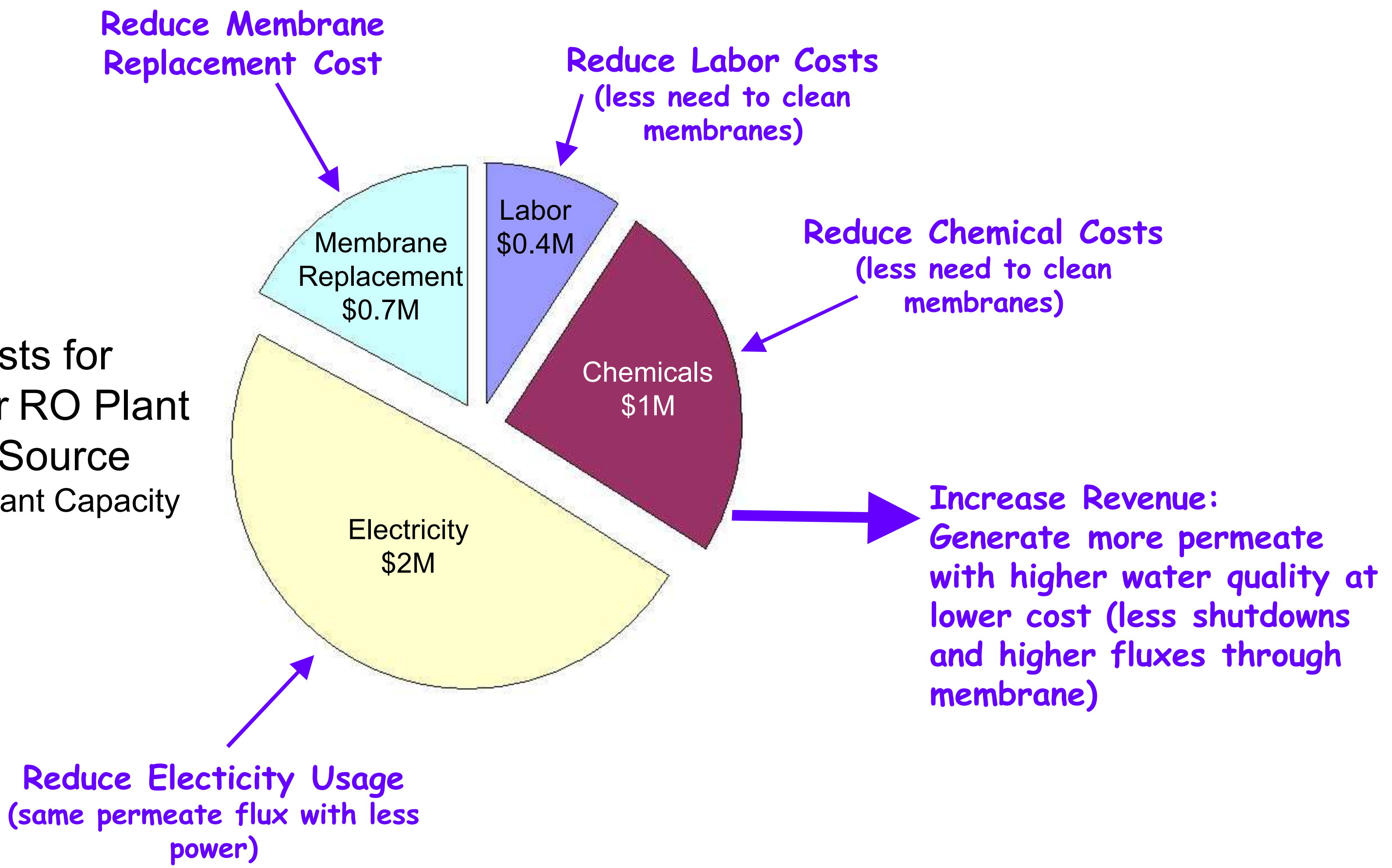
Biofouling Resistant Membranes Will Lead to Extreme Cost Savings for Water Treatment

Annual Costs for
Brackish Water RO Plant
Well Water Source
100,000 m^3/day Plant Capacity



Desalting Handbook for Planners
3rd Edition, July 2003
U. S. Department of the Interior, Bureau of Reclamation

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Biofouling Is Caused By Biofilms

Colonies of microorganisms attached to a surface and encased in extracellular polymeric substances (EPS, aka slime).

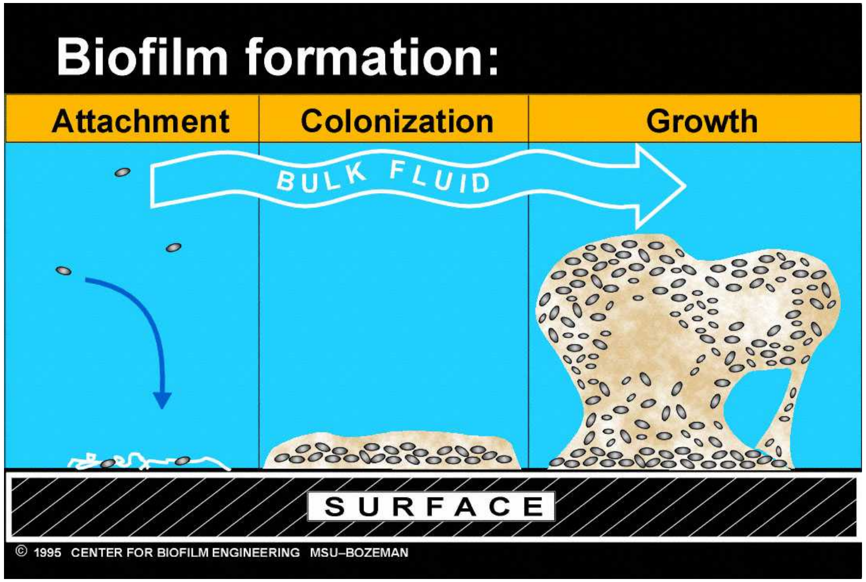
- Able to trap nutrients for their own growth
- Protected from anitbiotics and other anti-microbial agents

Industries Interested in Biofilms

- Medical
- Oil and gas
- Water distribution systems
- Water treatment
- Food
- Environmental engineering (bioremediation)

Potential Technologies

- Non-biofilm resistant antibiotics
- Drugs that prevent biofilm formation by interfering with intercellular communication (furanones)
- Biofilm resistant materials/coatings
- Bioremediation techniques using biofilms
- Sensors or monitoring systems



Reproduced with the permission of Center of Biofilm Engineering, Montana State University

Physical, Chemical, and Biochemical Technologies

- **Physical**
  - Micromixers
- **Chemical**
  - Polymer coatings
- **Biochemical**
  - Aptamers

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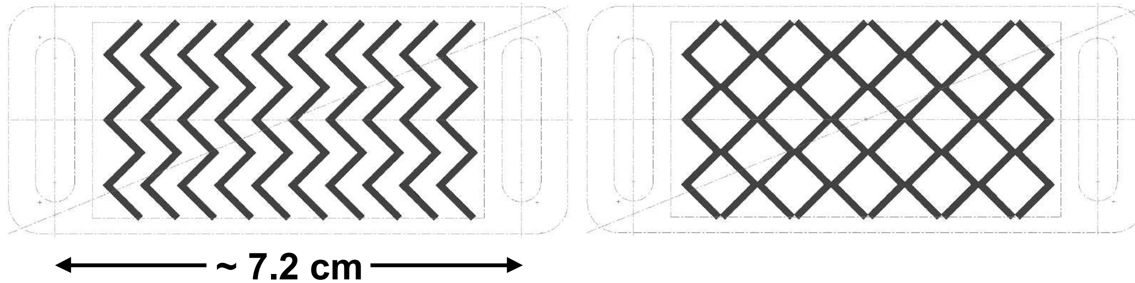
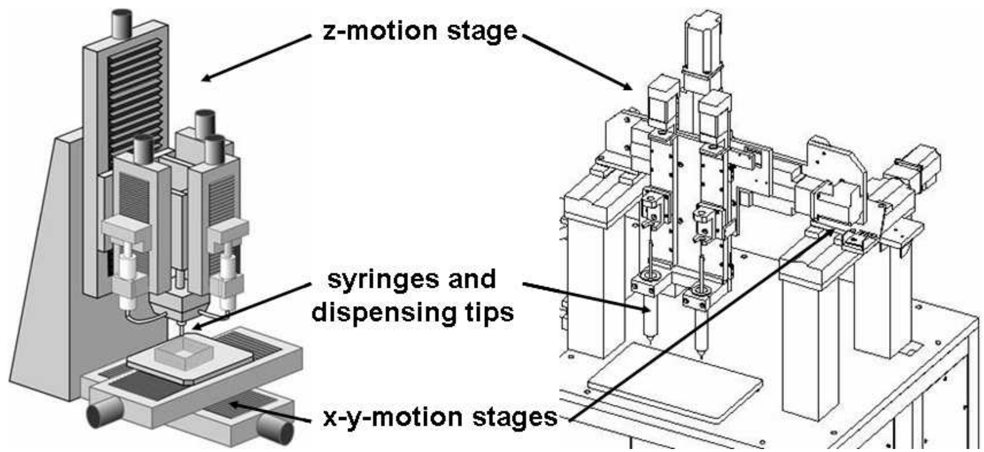
Micromixers Printed Using Robocasting

Micromixer Design

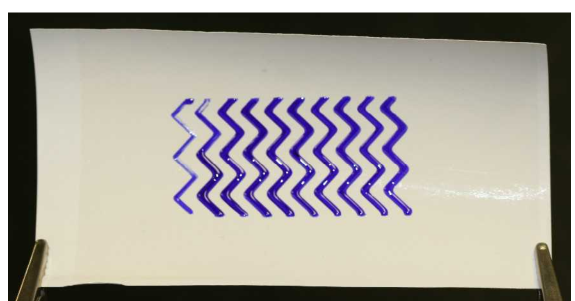


Micromixer Printing on Existing RO Membrane

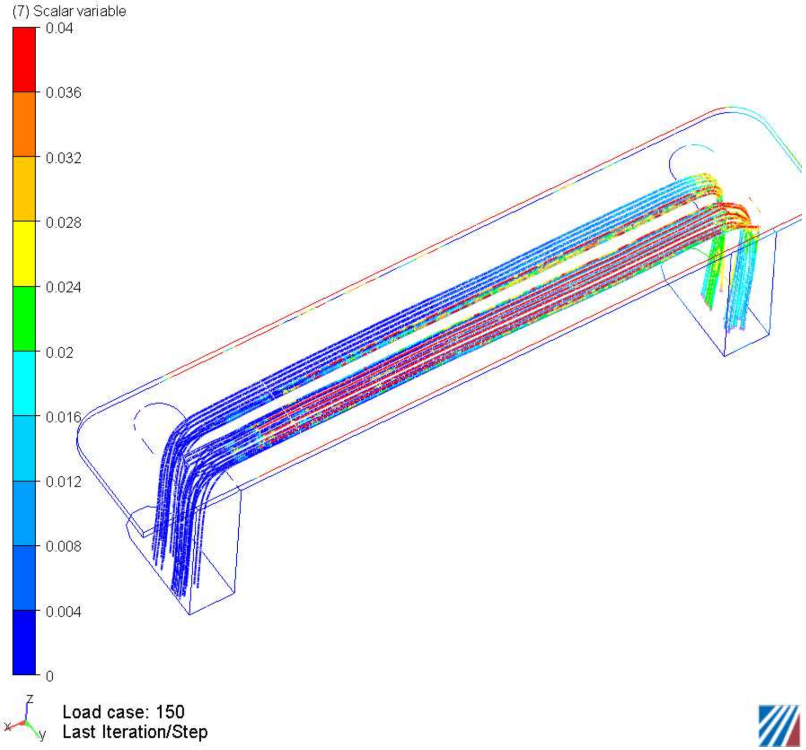


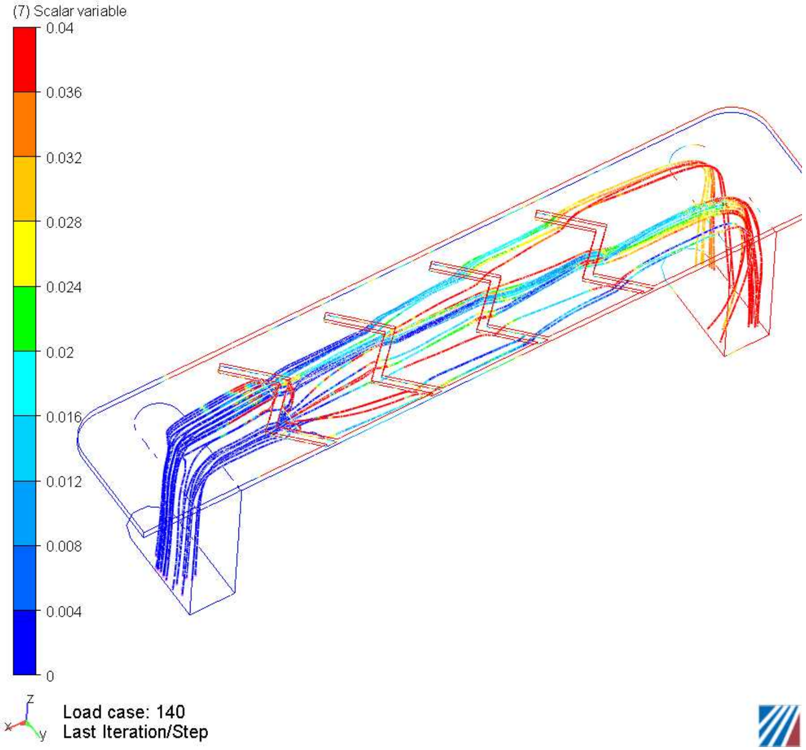
Robotic Syringe-Dispense Method (Robocasting)

Final Membrane



Use of Micromixers To Induce Localized Turbulence on Membrane Surface





- Flow lines (left to right) colored by scalar (tracer) applied to membrane surface without (left) and with (right) micromixers
- Greater scouring (and hence, greater scalar outlet concentrations) when micromixers are present

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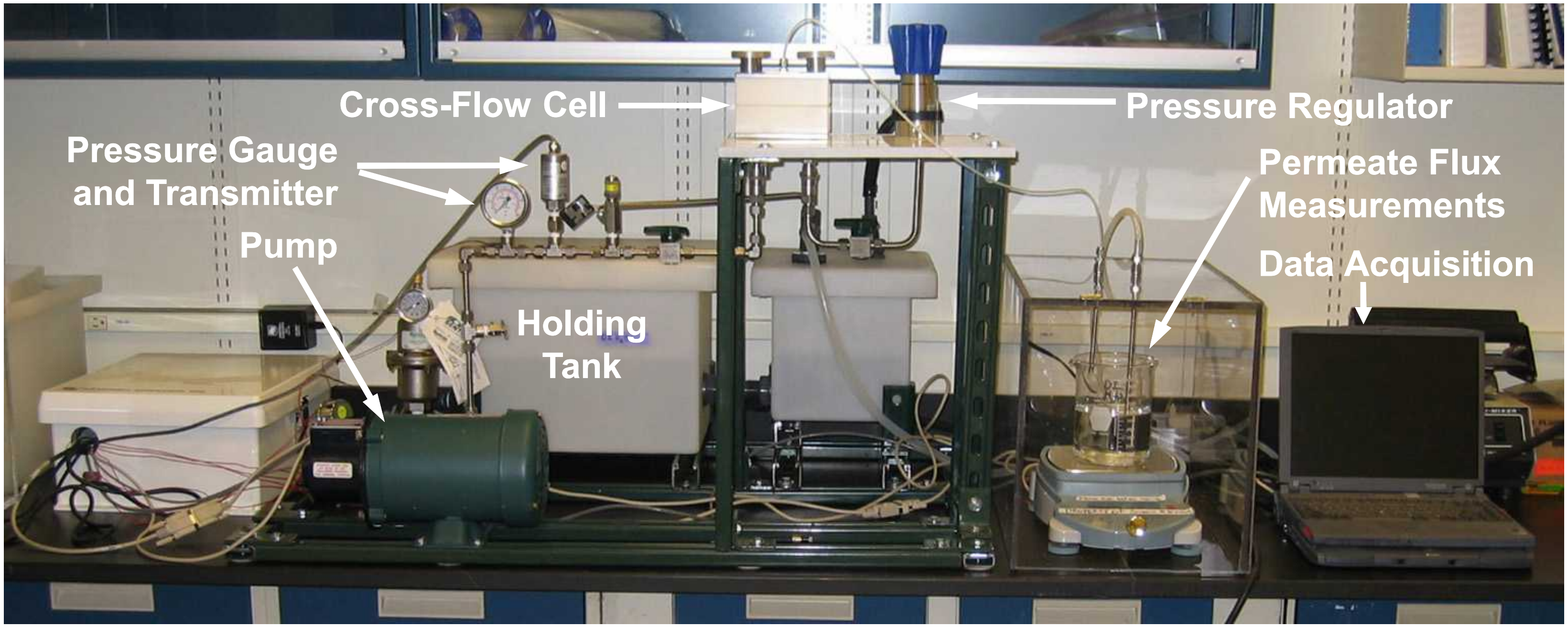
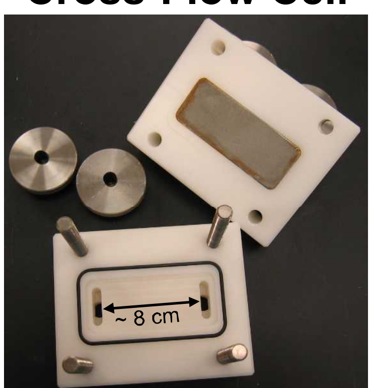
Cross-Flow Membrane Testing System



Cross-Flow Cell



- **Controlled Parameters**
  - Temperature
  - Flow
  - Pressure
  - Permeate Flux
- **Real-Time Data Acquisition**
  - Permeate flux, pressure, temperature, and flow
- **Post-Mortem Analysis**
  - Hyperspectral Imaging

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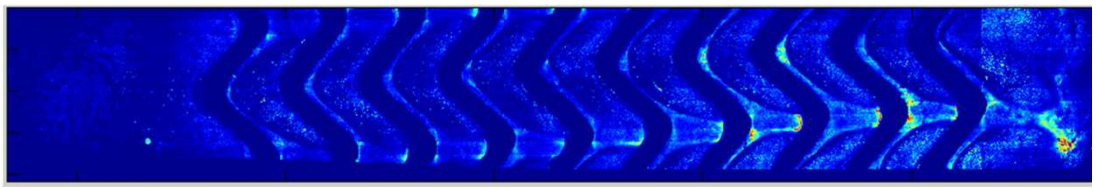
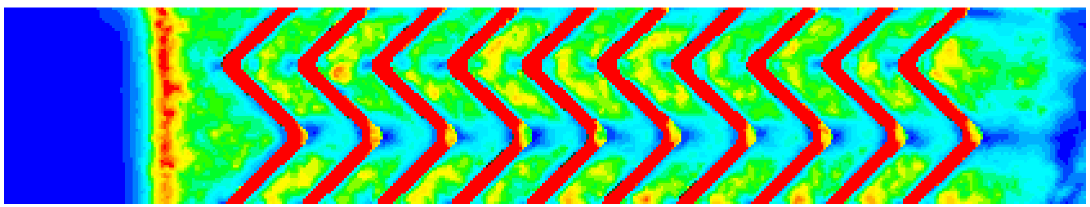
Correlation between Simulated Shear Stress and Observed Bacteria Adhesion

Flow Direction →

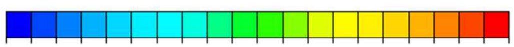


Hyperspectral fluorescence image of bacteria on the membrane surface



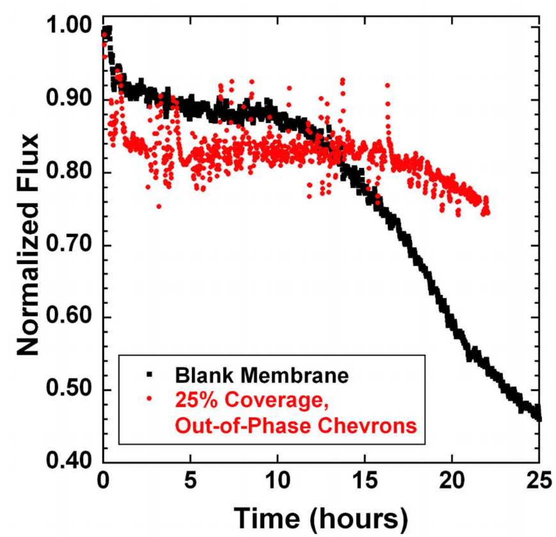
CFD simulation of shear stress

Shear Stress or Concentration



Low High

Permeate Flux decreases at a slower rate on membranes with chevrons than membranes without chevrons



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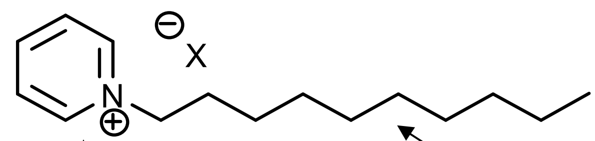
Quaternary Ammonium Compounds (QACs) as Antibacterial Agents

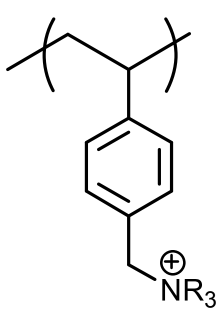
Mode of action:



1) Positive charge promotes electrostatic interaction with negatively charged cell surface

2) Lipophilic chain promotes diffusion into and/or through the cell wall

Immobilization of QACs on polymers:



- Polymers exhibited higher antimicrobial activities than corresponding low molecular weight model compounds.[1]
- QACs acting in concert are more effective than individual molecules.
- These polymers were all water soluble.

[1] Ikeda, I.; Tazuke, S.; Suzuki, Y. *Makromol. Chem*. **1984**, 185, 869.

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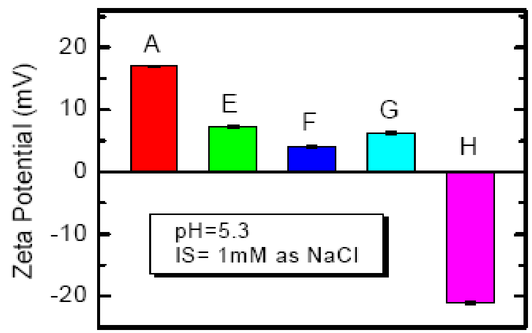
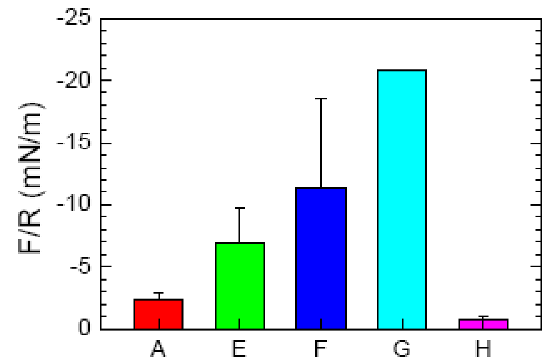
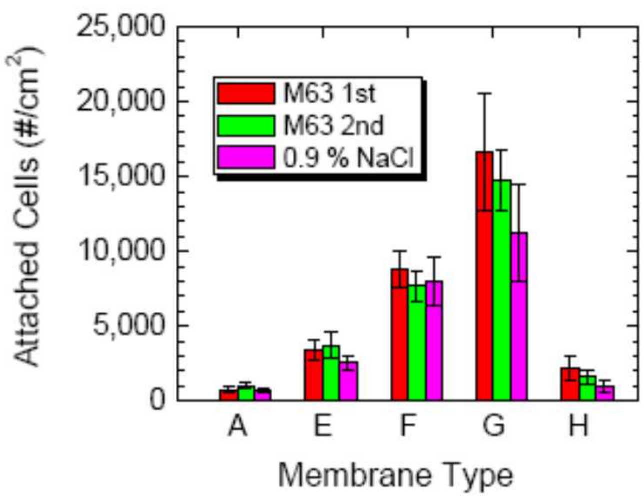
Testing of QAC Coatings

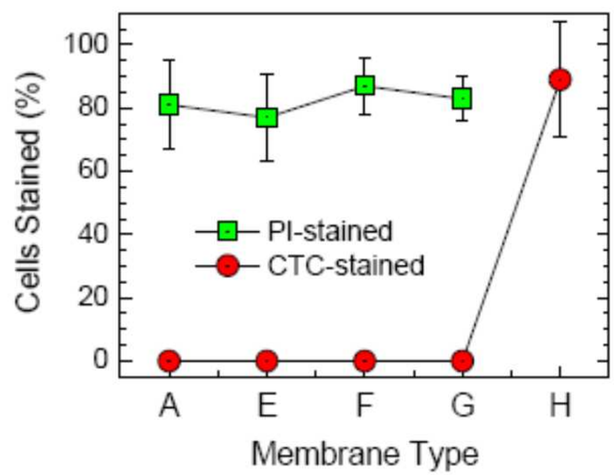




Zeta potential: positive charge of QAC coatings is greater with shorter alkyl chains

AFM force measurement (silica colloid probe): longer alkyl chains have greater attractive force





PI stains dead cells

CTC stains live cells

Adhesion and toxicity testing: (1) significant biotoxicity is observed
(2) longer alkyl chains attract more cells

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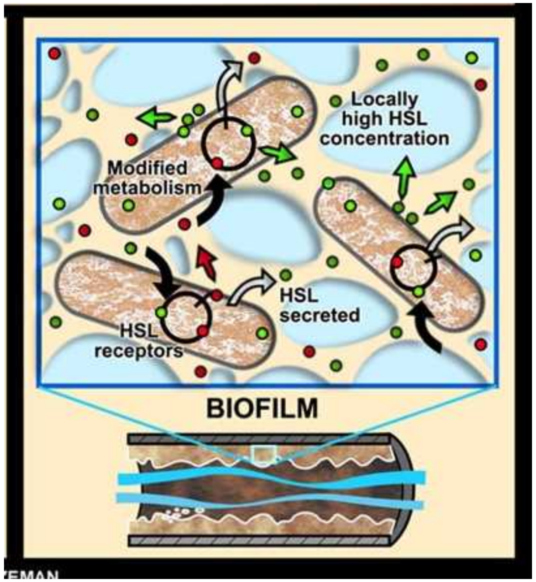
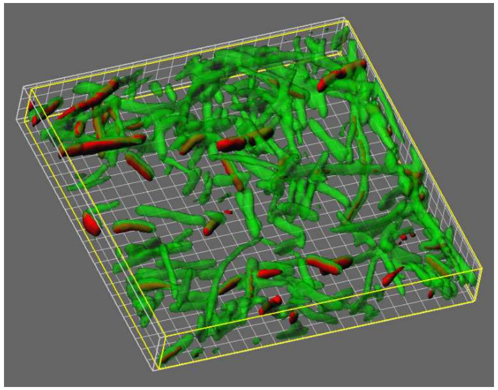
Cells In A Biofilm "Talk" To Each Other To Initiate Biofilm Formation

Quorum Sensing:
process in which bacteria in biofilms communicate with one another by producing and responding to chemical signaling molecules called **autoinducers.**

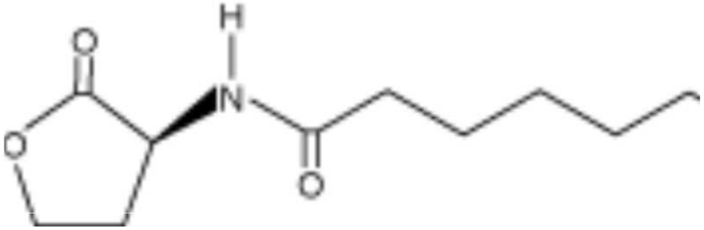


Pseudomonas fluorescens

Gram-negative, rod-shaped bacterium



Hyperspectral image of a hyperspectral image of a *P. fluorescens* biofilm stained with hexidium iodide and SYTO®9 using a 60× objective.



***P. fluorescens*-specific autoinducer, N-hexanoyl-L-homoserine lactone (C6-HSL)**

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Aptamers Can Bind to Autoinducers

Aptamer bound to neomycin (23 bases long)

DNA Aptamers

- Artificial single-stranded oligonucleotides
- Bind with high affinity and specificity to targets (comparable to affinity of antibodies)
- Produced by *in vitro* process allowing tight control of specificity and affinity. This process selects for aptamers on the basis of high affinity binding to a specific target, e.g., an autoinducer.
- Small, resistant to denaturation & degradation
- Fold around targets such that target becomes an intrinsic part of aptamer structure
- Chemically synthesized, allowing for low cost and easily scaled production

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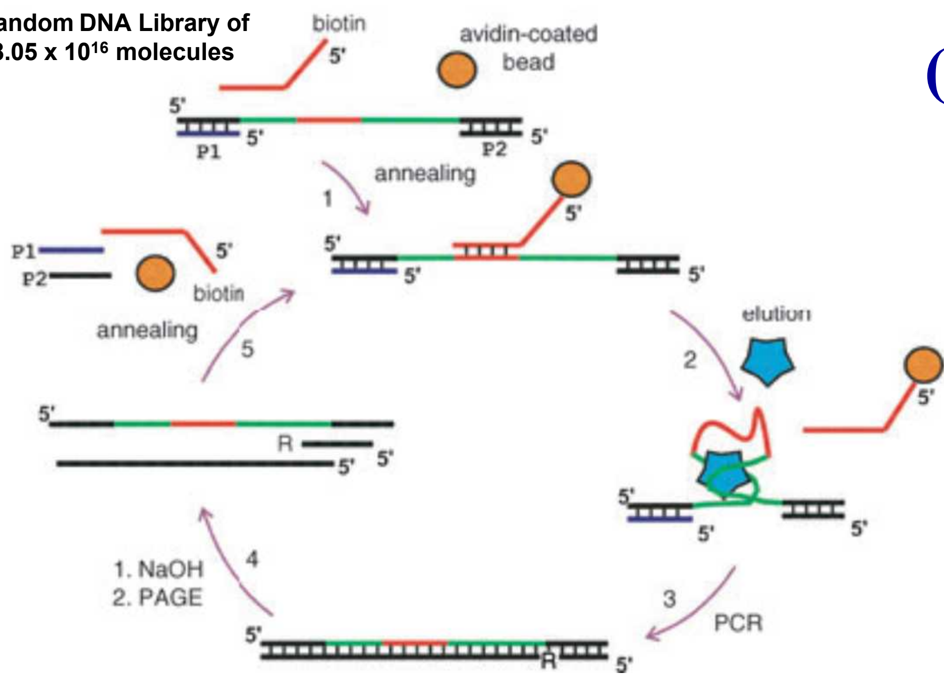
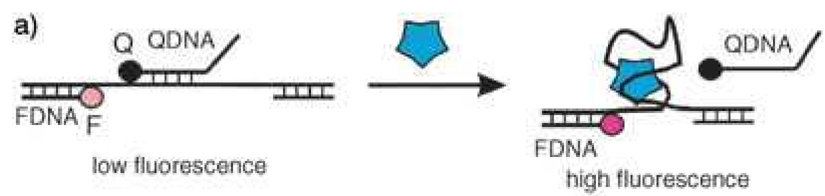
Aptamers Can Be Used As Signaling Molecules

- Fluorescent Signal
- Electrical Signal
- Inhibit Autoinducer Secretion

Random DNA Library of ~8.05 x 10^{16} molecules



The DNA *SELEX* Process (*Systematic Evolution of Ligands by EXponential Enrichment*) Used to Synthesize Aptamers



Nutiu, R. & Li, Y., *Angew. Chem. Int. Ed.*, **44:**1061-1065, 2005

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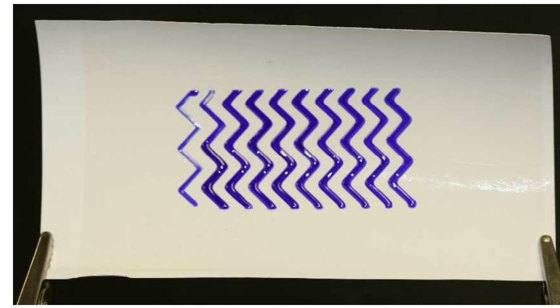
See Promise in the Technologies at Controlling Biofouling



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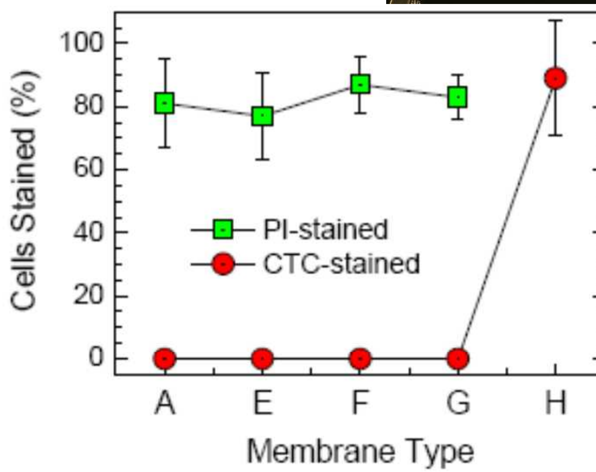

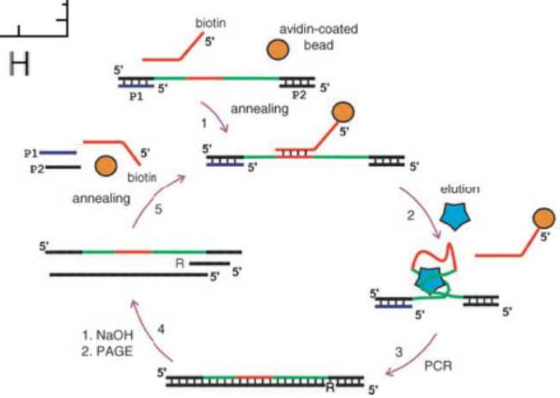

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