SAND2011-2568C

Biofouling & Corrosion Monitoring for MHK Technology

Advanced Marine Renewable Energy Instrumentation Workshop
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National Nuclear Security Administration

Sandia National Laboratories

Sandia's Water Power Research

SNL Water Power Research Program

MHK Technology with NREL, ORNL, and PNNL

System Design & Modeling: Develop tools to assist the industry in the design, development, and optimization of MHK devices

Advanced Materials and Manufacturing

Instrumentation, Testing and Evaluation

MHK Environmental with PNNL, ORNL, and ANL

Evaluating the effects of MHK technologies on the surrounding environment and resources

Support project planning and permitting

Conventional Hydro with PNNL, ORNL, and ANL

Hydropower Optimization: Seasonal Analysis

Grid Services and Integration Modeling

Reference Model with PNNL, ORNL, and NREL

Develop baseline cost of energy (COE)

Identify and evaluate key cost reduction pathways.

Advanced Materials Testing

Testing of Standard Components/Coatings/Materials From Marine, Oil, Gas, Wind Industry

Development of Novel or Improved Coatings/Materials

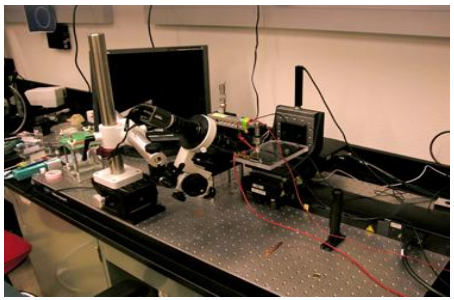
Testing of Environmental Impact

OAK RIDGE National Laboratory

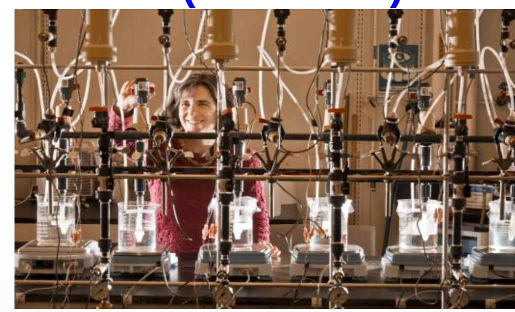
MHK Industry Requires Advances in Coatings Technology

Problems: corrosion, sediment and biological fouling, erosion, fatigue, cost, manufacturing

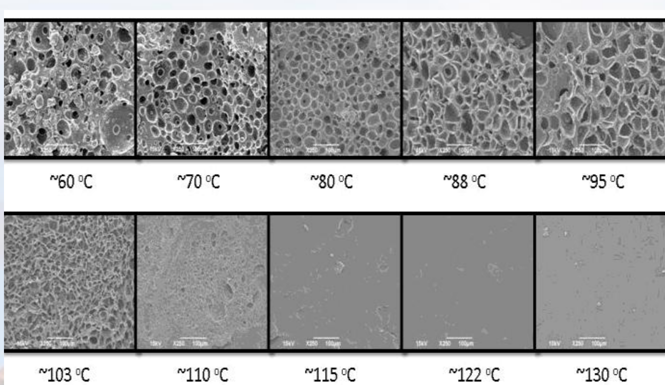
Corrosion & Reliability (D. Enos)



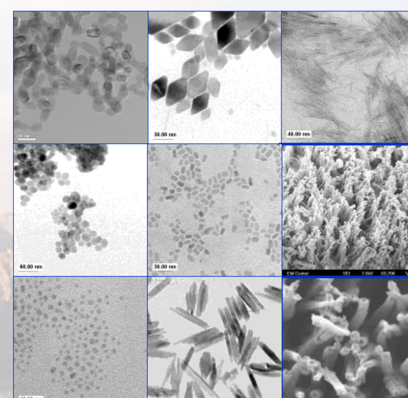
Biofoulilng Mitigation (S. Altman)



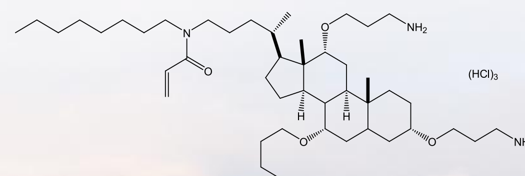
Organic Thin Film Synthesis (S. Dirk)

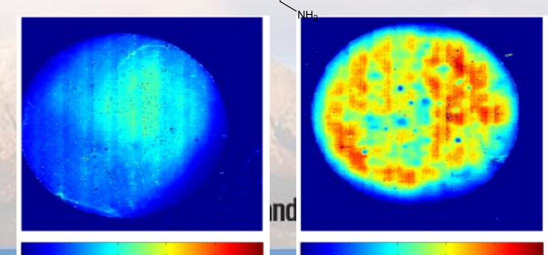


Nanoparticle, Thin Film & Powder Synthesis (BAHS)

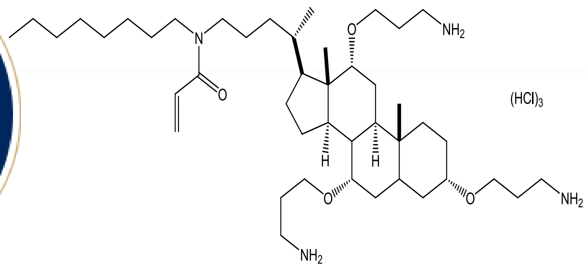


Antimicrobial Coatings Synthesis (M. Hibbs)

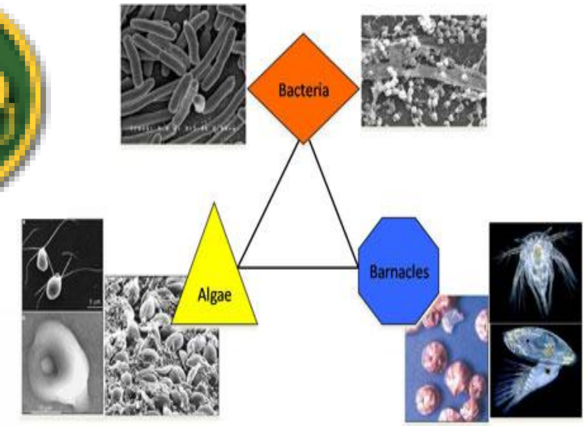




University Partners for MHK Advanced Materials



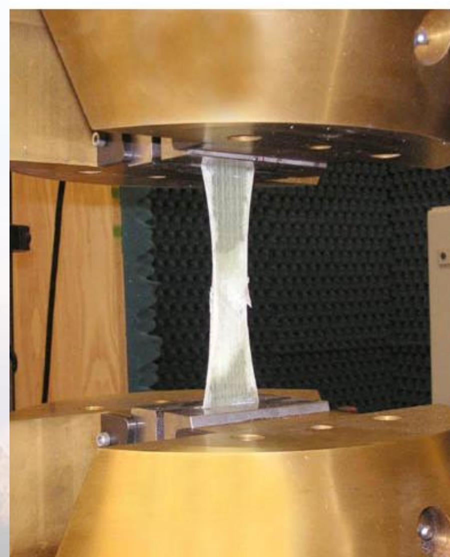
Ceragenins are antimicrobial peptide mimics synthesized by Dr. Paul Savage at BYU.



Marine Coatings Test Facility will aid in the development of antifouling coatings. (Shane Stafslien)

MONTANA STATE UNIVERSITY

Material & Manufacturing of Tidal/Current Designs. (John Mandell)



PENNSTATE 1855

ARL

ARL will be testing for cavitation erosion protection and fouling. (Bill Straka)

General MHK Materials

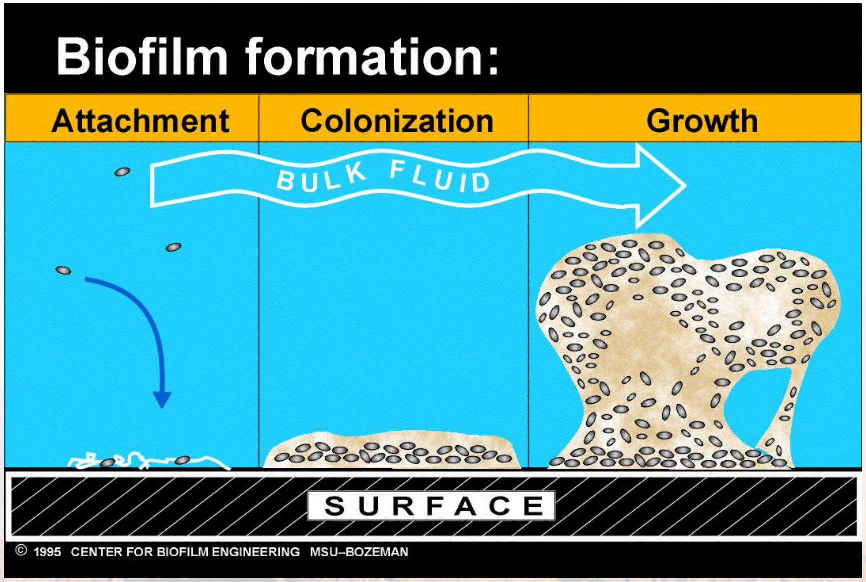
Metals	Fluids	Polymers	Composites	Inorganic	Protection
Stainless Steel	Ammonia	Polyvinylchloride (PVC)	Resin Reinforced Fiber	Marine Grade Concrete	Silicone Based Coating
Copper	Ammonia-water Solutions	Hapalon	Reinforced Rubber	Silica	Marine Grade Paints
Aluminum	Propylene	Rubber	Reinforced Concrete	Neodynium Magnets	Fouling Release Coatings
Magnetic Steel	Seawater	Polyethylene	Composite Concrete	Rare Earth Magnets	Cathodic Protection
Non-Magnetic Steel	Hydraulic Fluid	Foam	Glass Reinforced Plastic	Fiber Glass	Sacrificial Anodes
Metal Alloys	Biodegradable Hydraulic Fluid	Engineered Plastic	Glass Fiber Reinforced Polyester		Cleaning/ Polishing Coatings
		Rubbery Electroactive Polymer	Fiberglass Reinforced plastic (FRP)		
		High density polyethylene (HDPE)			

*information collected from company websites and other public resources

Biofouling Is Caused By Biofilms

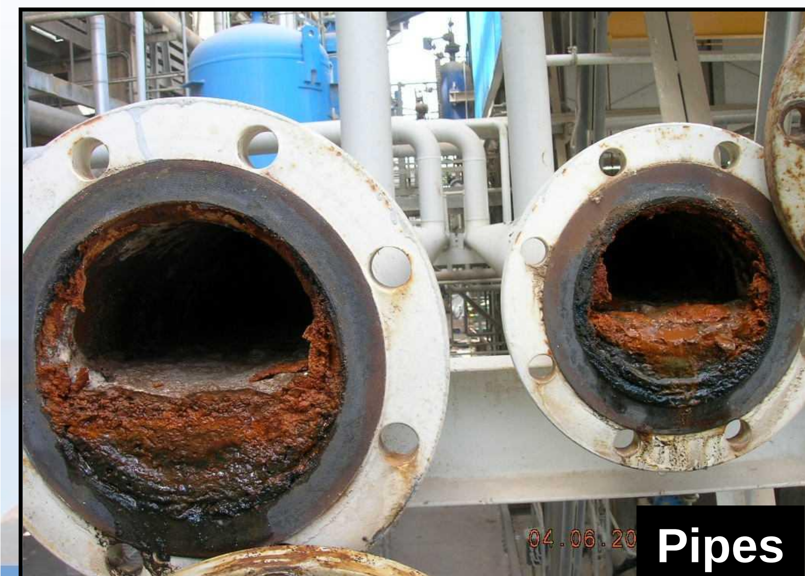
Colonies of microorganisms attached to a surface and encased in extracellular polymeric substances (EPS, aka slime).

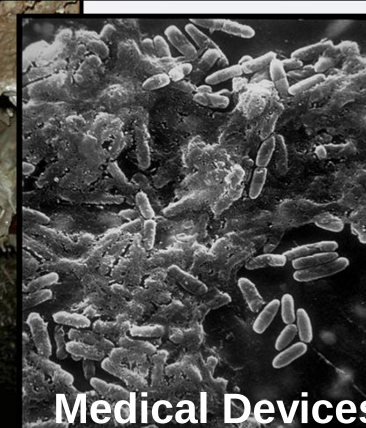
- **Able to trap nutrients for their own growth**
- **Protected from anitbiotics and other anti-microbial agents**



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

Biofouling Impacts Many Industries





Lessons Learned

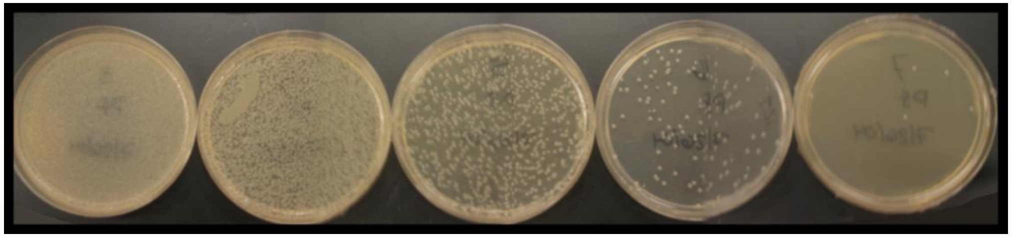
- **Biofouling increases cost**
  - Ships increases fuel cost by 15%
  - Navy ~$100 million for hull cleaning, antifouling paint removal/repainting, toxic water & grit disposal, OSHA, labor
- **Ocean Thermal Energy Conversion**
  - Warm Water Heat Exchangers
    - Calculated 25-250 µm thick biofilms would reduce 10-50% heat transfer coefficients
    - in the ***early stages*** of development (55 µm), later controlled/improved by chlorination

Guide to the Use of Materials in Water, M. Davies & P. J. B. Scott, NACE International, 2003.

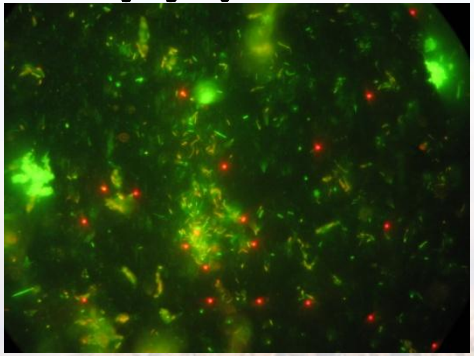
Quantifying Biofouling

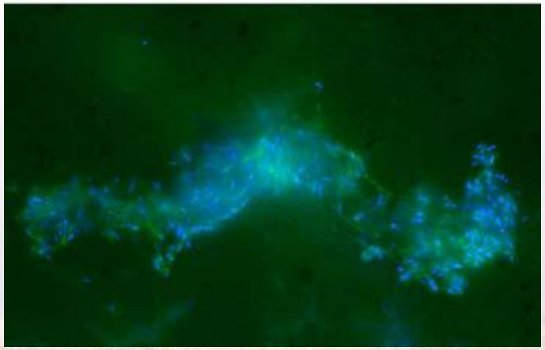
- Collect Samples of Biofilms

- Scrape and plate (viable cell counts)



- Microscopy (direct cell counts, thickness)





- Laboratory measurements (ATP, proteins, etc.)

To the best of our knowledge reliable methods for doing real-time biofouling testing in the field are not available.

Even in the research world the coupon method is the most prevalent method.

Reactors for Biofouling Testing

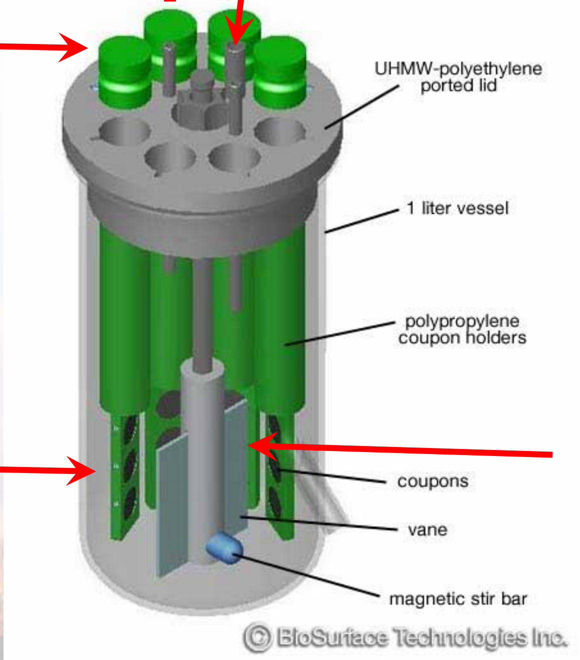
Drip-Flow Reactor

CDC Reactor

Sample after different time periods

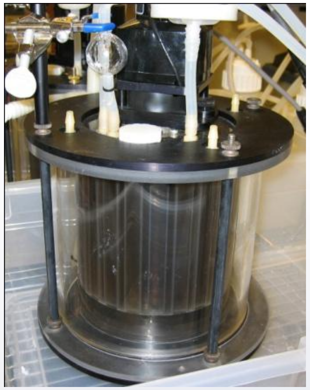
Inflow

8 rods



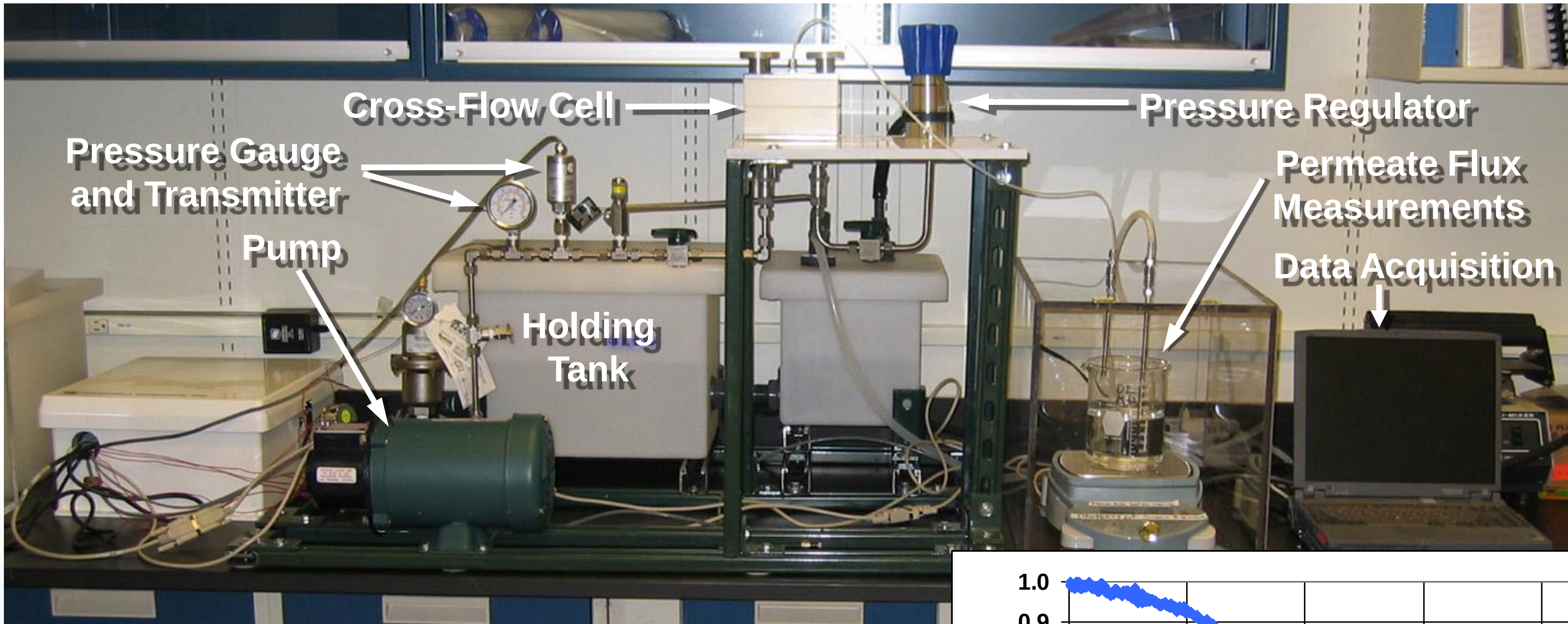
3 coupons per rod
24 samples total

Annular Reactor

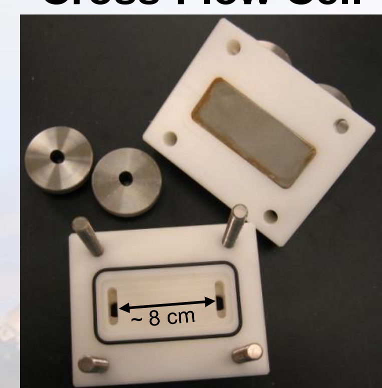


Stir bar provide a moderate shear environment

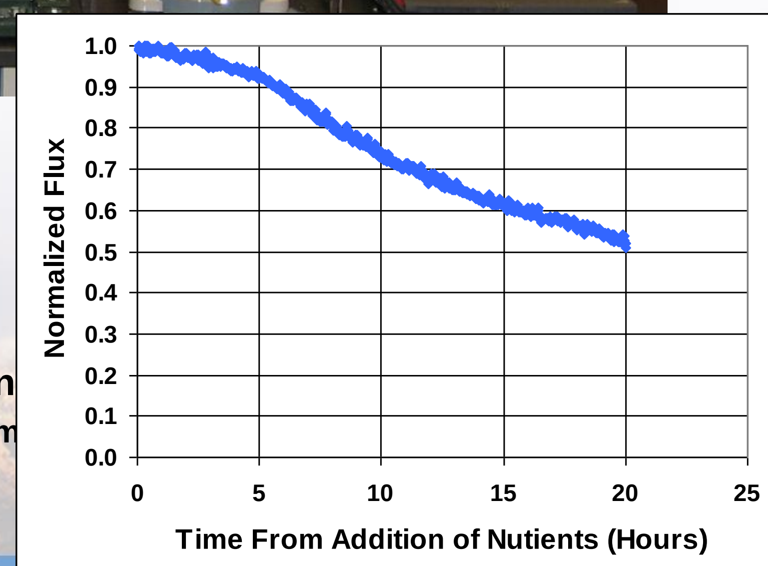
Cross-Flow Membrane Testing System For Testing Water-Treatment Membranes



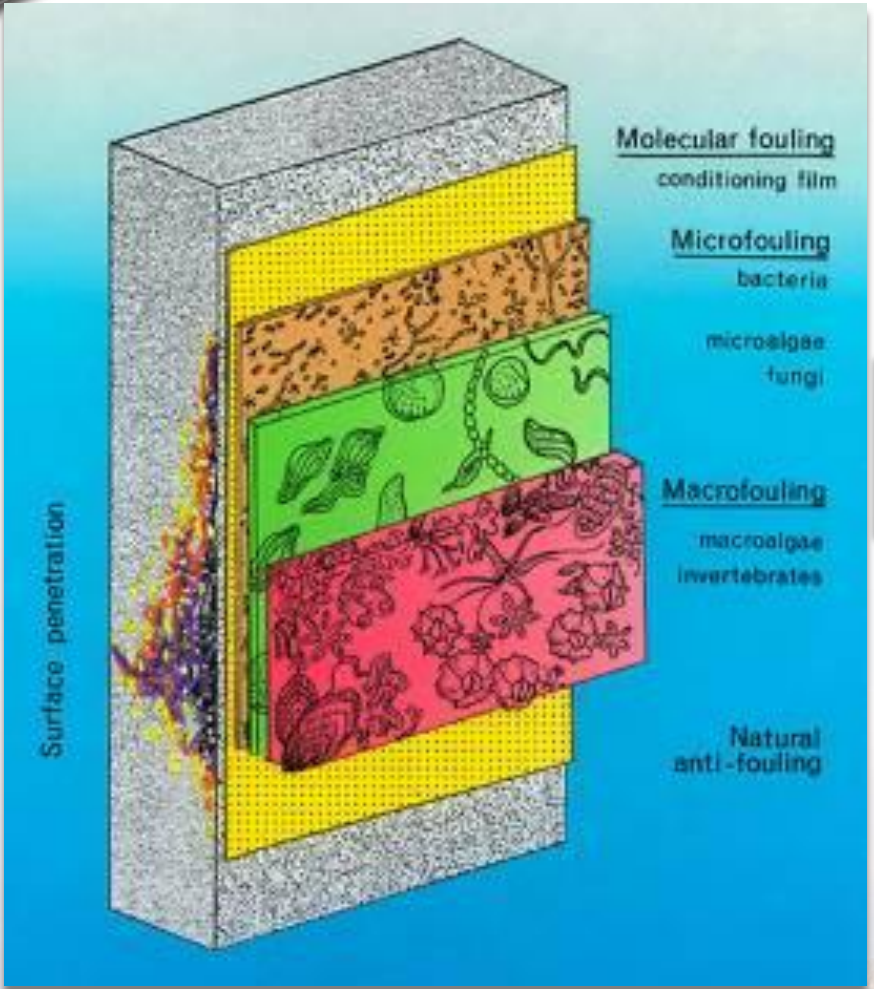
Cross-Flow Cell



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



Marine Fouling Occurs Over Both Time & Length Scales

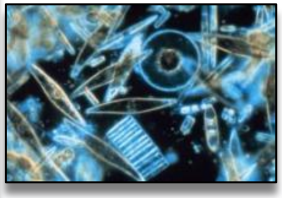


Molecular Fouling (1 min.)

↓

Bacteria (1-24h)

↓



Microalgae/Fungi (1 wk)

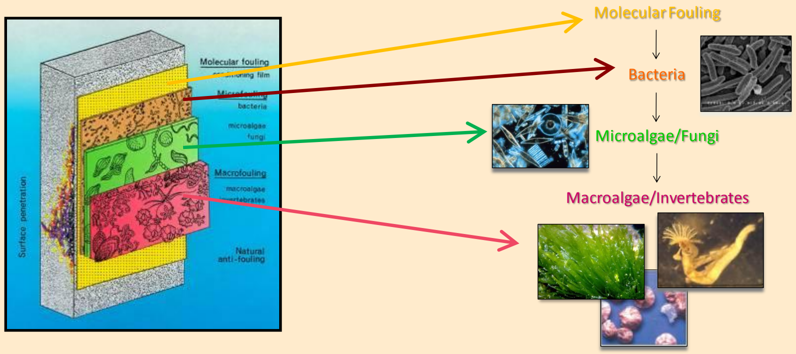
↓

Macroalgae/Invertebrates (2-3 wks)

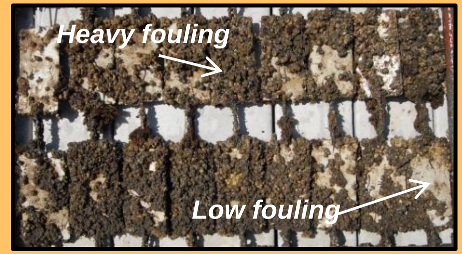
Performance Assessment of Antifouling (AF) Marine Coatings/Materials

Ocean Immersion Testing

Marine Fouling



Accumulation of Marine Fouling



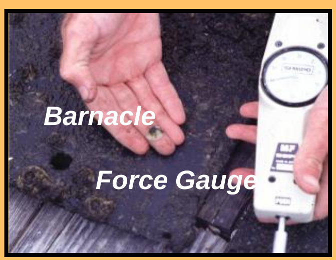
Fouling of AF materials at Florida Institute of Technology (Melbourne, FL)

Immerse AF coatings/materials in ocean and periodically assess fouling **(ASTM D6990-05)**

Each AF coating/material is given a fouling rating **(FR)** based on percent coverage of slime, soft and hard fouling colonization

(0 -100; FR of 100 = no fouling)

Marine Fouling Adhesion



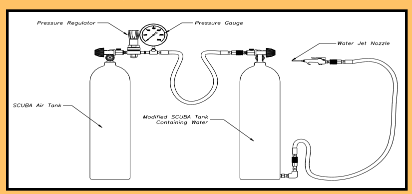
***Hard fouling adhesion* (ASTM D5618-94)**

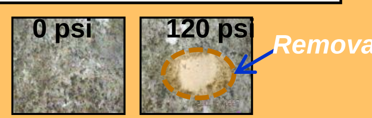
Hand held force gauge applied to the base of the organism and shear removal force is measured

Area of organism adhesive base is measured and used to calculate adhesion strength (megapascals):

Shear Force / Base Area = MPa

SCUBA "Water Jet" Setup





Slime and soft fouling adhesion

Pressurized SCUBA tanks used to apply a jet of water to fouled materials to assess the adhesion strength of slimes and soft fouling

Record the "water jet" pressure required to remove fouling:

(0 to 240 psi (0 to 1.65 Mpa)

Advantages

- Aggressive, real-world challenge with complex and dynamic biofouling communities
- Can obtain both short-term and long-term AF performance assessment data, including durability/weatherability
- Multiple testing sites around the world enables comprehensive assessments of overall performance and durability in different marine environments (i.e., salinity, pH, temp etc.)

Limitations

- Most testing sites are seasonal and/or prone to weather events that limit their ability to provide services year-round
- Limited capacity enables testing of only a small number of materials at one time
- Testing carried out on large raft panels, requiring large of amounts of material to be prepared (considerable expense)

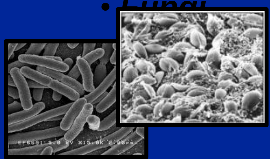
Performance Assessment of Antifouling (AF) Marine Coatings/Materials

Laboratory Evaluations

Marine Fouling Organisms

A wide variety of marine organisms are employed in laboratory assays to assess the performance of AF materials. Majority utilize a representative slime, soft or hard fouling species:

Slimes
- *Bacteria*
- *Microalgae (diatoms)*
- *Fungi*

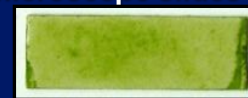


Soft Fouling
- *Macroalgae*

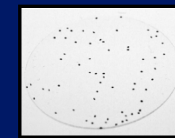
Hard Fouling
- *Barnacles*
- *Tubeworms*
- *Mussels*

Settlement and Growth Assays

Materials typically prepared on discs/coupons or microscope slides



Macroalgae (Ulva)



Barnacle cyprids

Mussels

Biofilm

Static Systems

Petri Dish

Aquarium Tank

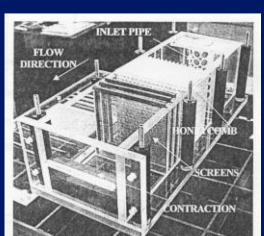
Dynamic Systems

Flow Cells

Biofilm Reactors

Adhesion Assays

Organisms that have attached to AF materials can be assessed for their adhesion strength using turbulent flow channels, water jet devices and motorized force gauges.



Turbulent flow Channel

Water Jet Device

Motorized Force Gauge

Advantages

- Can evaluate performance of materials very quickly to weed out poor performing materials and ID promising candidates
- Only requires a small amount of material for testing
- Substantially cheaper than ocean immersion testing
- Can carry out precisely controlled experiments with targeted fouling organism(s)

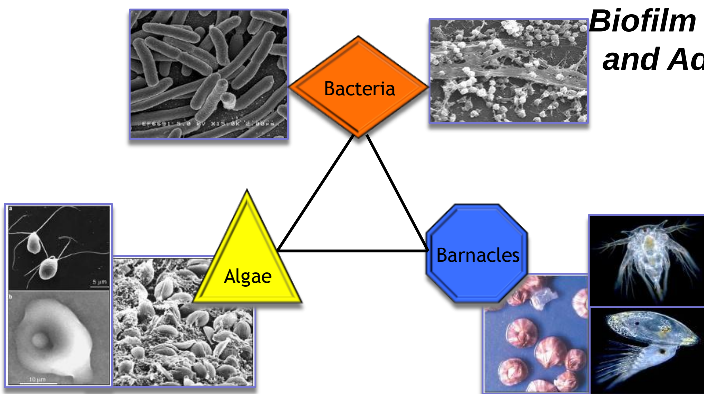
Limitations

- In most cases, can only assess the performance towards one organism at a time (limits community interactions)
- Testing is typically over a short period of time (hours, days or weeks) and can not be used for long-term performance testing
- Durability/weatherability hard to discern in laboratory

Performance Assessment of Antifouling (AF) Marine Coatings/Materials

High Throughput Laboratory Evaluations at NDSU

Marine Fouling Organisms



Biofilm Growth and Adhesion

Nauplii Toxicity

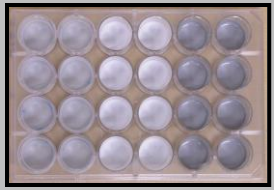
Microalgae Growth and Adhesion

Adult Adhesion

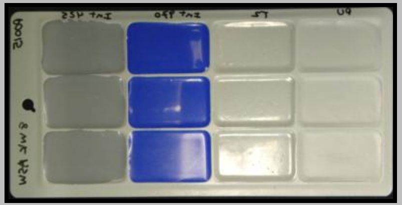
High Throughput Screening (HTS) Formats

AF coatings and materials are prepared on substrates amendable to automated HTS methods

Small amounts of material are solvent cast or adhered to multi-well substrates



24-Well Plates (Bacteria & Microalgae)



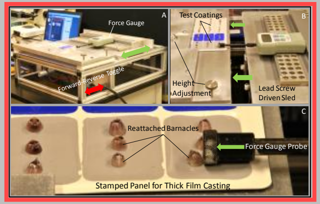
12-Well Aluminum Panels (Barnacles)

Automated Instrumentation

HTS workflow consists of a suite of automated instruments to rapidly evaluate the AF performance of marine coatings/materials prepared on array plates and panels

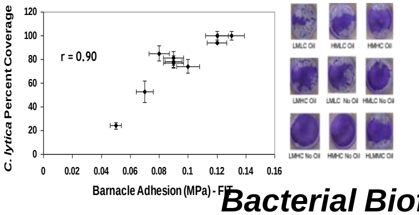
Water Jet Treatments

Inoculation, Rinsing and Staining



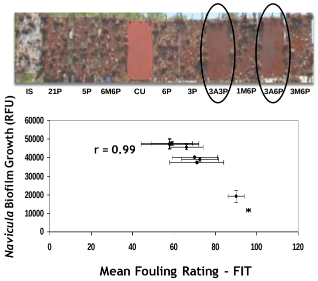
Force Gauge Measurements

Correlations to Ocean Immersion Testing

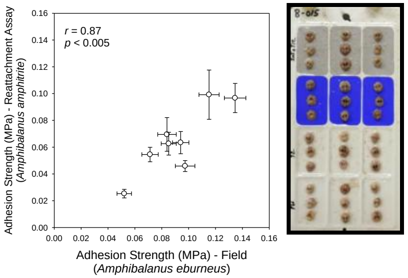


Bacterial Biofilm

Several correlations have been made between HTS laboratory assays and ocean immersion testing



Microalgae Biofilm



Adult Barnacles

Corrosion Monitoring

- **Corrosion performance of materials is usually assessed in a laboratory environment using standard electrochemical procedures – however, there are some tools available for field evaluation.**
  - **Coupons**
  - **Probes: Electrical Resistance (ER)/Inductive Resistance (IR), Hydrogen**
  - **Acoustic Emission**
  - **Sand/Errosion Monitors**
  - **Inspection: visible, magnetic flux, radiography, ultrasound, eddy current, thermography**

- **Exposure Coupons**
  - **General Corrosion**
  - **Microbiologically Influenced Corrosion**

- **Electrochemical Sensors**

Corrosion Test Coupons

- **Basic concept is to place the material you are concerned about in the exposure environment, then periodically remove and inspect the coupons to assess the degree of corrosion which may have taken place.**

- **Coupons replicate the properties of the specific structure of interest as closely as possible**
  - Material chemistry
  - Surface treatment (e.g., surface roughness, coating application)
  - Stress state (e.g., U-bend, C-ring, or other stress maintaining configuration)
  - Occluded geometries (e.g., crevice former)

- **Specimens removed at defined intervals and analyzed for degree of attack**
  - Micro- or Macro-scopic inspection for corrosion type, cracking, etc.
  - Weight change (for general corrosion)
  - Surface analysis (identification of surface deposits)

Electrochemical Corrosion Sensors

- Attempt to carry traditional electrochemical measurements to the field in order to assess corrosion rate
- Require inundated conditions (i.e., not useable for atmospheric corrosion measurements)
- Linear Polarization Resistance (LPR) or Electrochemical Impedance Spectroscopy (EIS) sensors
  - One or more specimen (depending on vendor) of material of interest
  - Wide variety of geometries available
  - Sample subjected to small electrochemical polarization (non-destructive) to determine polarization resistance which is in turn converted to a corrosion rate
- Resistance sensors
  - Electrical resistance is a function of the geometry of the conductor
  - Material loss will result in a change in the resistance and can be correlated to a degree of attack
  - Unable to distinguish between general and localized corrosion
- Galvanic corrosion rate sensors
  - Coupons of each material of interest connected through a zero resistance ammeter
  - Galvanic current as a function of time measured

Summary

- **Field testing vs. Lab testing**
  - "Swab-grow or grow-and-look" biofouling studies
    - Exposure Coupons
  - Corrosion
    - Exposure Coupons
- **Needs depend on variables**
- **Variables for Corrosion (chemistry, temperature, pH, Pressure, flow rate)**
- **Variables for Biofouling (location, season, water chemistry)**