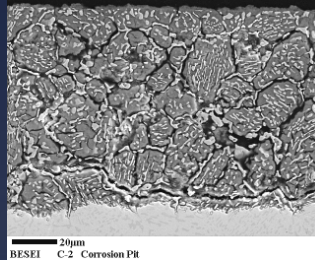
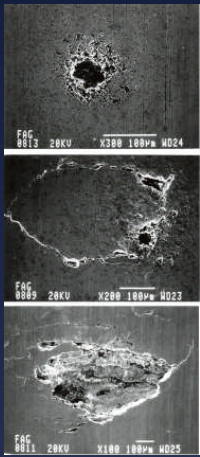


Measurement and Assessment of Bearing Degradation in Ester-Based Lubricant Systems



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Herb Chin, Bill Ogden, Gene Danko (Pratt & Whitney)
Balky Nair (Emisense Inc.)



Supported By: Pratt & Whitney, Emisense, Inc., Ceramatec, Inc., National Science Foundation (STTR)

Report Documentation Page

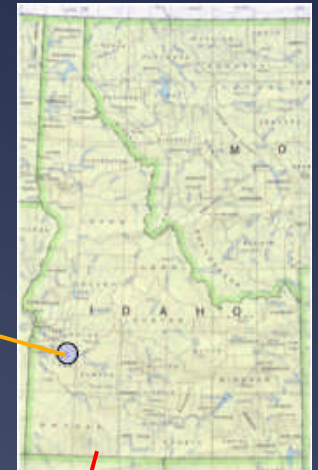
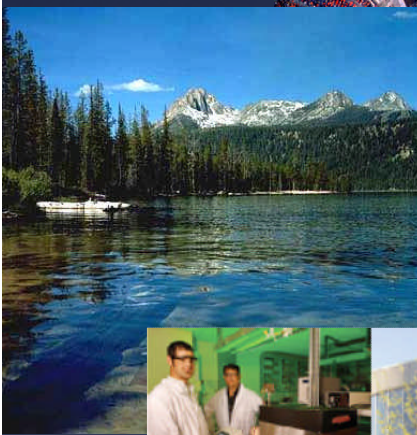
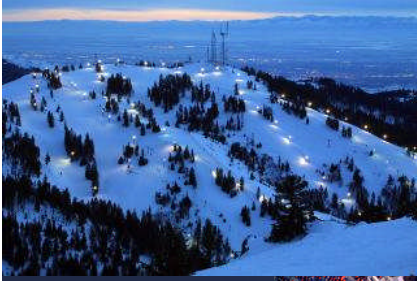
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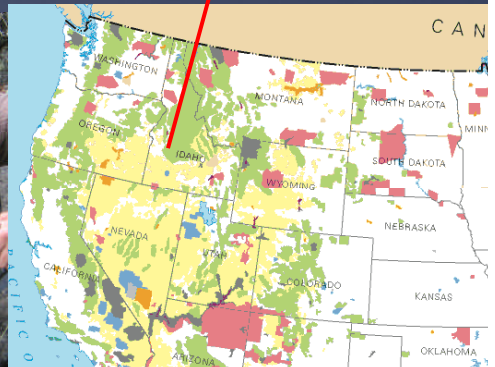
Boise State University

Department of Materials Science and Engineering



19,500 Students at BSU
College of Engineering 11 Years Old
Ranked #12 by U.S. News and World Report

Materials Science and Engineering 4 Years Old
First ABET Accredited MSE Program in Idaho
100+ Students
90%+ Undergrads Doing Paid Research, Including Corrosion



Project Overview

Oil Issues

- Additive Effects
- Seawater Contamination
- Chloride Concentrations
- Oxidation/Degradation

Corrosion Issues in Oils

- Alloy Microstructure
- Seawater Content (Emulsions)
- Chloride Concentrations
- Effect of Temperature

Materials Issues

- Sensor Circuitry
- Sensor Body
- Sensor Substrate
- Joining Brazes

Oil/Water
Electrochemical
Properties

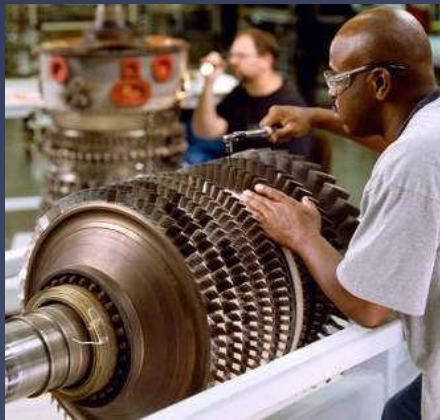
Corrosion Rates,
Mechanisms, Pitting of
Bearing Alloys

Sensor Optimization: Monitor Oil
Quality/Corrosion

Sensor Construction

Sensor Testing

Deployment of Sensor to
Application



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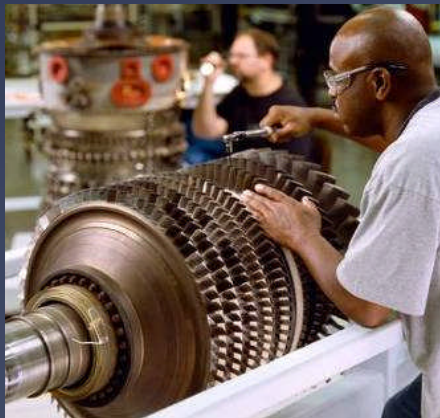
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Bearing Materials and Oils

Bearing Steels

| Material | C (Case) | Cr | V | Mo | Si | Mn | C | Co | Ni | Fe |
|----------|----------|----|-----|------|-----|------|------|-----|-----|------|
| M50 | -- | 4 | 1 | 4.25 | 0.3 | 0.3 | 0.8 | -- | -- | Bal. |
| P675 | ~2% | 13 | 0.6 | 1.8 | 0.4 | 0.65 | 0.07 | 5.4 | 2.6 | Bal. |

Compositions in wt%

Lubricant-Water Systems

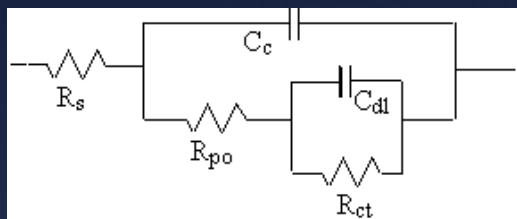


| Oils |
|---------------------|
| BP 2389 |
| BP Alo 16360 |
| BP Alo 16561 |
| Chevron 10W 40 oil |
| Chevron 15 W 40 |
| Chevron 5W-20 oil |
| Delo 400 |
| GTX 520 |
| Hatcol 3212 |
| Hatcol 3214 |
| Hatcol 4213 |
| Jet oil 254 |
| Mobil 10W 40 oil |
| Mobile 5W 20 oil |
| Pennziol 10W 40 oil |
| Pennziol SW 20 |
| Pennziol 5 W 30 |
| Turbo 1294 |
| Turbo 2380 |
| Turbo 2389 |
| Valvoline 410 |
| Valvoline 520 |

| Oil | Water, ppm | [Cl] (Moles) |
|---------------------------|------------|--------------|
| BP 16360 Valvoline 520 | 200-8000 | 0.001-1 |

| Polyol esters | Anti-oxidants | Anti-wear / Extreme Pressure | Corrosion Inhibitors | Rust Inhibitors | Anti-Foam Agents |
|---------------|---------------|------------------------------|----------------------|-----------------|------------------|
| 94-97% | 2-4% | 1-3% | <0.5% | <0.5% | ppm level |

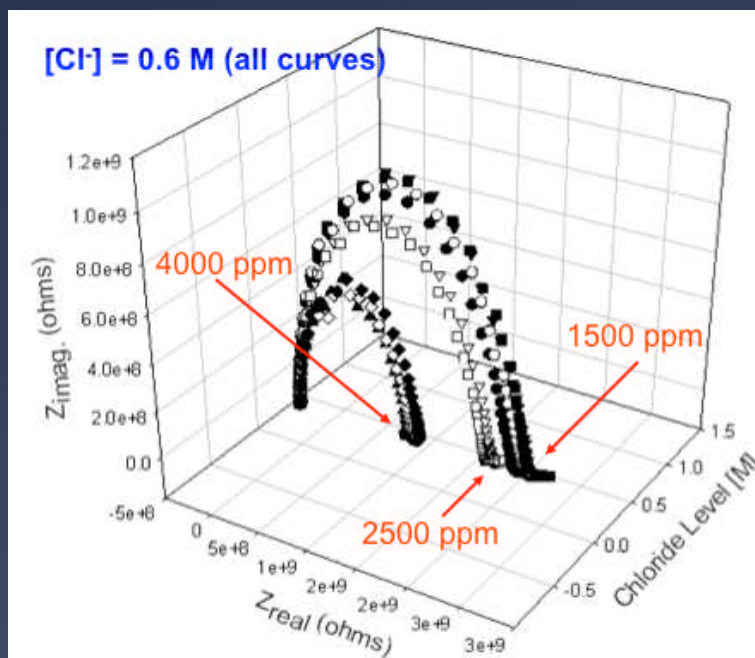
EIS Necessary in High Impedance Solutions



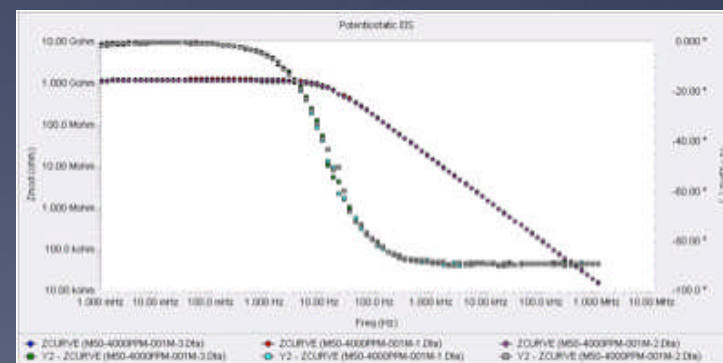
Unlike DC, AC E-chem can discern individual circuit components



BSU Cell

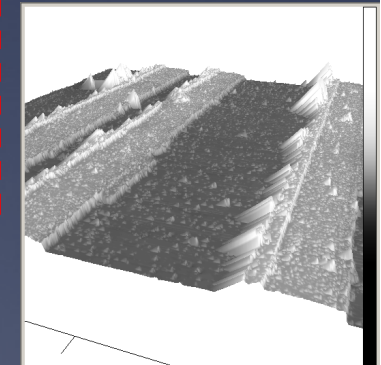
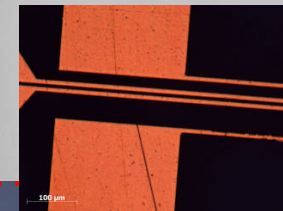
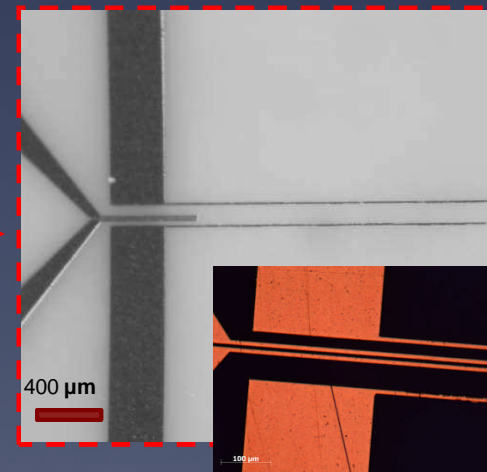
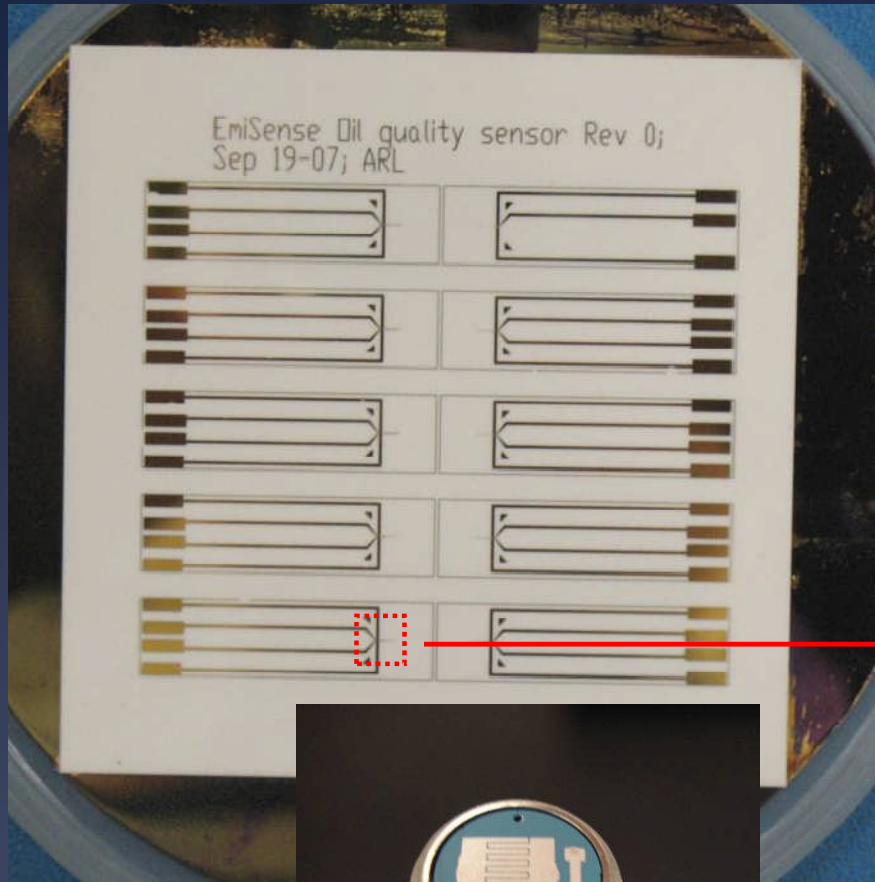


- 1,000,000 Hz – 0.001 Hz
- 10 mV AC
- 300s delay
- Polished to 1 μm
- 1 mm electrode spacing using Teflon sheet

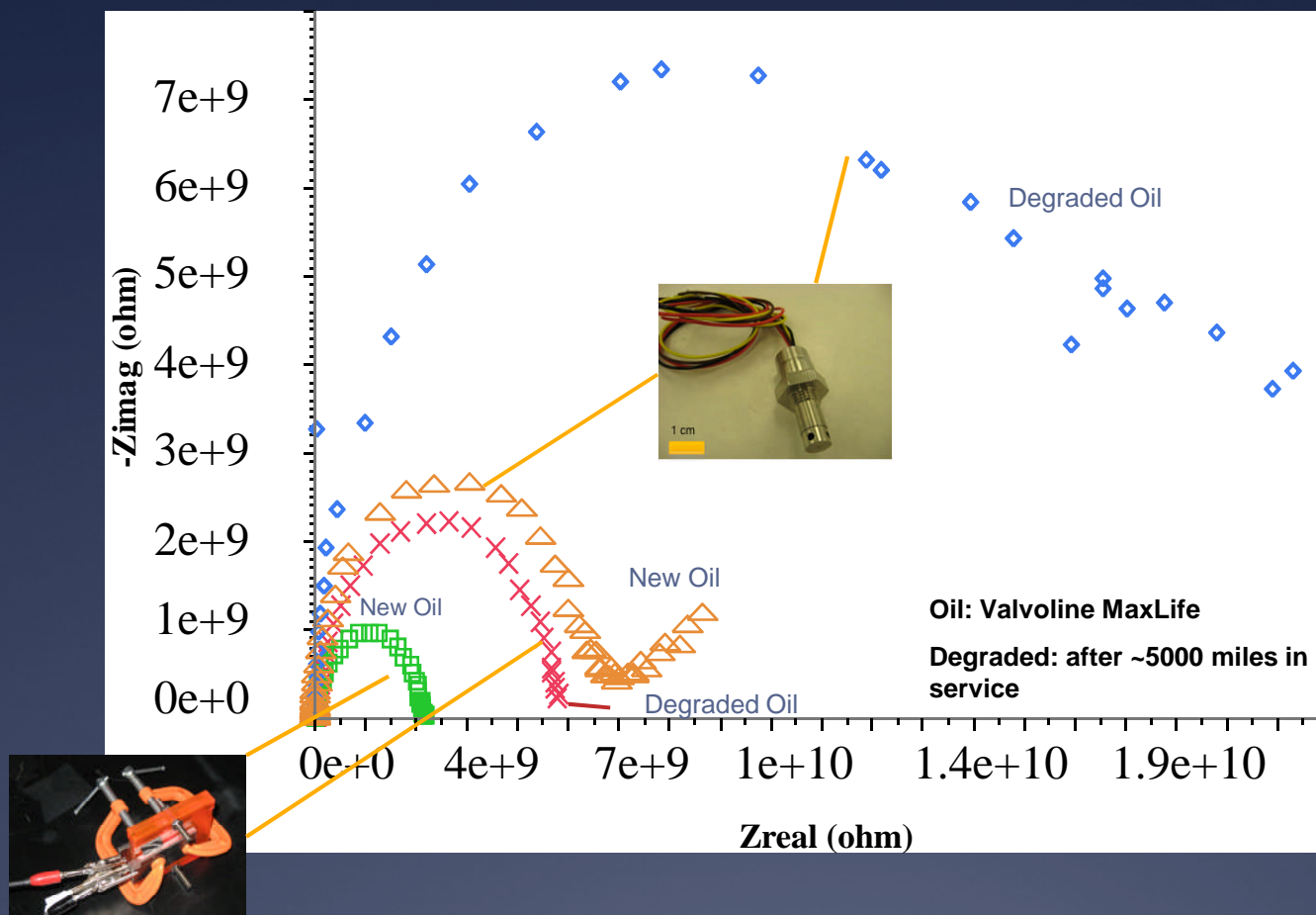


Oil Sensor Structures

Deposited Sensors



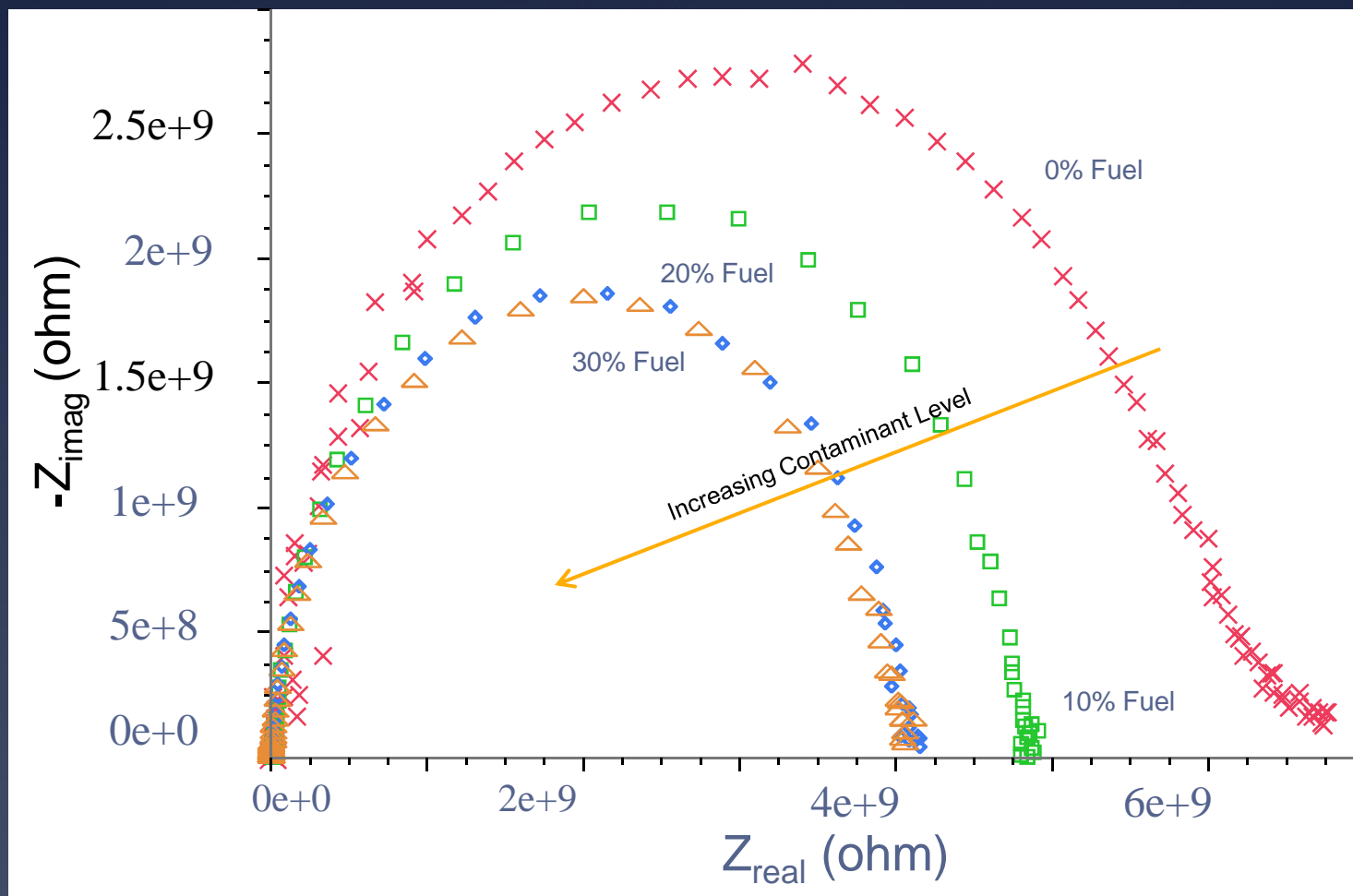
Influence of Oil Degradation on Impedance: Sensor vs Bulk Electrode



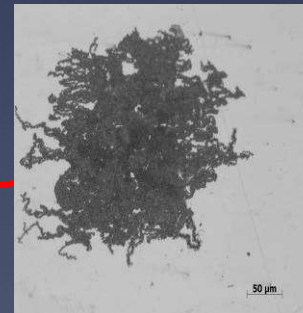
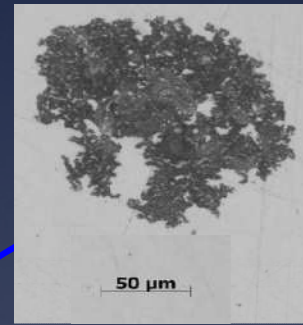
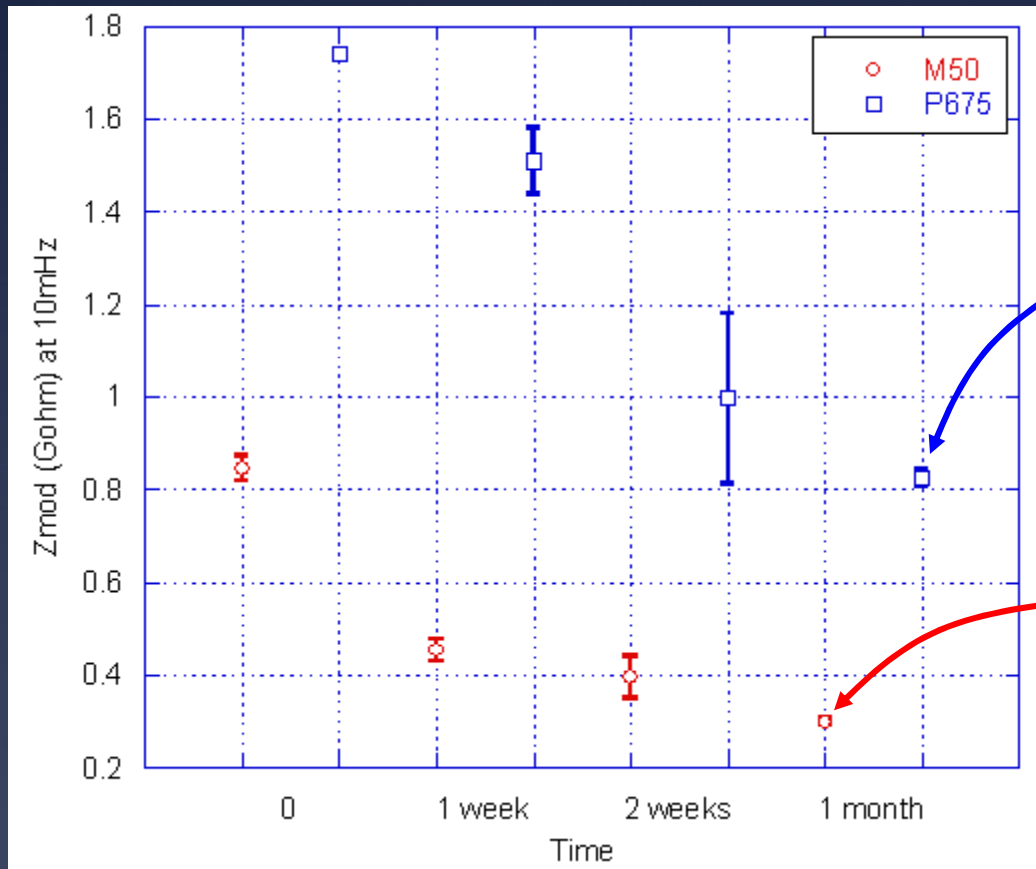
$$R_{\Omega} = \rho_{\text{sol.}} \left(\frac{L}{A} \right)$$

= 0.8 bulk electrode
 = 4.75 Emisense electrode

Sensing Diesel Fuel Contamination of Oil



Impedance Decreases with Immersion Time

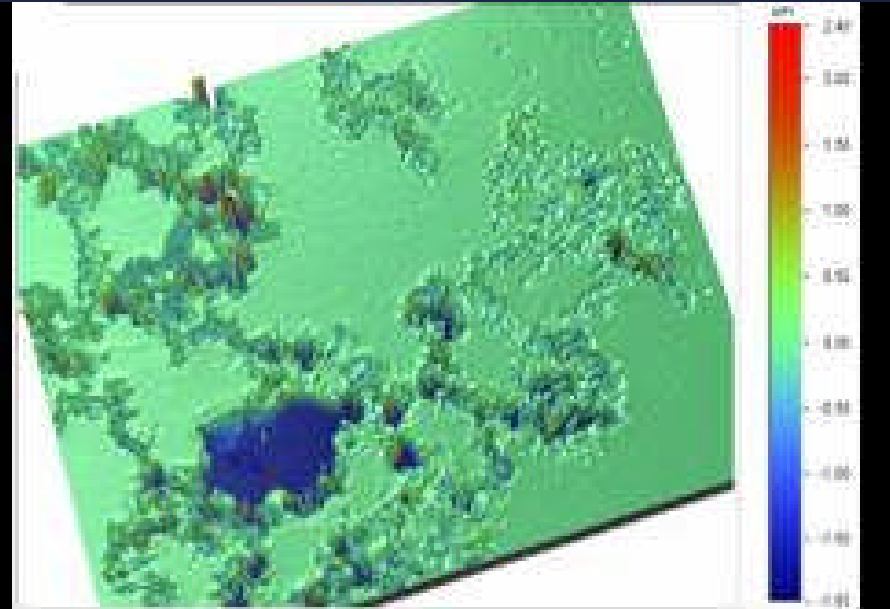
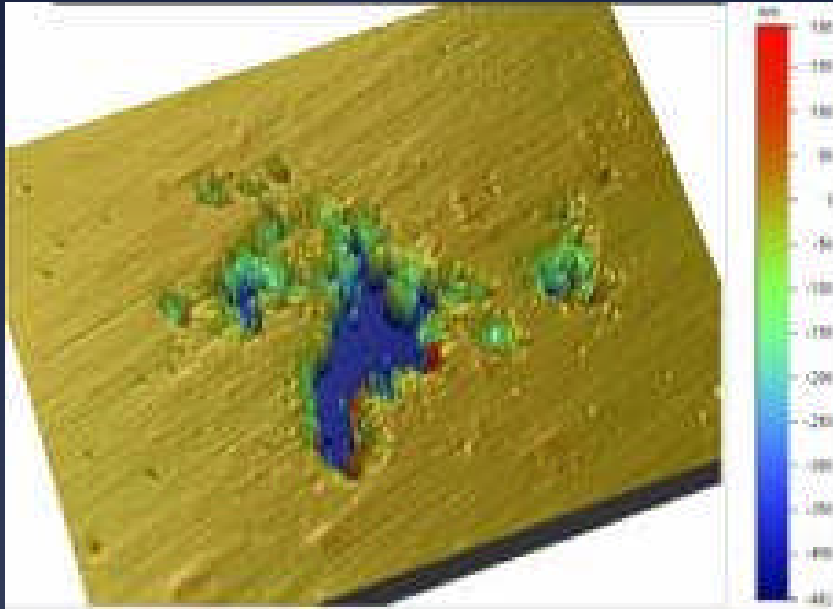


Conditions:

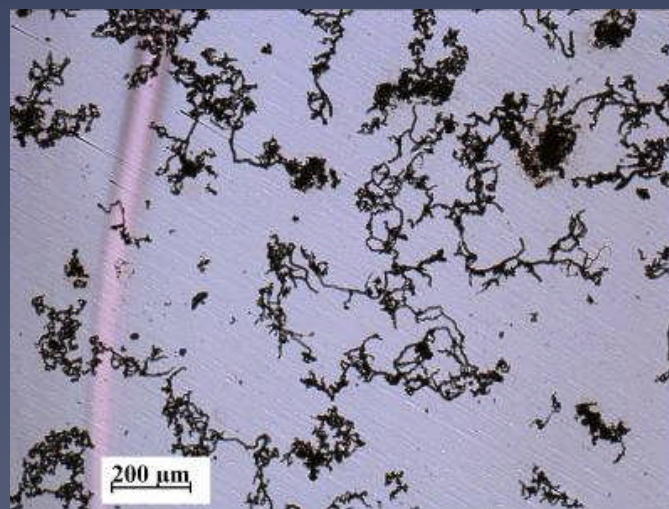
- Ambient aeration
- 2500 ppm 0.6 M NaCl
- Average of 3 runs

Filiform Corrosion?

AFM



Optical



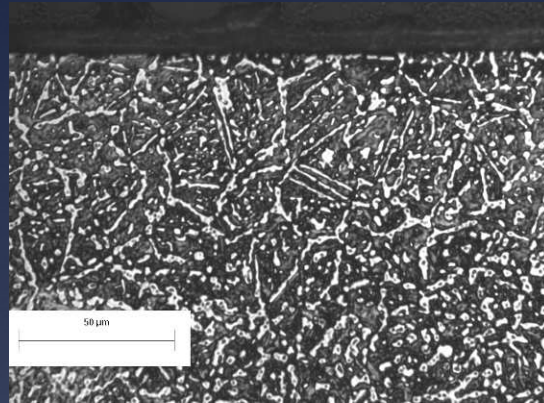
M50

Microstructure, Emulsion Characteristics vs. Corrosion

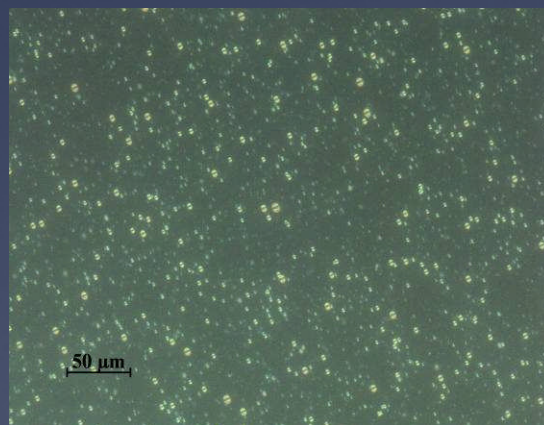
Objective:

Link alloy microstructure with corrosion behavior

Beginning Microstructure



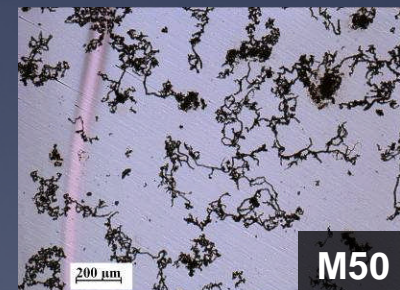
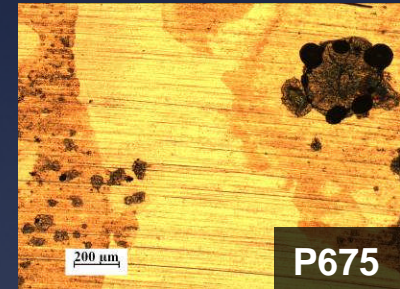
Seawater/Oil Emulsion



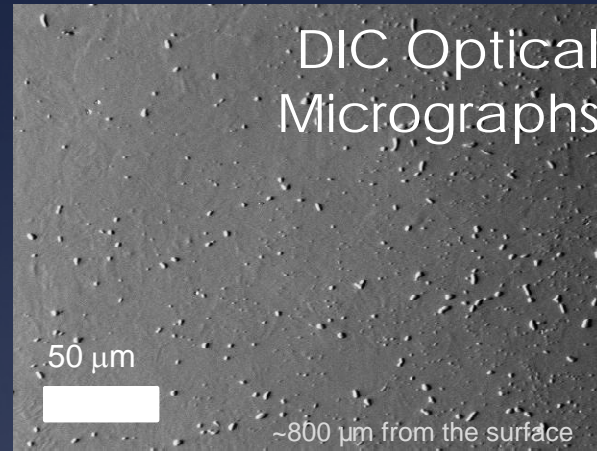
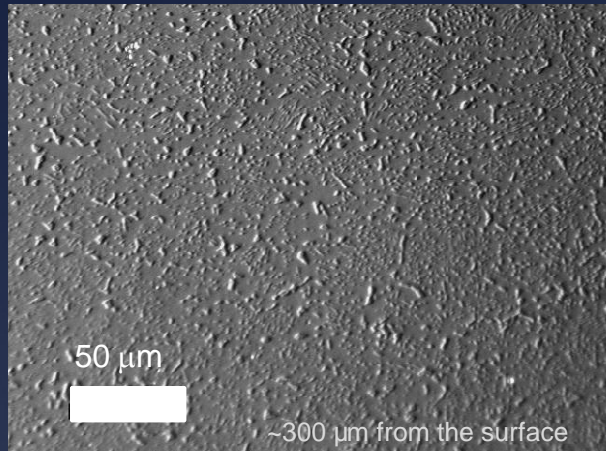
Influence of Microstructure

Influence of Seawater/Oil Emulsions

Types of Corrosion Damage Observed



Carbide Distribution in P675



Differential Interference Contrast

False topography resolves carbides from phase difference in reflected light



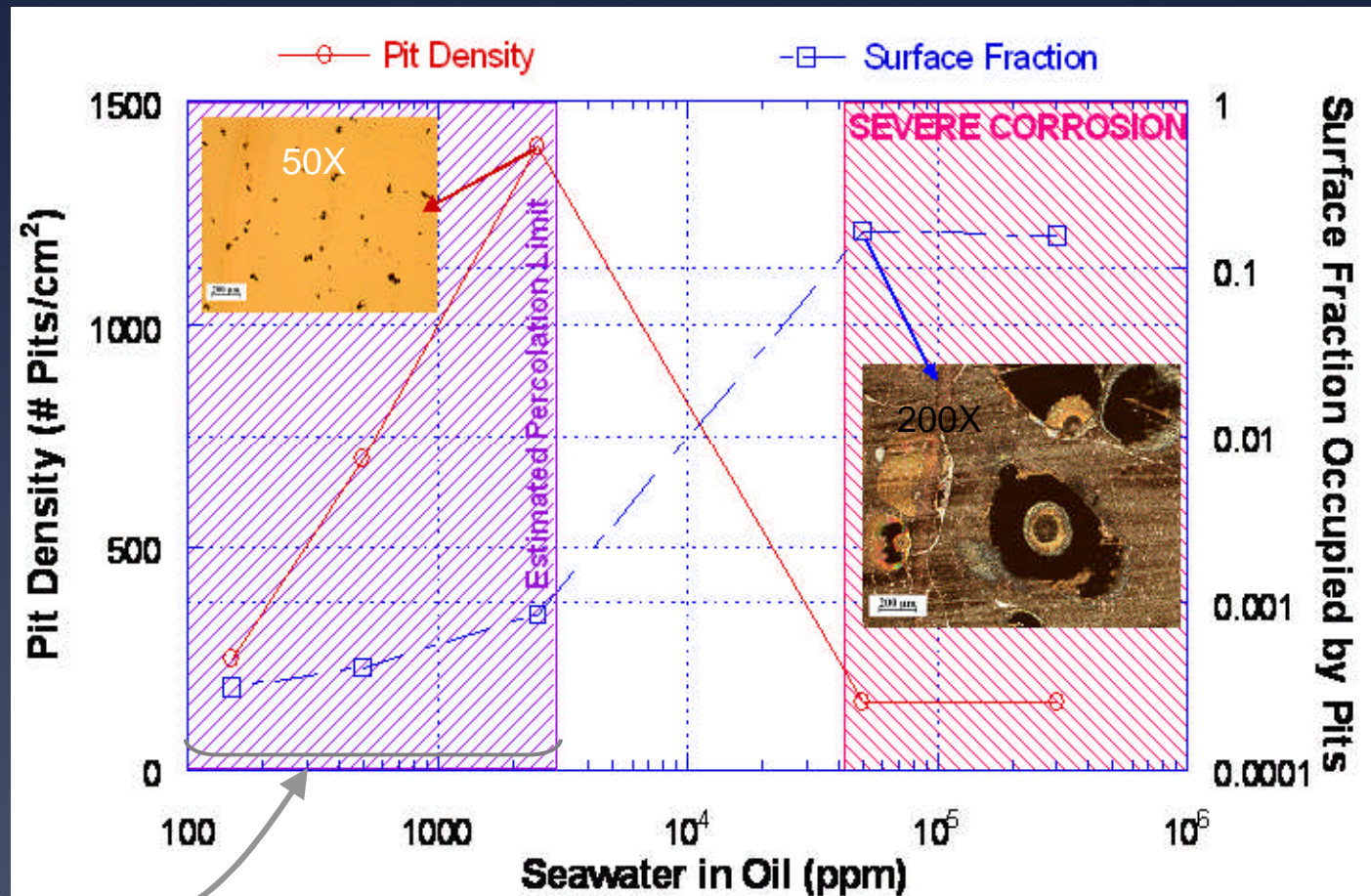
Pit Density and Area Fraction vs. Contamination Level

Below 3000 ppm Seawater content:

Pit density increases with water content

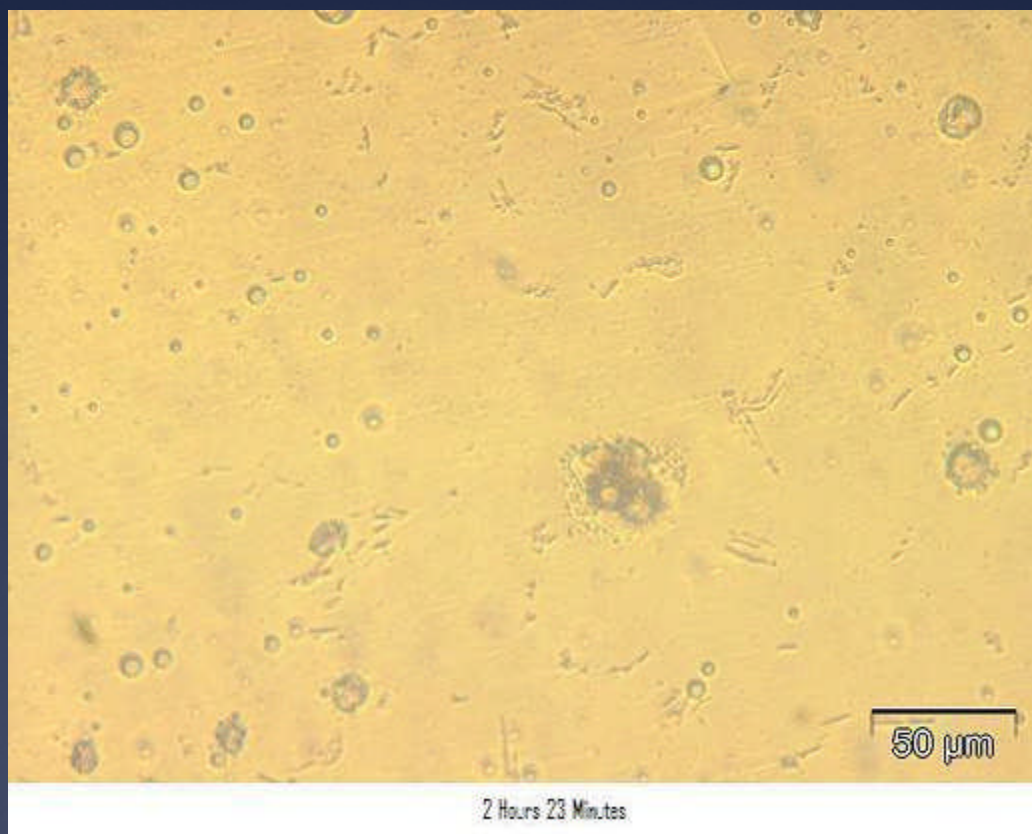
Surface fraction of attack increases but less rapidly than pit new pit formation

Propagation seems to occur by pit clustering adjacent to active corrosion sites and coalescence existing localized attack



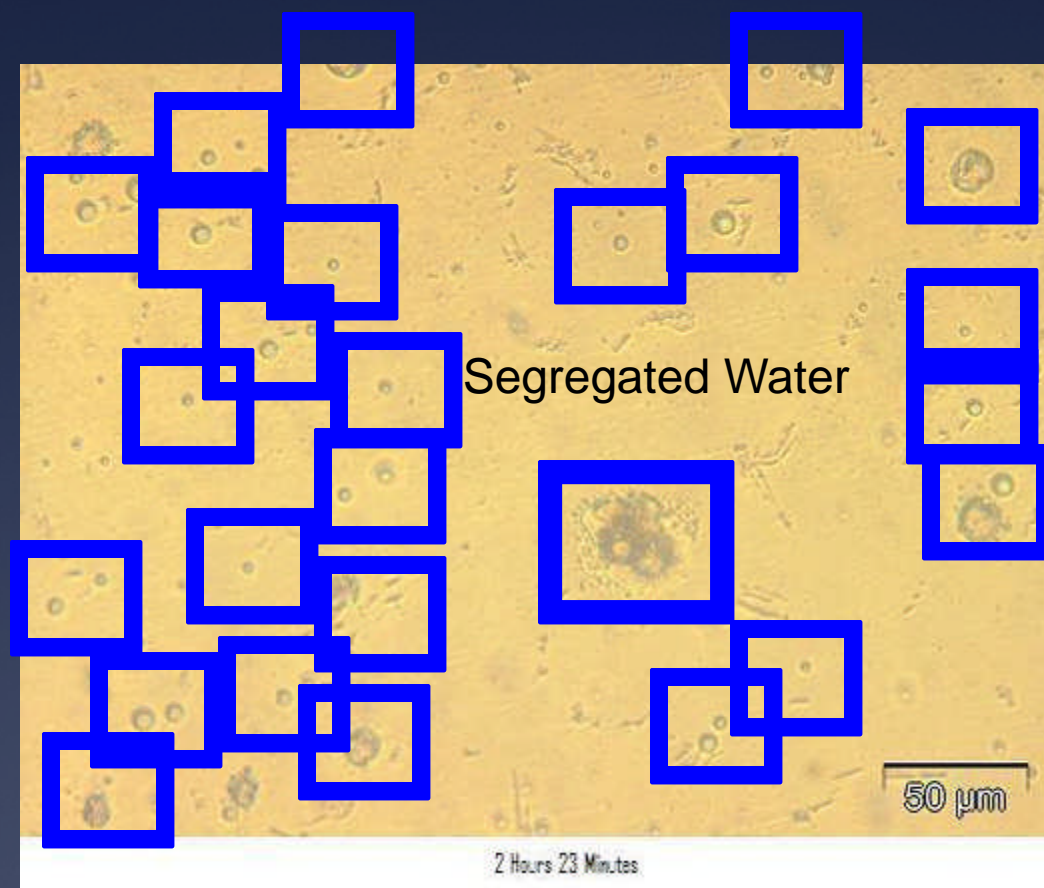
Pitting Below An Ester-Water Emulsion

M50
8000 ppm H₂O
1 M NaCl
24 hour series



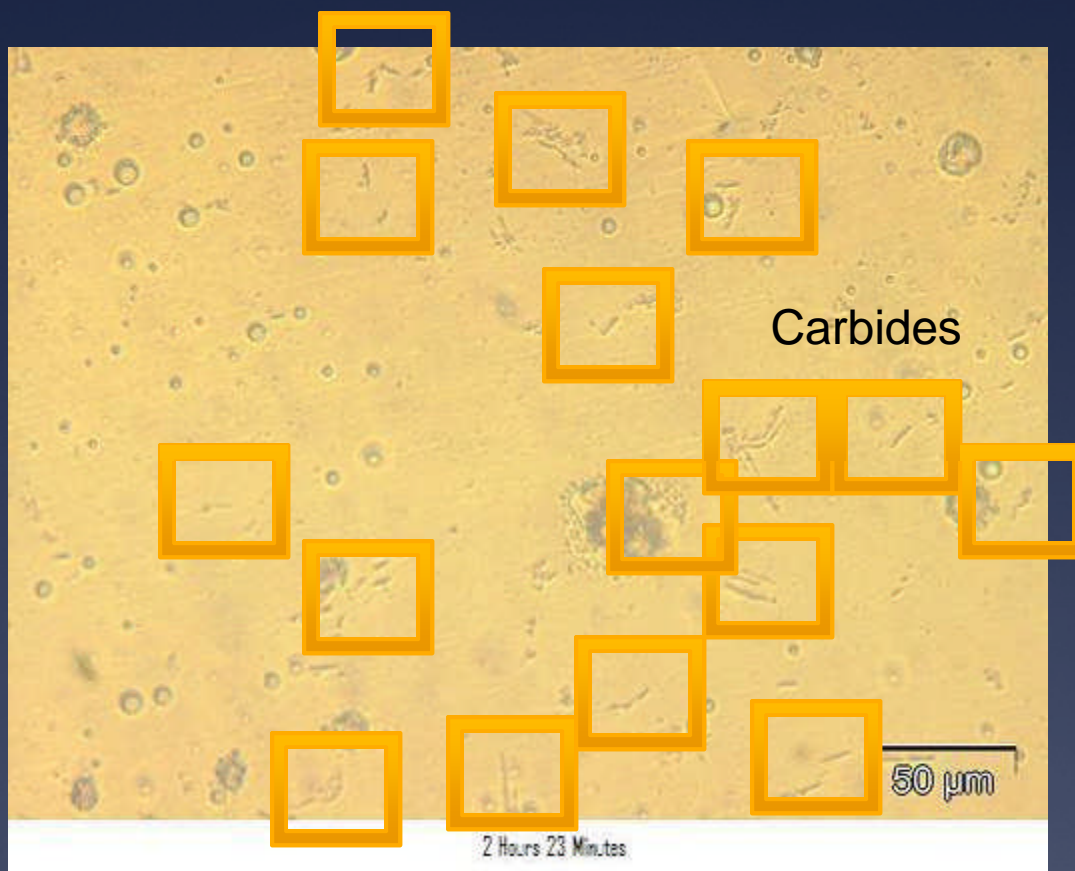
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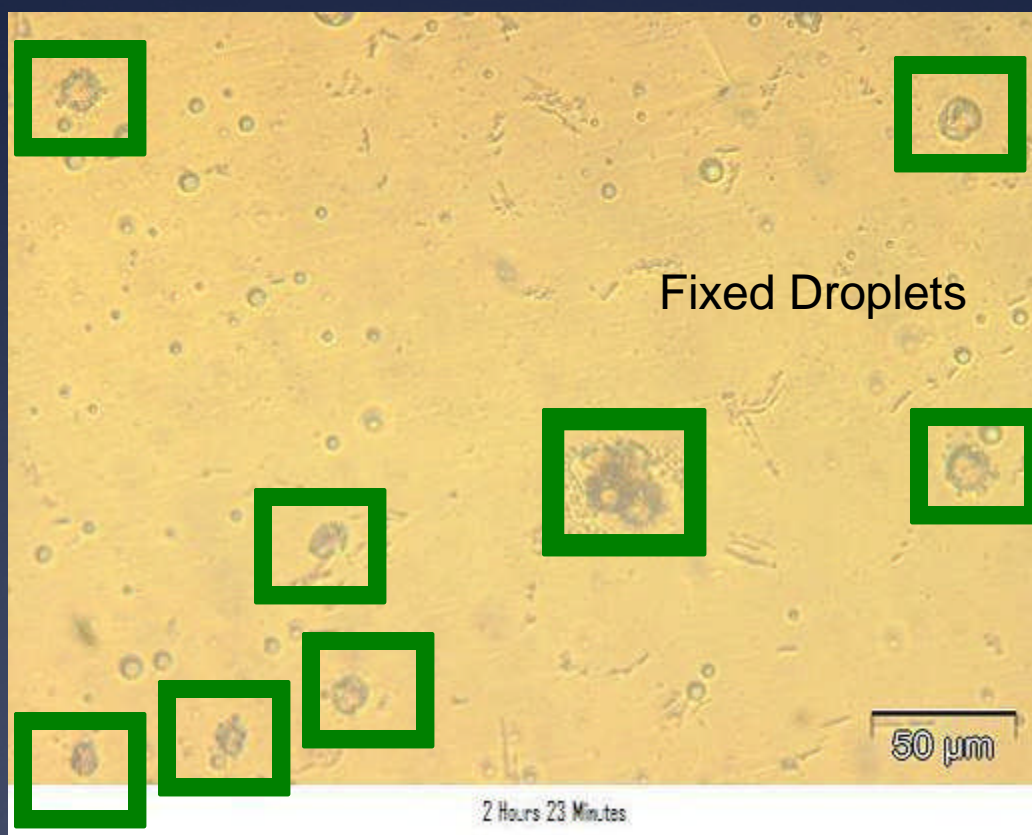
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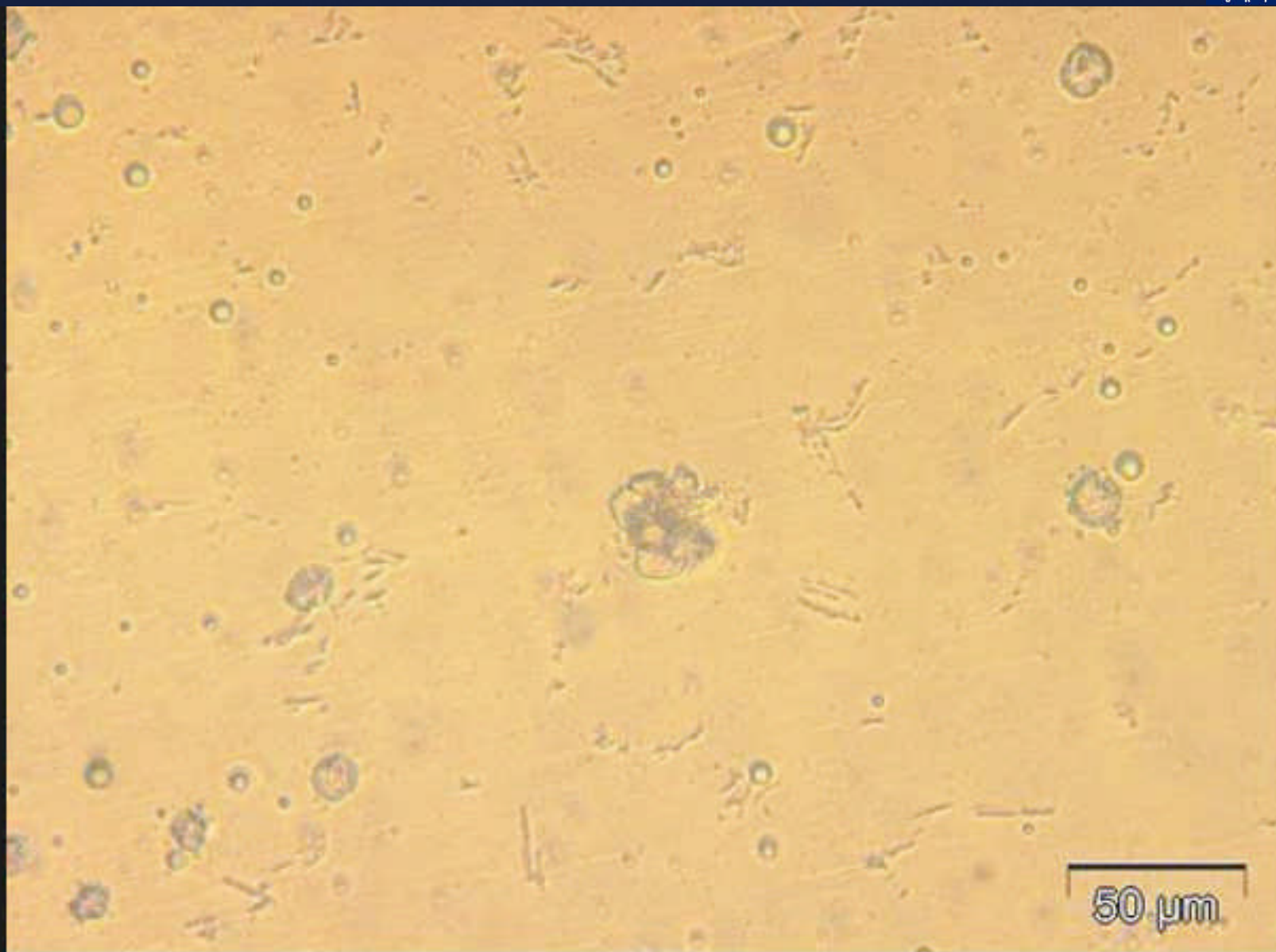
Carbides observed under fixed droplets

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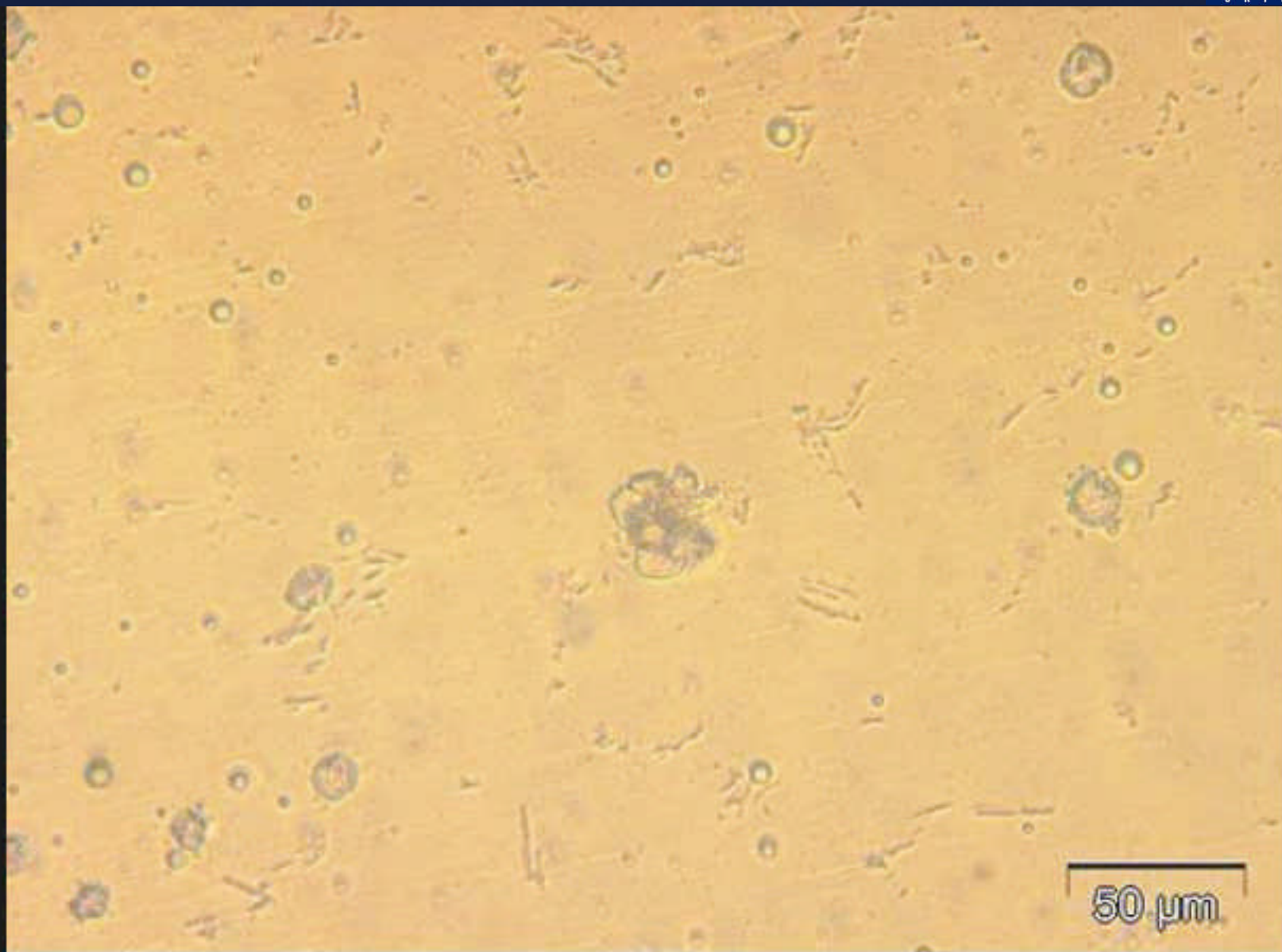


Carbides observed under fixed droplets



1 Hour 52 Minutes

Time Lapse Photography-OFF



1 Hour 52 Minutes

Time Lapse Photography-ON

Summary of Observations and "Speculations"

- M50 is susceptible to general corrosion and pitting initiating around carbides and grain boundaries
- P675 is much more resistant to general corrosion, but susceptible to localized attack due to larger surface carbides
- Localized attack can have a "filiform" appearance
- Oxygen availability is a likely limiting factor, regardless of oil contamination level
- Corrosion is possible over a wide range of salt and water contamination levels in oil, but severity (measured by pit depth) is greatest above the solubility limit for water
- Pit density increases with $[H_2O]$ with $[Cl^-]$ being a secondary effect
- Robust sensors developed for monitoring corrosion and oil quality can detect at, low f , statistically significant changes in...
 - H₂O contamination, oil degradation, impedance response of materials, immersion time

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Summary of Observations and "Speculations"

- **Pitting has been observed beneath immersion water droplets**
- **Droplets may adhere or cluster around carbides--these droplets tend to grow at the expense of mobile emulsion droplets**
- **"Free" droplets may migrate electrophoretically toward other droplets (i.e., droplet diffusion is not Brownian)**
- **Near rapidly forming pits, nanometer scale emulsions appear, possibly by spinodal decomposition**
- **Dissolved water may diffuse towards microgalvanic potential associated with corrosion beneath immersion droplet**
- **Some evidence that salt condenses out near corrosion pit**
- **Systems at rest likely to corrode more severely than systems in operation**

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End

Boise State University

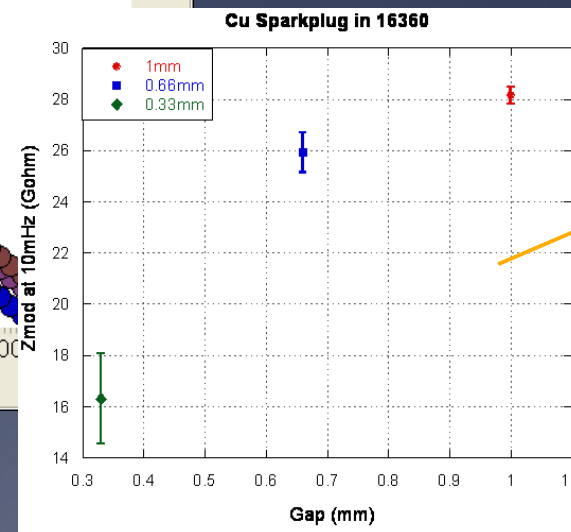
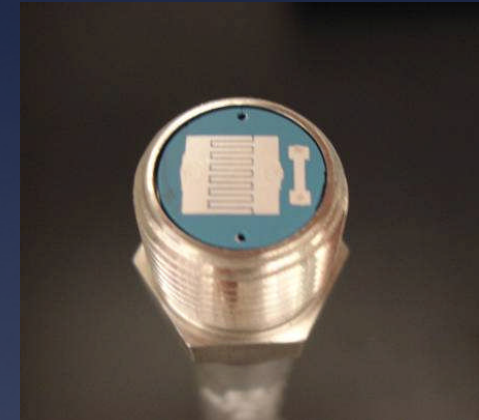
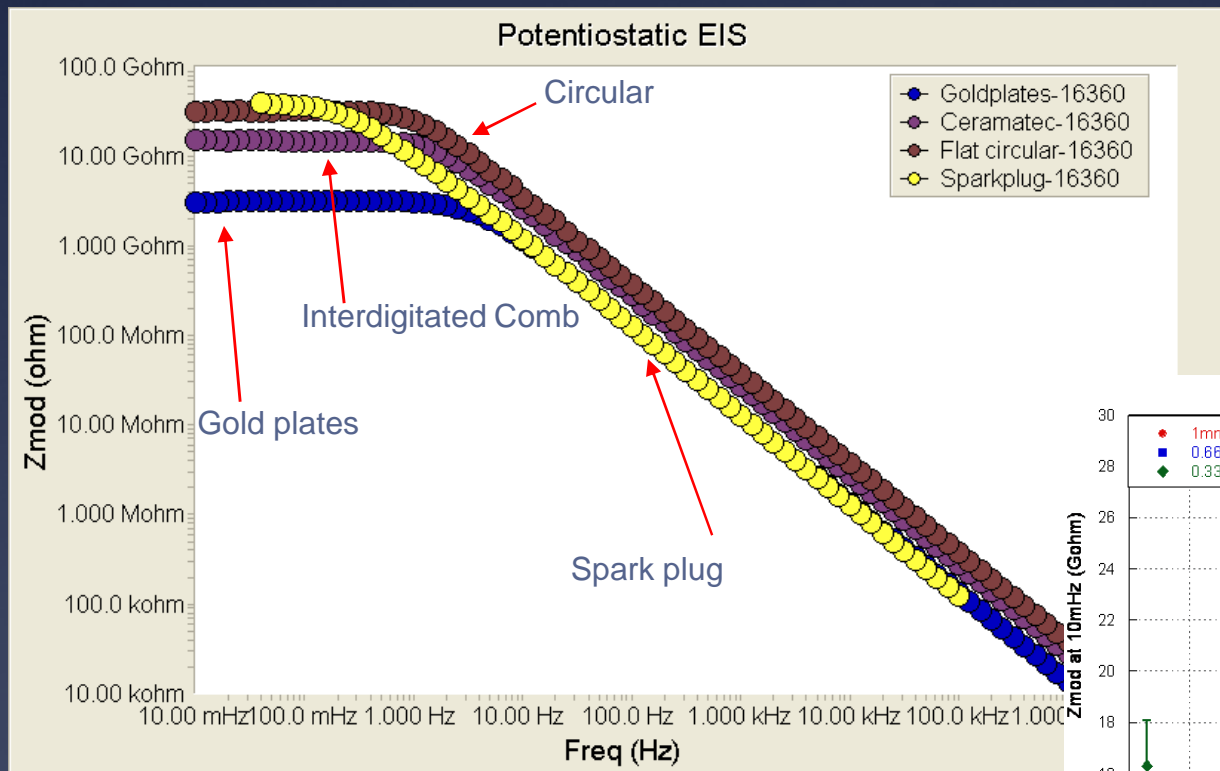
Department of Materials Science and Engineering



Sensor Geometry Effects

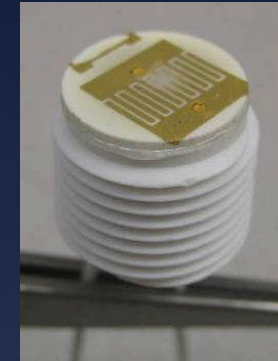
Multiple “capacitor type” configurations tested in 16360 Oil

- Maximize Area/Separation distance
- Minimize real estate to allow for multiple sensors

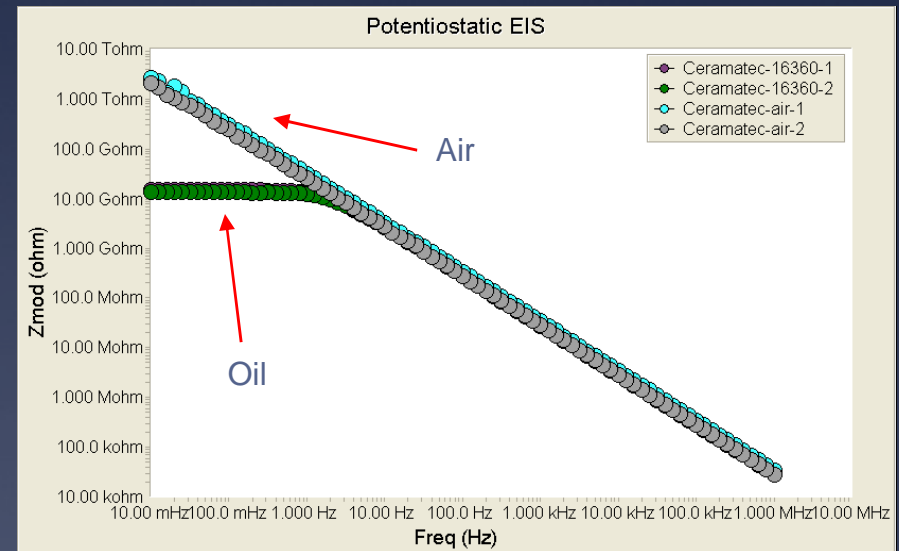
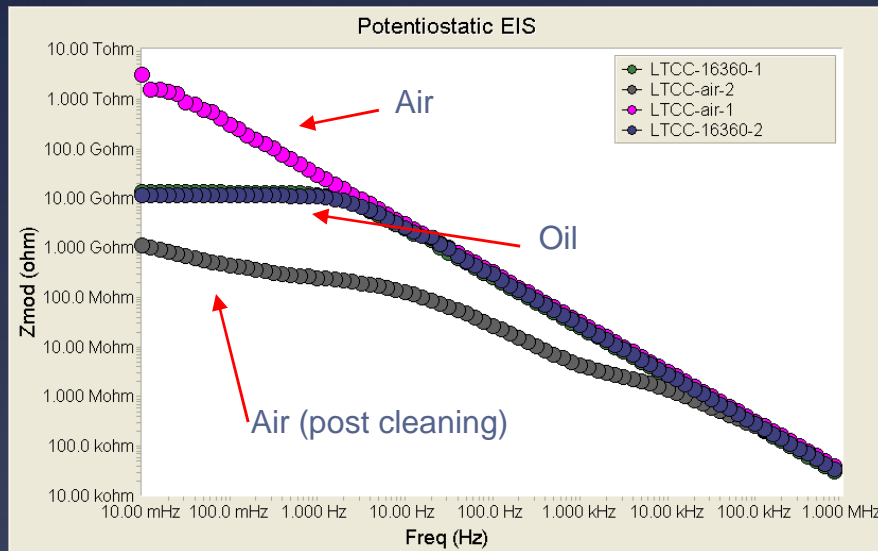


Sensor Materials Selection

LTCC vs. Alumina



1. Air
2. Oil
3. Clean, air again
4. Oil again



Polymer Seals Comparison

