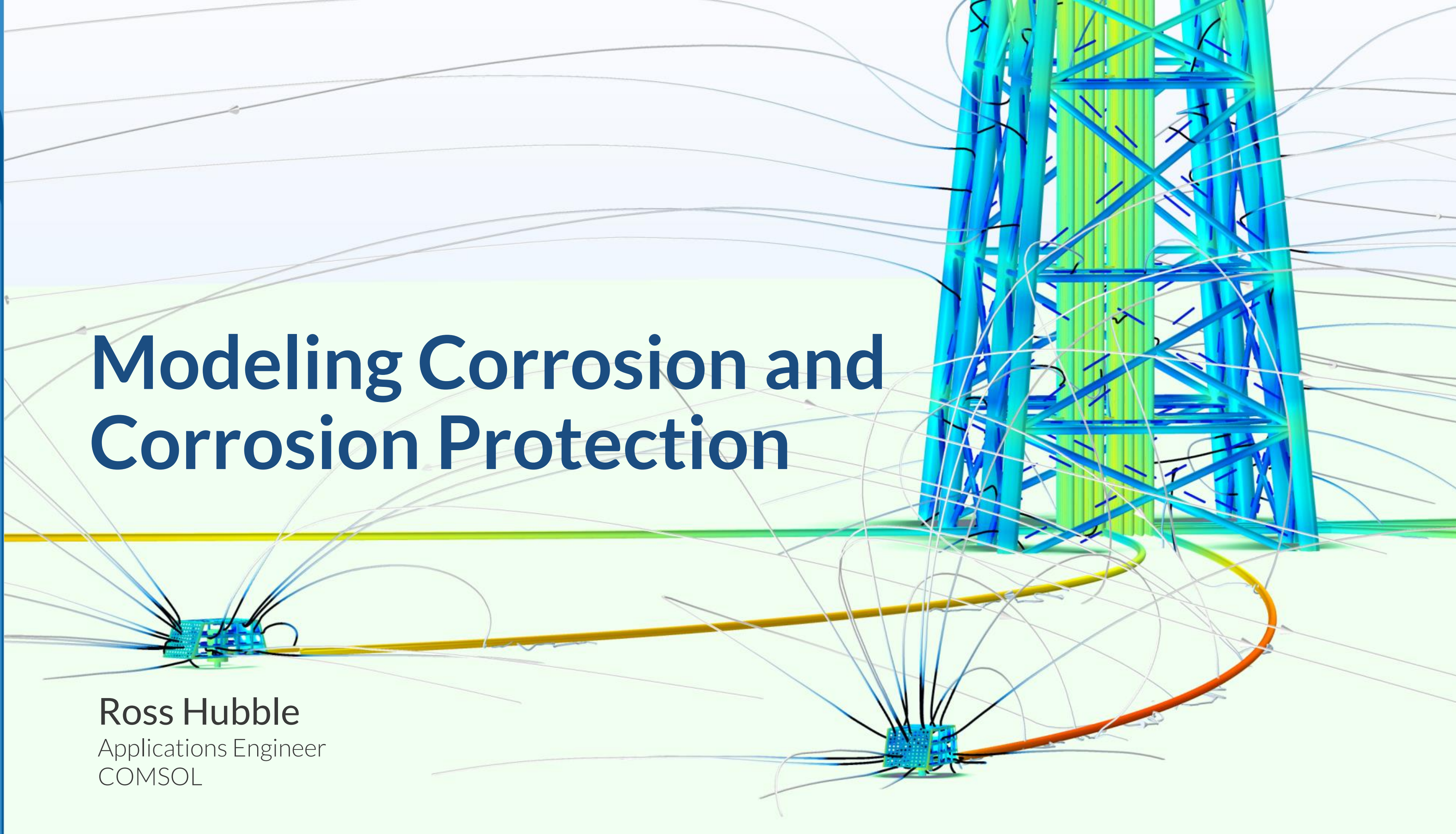
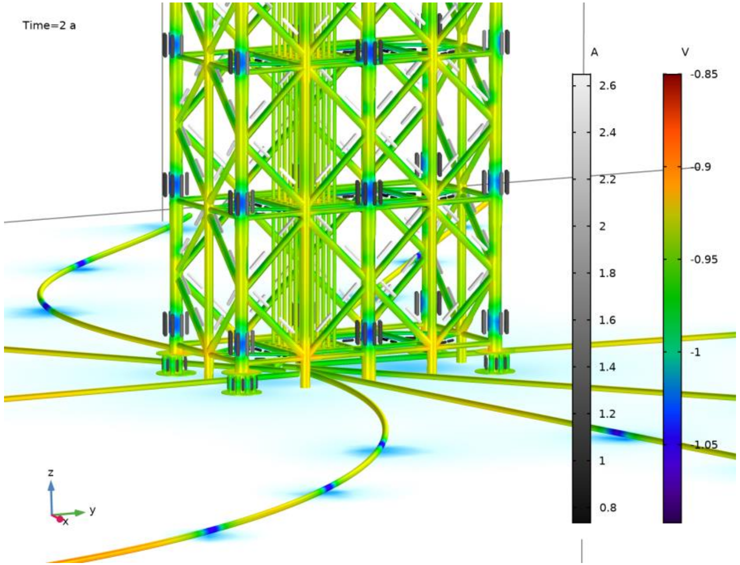


Modeling Corrosion and Corrosion Protection

Ross Hubble
Applications Engineer
COMSOL

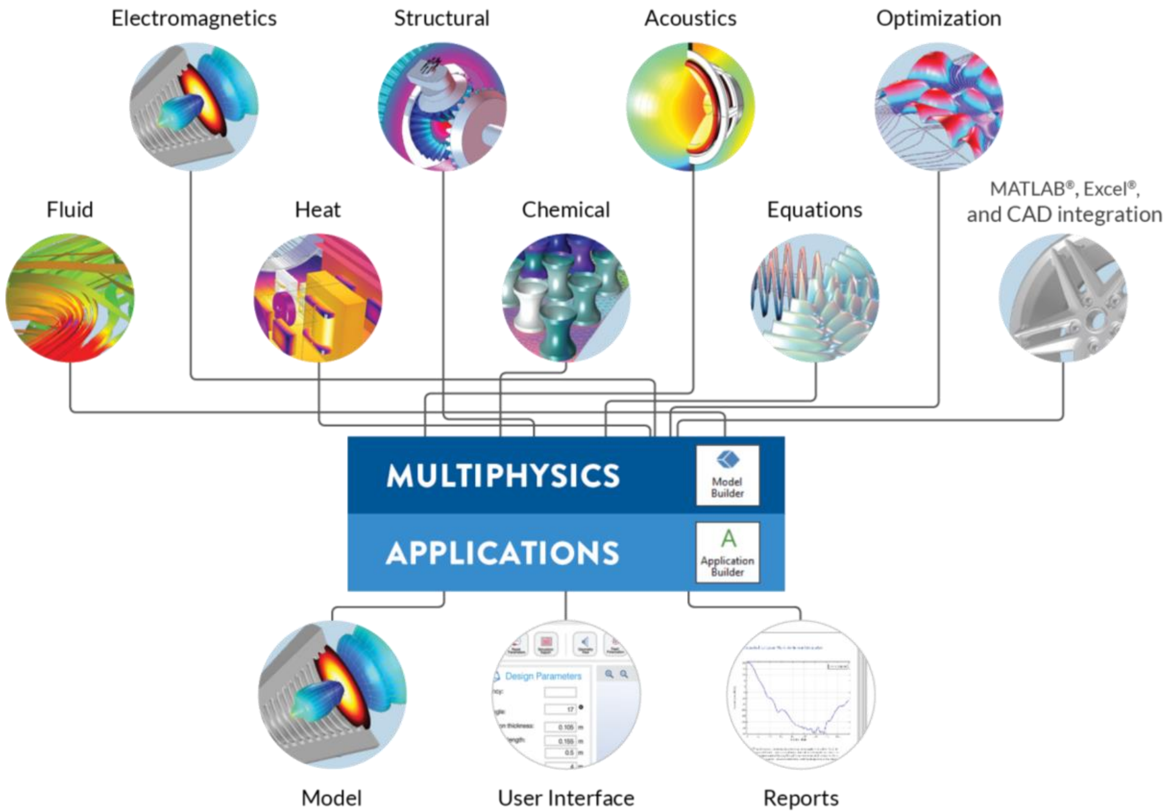
Agenda

- Introduction to numerical simulation in the COMSOL Multiphysics® software
- Essential electrochemistry for corrosion simulations
- Corrosion Module benefits and capabilities
- Live demo
  - Galvanic corrosion of a zinc nail
  - Cathodic protection of an oil platform
- Application examples
- Q&A session
- Concluding remarks



Potential distribution and anode output for a subsea oil platform jacket protected with sacrificial anodes

COMSOL Multiphysics®



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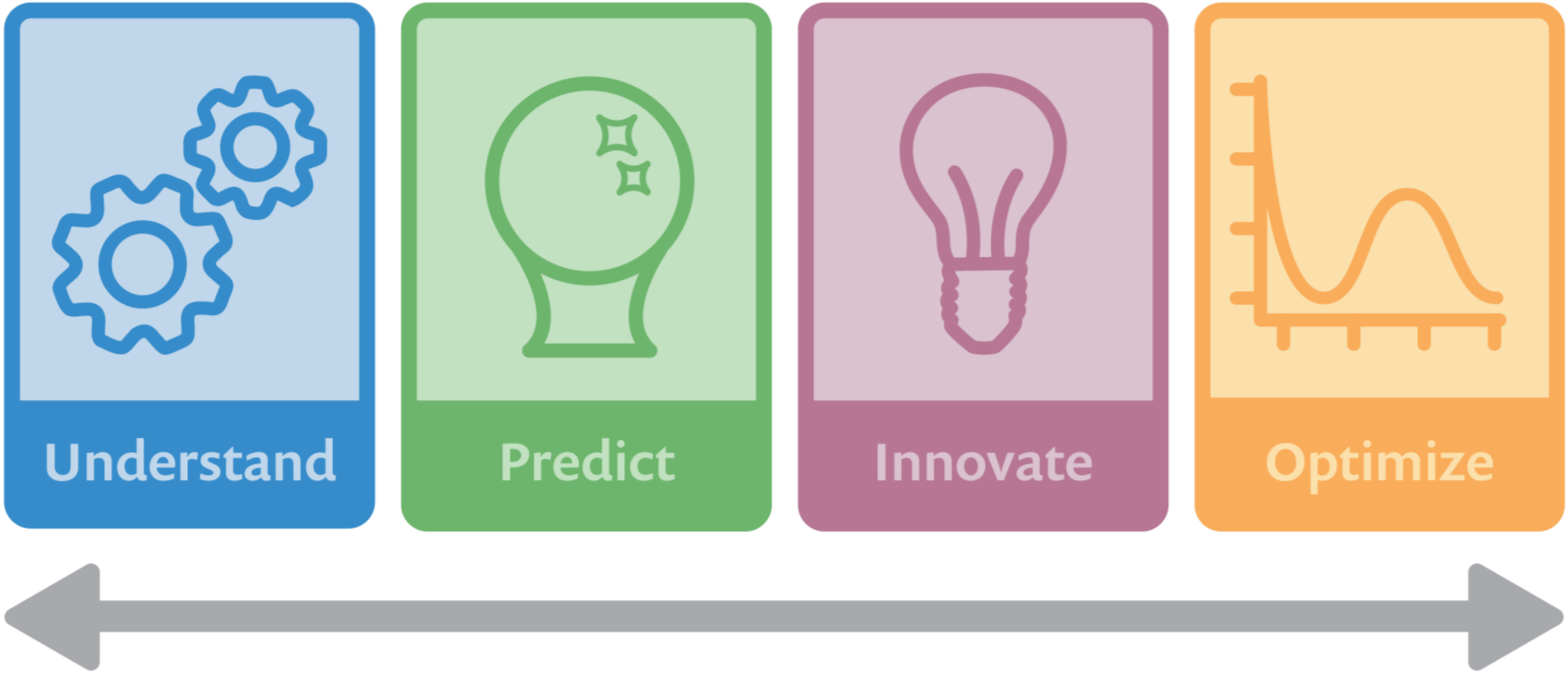

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- RF Module
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- CFD Module
  - Mixer Module
- Polymer Flow Module
- Microfluidics Module
- Porous Media Flow Module
- Subsurface Flow Module
- Pipe Flow Module
- Molecular Flow Module
- Metal Processing Module
- Heat Transfer Module

STRUCTURAL & ACOUSTICS

- Structural Mechanics Module
  - Nonlinear Structural Materials Module
  - Composite Materials Module
  - Geomechanics Module
  - Fatigue Module
  - Rotordynamics Module
- Multibody Dynamics Module
- MEMS Module
- Acoustics Module

CHEMICAL

- Chemical Reaction Engineering Module
- Battery Design Module
- Fuel Cell & Electrolyzer Module
- Electrodeposition Module
- Corrosion Module
- Electrochemistry Module

MULTIPURPOSE

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- Particle Tracing Module
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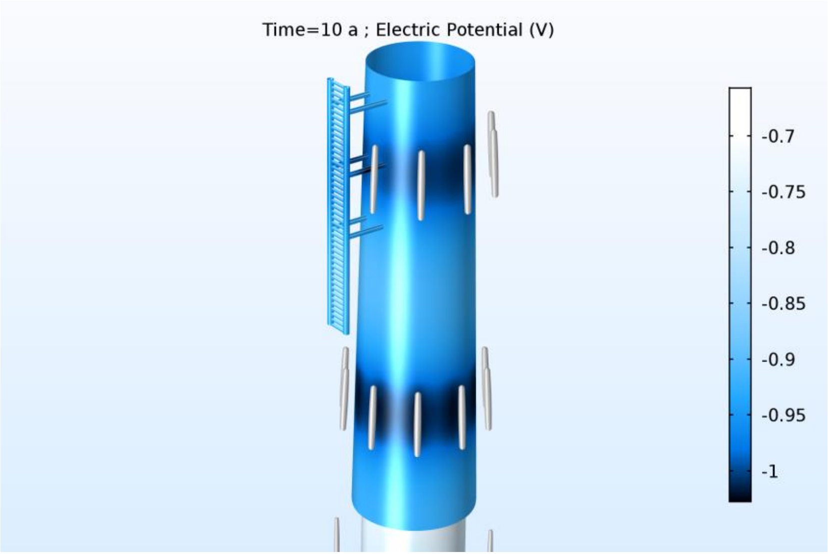
Corrosion Module

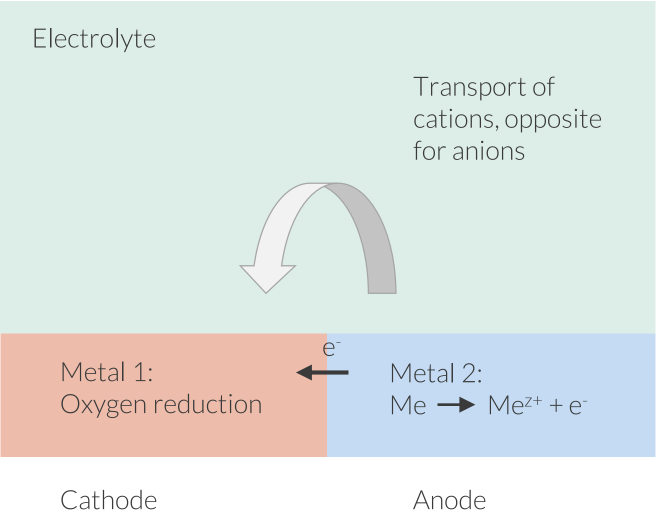
- Space-dependent modeling of corrosion
  - Investigate corrosion processes in the context of a given geometry
- Space-dependent models of corrosion protection
  - Understand, design, and optimize corrosion protection systems



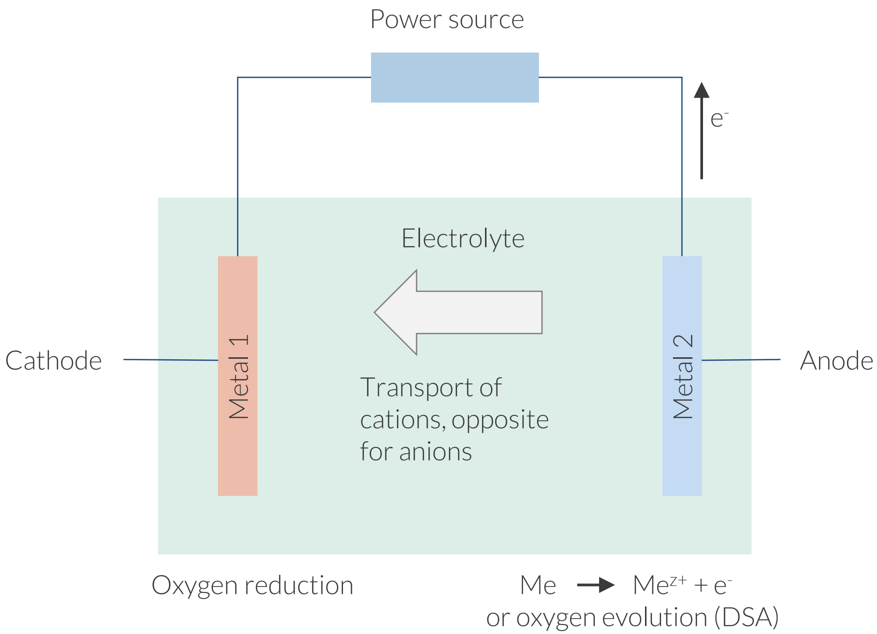
Electrolyte potential in seawater surrounding a monopile support structure used for offshore wind turbines protected by sacrificial anodes. A part of the boat landing ladder is temporarily underwater.

Electrochemistry

The Galvanic Cell

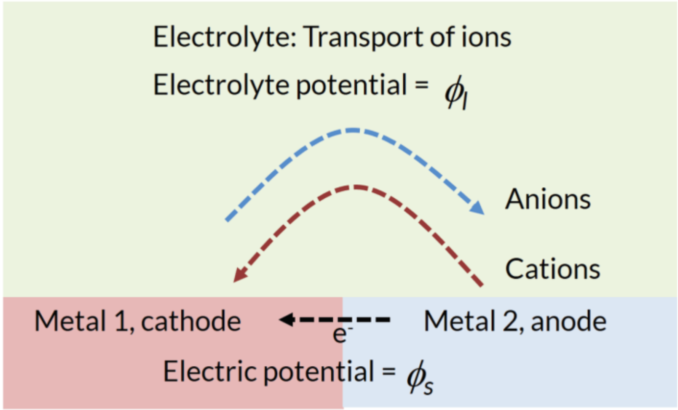


System without external circuit;
for example, with sacrificial anodes

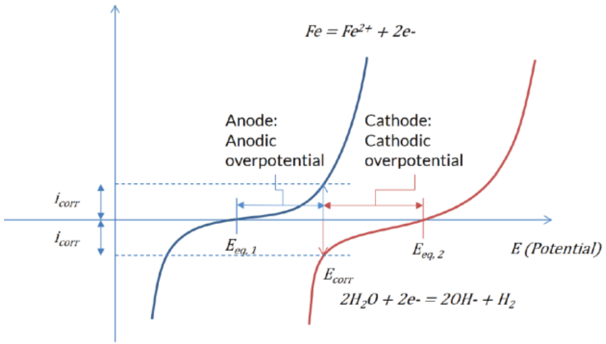


System with external circuit; for example,
impressed current cathodic protection

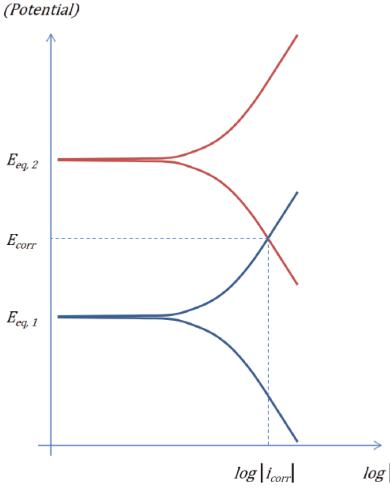
The Galvanic Cell



A galvanic cell where metal 1 acts as the cathode and metal 2 as the anode. The circuit is closed by the presence of an electrolyte, which covers both metal surfaces.



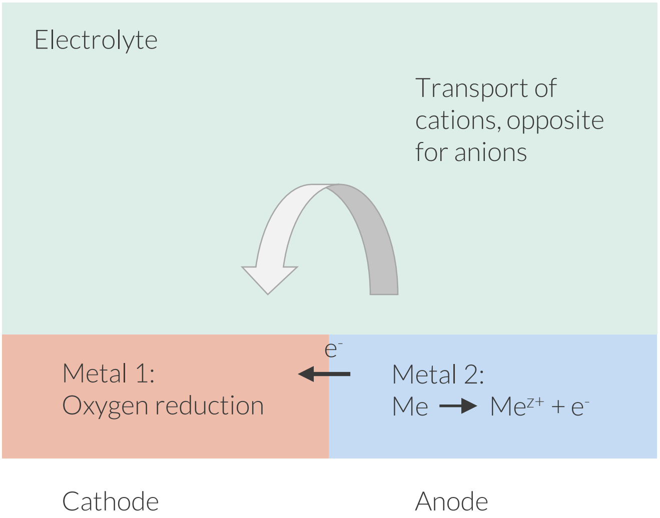
The Butler–Volmer expression for the reaction at the less noble metal surface (blue) and the more noble metal surface (red)



Evans diagram for two electrode reactions in the absence of ohmic and mass transport losses

Described Phenomena

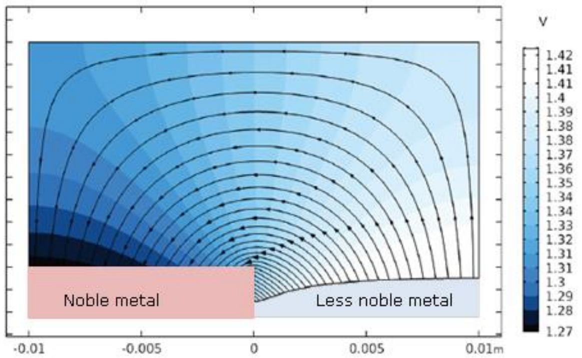
- Material, current, and charge conservation in the electrolyte
- Electric current conservation in the metallic structures
- Electrode kinetics with activation and concentration overpotential
- Multiple reactions at the metal surface; the mixed potential determines if a surface corrodes or is protected
- Effect of geometry deformations and formation of resistive films on electrode surfaces



System without external circuit; for example, with sacrificial anodes

Described Processes

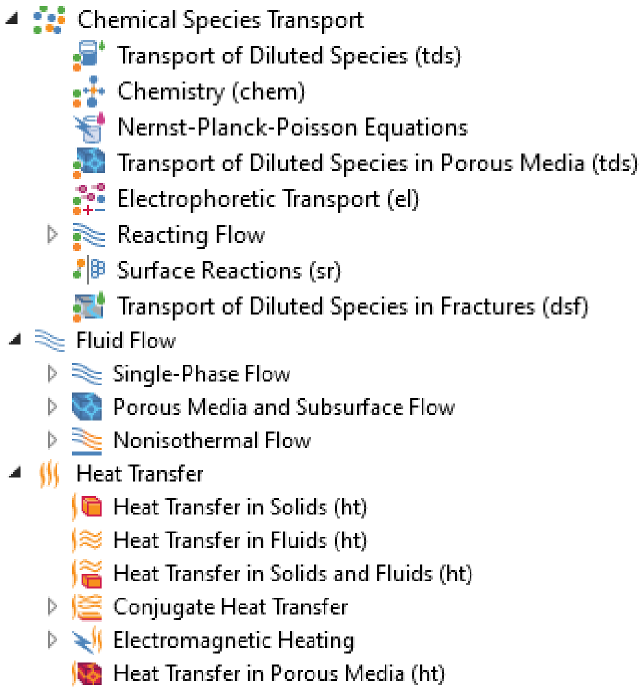
- Space-dependent models of corrosion of metallic structures in an electrolyte
  - Galvanic corrosion
  - Atmospheric corrosion
  - Corrosion due to stray currents
  - Crevice corrosion
  - Pitting corrosion
  - Stress-induced corrosion (stress corrosion cracking)
- Space-dependent models of corrosion protection
  - Cathodic protection with sacrificial anodes
  - Cathodic protection using external current; impressed current cathodic protection (ICCP)
  - Anodic protection; for example, small passivating currents that stabilize oxide films



Streamlines of the current density and isopotential curves in the electrolyte in a galvanic cell. The initial surface of the noble metal and the less noble metal is horizontal at the initial state. After 72 h, the less noble metal is corroded through anodic dissolution.

Electrochemical Interfaces

- Material transport
- Fluid flow
  - Laminar flow
  - Flow in porous media
- Heat transfer
  - Joule heating in the electrolyte and the electrodes
  - Activation losses



Electrochemical Interfaces

- Current and potential distribution:
  - Charge and current balances
- Corroding surfaces:
  - Electrode reactions coupled to surface species balances
  - Fixed and moving boundaries coupled to surface species balances
- Stationary and transient studies

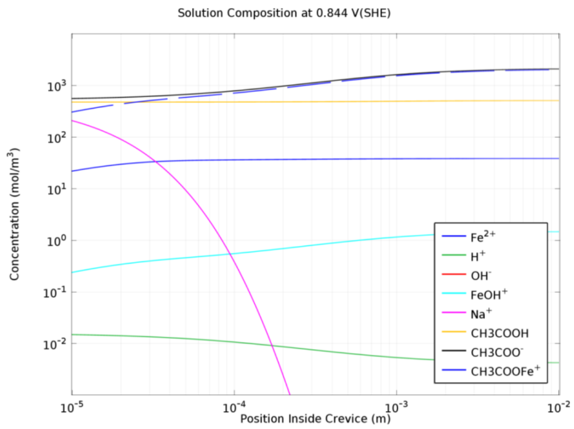
- Electrochemistry
  - Primary and Secondary Current Distribution
    - Primary Current Distribution (cd)
    - Secondary Current Distribution (cd)
    - Current Distribution, Boundary Elements (cdbem)
    - Current Distribution, Shell (cdsh)
    - Current Distribution, Pipe (cdpipe)
  - Tertiary Current Distribution, Nernst-Planck
    - Tertiary, Electroneutrality (tcd)
    - Tertiary, Water-Based with Electroneutrality (tcd)
    - Tertiary, Supporting Electrolyte (tcd)
  - Electroanalysis (tcd)
  - Electrode, Shell (els)
  - Corrosion, Deformed Geometry
    - Corrosion, Primary
    - Corrosion, Secondary
    - Corrosion, Tertiary with Electroneutrality
    - Corrosion, Tertiary with Supporting Electrolyte

Corrosion Module

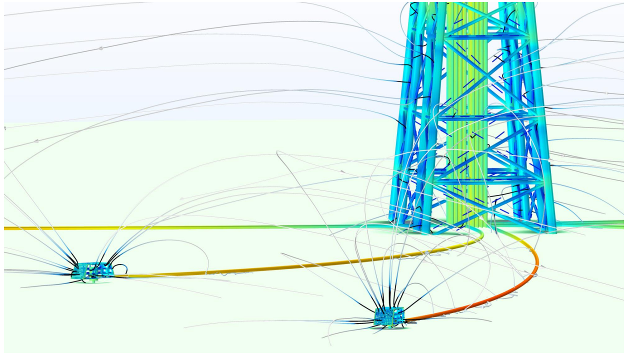
Benefits and Capabilities

Multiphysics and Multiscale

- Computational complexity
  - Detailed system of physics and chemistry
  - Large, detailed geometries
- Crevice or pitting corrosion with full description of chemistry
- Influence of groundwater, heat transfer, and gas diffusivity on buried pipelines and concrete reinforcement
- Large-scale corrosion protection models of a complete oil field or a nuclear plant



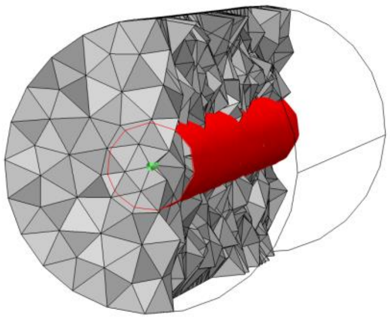
Calculated concentration profiles along the depth of a crevice



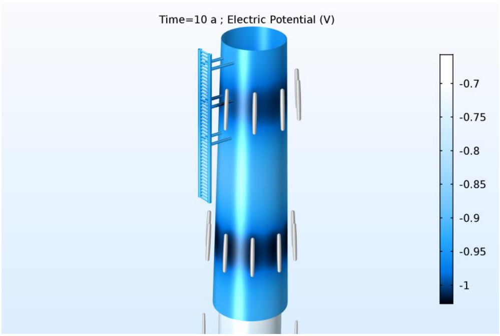
Current streamlines and potential distribution on an oil platform jacket with remote wellheads

Numerical Models and Technology

- Finite element method (FEM)
- Boundary element method (BEM)
- Edge-based electrodes for slender structures
- Sacrificial anodes dissolve over time
- Surface depositing and dissolving species with moving mesh
- 1D pipe formulation for internal corrosion in long pipes
- Methods for impedance spectroscopy (EIS) and cyclic voltammetry



FEM mesh showing a sacrificial edge anode with its virtual radius shown in red

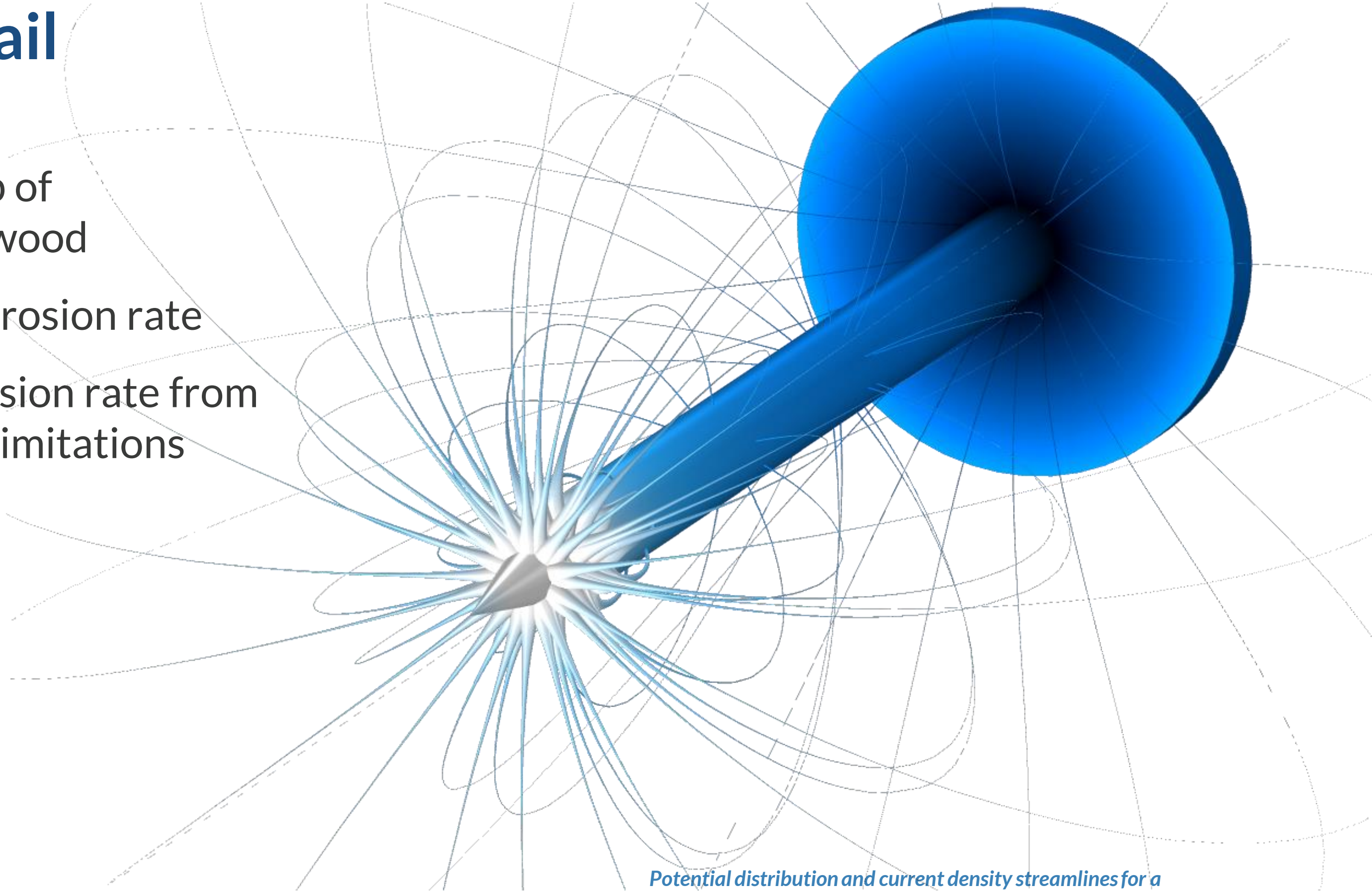


Edge-based sacrificial anodes on a monopile that change shape and anode resistance as they are dissolved over time

Demonstration

Galvanized Nail

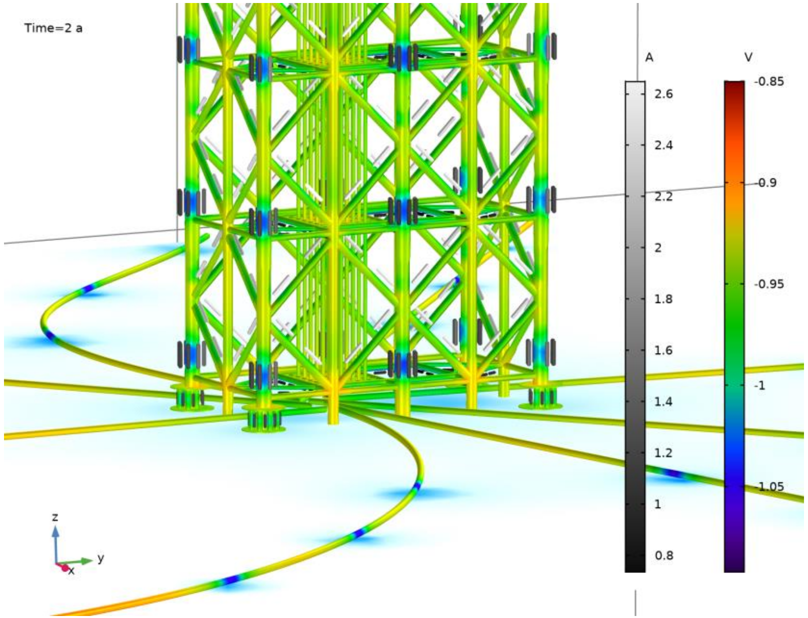
- Iron exposed at tip of galvanized nail in wood
- Determine the corrosion rate
- Influence on corrosion rate from oxygen transport limitations



Potential distribution and current density streamlines for a galvanized nail with exposed iron on the tip

Cathodic Protection of an Oil Platform

- Cathodic protection can be achieved by an impressed external current or by using sacrificial anodes
- The first step in the design of a cathodic protection system is usually to investigate the potential of the steel structure assuming a constant cathodic current (oxygen reduction)



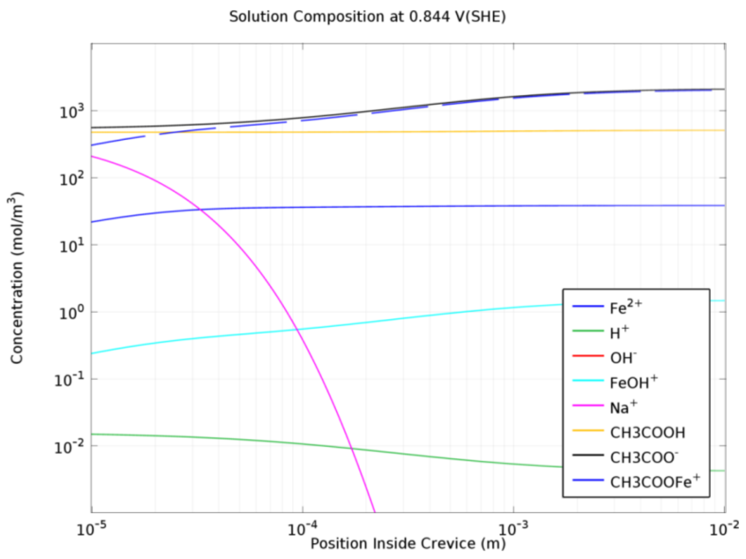
Potential distribution and anode output for a subsea oil platform jacket protected with sacrificial anodes

Tutorials

In the Application Library

Crevice Corrosion

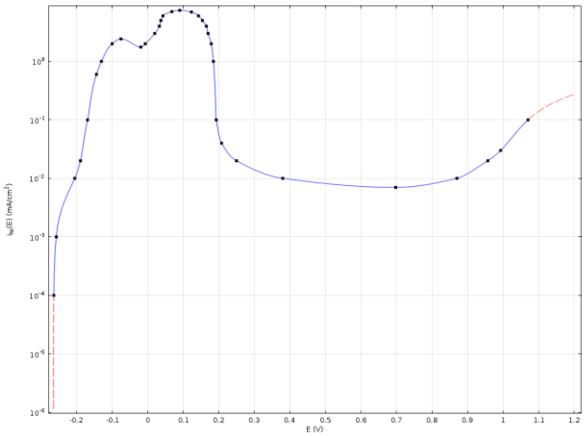
- Crevice corrosion of stainless steel in water:
  - The role of parameters such as pH inside the crevice, external potential, acid/base concentration of the solution, and crevice geometry is studied



Calculated concentration profiles along the depth of a crevice

Crevice Corrosion with Deformation

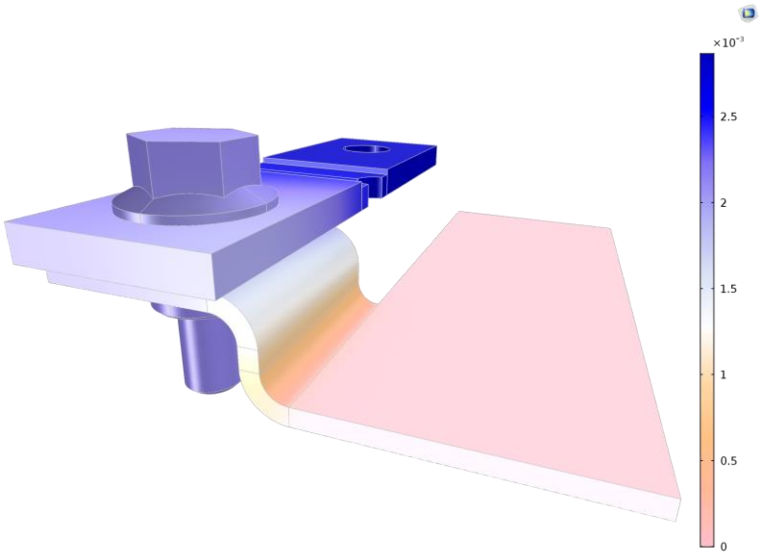
- Crevice corrosion of nickel in acid of high conductivity
- Simulation of corrosion of Ni in a lab cell



Top: Polarization curve taken from experimental data
Bottom: Electrolyte potential and simulated geometry after 72 h

Atmospheric Corrosion

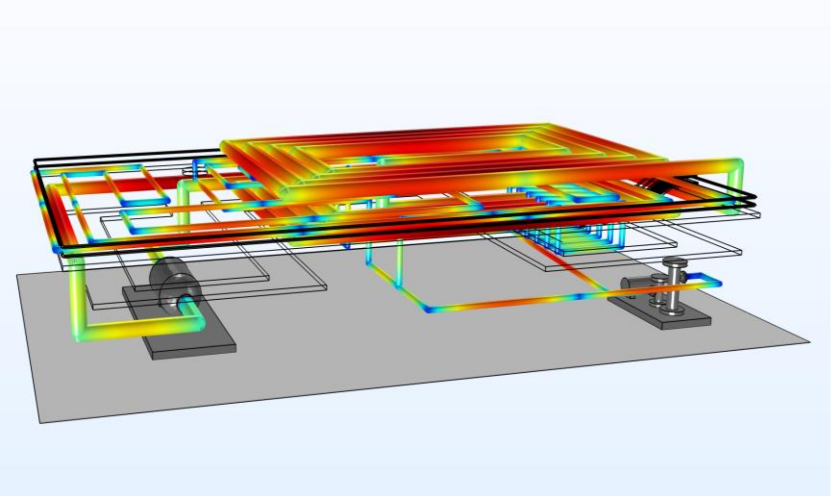
- Galvanic corrosion mediated by a thin moisture film
- The film thickness depends on the relative humidity of the surrounding air
- Atmospheric corrosion of a connector in a battery application
- The bolt and the two metal parts consist of different metals



The figure shows the electrolyte potential distribution in a thin moisture film formed on top of the metal surfaces

Internal Corrosion in Pipes

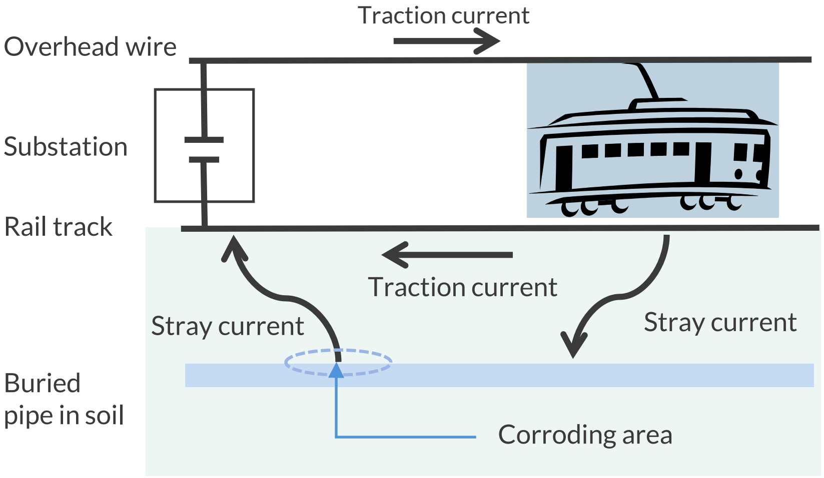
- Internal pipeline corrosion modeling in 3D
- Tangential (1D) formulation of the charge balance equation along edges in 3D:
  - Computation time and memory significantly reduced compared to full 3D
- Corrosion protection system modeling is facilitated by tailor-made features

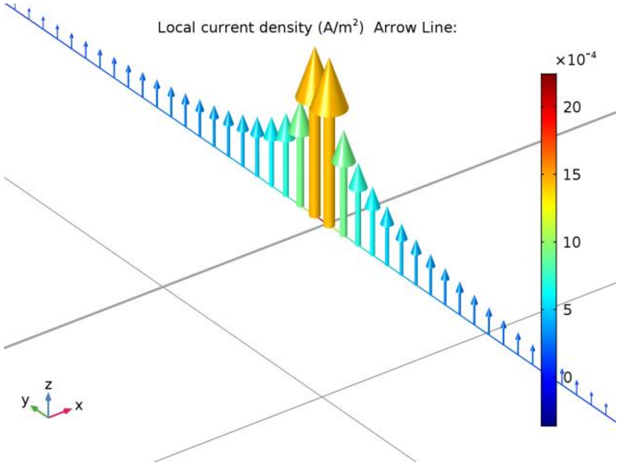


Pipe potential in a piping system that is protected by sacrificial anodes. The red areas indicate the highest potentials, revealing the least protected parts. From the Corrosion Module Application Library.

Corrosion Due to Stray Currents

Corrosion initiated by metallic structures being subjected to an external electric field

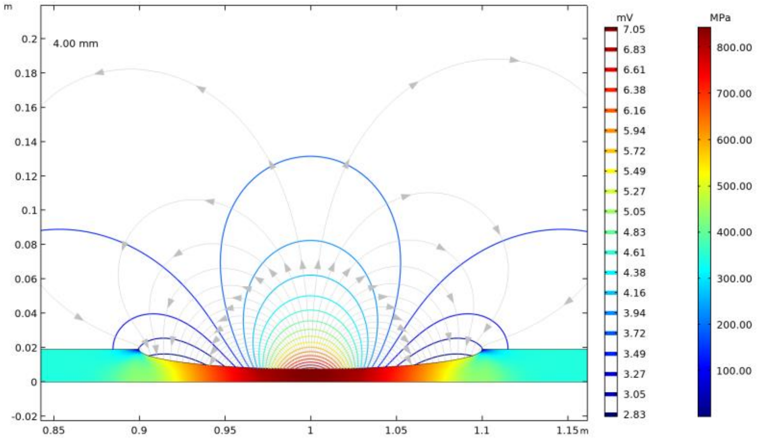




Left: Principle of stray current corrosion caused by the traction current of a railway track
Right: Induced stray current corrosion current density at the crossing of two neighboring metal conductors

Stress-Induced Corrosion

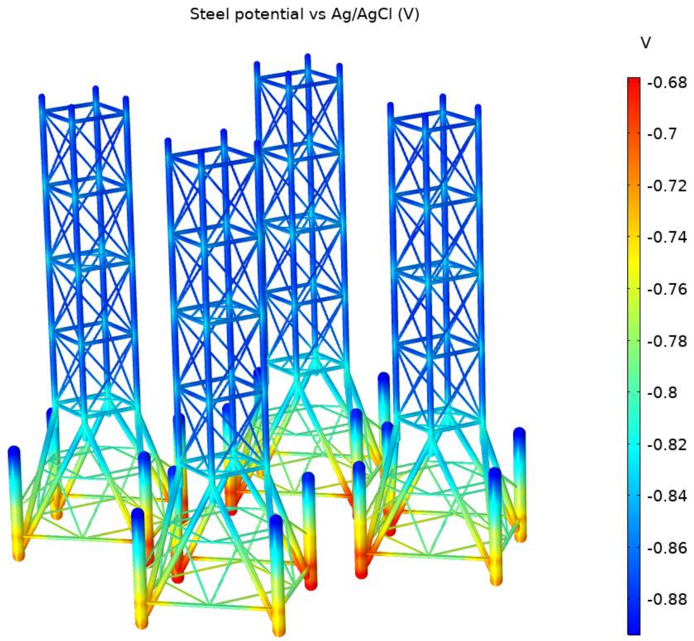
- A body load applied on a metal object will result in stresses on the electrolyte-electrode interface
- By including stress contributions to the electrode reaction thermodynamics, a nonuniform stress distribution will result in a driving force for corrosion reactions



Stresses in a solid metal electrode and the resulting potential distribution and current streamlines in the adjacent electrolyte domain

The Corrosion Module Application Library

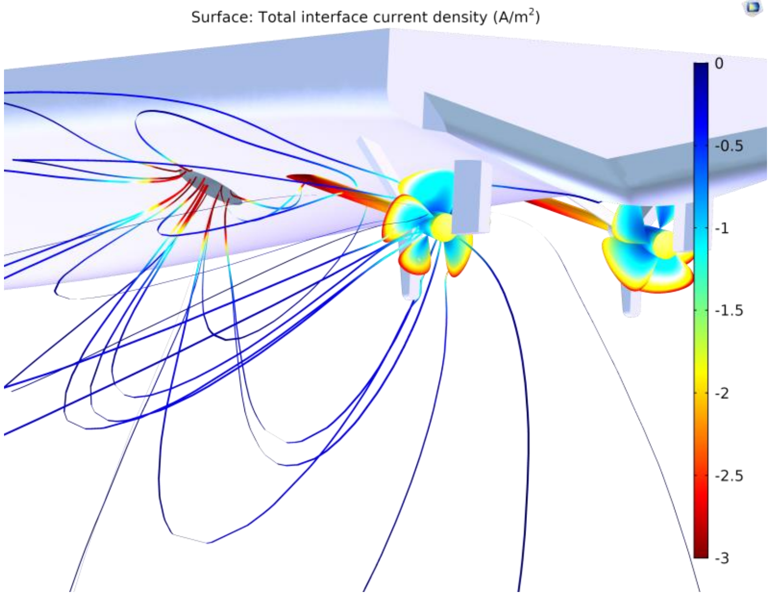
- Cathodic protection
  - Ship hull
  - Offshore structures
  - Rebar in concrete
- Galvanic corrosion
  - With or without deformation
  - Atmospheric corrosion
  - Localized corrosion
  - Crevice corrosion
  - Underdeposit corrosion
  - CO_2 corrosion
- General electrochemistry
  - Impedance spectroscopy
  - Cyclic voltammetry



Steel potential versus Ag/AgCl reference for a protected underwater oil rig structure

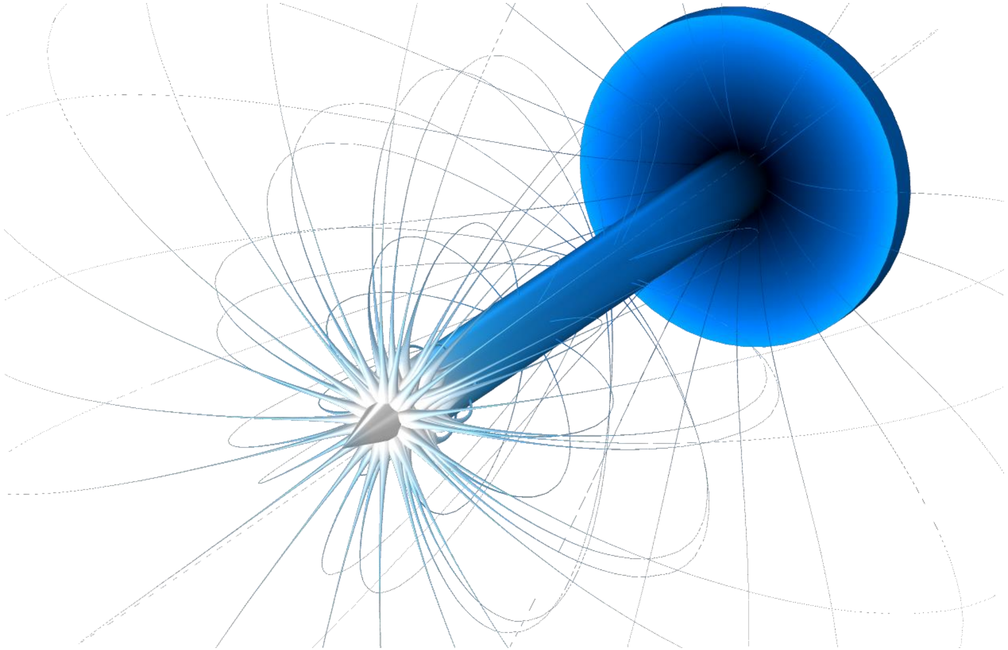
Concluding Remarks: Corrosion Module

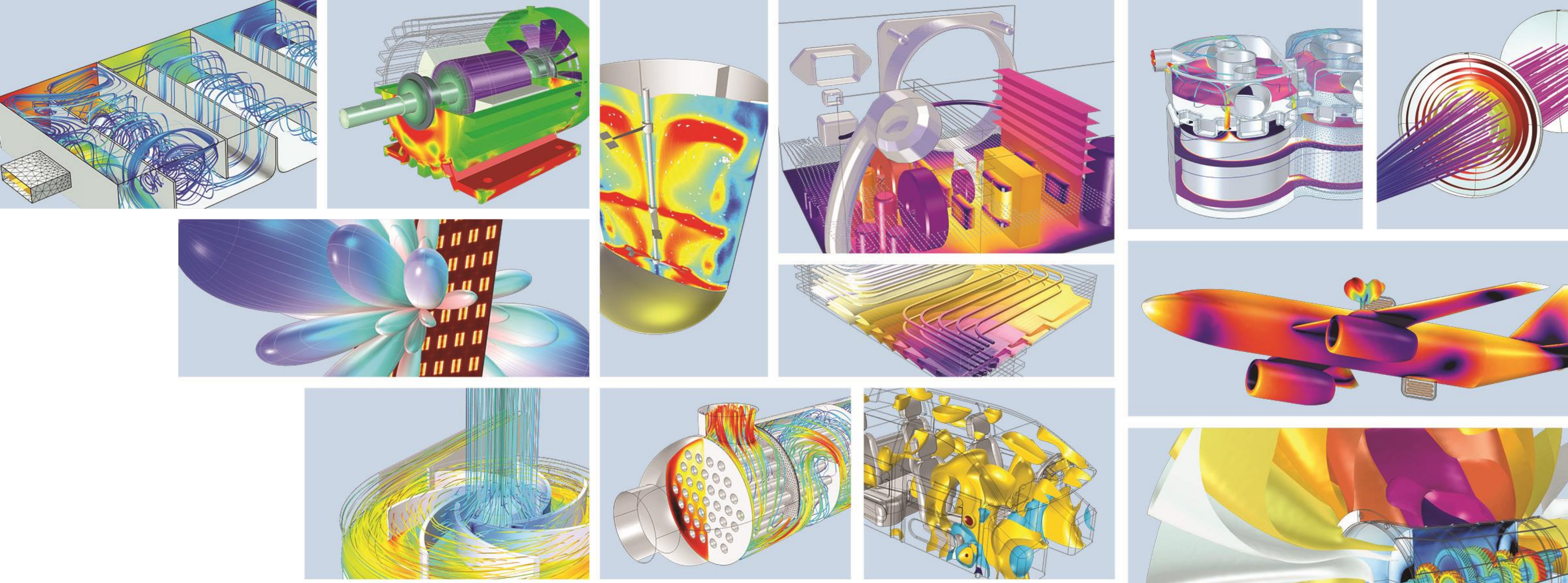
- Modeling of corrosion processes and corrosion protection
- Multiphysics and multiscale
- Descriptions for multiple levels of detail
- Optimization and validation of design
- Tailored functionality for performance and ease of use

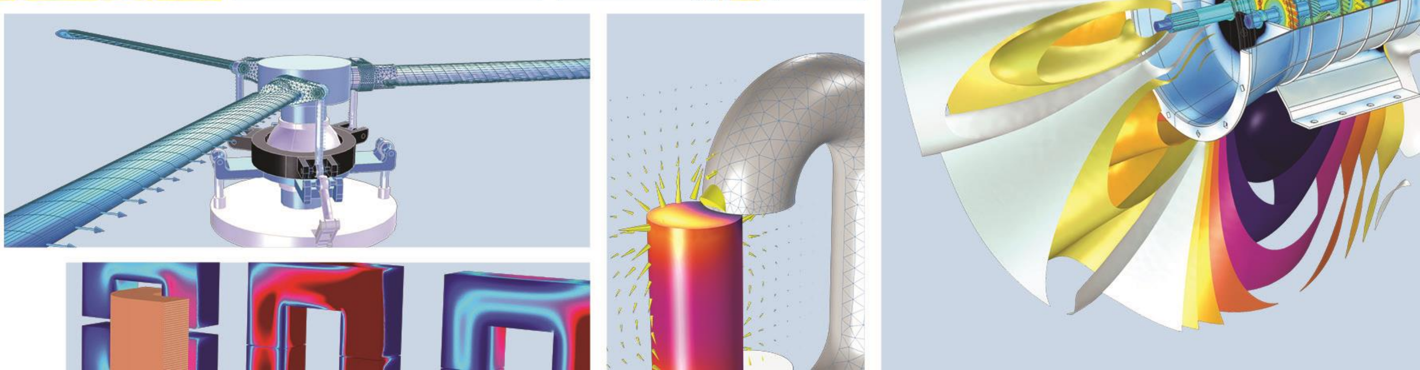


Current density and streamlines around impressed-current, cathodically protected propellers on a ship

Q&A







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