Current Research in the Modeling of Microbiologically Influenced Corrosion (MIC)

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NACE CORROSION 2019 FORUM: An Update of MIC Research and Developments for the Onshore and Off shore Oil and Gas Industry

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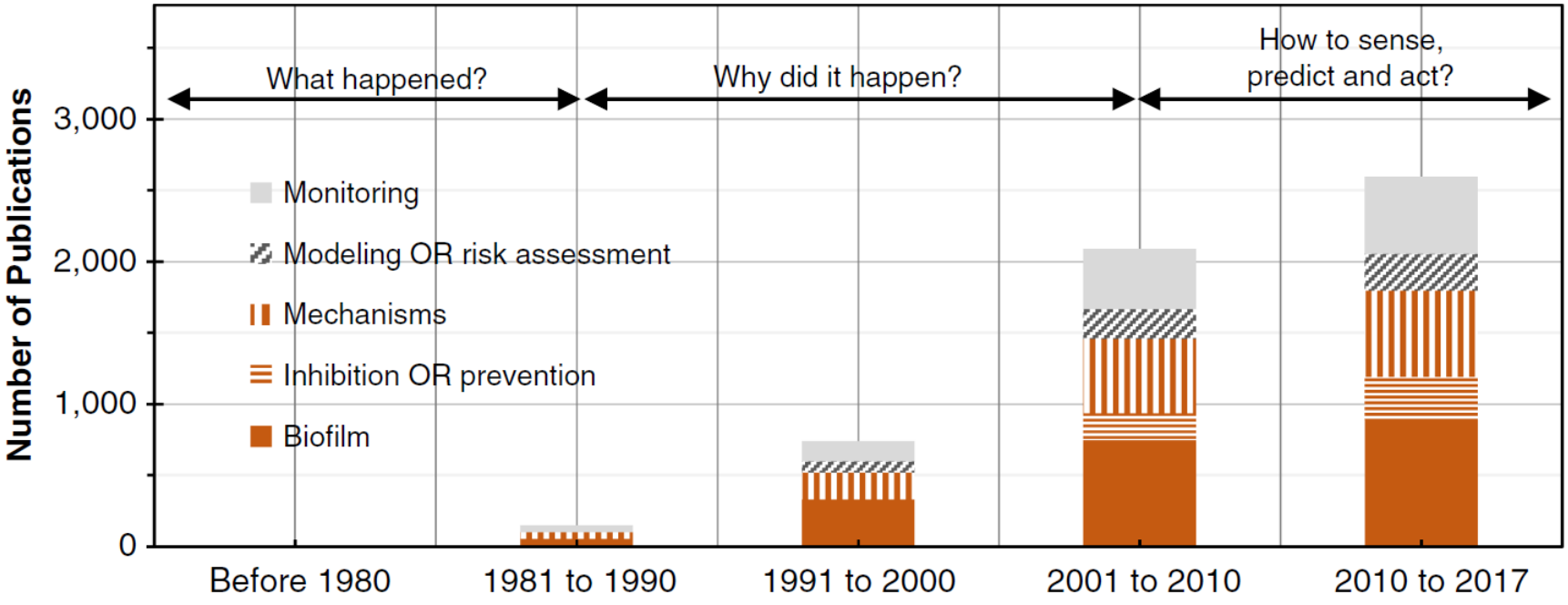
Presentation Overview

- Introduction
- Objective of this Presentation
- Overview of Models Being Developed
  - Molecular Modeling
  - Mechanistic Modeling
  - Risk-Based Modeling
- Conclusions & Next Steps

Introduction

- Microbiologically Influenced Corrosion (MIC) is a complex form of materials degradation caused by the biological activity of microorganisms.
- Characterized by the presence of microbiological populations within a biofilm or semi-solid deposit resulting in localized and accelerated corrosion.
- While MIC has been actively studied for decades, there is still a significant gap in the ability to accurately predict MIC rates.
- This is due, in part, to a limited understanding of all the microbiological communities involved in MIC, and the complexity of biological, chemical and operational parameters responsible for MIC.

Historical Evolution of MIC Research



Source: Hashemi, Bak, Khan, Hawboldt, Lefsrud, Wolodko (2018) CORROSION, v.74, n.4

Why are MIC Models Required?

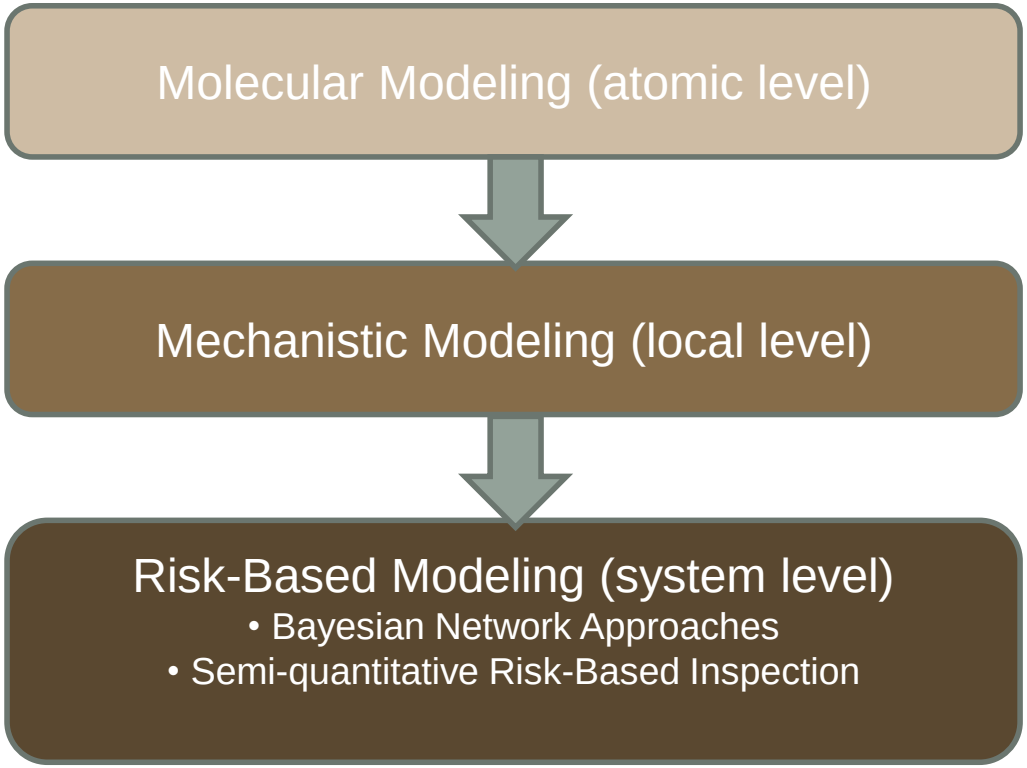
- The oil and gas industry uses models for several purposes:
  - predicting the effects of corrosion on asset integrity for both asset design and operation
  - materials selection
  - establishment of mitigation and monitoring programs
  - resource prioritization and optimization of risk-based inspection (RBI)

Objective of this Presentation

- This presentation provides a summary of current activities related to the development of MIC based models.
- This work is part of an on-going joint industry-academic project entitled “Managing Microbial Corrosion in Canadian Offshore & Onshore Oil Production Operations.”

Modeling Approaches

- As part of this project, a variety of models are being developed at various length-scales to better understand MIC mechanisms, and to better predict the risk associated with MIC threats.



Molecular Modeling of MIC Mechanisms

Background - Molecular Modeling

- Molecular modeling approaches are computational methods used to model the behavior of processes at the atomistic and molecular levels.
- These types of models are established methods used in the fields of medicine (drug design), computational chemistry, computational biology and materials science to study molecular systems ranging from specific chemical processes to large biological molecules.
- It offers a possible approach to better understand complex chemical and biological behaviors and interactions (e.g. has potential application to MIC!)

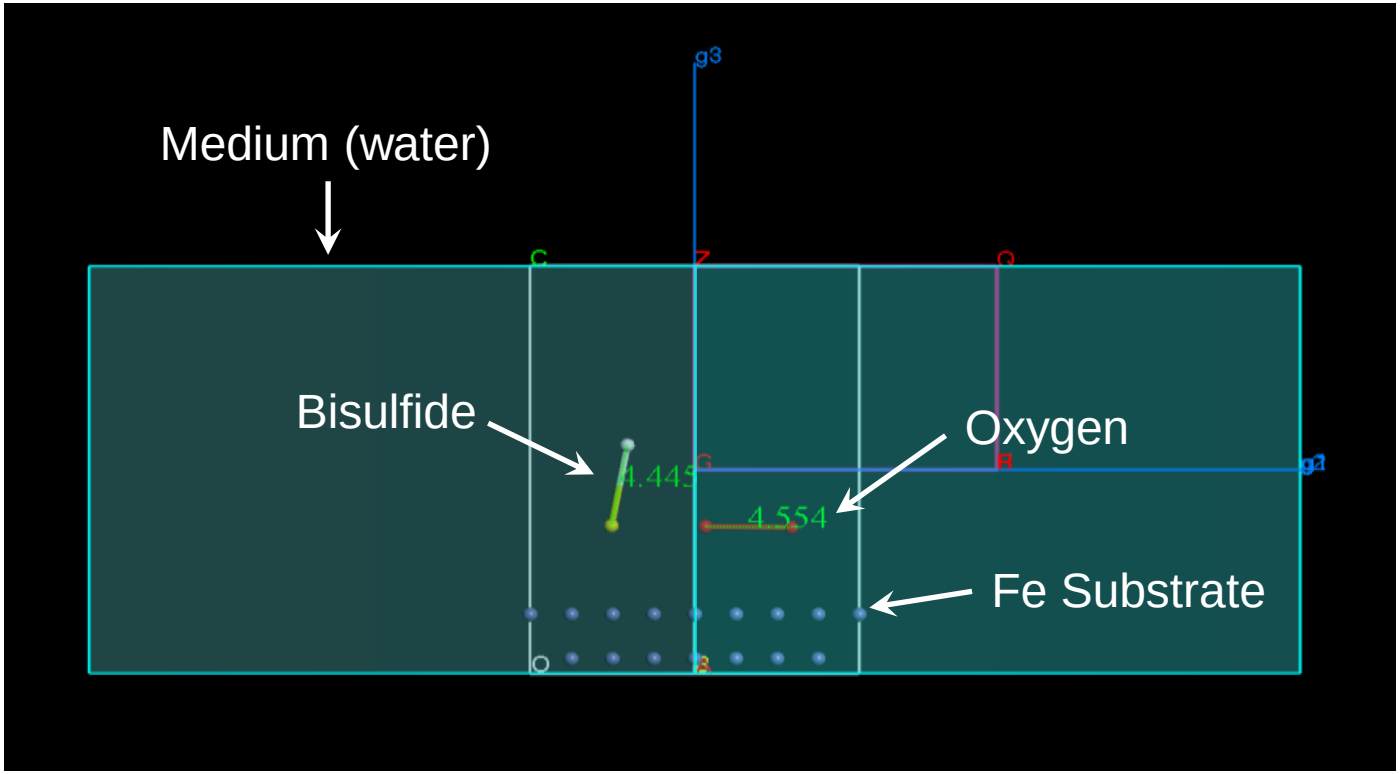
Molecular Modeling (Khan et al. - MUN)

- A preliminary study was conducted to demonstrate the use of molecular modeling techniques for predicting MIC based reactions at the biofilm-substrate interface (atomistic level).
- The aim was to investigate the interactions of two adsorbates (sulfide and oxygen) commonly found in SRB-based MIC environments with the steel (Fe) substrate in a water medium.
- Results show the changes in the bond length of bisulfide (HS-, an important MIC intermediate), can be an indicator of sulfide production in the biofilm where SRB is active, and a potential indicator for pit initiation at the metal surface.

Molecular Modeling (cont.)

- Next Steps: This model will be extended to test for the effect of more complex molecules such as lactate or phosphates on microbiologically initiated pitting.
- Knowledge gained from this approach could find useful applications in corrosion inhibition studies, and will help to better understand mechanisms for MIC initiation and growth.

Molecular Modeling (Khan et al. - MUN)



Molecular Model of Simulated MIC Surface

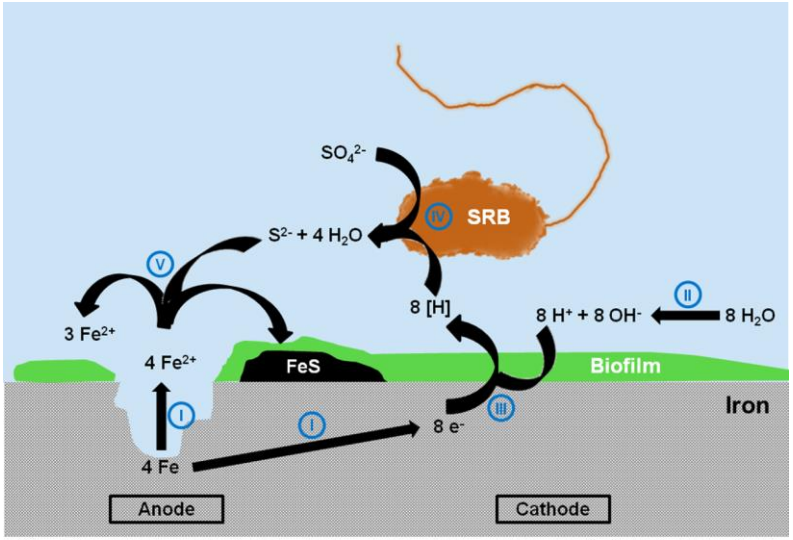
Source: Ezenwaa, Khan, Hawboldt, Eckert, Skovhus (2019) A preliminary molecular simulation study on the use of HS- as a parameter to assess the effect of surface deposits on the SRB-initiated pitting on metal surfaces, NACE Corrosion 2019

Mechanistic Modeling

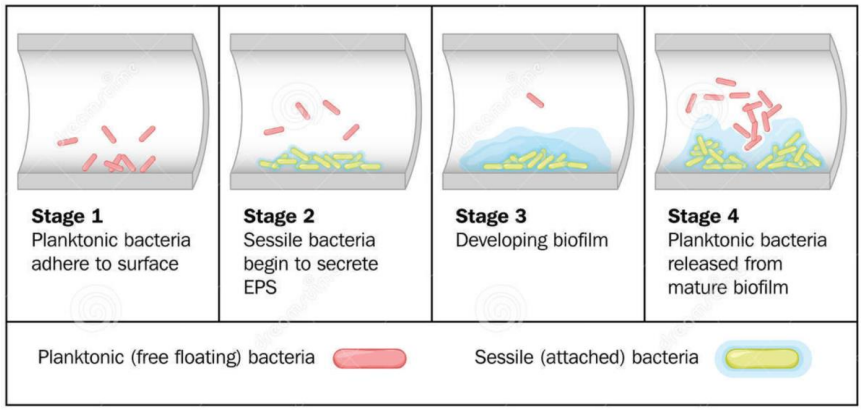
Background - Mechanistic MIC Models

- Mechanistic models predict corrosion rates by attempting to simulate actual physical, chemical and/or biological processes within an MIC environment, such as a biofilm or under solid deposits.
- Mechanistic models are typically semi-empirical in nature, and require calibration with limited experimental data (laboratory or field).
- A significant number of mechanistic MIC models have been developed over the past two decades.
- The majority of these models have focused on Sulfate Reducing Bacteria (SRB).

Background - Mechanistic MIC Models



Scheme of iron corrosion by SRB based on reactions as suggested by the cathodic depolarization theory. I, iron dissolution; II, water dissociation; III, proton reduction; IV, bacterial sulfate reduction and V, sulfide precipitation.
Source: Mechanisms of Microbiologically Influenced Corrosion: A Review
World Applied Sciences Journal 17 (4): 524-531, 2012



Source: https://it.dreamstime.com/illustrazione-di-stock-formazione-di-biofilm-image73998615

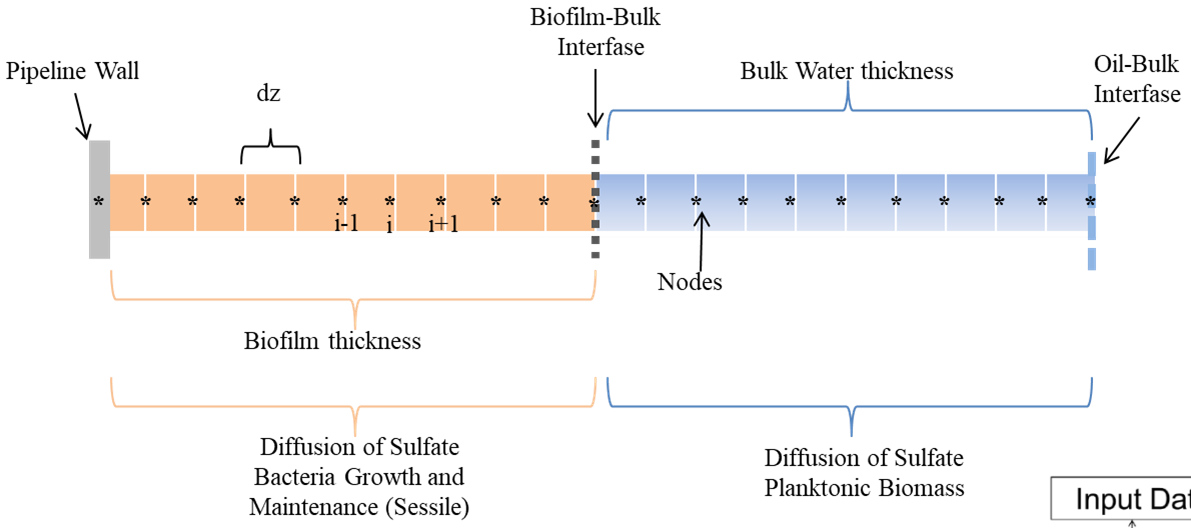
Example Parameters

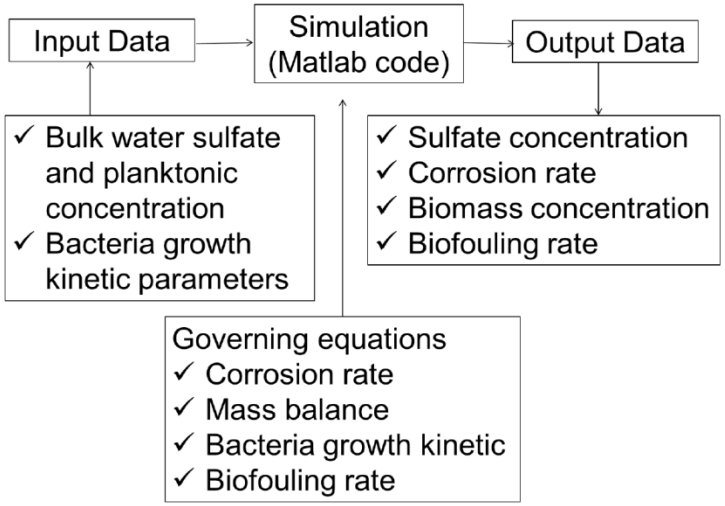
- **Bulk Fluid Properties:**
  - Fluid Chemistry
  - pH, T, P
  - Flow Rates
- **Bio-film Properties:**
  - Biotic factors (counts, growth rates, community analysis)
  - Mass Transport (nutrients, metabolites, other chemistries)
  - Geometric (biofilm thickness)
  - Temporal factors (e.g. biofilm formation, growth and detachment)
- **Surface Properties:**
  - Substrate Metallurgy
  - Electrochemical potential (local chemistry at surface)
- **Functional Aspects:**
  - Mitigation parameters (biocide application, pigging frequency)

Mechanistic Model #1 (Haile et al. – Innotech/UofA)

- A mechanistic model was developed to predict localized corrosion rates due to SRB in a biofilm environment under stagnant flow conditions.
- This model takes into consideration the bacteria growth kinetics, sulfate concentration throughout the biofilm, sessile SRB growth, and the biofouling rate.
- The model is currently being validated against experimental data taken from the literature.
- Next Steps: This model will be extended to account for the effect of varying bulk fluid flows, and will be coupled to a computational fluid mechanics (CFD) model simulating dead-leg configurations in pipeline applications.

Mechanistic Model #1 (Haile et al. – Innotech/UofA)





Mechanistic Model of SRB Based MIC

Source: Peralta Gil, Marciales, Haile and Wolodko (2019) A Mechanistic Model for Predicting Corrosion Rates in SRB Dominated MIC, *in preparation*

Risk-Based Modeling

Risk-Based MIC Models

- Risk-based MIC models are practical approaches used to help predict and identify the potential magnitude and location of MIC threats in oil and gas infrastructure such as production facilities or pipelines (systems level assessments).
- Currently used by industry for planning inspection and maintenance activities of assets to ensure optimal safety and reliability in resource-constrained operations.

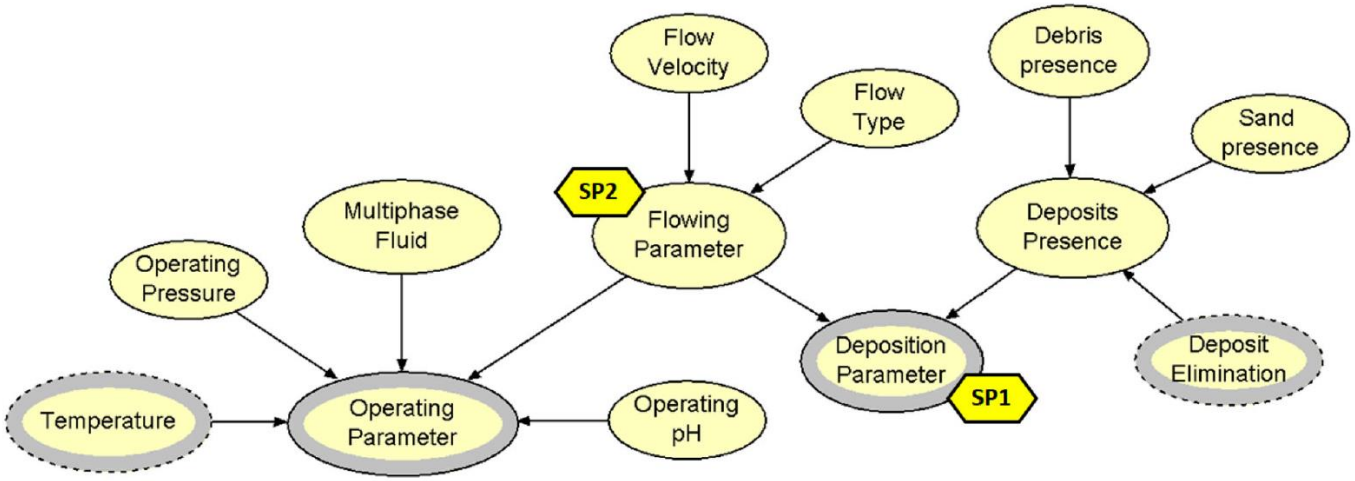
Quantitative Risk Modeling (Khan et al. – MUN)

- This model aims to relate the different factors that influence MIC to determine the potential of MIC occurring with an acceptable level of certainty.
- This first phase focuses on developing a MIC threat assessment model using a Bayesian Network (BN) approach which incorporates a wide range of factors including:
  - operating parameters
  - fluid chemistry
  - settlement parameters
  - material parameters
  - operating history
  - mitigation parameters
  - microbiological factors

Quantitative Risk Modeling (Cont.)

- The model is built upon 60 influencing factors that form 20 screening parameters, and was tested against MIC case studies available in the public domain.
- The model is able to adapt to missing data and also able to consider new data as it becomes available.
- The accuracy of the model was found to be highly dependent on the reliability of data from the field and laboratory tests.
- Next Steps: This model will be further tested and validated against several types of environmental archetypes such as crude oil systems, water lines (produced and sea water), multiphase systems, and storage tanks.

Quantitative Risk Modeling (cont.)



Sub-network	Ideal case (lower limit)	Practical case (average)	Worst case (upper limit)
Operating parameter	94%	99%	99%
Fluid chemistry	75%	86%	95%
Material parameter	62%	76%	85%
Operating history	69%	83%	99%
Settlement parameter	78%	87%	91%
Mitigation parameter	28%	18%	4%
MIC symptoms	69%	84%	98%
MIC potential	71%	82%	96%

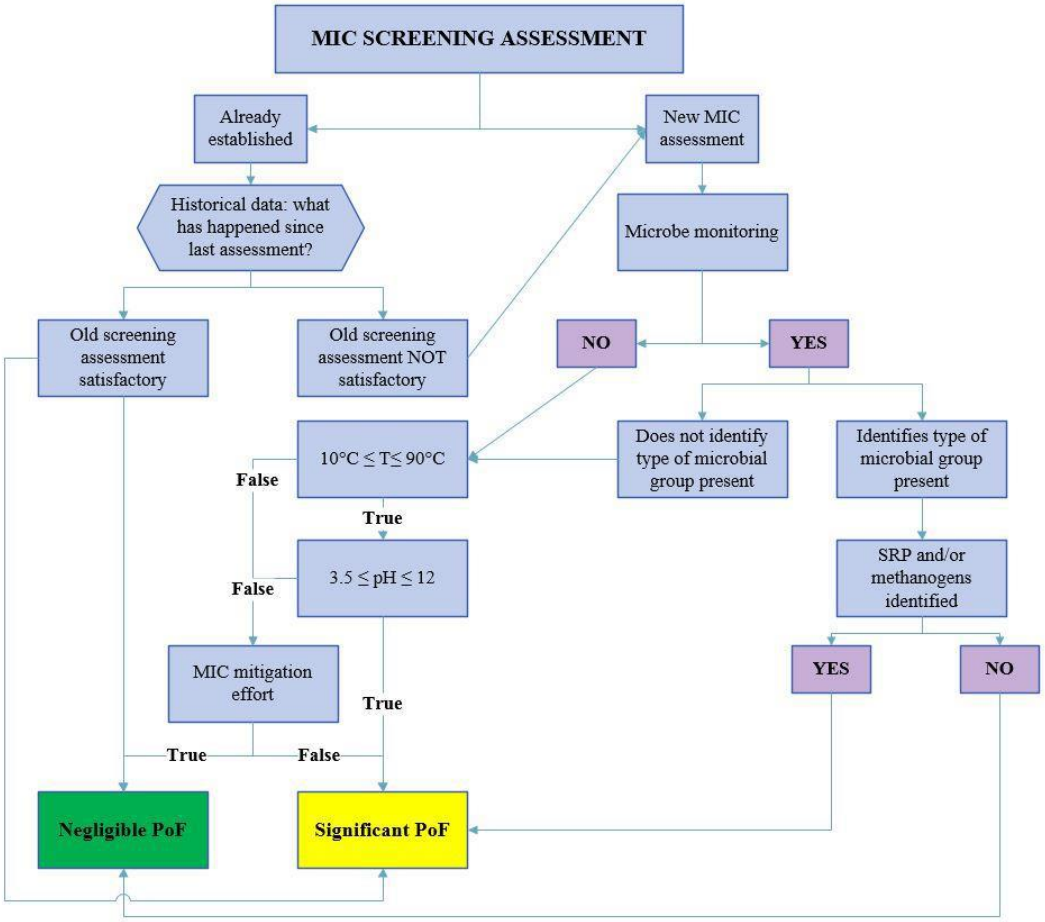
Example Sub-Network Model and Resulting MIC Potential for Case Study

Source: Taleb-Berrouane, Khan, Hawboldt, Eckert, Skovhus (2018) Model for microbiologically influenced corrosion potential assessment for the oil and gas industry, *Corrosion Engineering, Science and Technology*, DOI:10.1080/1478422X.2018.1483221

MIC RBI Modeling (Eckert, Skovhus, Wolodko – DNV GL/VIA University College/UofA)

- A new semi-quantitative assessment tool is currently under development to help assist operators in determining the risk of MIC threats in assets.
- The model consists of a screening flowchart and a ranking tool based on calculated Probability of Failure (PoF).
- The semi-quantitative nature allows for input of key parameters based on both quantitative models/datasets and qualitative assessments.
- Next Steps: This modeling activity was recently initiated (Fall 2018), and extends previous approaches by integrating MMM techniques and a variety of archetypes.

MIC Risk-Based Inspection Modeling (cont.)



Example of RBI Screening Tool

Source: Skovhus, Andersen, Hillier (2016) Management of Microbiologically Influenced Corrosion in Risk Based Inspection Analysis, SPE-179930-MS

Conclusions and Next Steps

Conclusions & Next Steps

- MIC models are continuing to evolve, and are being used to examine MIC threats at various length-scales.
- Taken holistically with other data and information, models can provide key insights for decision making purposes.
- One of the main gaps in advancing these models, however, is the need for quality datasets both from well designed laboratory experiments and from actual field studies for model validation.
- Models also need to be expanded to include new microbiological species and their mechanisms (including consortia), and more advanced microbiological detection & characterization methods (such as MMM).

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  - Yessica Peralta Gil (University of Alberta)
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- Project website: www.geno-mic.ca

Thank you for your attention!

Questions?