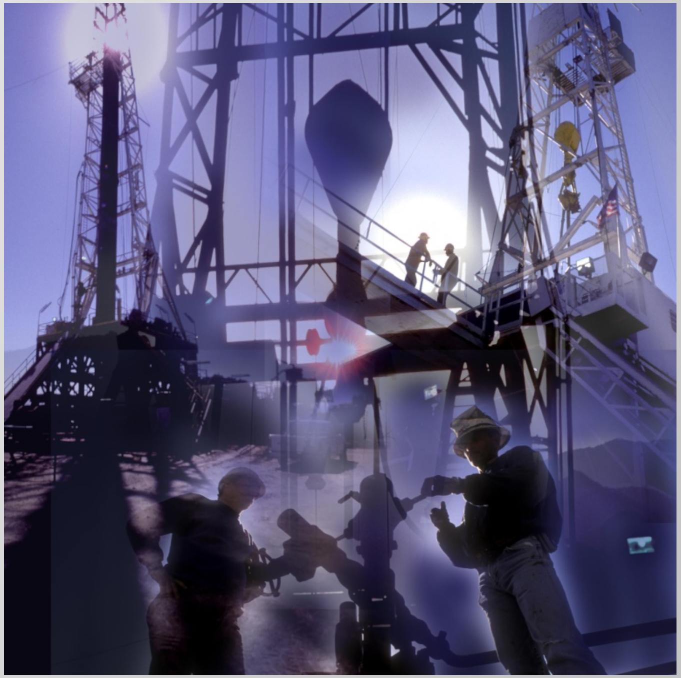
Characterizing the Behavior of Metal-Based Systems Used for Control Devices in Extreme Environments



Jeffrey A. Hawk
SMT, ME&M, NETL, Albany, OR

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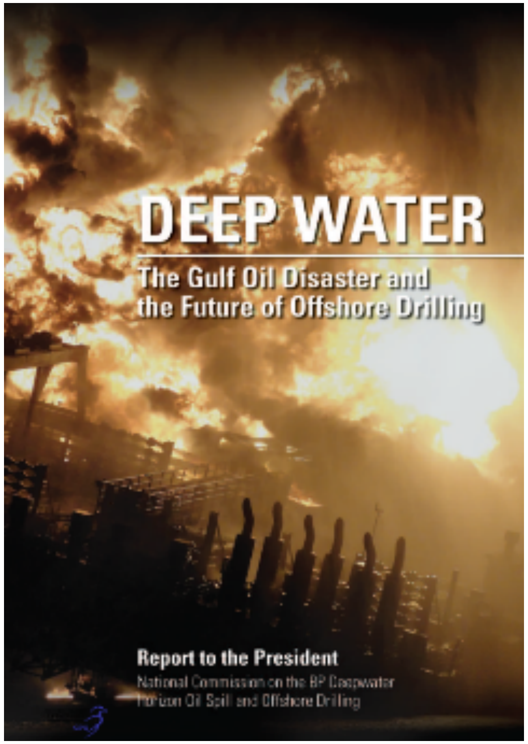
the ENERGY lab

U.S. DEPARTMENT OF ENERGY | National Energy Technology Laboratory

2016 Mastering the Subsurface Through Technology Innovation and Collaboration: Carbon Storage and Oil and Natural Gas Technologies Review Meeting

Wellbore Integrity Drivers Resulting from Macondo

National Commission on the BP Deepwater Horizon Oil Spill Offshore Drilling Recommendations



A. Improving the Safety of Offshore Operations

1. The Need for a New Approach to Risk Assessment and Management

   - "… neither the industry's nor the federal government's approaches to managing and overseeing the leasing and development of offshore resources have kept pace with *rapid changes in the technology, practices, and risks* associated with the *different geological and ocean environments* being explored and developed for oil and gas."
   - "Also missing has been any *systematic updating of the **risk** assessment and **risk** management tools* used as the basis for regulation."

B. Safeguarding the Environment

2. The Need for Greater Interagency Consultation

   - Actions needed to implement these recommendations:
     - The Department of Energy, NOAA, the U.S. Geological Survey, and other interested agencies should *establish a joint research program to systematically collect critical scientific data, fill research gaps*

Post-Macondo Technology Re-Focusing:
Risk Reduction Technologies

Selected Ultra-Deepwater Technologies Related to Deepwater Challenges

Operations Risk Reduction

- Geologic Uncertainty
- UDW Drilling and Completions Operations

Surface Facilities and Subsea Equipment Risk Reduction

- Surface Systems and Umbilicals (Wellbore Stability)
- Subsea Systems Reliability / Automated Safety Systems

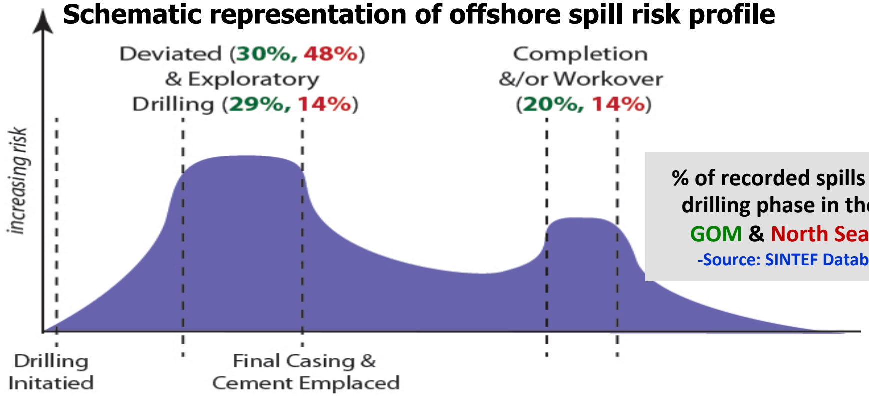
Technology Focus on Safety & Environmental Sustainability

NETL's Offshore Portfolio-
Targeting Prevention of Top Offshore Spill Risks

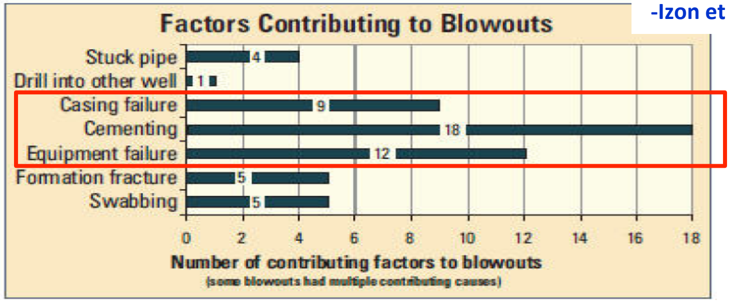
Key Drivers for the Offshore Portfolio:

- Recent offshore events, such as Katrina/Rita (2005) & Deepwater Horizon spill (2010)
- 2010 Executive Order 13547, Interagency Ocean Policy Task Force (IOPTF)
  - Executive agencies (including DOE) challenged to enhance national stewardship of the ocean, coasts, & Great Lakes
- 2012 Challenges Identified by DOI's OESAC Spill Prevention Subcommittee
  - Deep water and offshore frontier areas face production risks that are fundamentally distinct from onshore operations

Schematic representation of offshore spill risk profile



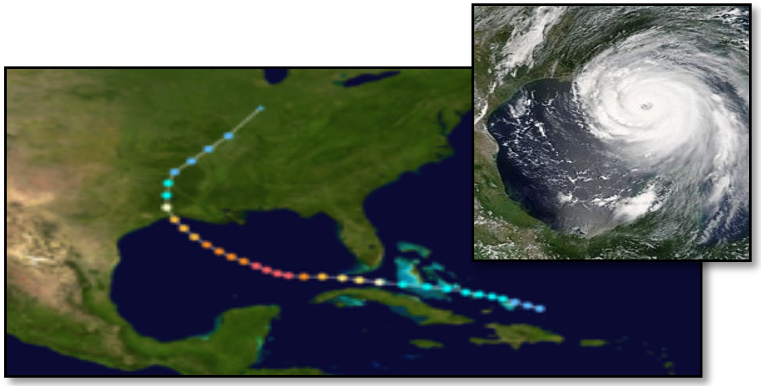
% of recorded spills & drilling phase in the GOM & North Sea
-Source: SINTEF Database



-Izon et al. 2007

NETL ORD's Offshore Portfolio Target Key E&P Risks Associated with Extreme Offshore Hydrocarbons:

- Cementing Failures
- Equipment & Casing Failures
- Higher risk targets, "exploratory" systems



Ultra-Deepwater

Energy Data eXchange

Goals and Objectives

Programmatic Goal(s)

- Develop scientific base to be able to apply quantitative risk assessment formalism to evaluate the exploration and production of deep water (DW) and ultra-deep water (UDW) resources as they pertain to down hole, metal-based systems.

Challenges

- Unknown / ill defined material mechanical behavior and environmental performance measures for ultra-deep well sour service conditions.
- Lack of good environment-mechanical performance understanding for ultra-high strength steels & Ni-base alloys as functions of pH, H_2S concentration, chloride content, and temperature (i.e., ultra-deep well sour environment).
- Knowledge gap in how surface modification treatments can improve the corrosion and/or fatigue resistance of various materials in ultra-deep well sour environments.

Project Objectives

- Assess current materials of construction for drilling, completion and production activities, BHA, BOP, etc., as well as other associated equipment, to include primary failure mechanisms, failure frequency, root cause of failure, etc.
- Evaluate and characterize persistent materials issues, especially those with catastrophic failure potential, such as fatigue, in typical DW (sweet & sour) and UDW (sour) environments.

Expected Benefits

Expected Benefit(s)

- Better and more complete understanding of material behavior in DW and UDW environments especially with respect to metal-based materials related component failures.
- A model on the effect of environment on fatigue crack growth rate in sour service environment on high strength steels used in deep well drilling that can be used for fatigue life prediction.
- Evaluation of the effect of surface treatment (e.g., hammer peening, Low Plasticity Burnishing, or some other surface modification technique) on corrosion resistance and/or fatigue strength in UDW environments. Potential for extending useful life of down-hole assembly and/or drill pipe.
- Understand critical aspects of uncertainty and risk related to metal-based systems used in DW and UDW environments.

General Background

- **Newly developed steel *Drill Pipe* provides significant advantage:**
  - Higher strength
  - Better strength to weight ratio
  - Improved fatigue performance
- **Primary areas of concern are**
  - Sulfide Stress Corrosion Cracking
  - Fracture Toughness
  - Fatigue Crack Growth Rates
- **Role of environmental variables**
  - pH, p_{H2S}, Chloride, Temperature
- **Quenched and Tempered Martensitic Steel with an YS of 165ksi**

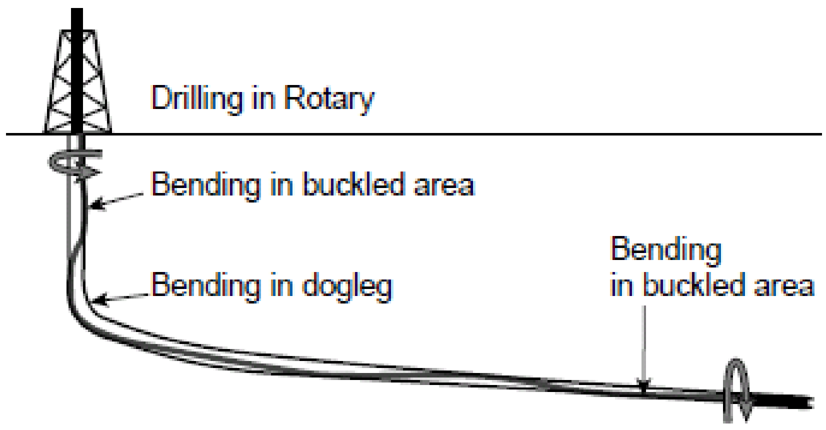
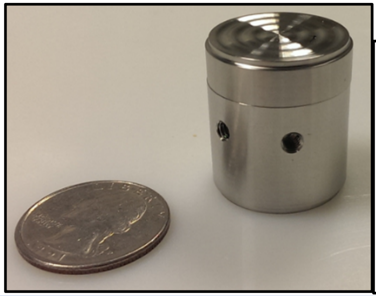
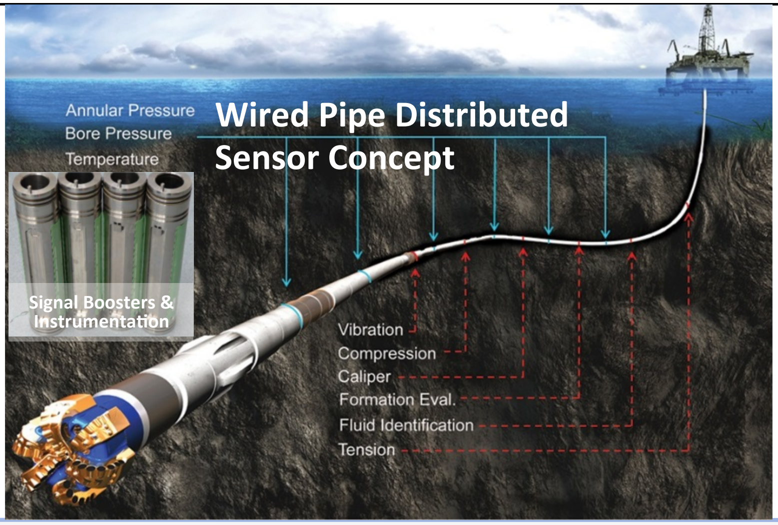


Figure 1

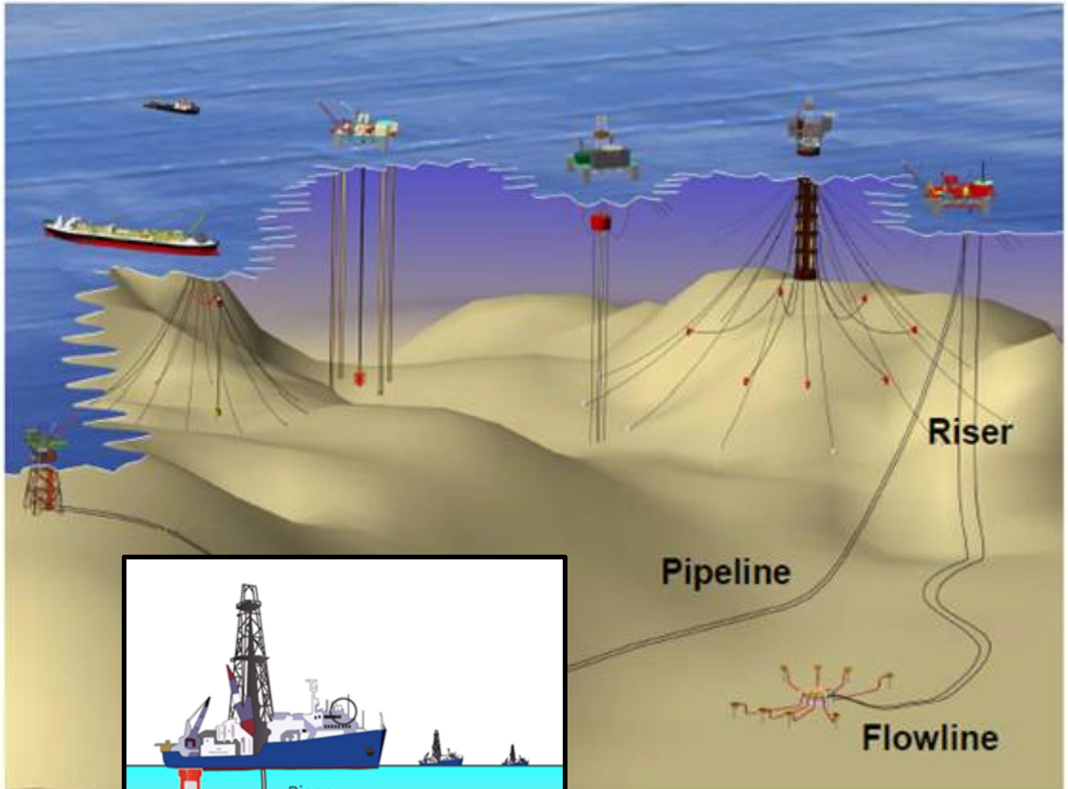
Fatigue may occurs when drillstring is crooked and rotated.

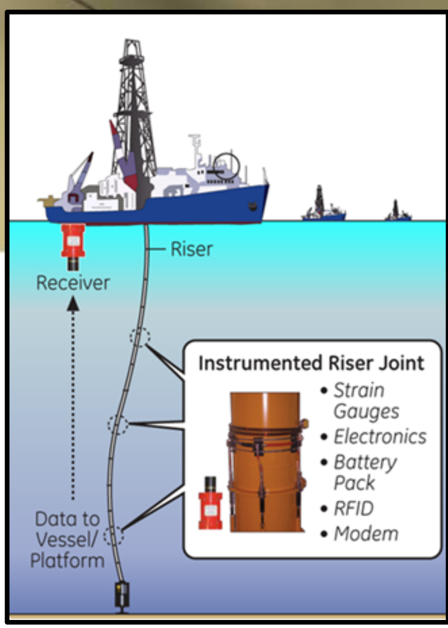


Enabling Technology: First HPHT DP Cell: Tested to 150 psi DP (2 X Full Scale) with Static Pressure Protection to 22,500 psi. Accurate to 0.5% Full Scale – testing 2 psi full scale device – to sense 0.2 ppg change over a one foot interval



Offshore Pipelines – Risers and Flowlines





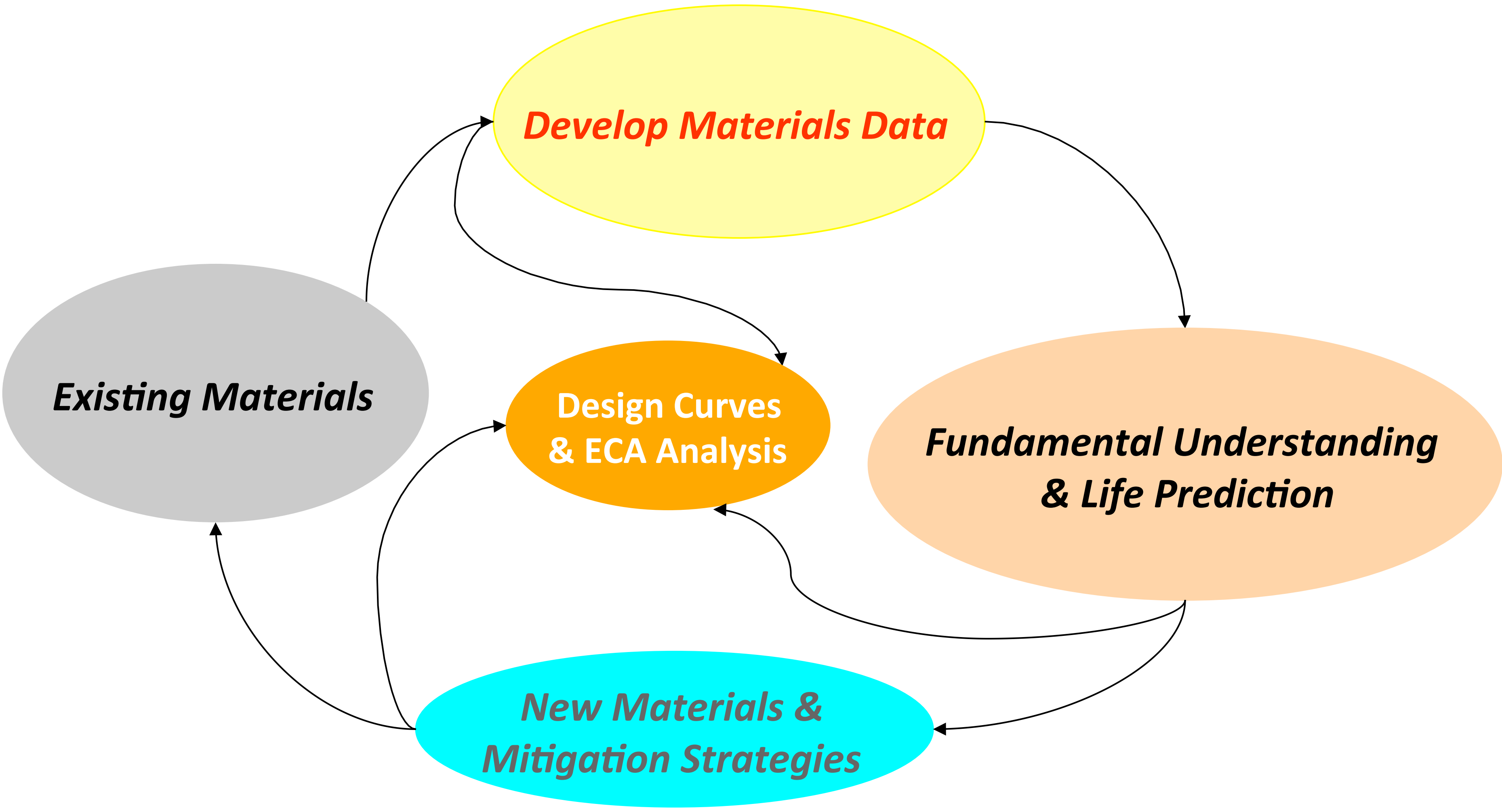
Risers and flow lines are used in offshore oil and gas production.

They are primarily used for transporting oil and gas fluids.

They experience harsh environments and various loading conditions.

New Design Methodology and Algorithm for Improved Performance in Hazardous Sea Conditions

Conceptual Framework for Ultra Deep Well - HP-HT Sour Service Materials Performance



Facets of Corrosion Fatigue of Importance to Oil & Gas Industry

Corrosion Fatigue in the Oil & Gas Industry

Materials Properties & Processing Factors

- *YS effects*
- *Compositional effects*
- *Weld fillers*
- *Weld processing*
- *Reeling operations*

CRA's

- *Ni-based alloys*
- *Clad Ni-based alloys*
- *HS weldable Ti-alloys*
- *Duplex/Superduplex*
- *HSLA steels*
- *Surface modification*

Modeling Environmental & Micromechanical Properties

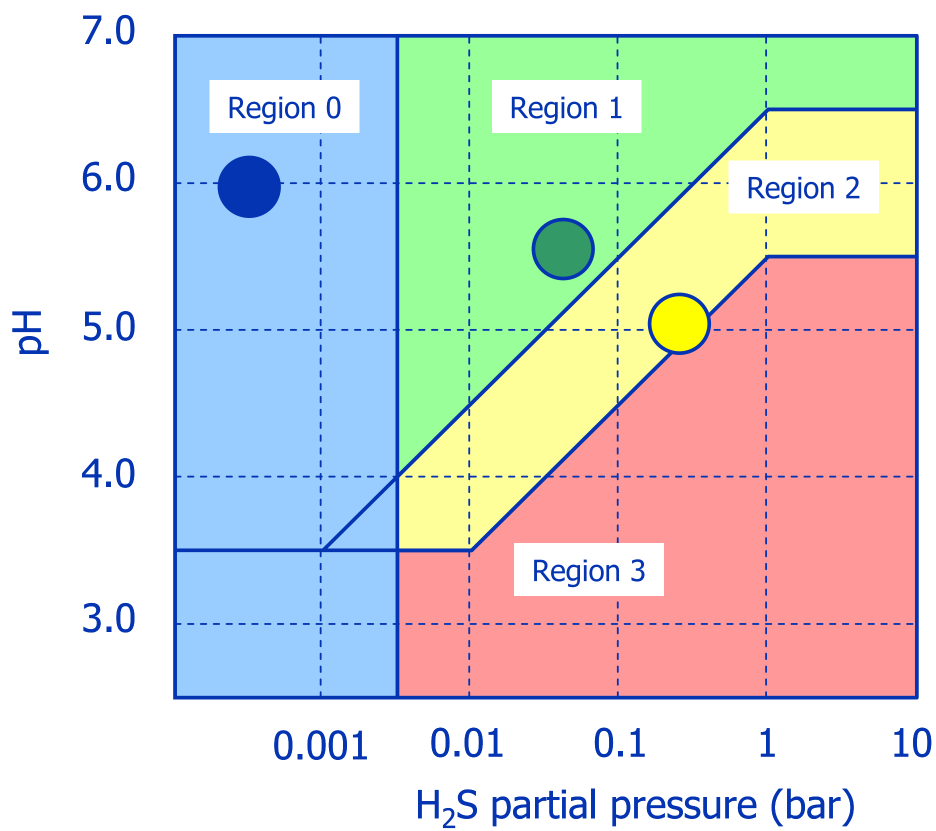
- *H_2S Effects*
- *pH limits*
- *Trapped hydrogen*
- *ΔK effects*
- *da/dN predictions*

Development of RP/ Guidelines

- *Recommended practices*
- *Industry Standards*
- *Design Guidelines*

Environmental Aspects : Resistance to SSC

What is the effect of environmental parameters on FCGR and FT?

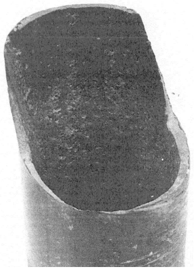


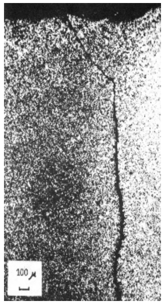
- **Environmental Variables**
  - pH
  - p_{H2S}, chloride content
  - Temperature
- **Loading Variables**
  - ΔK, R-ratio
  - *Frequency (f)*
  - Soaking time
- **Materials of Interest**
  - UD-165
  - S-135
  - C-110
  - Line Pipe Steels (X52/X65/X70/X80)
  - High strength nickel superalloys

Goal of relating material & mechanical properties to the loading conditions and environmental variables.

Experience with HPHT and Deep Well Conditions

- **Supercritical CO_2 environments containing water: 50°C (122°F) and 15 MPa (2176 psi)**
  - Tested ability to measure corrosion of carbon steel transmission pipelines in low conductivity solutions.
- **Sodium chloride solutions (brines) with varying pH containing H_2S: 200°C (392°F) and 1.5 MPa (218 psi).**
  - Studying kinetic and mechanistic aspects of environmentally assisted cracking (hydrogen embrittlement, stress corrosion cracking, corrosion fatigue) initiation step for developing best practices for corrosion protection of drilling materials (S-135 and UD-165).
- **Cement-simulated pore solutions: containing CO_2: 100°C (212°F) and 10 MPa (1450 psi)**
  - Studying corrosion mechanisms of casing alloys (L-80 and Q-125) for improving effectiveness of cathodic protection, development of cement-based corrosion coatings, and development of new alloys.
  - Note: Corrosion studies in a cement-simulated pore solution containing CO_2 and H_2S are in progress.





Summary of NETL Collaborative Research on Metal Based Systems (from 2009)

1) Materials Performance in Extreme Ultra-Deep Well & Sour Gas Environments: Effect of Pitting on Fatigue Performance of Drill String Alloys *Oregon State University (Kruzic & Rozman) & NETL (Ziomek-Moroz & Hawk)*

2) Corrosion-Fatigue of UD-165 Drill Pipe *NETL (Ziomek-Moroz & Hawk) & DNV (Thodla & Gui)*

3) Sour Service Fatigue Crack Growth Rate & Fracture Toughness Testing Program for High Strength Steels *NETL (Ziomek-Moroz & Hawk) & DNV (Thodla & Gui)*

4) Ni-Base Corrosion Resistant Alloys for Bottom Hole Assemblies (BHA) in Ultra-Deep Drilling *West Virginia University (Liu & Chen) & NETL (Hawk)*

5) Corrosion-Fatigue Performance of High-Strength Riser Steels in Seawater & Sour Brine Environment *Southwest Research Institute (Hudak) & NETL (Hawk)*

6) Materials Performance in High-Pressure, High-Temperature (HPHT) Ultra-Deep Drilling Environments *NETL (Ziomek-Moroz & Hawk)*

Summary of NETL Collaborative Research on Metal Based Systems (from 2009)

7) Assessment of Materials Related Offshore Failures *DNV (Padgett & Rollins) & NETL (Hawk)*

8) Catalytic Properties of H_2S in Corrosion Degradation of High Strength Steel Pennsylvania State University (Lvov) & *NETL (Ziomek-Moroz)*

9) Electrochemical Sensor Development Pennsylvania State University (Lvov) & *NETL (Ziomek-Moroz)*

10) Effect of YS on the FCGR of Line Pipe Steels in Sour Environments *DNV (Thodla & Gui) & NETL (Ziomek-Moroz & Hawk)*

11) Environmentally Assisted Fatigue and Fracture of Ni-Based Alloys for HP/HT Applications *DNV (Thodla & Gui) & NETL (Ziomek-Moroz & Hawk)*

12) Materials Properties for Offshore DW / UDW Environments: Property Collation, Database Development and Analysis & Data Trends *NETL (Hawk, Rozman & Ziomek-Moroz) & DNV (Thodla)*

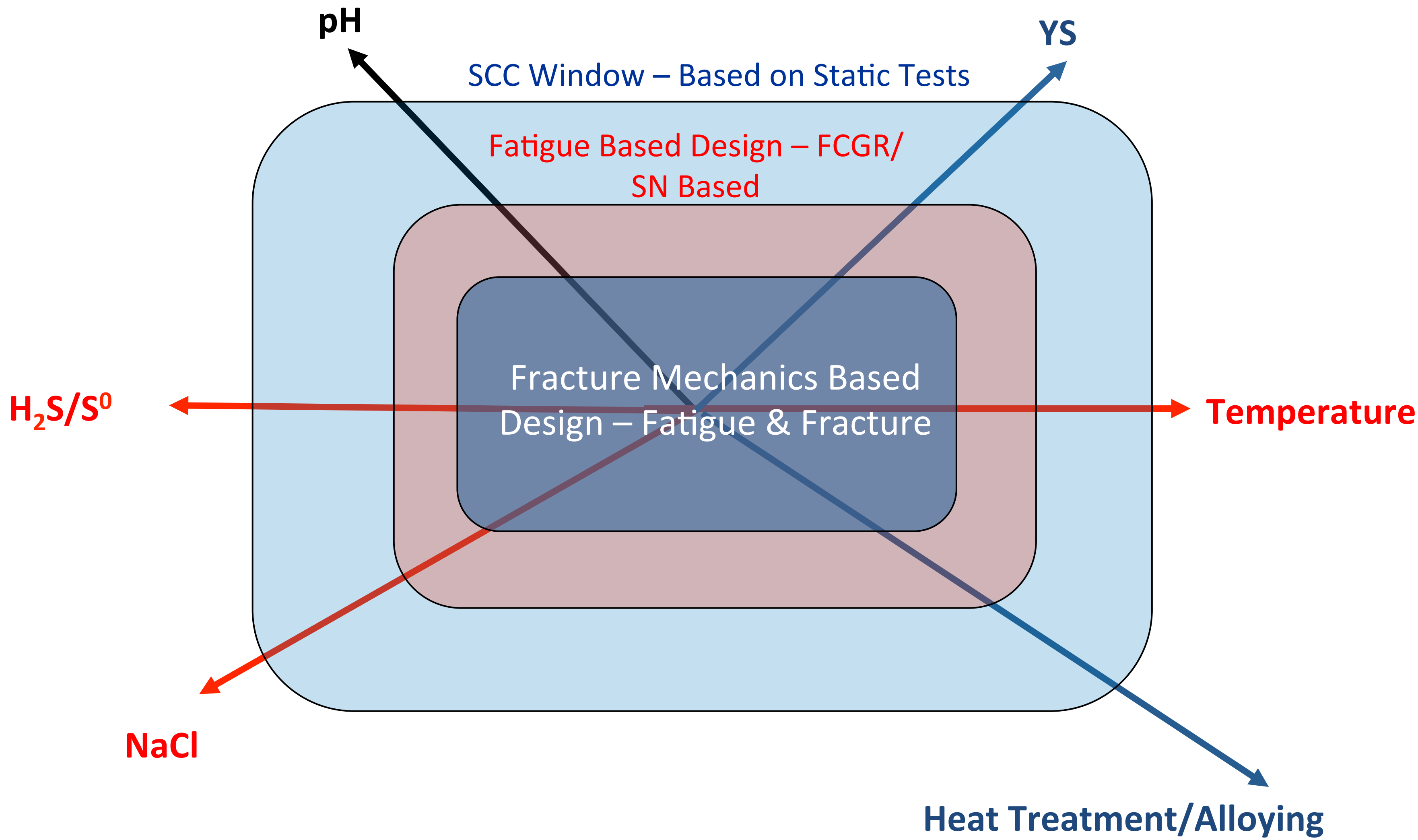
Ultra-Deep Well HP/HT Applications

- HP/HT Challenges involve T > 350°F and P > 15 ksi.
- Environmental Conditions
  - Sour Production
    - High H_2S/Elemental S
    - High Cl^-
  - Seawater with CP
    - Low T (40°F)
    - Elevated T?
- Challenges involve
  - Design
  - Installation
  - Materials
  - Operation

- Typical subsea materials used are high strength steels; however, the elevated temperature & pressure generally requires the use of high strength nickel based alloys and/or cladded construction.
- Modification of design philosophy (Fracture & Fatigue vs. Stress Based)
  - *Environmentally Assisted Fatigue & Fracture become critical in design*

Implications of Design Philosophy

Stress Based vs. Fracture Mechanics Based



Selected Accomplishments to Date

- UD-165 has slightly better HCF behavior than does S-135 in absolute terms. Yield stress compensated behavior very similar between the two alloys. Both S-135 and UD-165 are susceptible to localized corrosion in simulated $CaCl_2$ completion fluid. Accelerated corrosion experiments indicate UD-165 is more susceptible to localized pitting. After pitting the superior fatigue strength of UD-165 relative to S-135 is negated.
- Fatigue crack growth rate (FCGR) of steels in sour environments is hydrogen driven. FCGR is controlled by the diffusion of hydrogen through the fracture process zone & depends on a critical concentration of hydrogen.
- Role of yield stress & microstructure of line pipe steels on FCGR behavior was quantified in sour environments for a variety of steels used in drilling, completion, production & transmission.
- Pitting corrosion & corrosion fatigue crack growth behavior of OG alloy 718 were investigated in NaCl solution:
  - *Determined the influencing factors on the pitting corrosion resistance of oil-grade alloy 718 in NaCl solution*
  - *Explored the influencing factors on the corrosion fatigue crack growth behavior of oil-grade alloy 718 in NaCl solution*

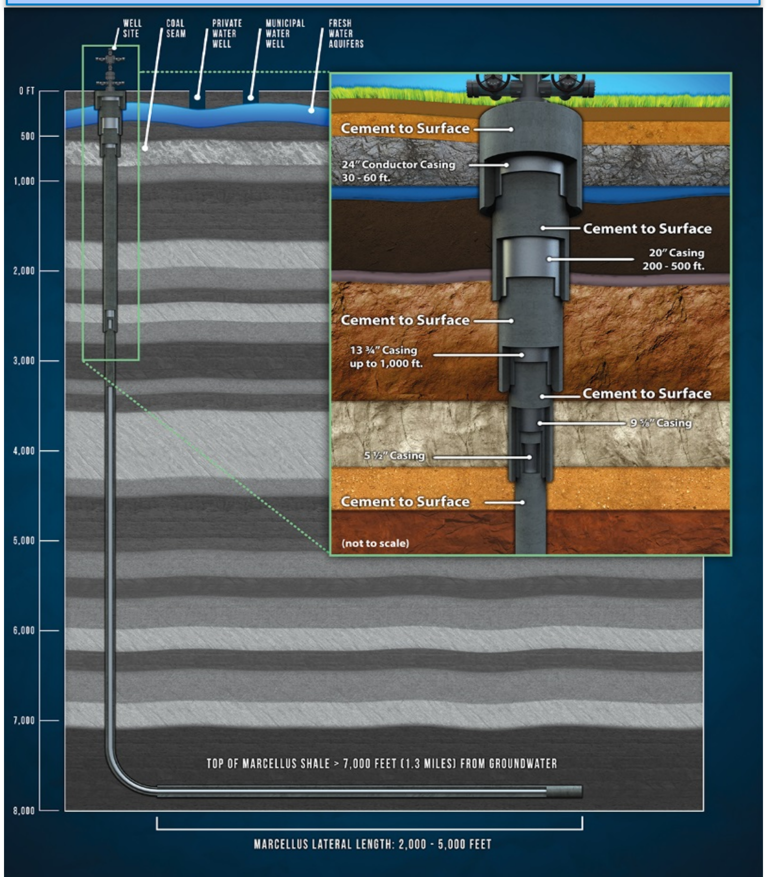
Selected Accomplishments to Date

- Effect of machine hammer peening & heat treatment on corrosion resistance of OG alloy 718 in NaCl solution were determined:
  - *Characterized the surface modifications induced by machine hammer peening & heat treatment*
  - *Improved pitting corrosion resistance of OG alloy 718 in NaCl solution via machine hammer peening*
  - *Improved understanding of deformation mechanism & corrosion mechanism of OG alloy 718 after machine hammer peening*
- Catalytic properties of H_2S in corrosion degradation of high strength steels show that the increase of H_2S concentration in the solution correlates with an increased amount of S detected on the steel surface by EDS. With temperature increase from 85^{o}C to 200^{o}C, the steel samples corroded more severely due to the accelerated corrosion rate.
- The toughness of OG 718 decreased as chloride content in solution increased, especially as the temperature increased. The effect on alloy 625+ was less pronounced except at the highest test temperature (>200°C).

Synergy Opportunity

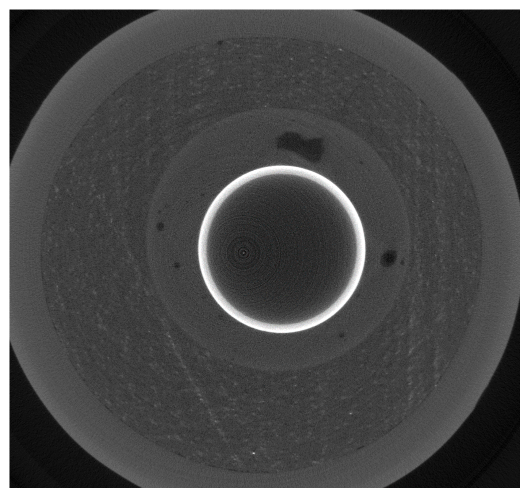
Evaluation of Barrier Interface Integrity under Subsurface Conditions

Evaluate the physical, chemical, & temporal integrity of formation / cement / casing systems used in extreme offshore settings at *in situ* conditions



Leading to the development of:

- Cement with enhanced mechanical and chemical stability that provides corrosion protection to casing
- Monitoring devices for stability of casing/cement/ formation system
- Mitigation methods for preventing casing/cement/ formation degradation
- Better fundamental understanding of the wellbore interface interactions affecting overall wellbore integrity



Summary & Key Findings

- **Key Findings**
  - The addition of H_2S increased the corrosion rate of UD-165 at pH 7.5 and 12.3, but decreased the corrosion rate at pH 10.5.
  - Unlike the H_2S free tests, the corrosion rates with $[H_2S]=2.63\times10^{-3}$ mol/kg (p_{H2S}=1.2 psi) were not limited by the mass transport in the solution at steady state.
  - With H_2S concentration of 2.63×10^{-3} mol/kg (p_{H2S}=1.2 psi), the corrosion products changed from Fe, S-rich to oxides with pH increase, according to both the Pourbaix diagram and the EDS surface analysis.
  - At pH values of 7 and 9 at 20°C, FCGR as function of frequency is linear with approximately a -0.5 gradient. This indicates that FCGR is controlled by hydrogen diffusion.
  - At a pH value of 12 at 20°C, FCGR as function of frequency is non-linear indicating possible crack closure due to corrosion product formation at the crack tip.

Summary & Key Findings

- **Key Findings (cont.)**
  - Scanning electron microscopy investigations of exposed specimens after FCGR experiments in pH = 7 and 9 solutions at 20°C revealed the presence of Fe and S-rich corrosion products that, in this case, did not serve as a diffusion barrier to S and H species at the crack tip.
  - Scanning electron microscopy investigations of exposed specimens after FCGR experiments in pH = 12 solutions at 20°C revealed the presence of corrosion products at the crack tip, effectively plugging it.
  - Hammer peening alters (improves) fatigue behavior of OG 718. Effect of hammer peening & subsequent heat treatment also influence corrosion behavior of OG 718 in some instances.
  - Crack growth behavior and fracture toughness of OG 718 is less robust than that of alloy 625+ (IN725) in a variety of DW and UDW sour conditions. Increasing temperature changes mode of failure from transgranular to intragranular.

Summary & Key Findings (cont.)

- **Lessons Learned**
  - Collaboration essential for making sustained progress in understanding the interrelationships between metal-based systems and variables found in DW and UDW environments. No one laboratory possesses all requisite test capabilities and expertise for understanding metal-based materials response to DW and UDW environmental conditions.
- **Future Plans**
  - Test drill pipe steels as function of temperature under quasi-static and dynamic conditions
  - Test precipitation strengthened nickel superalloys used in oil patch applications under dynamic conditions as function of temperature
  - Collect mechanical property information available in the literature for conditions applicable to DW and UDW conditions
  - Develop database framework for housing mechanical property information; note gaps in information

Peer Reviewed Publications

1) Ramgopal Thodla, Feng Gui, Jeffrey A. Hawk, and Margaret Ziomek-Moroz, “Corrosion Fatigue Performance of High Strength Drill Pipe in Sour Environments,” *CORROSION 2011*, Paper No 11108, (2011), 10 pages.
2) Kyle A. Rozman, “Corrosion and Fatigue of Oil Well Drilling Steels,” M.S. Thesis, March 2011, Oregon State University.
3) Margaret Ziomek-Moroz, Sophie Bullard, Kyle A. Rozman, and Jamie J. Kruzic, “Effects of Inclusions in HSLA Carbon Steel on Pitting Corrosion in $CaCl_2$,” *ECS Transactions*, Vol. 35, 2011, p. 11.
4) Margaret Ziomek-Moroz “Environmentally Assisted Cracking of Drillpipes in Deep Drilling Oil and Natural Gas Well,” *Journal of Materials Engineering and Performance*, Vol. 61, 2012, p. 1061.
5) Margaret Ziomek-Moroz, Jeffrey A. Hawk, Ramgopal Thodla, and Feng Gui, “Environmentally Assisted Cracking of Ultra Strength Low Alloy Steel in Sour Environments,” *CORROSION 2014*, Paper No. 3912, (2014), 10 pages.
6) Justin Beck, Ruishu Feng, Serguei N. Lvov, and Margaret Ziomek-Moroz, “Study of the Catalytic Behavior of *H_2S on the Corrosion of High Strength Carbon Steel in Deaerated Marine Environments,” CORROSION 2014*, Paper No.4191, (2014), 12 pages.
7) Kyle A. Rozman, Margaret Ziomek-Moroz, Sophie Bullard, Jamie J. Kruzic, and Jeffrey A. Hawk, “Localized Corrosion and Fatigue Behavior of Ultra-deep Drilling Alloys,” NETL-TRS-1-2014; U.S. Department of Energy, National Energy Technology Laboratory: Morgantown, WV , 2014; 28 pages.
8) Margaret Ziomek-Moroz, Jeffrey A. Hawk, W. Keith Collins, Ramgopal Thodla, and Feng Gui “The Consequence of Stress Intensity on Fatigue Crack Propagation in High-Strength Steels in Sour Environment” *ECS Transactions*, Vol. 61, 2014, p 37.
9) Ruishu Feng, Justin Beck, Serguei N. Lvov, and Margaret Ziomek-Moroz, “Effects of Hydrogen Sulfide on the Corrosion Behavior of High Strength Steel in Alkaline Solutions” ” *ECS Transactions*, Vol. 61, 2014, p. 97.

Peer Reviewed Publications

10) Jared S. Nutter, "Corrosion Fatigue Crack Propagation of Oil-Grade Alloy 718 in NaCl Solution," M.S. Thesis, August 2013, West Virginia University.

11) Ting Chen, Jarad Nutter, Hendrik John, W. Chen, J. Stevens, Jeffrey A. Hawk and Xingbo Liu, "Effect of Aging Treatment on Pitting Corrosion and Corrosion Fatigue Crack Growth Behavior of Oil-Grade Alloy 718," *8th International Symposium on Superalloy 718 and Derivatives*, E. Ott, A. Banik, X. Liu, I. Dempster, K. Heck, J. Anderson, J. Groh, T. Gabb, R. Helmink, and A. Wusatowska, Eds., The Minerals, Metals & Materials Society, Warrendale, PA (2014) 593-608.

12) Ting Chen, "Pitting Corrosion and Corrosion Fatigue Crack Growth Behavior of Oil-Grade Alloy 718 in NaCl Solution," Ph.D. Dissertation, October 2013, West Virginia University.

13) Ting Chen, Hendrik John, Jing Xu, Quihong Lu, Jeffrey A. Hawk and Xingbo Liu, "Influence of Surface Modifications on Pitting Corrosion Behavior of Nickel-base Alloy 718. Part 1: Effect of Machine Hammer Peening," *Corrosion Science*, 77 (2013) 230-245

14) Ting Chen, Hendrik John, Jing Xu, Quihong Lu, Jeffrey A. Hawk and Xingbo Liu, "Influence of Surface Modification on Pitting Corrosion Behavior of Oil-Grade Alloy 718. Part 2: Effects of Aging Treatment," *Corrosion Science*, 78 (2014) 151-161 .

15) Ting Chen, Jared Nutter, Jeffrey Hawk and Xingbo Liu, "Corrosion Fatigue Crack Propagation of Oil-grade Nickel-base Alloy 718. Part 1: Effect of Corrosive Environment," *Corrosion Science*, 89 (2014) 146-153.

16) Ruishu Feng, Justin Beck, Serguei N. Lvov, and Margaret Ziomek-Moroz, "Effects of Hydrogen Sulfide on the Corrosion Behavior of High Strength Steel in Alkaline Solutions," *ECS Transactions*, 61 (20) 97-114, 2014.

17) Kyle A. Rozman, Margaret Ziomek-Moroz, Sophie Bullard, Jamie J. Kruzic, and Jeffrey A. Hawk, Localized Corrosion and Fatigue Behavior of Ultra-Deep Drilling Alloys; NETL-TRS-1-2014, U.S. Department of Energy, National Energy Technology Laboratory: Morgantown, WV, 2014; p 28.

Peer Reviewed Publications

18) Margaret Ziomek-Moroz, Jeffrey A. Hawk, W. Keith Collins, Ramgopal Thodla, and Feng Gui, "The Consequence of Stress Intensity on Fatigue Crack Propagation in High-Strength Steels in Sour Environment," *ECS Transactions*, 61 (20) (2014) 37-47.

19) Ting Chen, Jared Nutter, Jingsheng Bai, Jeffrey Hawk and Xingbo Liu, "Corrosion Fatigue Crack Propagation of Oil-grade Nickel-base Alloy 718. Part 2: Effect of Aging Treatment," *Corrosion Science*, **98** (2015) 280-290.

20) Margaret Ziomek-Moroz, Jeffrey A. Hawk, Ramgopal Thodla, and Feng Gui, "Sour Environment Temperature Effects on Fatigue Crack Propagation in Ultra-high Strength Low Alloy Martensitic Steel," *CORROSION 2015*, Paper No. 5843, (2015), 9 pages.

21) Serguei N. Lvov, Ruishu Feng, Justin Beck, Rosemary Cianni, and Margaret Ziomek-Moroz, "Corrosion of Carbon Steels in H_2S-Containing Alkaline Brines," *CORROSION 2015*, Paper No. 6119, (2015) 15 pages.

22) Serguei N. Lvov, Derek Hall, Justin Beck, and Margaret Ziomek-Moroz, "Review of pH and Reference Electrodes for Monitoring Corrosion in HPHT Extreme Environments," *CORROSION 2015*, Paper No. 6117, (2015) 14 pages.

23) Ramgopal Thodla, Liu Cao, Jeffrey A. Hawk, and Margaret Ziomek-Moroz, "Relationship Between Localized Corrosion and Stress Corrosion Cracking of Nickel Based Alloys in HPHT Oil and Gas Environments," NACE CORROSION 2016 Conference & Exposition, Paper No. 7113, NACE International, Houston, TX, 2016, 15 pages.

24) Ramgopal Thodla, Jeffrey A. Hawk, and Margaret Ziomek-Moroz, "Sour Service Fatigue and Fracture Behavior of High Strength Steels," NACE CORROSION 2016 Conference & Exposition, Paper No. 7183, NACE International, Houston, TX, 2016, 15 pages.




Questions?

For Further Information, Contact NETL

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