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U.S. DEPARTMENT OF ENERGY

Subsea Bolts Performance and Critical Drill-through Equipment Fastener Study

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Outline

- Background
- LBNL bolt research goals
  - Standard review and gap analysis
  - Materials corrosion under subsea environment
- Overview of current progress
- Future work

Background

- Over the past decade, a number of fastener/bolt failures on OCS associated with
  - LMRP
  - Subsea BOP components
- **It is needed for an independent assessment of critical drill through equipment fasteners in offshore oil and gas operations**

➢ Identify fastener systems currently in use
(offshore & onshore; domestic & global)

➢ Assess design, manufacture, installation, maintenance & inspection processes

➢ Evaluate the performance of current fastener systems

➢ Identify similarities & differences in industry standards & regulations globally

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LBNL Project Research Goals

- ❑ Standard review and gap analysis
- ❑ Lab experiments:
  Bolting materials corrosion under subsea environment

- ➢ Review industry codes & identify existing standards or regulations *underlying failure mechanisms*
- ➢ Evaluate performance of existing fastener systems
  manufacturing, corrosion protection, installation, maintenance, inspection
- ➢ Identification of similarities & differences in industry standards & regulations
- ➢ Evaluation of alternative fastener designs used by global industries
- ➢ Recommendation -
  - Methodology for the selection for material properties & other critical parameters
  - Modification & improvement of existing industry standards

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Industry Standards Review

American Petroleum Institute - 17

American Society of Mechanical Engineers (ASME) - 1

American Society for Testing Materials (ASTM) - 47

Bolt Council – 2

British Standards Institution (BSi) - 10

Desalinization Industry – 1

DNV-GL – 11

Dept. of Energy-Sandia – 1

Federal Standards – 3

Industrial Fasteners Institute – 4

International Regulators' Forum (IRF) member country regulations on bolts (a specific requirement or a referenced standard)

http://www.irfoffshoresafety.com/

Int'l Organization for Standardization (ISO) – 31

Japanese Industrial Standard (JIS) – 1

Military Standards – 10

Nat'l Association of Corrosion Engineers (NACE) – 21

NASA – 1

Navy Standards – 8

NORSOK – 1

Nuclear Regulatory Commission – 7

Society of Automotive Engineers (SAE) – 4

United States Coast Guard (USCG) – 2

Biomedical Industry Standards:

Dental Industry Standards – 3

Bone and Joint Substitute Standards - 10

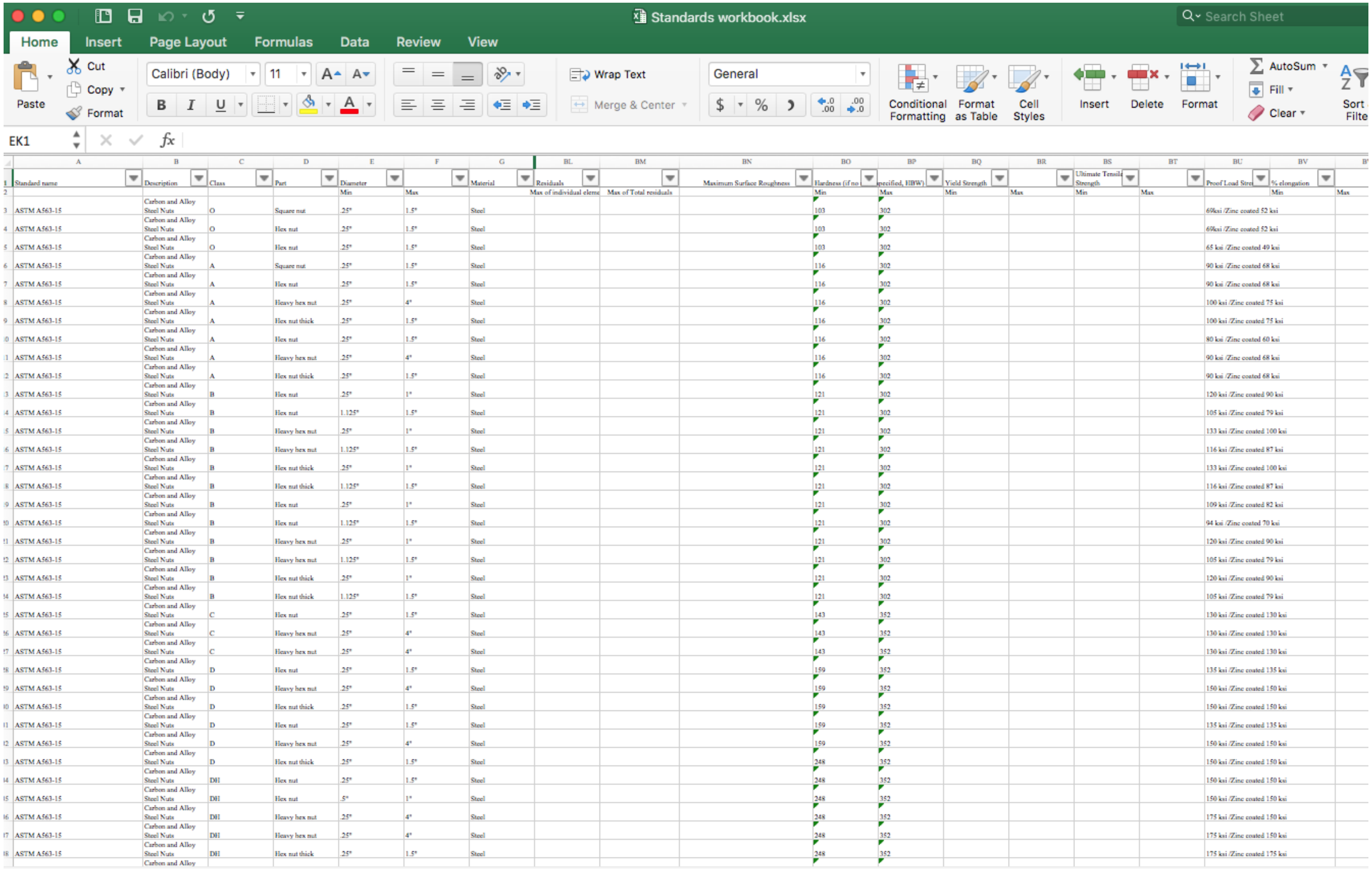
…. ....

Total over 200 items ...

Industry Standards & Gap Analysis
Critical Attributes for Subsea Bolts

- Material Specifications
  - Hardness
  - Yield Strength (YS)
  - Ultimate Tensile Strength (UTS)
  - Elongation
- Procurement
  - Heat treatment
  - Coatings (thicknesses)
  - Shear stress
  - Fatigue Life
  - Threading
- Corrosion Treatment
  - Cathodic Protection (CP)
- Installation
- Quality Analysis/Control
- In Service Inspection (ISI)
- Human Factors

Industry Standards & Gap Analysis



	A	B	C	D	E	F	G	BL	BM	BN	BO	BP	BQ	BR	BS	BT	BU	BV	BW
1	Standard name	Description	Class	Part	Diameter		Material	Residuals		Maximum Surface Roughness	Hardness (if no	pecified, HBW)	Yield Strength		Ultimate Tensile Strength		Proof Load Stre	% elongation	
2					Min	Max		Max of individual eleme	Max of Total residuals		Min	Max	Min	Max	Min	Max		Min	Max
3	ASTM A563-15	Carbon and Alloy Steel Nuts	O	Square nut	.25"	1.5"	Steel				103	302					69ksi /Zinc coated 52 ksi		
4	ASTM A563-15	Carbon and Alloy Steel Nuts	O	Hex nut	.25"	1.5"	Steel				103	302					69ksi /Zinc coated 52 ksi		
5	ASTM A563-15	Carbon and Alloy Steel Nuts	O	Hex nut	.25"	1.5"	Steel				103	302					65 ksi /Zinc coated 49 ksi		
6	ASTM A563-15	Carbon and Alloy Steel Nuts	A	Square nut	.25"	1.5"	Steel				116	302					90 ksi /Zinc coated 68 ksi		
7	ASTM A563-15	Carbon and Alloy Steel Nuts	A	Hex nut	.25"	1.5"	Steel				116	302					90 ksi /Zinc coated 68 ksi		
8	ASTM A563-15	Carbon and Alloy Steel Nuts	A	Heavy hex nut	.25"	4"	Steel				116	302					100 ksi /Zinc coated 75 ksi		
9	ASTM A563-15	Carbon and Alloy Steel Nuts	A	Hex nut thick	.25"	1.5"	Steel				116	302					100 ksi /Zinc coated 75 ksi		
10	ASTM A563-15	Carbon and Alloy Steel Nuts	A	Hex nut	.25"	1.5"	Steel				116	302					80 ksi /Zinc coated 60 ksi		
11	ASTM A563-15	Carbon and Alloy Steel Nuts	A	Heavy hex nut	.25"	4"	Steel				116	302					90 ksi /Zinc coated 68 ksi		
12	ASTM A563-15	Carbon and Alloy Steel Nuts	A	Hex nut thick	.25"	1.5"	Steel				116	302					90 ksi /Zinc coated 68 ksi		
13	ASTM A563-15	Carbon and Alloy Steel Nuts	B	Hex nut	.25"	1"	Steel				121	302					120 ksi /Zinc coated 90 ksi		
14	ASTM A563-15	Carbon and Alloy Steel Nuts	B	Hex nut	1.125"	1.5"	Steel				121	302					105 ksi /Zinc coated 79 ksi		
15	ASTM A563-15	Carbon and Alloy Steel Nuts	B	Heavy hex nut	.25"	1"	Steel				121	302					133 ksi /Zinc coated 100 ksi		
16	ASTM A563-15	Carbon and Alloy Steel Nuts	B	Heavy hex nut	1.125"	1.5"	Steel				121	302					116 ksi /Zinc coated 87 ksi		
17	ASTM A563-15	Carbon and Alloy Steel Nuts	B	Hex nut thick	.25"	1"	Steel				121	302					133 ksi /Zinc coated 100 ksi		
18	ASTM A563-15	Carbon and Alloy Steel Nuts	B	Hex nut thick	1.125"	1.5"	Steel				121	302					116 ksi /Zinc coated 87 ksi		
19	ASTM A563-15	Carbon and Alloy Steel Nuts	B	Hex nut	.25"	1"	Steel				121	302					109 ksi /Zinc coated 82 ksi		
20	ASTM A563-15	Carbon and Alloy Steel Nuts	B	Hex nut	1.125"	1.5"	Steel				121	302					94 ksi /Zinc coated 70 ksi		
21	ASTM A563-15	Carbon and Alloy Steel Nuts	B	Heavy hex nut	.25"	1"	Steel				121	302					120 ksi /Zinc coated 90 ksi		
22	ASTM A563-15	Carbon and Alloy Steel Nuts	B	Heavy hex nut	1.125"	1.5"	Steel				121	302					105 ksi /Zinc coated 79 ksi		
23	ASTM A563-15	Carbon and Alloy Steel Nuts	B	Hex nut thick	.25"	1"	Steel				121	302					120 ksi /Zinc coated 90 ksi		
24	ASTM A563-15	Carbon and Alloy Steel Nuts	B	Hex nut thick	1.125"	1.5"	Steel				121	302					105 ksi /Zinc coated 79 ksi		
25	ASTM A563-15	Carbon and Alloy Steel Nuts	C	Hex nut	.25"	1.5"	Steel				143	352					130 ksi /Zinc coated 130 ksi		
26	ASTM A563-15	Carbon and Alloy Steel Nuts	C	Heavy hex nut	.25"	4"	Steel				143	352					130 ksi /Zinc coated 130 ksi		
27	ASTM A563-15	Carbon and Alloy Steel Nuts	C	Heavy hex nut	.25"	4"	Steel				143	352					130 ksi /Zinc coated 130 ksi		
28	ASTM A563-15	Carbon and Alloy Steel Nuts	D	Hex nut	.25"	1.5"	Steel				159	352					135 ksi /Zinc coated 135 ksi		
29	ASTM A563-15	Carbon and Alloy Steel Nuts	D	Heavy hex nut	.25"	4"	Steel				159	352					150 ksi /Zinc coated 150 ksi		
30	ASTM A563-15	Carbon and Alloy Steel Nuts	D	Hex nut thick	.25"	1.5"	Steel				159	352					150 ksi /Zinc coated 150 ksi		
31	ASTM A563-15	Carbon and Alloy Steel Nuts	D	Hex nut	.25"	1.5"	Steel				159	352					135 ksi /Zinc coated 135 ksi		
32	ASTM A563-15	Carbon and Alloy Steel Nuts	D	Heavy hex nut	.25"	4"	Steel				159	352					150 ksi /Zinc coated 150 ksi		
33	ASTM A563-15	Carbon and Alloy Steel Nuts	D	Hex nut thick	.25"	1.5"	Steel				248	352					150 ksi /Zinc coated 150 ksi		
34	ASTM A563-15	Carbon and Alloy Steel Nuts	DH	Hex nut	.25"	1.5"	Steel				248	352					150 ksi /Zinc coated 150 ksi		
35	ASTM A563-15	Carbon and Alloy Steel Nuts	DH	Hex nut	.5"	1"	Steel				248	352					150 ksi /Zinc coated 150 ksi		
36	ASTM A563-15	Carbon and Alloy Steel Nuts	DH	Heavy hex nut	.25"	4"	Steel				248	352					175 ksi /Zinc coated 150 ksi		
37	ASTM A563-15	Carbon and Alloy Steel Nuts	DH	Heavy hex nut	.25"	4"	Steel				248	352					175 ksi /Zinc coated 150 ksi		
38	ASTM A563-15	Carbon and Alloy Steel Nuts	DH	Hex nut thick	.25"	1.5"	Steel				248	352					175 ksi /Zinc coated 175 ksi		
		Carbon and Alloy																	

Conventional way of reading & making notes is not going to work …

Access

A Data Base

Gap Analysis Methodology

- ❑ An efficient and robust method of cataloguing industry standards
- ❑ Microsoft Access RDS and SQL programming queries

Library of Industry Standards

- **Need to Identify**
  - **Relevant Attributes**
  - **Applied Environment**
  - **Main Ideas (Abstract)**
  - **Review of Relevant Attributes (Specific)**
  - **Notes**
- **Used as a resource for Gap Analysis**

ASTM A193/A193M – 15a: Standard Specification for Alloy-Steel and Stainless Steel Bolting for High Temperature or High Pressure Service and Other Special Purpose Application

Relevant attributes: Tensile Strength, Yield Strength, Hardness, Heat Treatment, Temperature

Applied Environment: General High Pressure Service

Offshore condition?

- No, only high pressure or high temperature.

Main Ideas:

- This specification covers alloy and stainless steel bolting materials and bolting components for pressure vessels, valves, flanges, and fittings for high temperature or high pressure service, or other special purpose applications.

Heat Treatment:

- Ferritic Steels
  - Ferritic steels shall be allowed to cool to a temperature below the cooling transformation range immediately after rolling or forging. Bolting materials shall then be uniformly reheated to the proper temperature to refine the grain (a group thus reheated being known as a quenching charge), quenched in a liquid medium under substantially uniform conditions for each quenching charge, and tempered.
  - Use of water quenching is prohibited for any ferritic grade when heat treatment is performed after heading or threading.
  - Notes for specific grades are describes in 6.1.2-6.1.5.
- Austenitic Stainless Steels
  - All austenitic stainless steels shall receive a **carbide solution** treatment.
  - Specific notes about classes of steels described in section 6.2.1-6.2.5.

Tensile Properties (Tensile Strength, Yield Strength):

- Table requirements must be satisfied at room temperature after heat treatment.
- Stainless strain hardened bolting components shall be tested full size after strain hardening to determine tensile strength and yield strength.

Hardness:

- Table requirements must be satisfied via testing conforming to Specification A962/A962M or Test Methods F606. More specifications described in section 9.2.

Notes:

- A962/962M has information regarding manufacturing process among other things.
- Table 4 and 5 describe the Markings of Ferritic and Austenitic Steels (Class and grade).

Example – ASTM A193/A193M – 15a

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Industry Standards & Gap Analysis

Hydrogen Embrittlement – Hardness Threshold

- **Discrepancies in hardness threshold to avoid hydrogen embrittlement** (*examples*)**.**
  - NACE MR0175/ISO 15156 has the most strict regulations. Specific to sour service environments. The maximum allowed hardness is 22 HRC.
  - vs. Industrial Fasteners Institute – “Susceptible fastener products have specified hardness above 39 HRC”
  - vs. NORSOK – “In marine/subsea applications, acceptable hardness range is 32-39 HRC.”
  - vs. API 17A – “Resistance against hydrogen embrittlement should be controlled by specifying that the actual hardness of the material is less than 300 HV10 [31 HRC]…”
  - vs. API 17A – “Section 6.4: Bolting materials for subsea applications includes ASTM A320 L7, ASTM A320 L43, ASTM A193 B7, and ASTM A193 B8M Class 1”; none match MR0175/ISO 15156

Industry Standards & Gap Analysis

Hydrogen Embrittlement – Hardness Threshold

- **Discrepancies in hardness threshold to avoid hydrogen embrittlement (cont.)**
  - API 17A: Recommended Practice for Design and Operation of Subsea Production Systems (2002).
  - "For stainless steels and non-ferrous materials, resistance against hydrogen embrittlement should be controlled by specifying that the actual hardness of the material is less than 300 HV10 [31 HRC] for the base material…
  - API 16F: Specification for Marine Drilling Riser Equipment (2010)
  - Maximum hardness for primary load-carrying components shall not exceed 35 HRC without approval from the purchaser.
  - …..

Industry Standards & Gap Analysis
Corrosion Protection – Heat Treatment

- **Discrepancies in heat treatment for corrosion protection.**
  - NACE MR0175/ISO 15156: All parent materials must undergo heat treatment.
  - ISO 21457: Hydrogen embrittlement may occur on fasteners caused by hydrogen introduced from chemical cleaning related to coating operations, e.g. electrolytic plating and HDG. Baking in accordance with ISO 9588 should be performed for chemical cleaned fasteners with an actual tensile strength greater than 1 000 MPa or hardness greater than 31 HRC.
  - ASTM F1941/F1941M (ED Coating on Mechanical Fasteners) – 15:

    6.4.1 Baking is not mandatory for fasteners with specified maximum hardness 39 HRC and below.

Industry Standards & Gap Analysis

Corrosion Protection – Heat Treatment

- **Discrepancies in heat treatment for corrosion protection (cont.)**
  - ASTM B633 Service Condition 4 (very severe) – “Exposure to harsh conditions, or subject to frequent exposure to moisture, cleaners, and saline solutions, plus likely damage by denting, scratching, or abrasive wear. Examples are: plumbing, pole line hardware.”
  - ASTM B633 – 15 (ED Coating of Zn on Fe/Steel): Pre/post treatment for the purpose of reducing risk of HE – all parts having an UTS > 31 HRC …shall be heated for stress relief.
  - Many do not include subsea conditions

Industry Standards & Gap Analysis
Bolting Materials for Sour Service

- There is only one internationally recognized standard for materials to be used in sour service environments:
  - NACE MR0175/ISO 15156 – petroleum and natural gas industries; Materials for use in H_2S-containing environments in oil and gas production
    - Defines sour water as containing at least 0.05 psi of H_2S
    - Section A.2.2.4: Bolt materials <u>must</u> be either sulfide corrosion resistant materials or ASTM A193 B7M and ASTM A320 L7M overlayed with below materials.
    - Nitriding to a max depth of 0.15mm is acceptable if conducted at a temperature lower than critical temperature

Austenitic stainless steels	Martensitic stainless steels	Duplex stainless steels	Precipitation-hardened stainless steels	Cobalt-based alloys	Titanium alloys
S31600, S31603, S20910, J93254, N08926, J95370, N04400, N04405, N10276	S41000, S41500, S42000, J91150, J91151, J91540, S42400, S41425	S31803	N07031, N07048, N07626, N07716, N07725, N07773, N07924, N09777, N09925, N09935, N09945, S66286	R30003, R30004, R30035, BS HR.3, R30605, R31233	R50400, R56260, R53400, R56323, R56403, R56404, R58640, R05200

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Industry Standards Gap Analysis: Report TOC

Table of Contents

Corrosion Tests

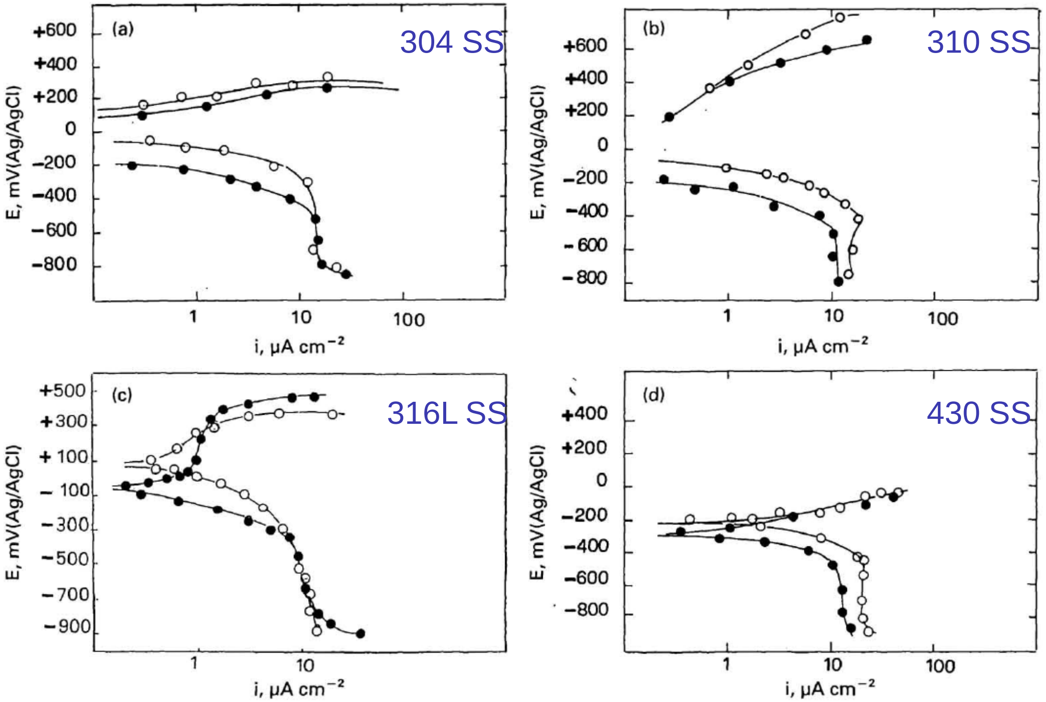
- Subsea environment:
  - High pressure
  - Media with CO_2, Cl^-, or H_2S
  - Other – T, O_2, etc.

- **Total pressure** dependence measurements
- **Oxygen partial pressure** dependence measurements
- **Temperature** dependence measurements

Influence of Total Pressure

With increasing pressure, 316L and 430 stainless steels exhibit moderately larger corrosion current (higher corrosion rate); pressure shows no distinct effect on 304 and 310 SS.

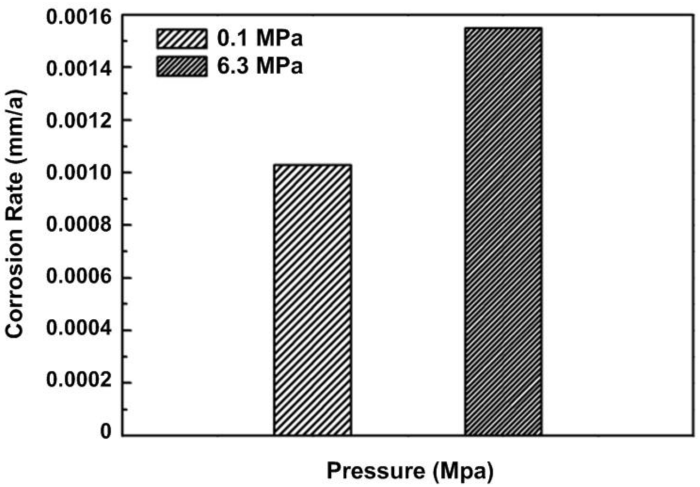
Pressure ↑ ↑ corrosion rate ↑



● 1 bar; ○ 300 bar
a 304; *b* 310; *c* 316L; *d* 430

1 *Polarisation of stainless steel specimens after 4 h preimmersion in sea water at given pressures*

A. M. Beccaria, et al., *British Corrosion Journal*, 30 (2013) 283-287



Corrosion rate of X60 pipeline steel under different pressures.

X. Fang, et al., *Corrosion Science and Protection Technology*, 25 (2014) 431-435.

Influence of Oxygen Concentration

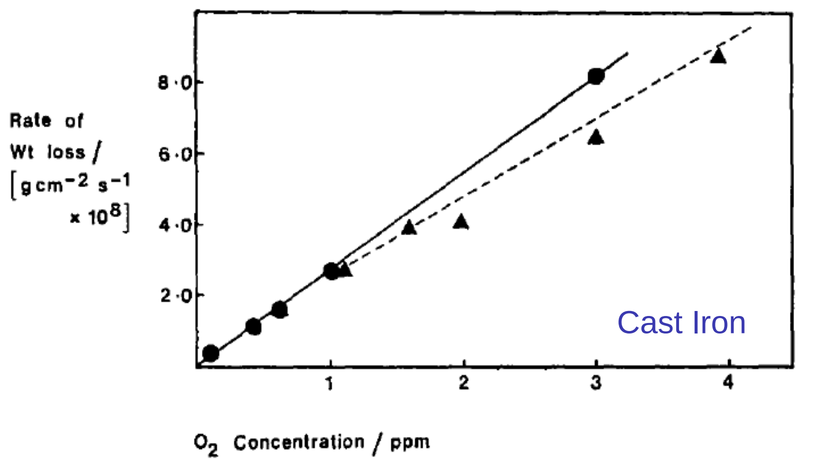


FIG. 9. The dependency of initial corrosion rates upon O_2 concentration; circles, from initial corrosion rates; triangles, from 6 h experiments.

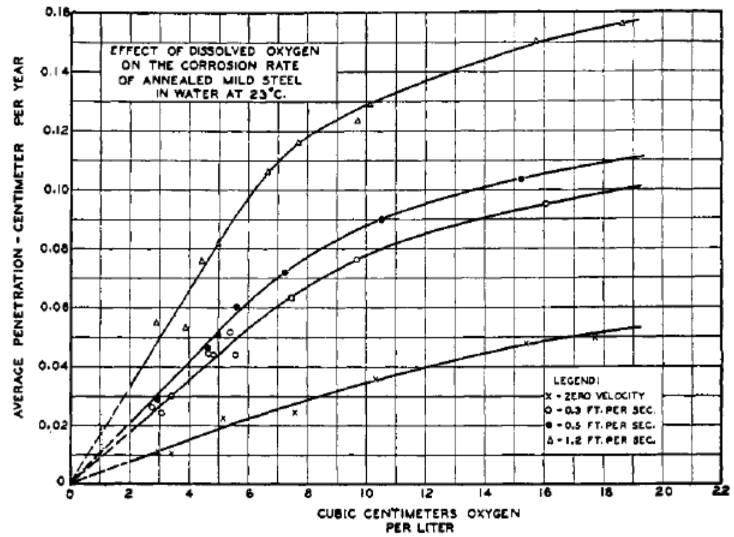


Figure 4

Low Carbon Steel

D. C. Smith, et al., *Corrosion Science*, 19 (1979) 379-394

G. L. Cox, et al., *Industrial & Engineering Chemistry*, 23 (1931) 1012-1016

The corrosion rate increases with the increasing oxygen concentration.

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Influence of Temperature

With increasing temperature, the pitting potential and passive current density increased.

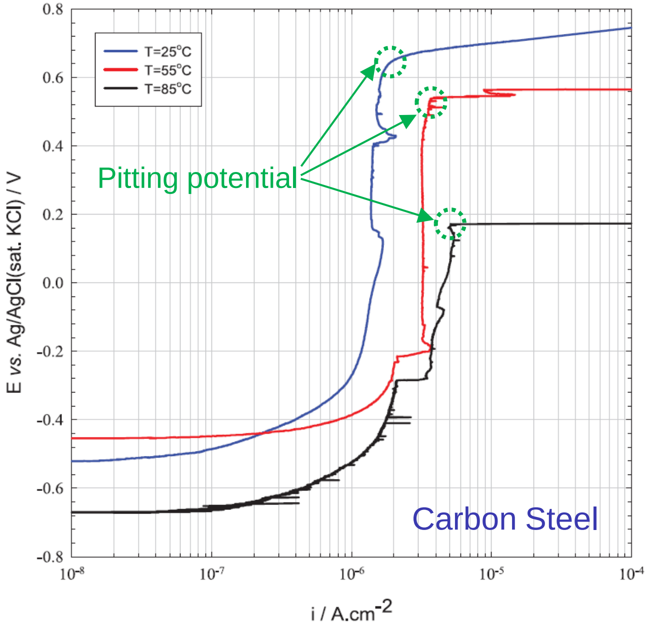

Fig. 7. Potentiodynamic scans performed on carbon steel in saturated $Ca(OH)_2$ + 0.1 M NaCl as a function of temperature (scan rate of 0.1667 mV s^{-1}).

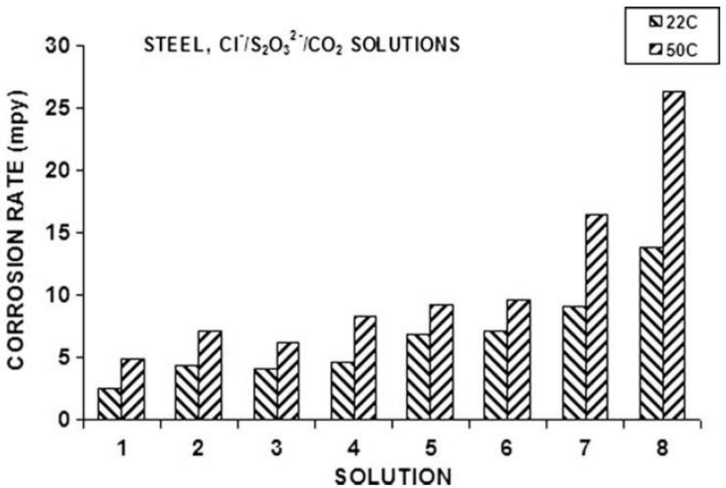

Fig. 1. Effect of temperature on the corrosion rates of steel in $Cl^-/S_2O_3^{2-}$/sat. CO_2 system; (1) 1 M NaCl, (2) 1 M NaCl + CO_2 (sat.), (3) 1 M NaCl + 0.01 M $Na_2S_2O_3$, (4) 1 M NaCl + 0.1 M $Na_2S_2O_3$, (5) 1 M NaCl + 1.0 M $Na_2S_2O_3$, (6) 1 M NaCl + 0.01 M $Na_2S_2O_3$ + CO_2 (sat.), (7) 1 M NaCl + 0.1 M $Na_2S_2O_3$ + CO_2 (sat.) and (8) 1 M NaCl + 1.0 M $Na_2S_2O_3$ + CO_2 (sat.).

S. Sharifi-Asl et al., *Corrosion Science,* 98 (2015) 708-715 H.M. Ezuber et al., *Materials and Design,* 30 (2009) 3420–3427

Corrosion Study Timeline

Timeline	Months							
Task	09/2016	10/2016	11/2016	12/2016	01/2017	02/2017	03/2017	04/2017
Sample production (US Bolts)								
Experiment preparation and set up								
Ambient total pressure test (4 ^oC) *								
5000 psi total pressure test (4 ^oC)								
Oxygen partial pressure ≤ 0.4ppb (25 ^oC) *								
Oxygen partial pressure ~ 21% (25 ^oC)								
Mechanical test & SEM, XRD analysis								
Summary and Report								

* Temperature dependence results will be obtained from the data based on these tests.

Subsea Bolts Performance and Critical Drill-through Equipment Fastener Study

Part I
Industrial Standard Review and Gap Analysis

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Part II.
Materials corrosion under subsea environment

6. --- ---

Acknowledgements

- Roy A. Lindley (ANL)
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BSEE
Bureau of Safety and Environmental Enforcement

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