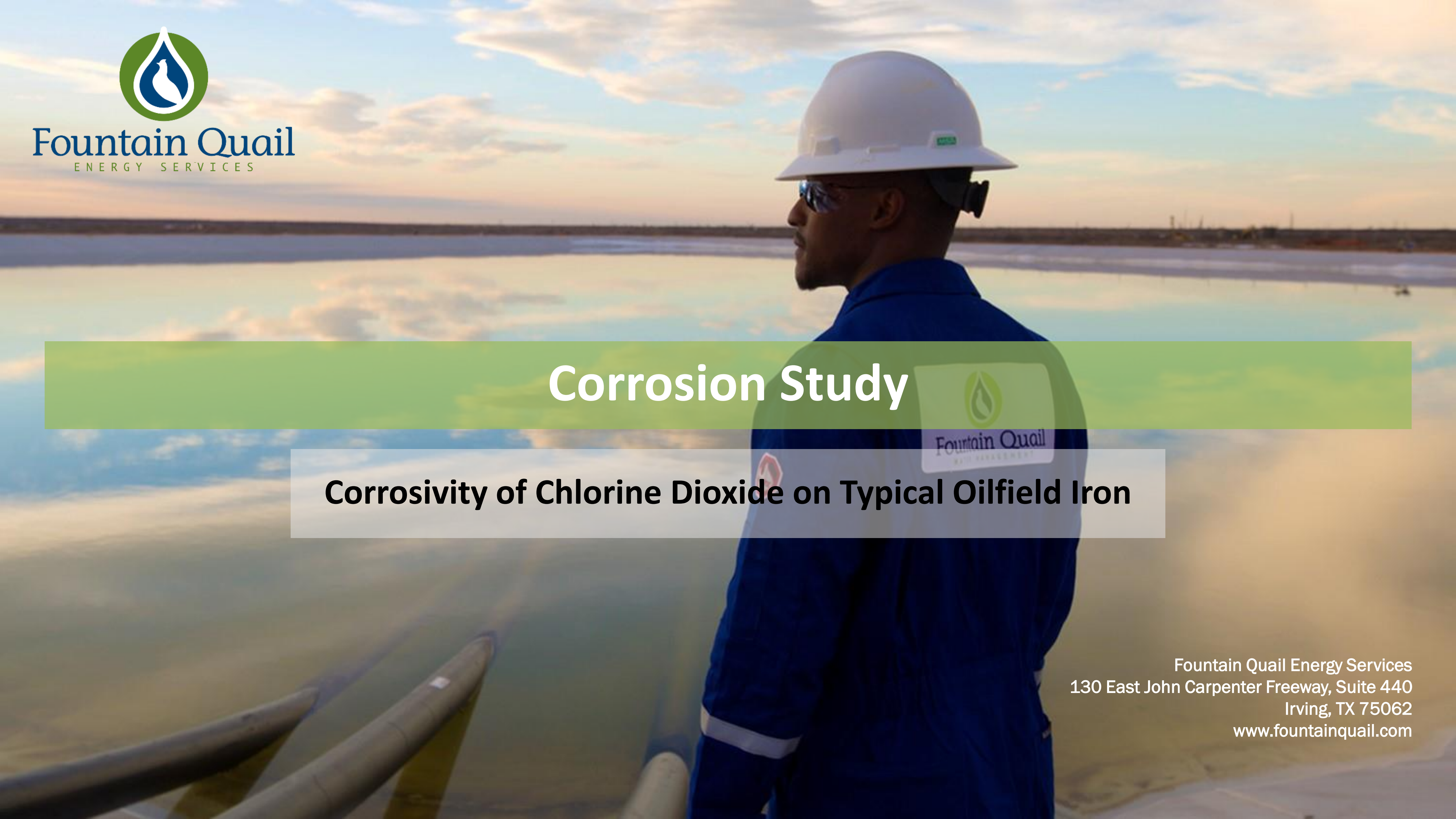

Corrosion Study

Corrosivity of Chlorine Dioxide on Typical Oilfield Iron

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Introduction

- Background
- Test Goals and Procedure
- Summary
- Equipment
- Fluid System
- Test Execution
- Results and Analysis

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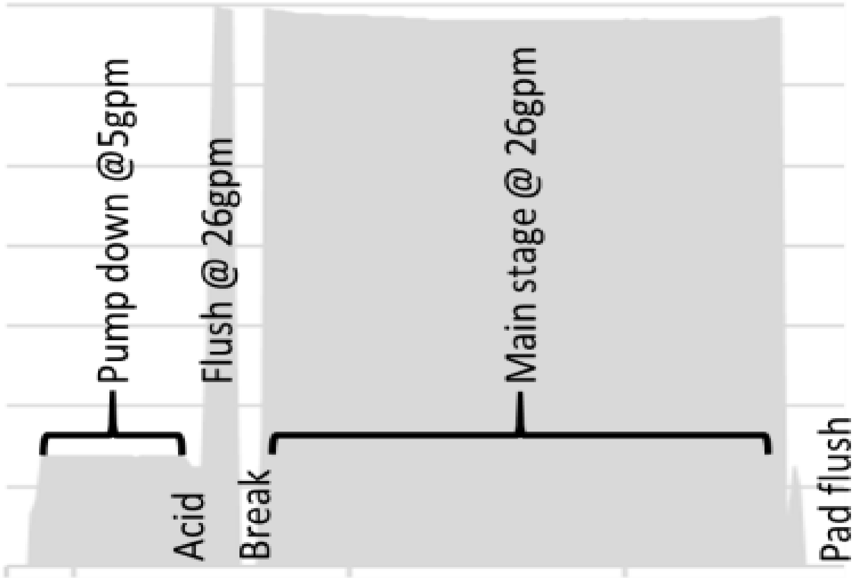
Background

- Concern about impact of chlorine dioxide ClO_2 on fluid ends and flow iron
- Current corrosion studies unrepresentative (static vs. dynamic tests)
- A test was needed that simulated flow conditions, fluid chemistry, and typical alloys used in hydraulic fracturing

Goal

Determine the effect chlorine dioxide (ClO_2) has on common field iron used in hydraulic fracturing flow and pressure pumping equipment at

a. Typical dose rates
b. In a traditional slick water hydraulic fracturing fluid chemistry
c. Using both fresh and brine water solutions
d. In a dynamic flow environment

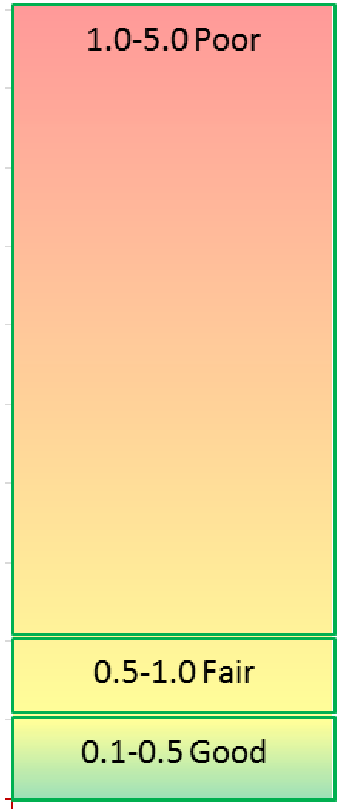


Plan

- Design a test to simulate flow conditions, alloys, and typical fluid chemistries
- Use fresh and brine solutions
- Mimic the steps in a conventional frac stage
- Establish a baseline using fluid systems without ClO_2, then repeat with ClO_2
- Repeat each stage and fluid system to reduce uncertainty
- Measure critical parameters to ensure consistency between stages
- Quantify corrosion rates using multiple sensors
- Analyze data to assess impact of ClO_2 on selected alloys

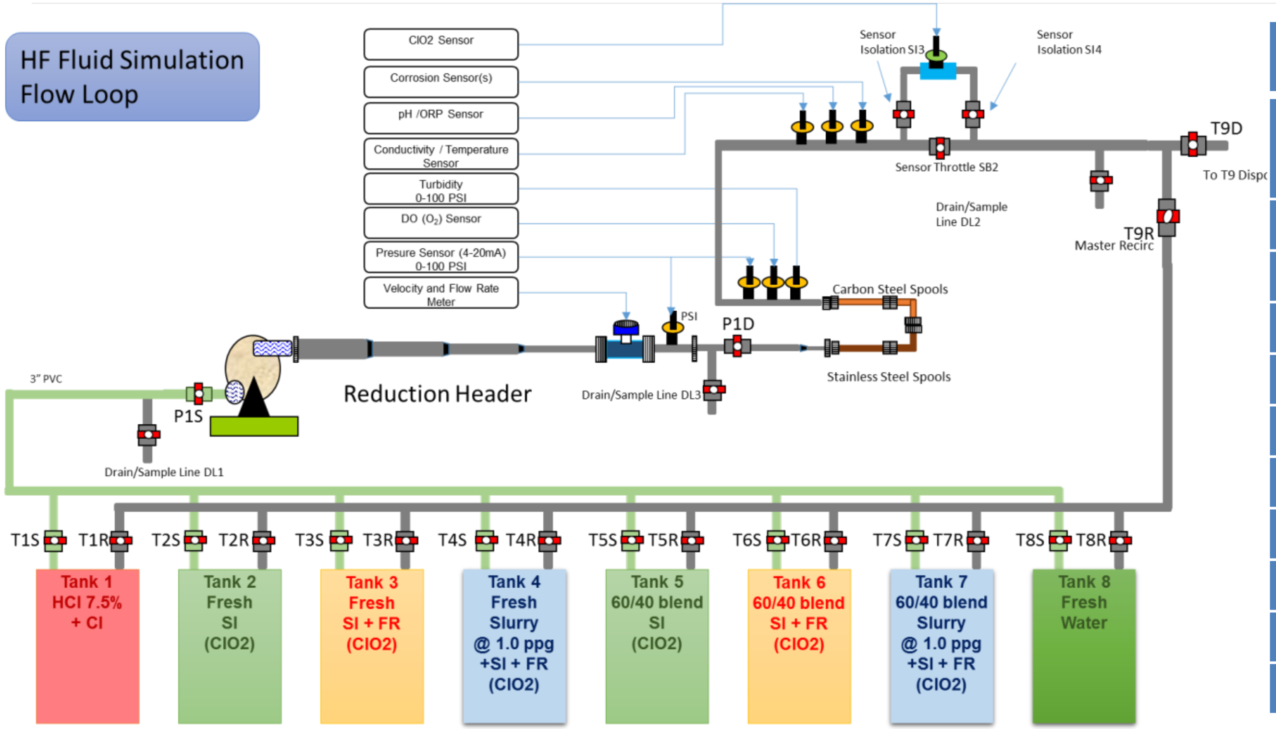
Summary

- Carbon steel (CS) corrosion rates were poor (1-5 mm/yr)
- Stainless steel (SS) corrosion rates were good (<0.5 mm/yr)
- Corrosion rates of CS in brine were over 30% higher than fresh
- Overall there does not appear to be any statistically significant impact of the ClO_2 in either fresh nor brine water solutions
- ClO_2 did not increase O_2 levels in any of the fluid systems used



Corrosion ranges taken from Corrosion Engineering (1986) by Mars G. Fontana, McGraw-Hill Book Co., NY, ISBN: 0-07-021463-8

Test Fixture and Flow Plan



	4" Pipe		¾" Pipe		Flow Loop	
Stage Simulation	Flow (BPM)	Velocity (FPS)	Flow (GPM)	Velocity (FPS)	Run Time (Minutes)	Volume (gal)
Water only	2.0	2.1	3.0	2.2	3.0	9.0
Pump Down	3.5	3.8	5.0	3.6	32.0	160.0
Break	3.0	3.2	4.5	3.3	2.0	9.0
Acid Phase	7.0	7.5	10.5	7.3	1.0	10.5
Flush	17.5	18.8	26.0	18.8	6.0	156.0
Pause					5.00	
Water Pad	17.5	18.8	26.0	18.8	5.0	130.0
Slurry	17.5	18.8	26.0	18.8	100.0	2,600.0
Flush	17.5	18.8	26.0	18.8	6.0	156.0
Total					160.0	

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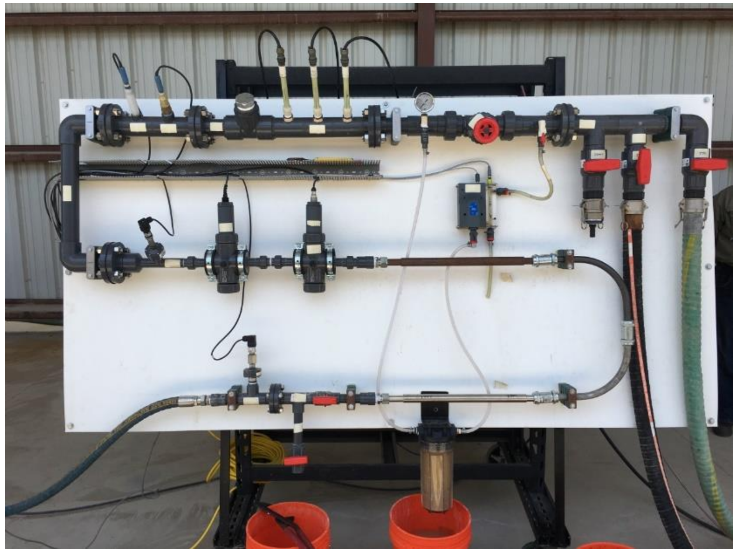
Test Facility

Instrumentation

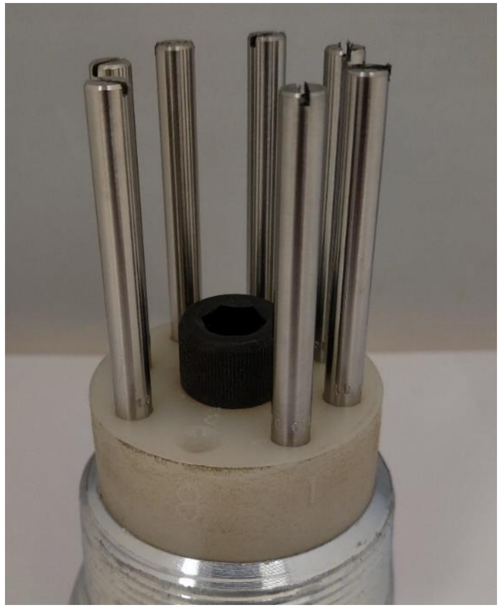
- Chlorine Dioxide (ClO_2):Kuntze Zircon™ DIS Sensor Model No:231512110
- Dissolved Oxygen (DO): Endress+Hauser: Oxymax COS61D Model No: COS61D-1014/0
- Conductivity: Endress+Hauser: Condumax CLS21D Model No: CLS21D-C1N1
- Turbidity: Endress+Hauser: Turbimax CUS51D Model No: CUS51D-10V6/0
- pH & ORP: Endress+Hauser: Memosens CPS16D Model No: CPSD16D-1009/0
- Pressure: Burkert Type 8323 S 0-200psig
- Flow: Endress+Hauser ProMass 100 Flowmeter



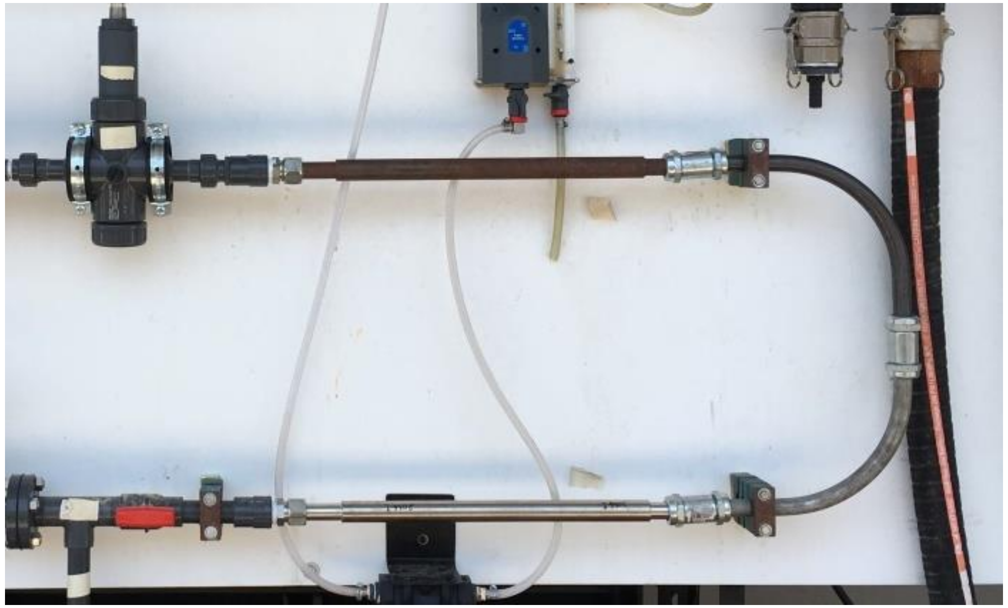
Corrosion Monitoring

Three methods of measuring corrosion were used

LPR Probes using 304SS, 316SS, and 4130CS electrodes



Seven cylinder coupons (4130CS, 4140CS, 4150CS, 4340CS, 17-4SS, 304SS, 316SS)



7.3ft of 0.75” ID tubular components (CS, 304SS)

Test Plan – Fluid Summary

- The simulated frac fluid consisted of friction reducer, scale inhibitor, and 100 mesh sand at 1ppg
- The acid phase used 7.5% HCl with corrosion inhibitor @ 2.5 gpt
- On Day 3 and 4 water was treated with ClO_2 to a 5ppm residual before beginning each stage

Scale Inhibitor @ 0.25gpt

SC-30 sourced from X-CHEM (0.25gpt)

0.5 – 1.5%	Sodium hydroxide

Friction Reducer @ 1.0gpt

TFR-24La sourced from Tucker Energy Services (1.0gpt)

15-20%	Petroleum Distillate
< 1%	Ammonium Chloride
<1%	Oleic Acid Diethanolaide
50 -60%	Water

Corrosion Inhibitor @ 2.5gpt

TCA-6038 sourced from X-CHEM (2.5gpt)

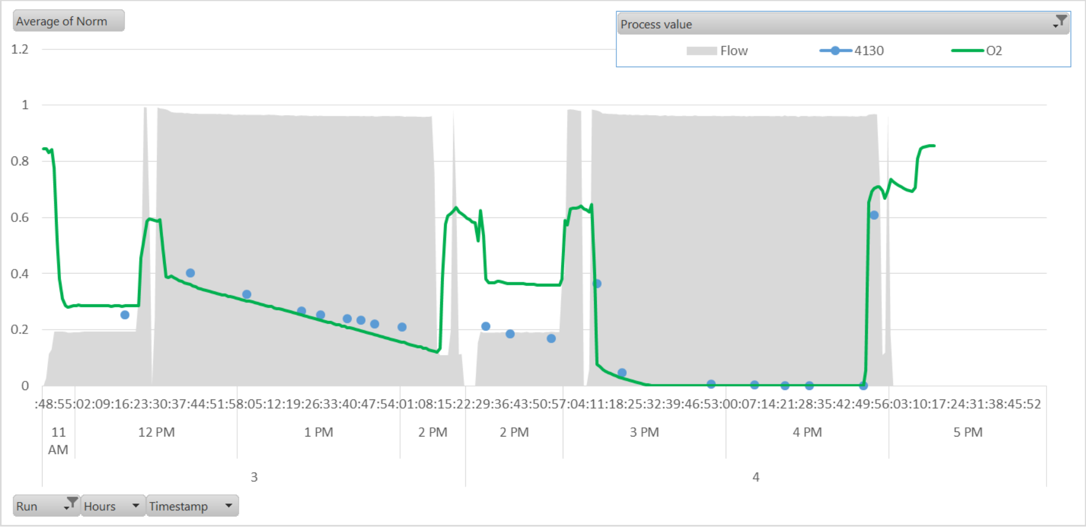
50 -70%	Methanol
20-30%	Pyridine Benzyl Quaternary Ammonium Chloride
5-10%	Water

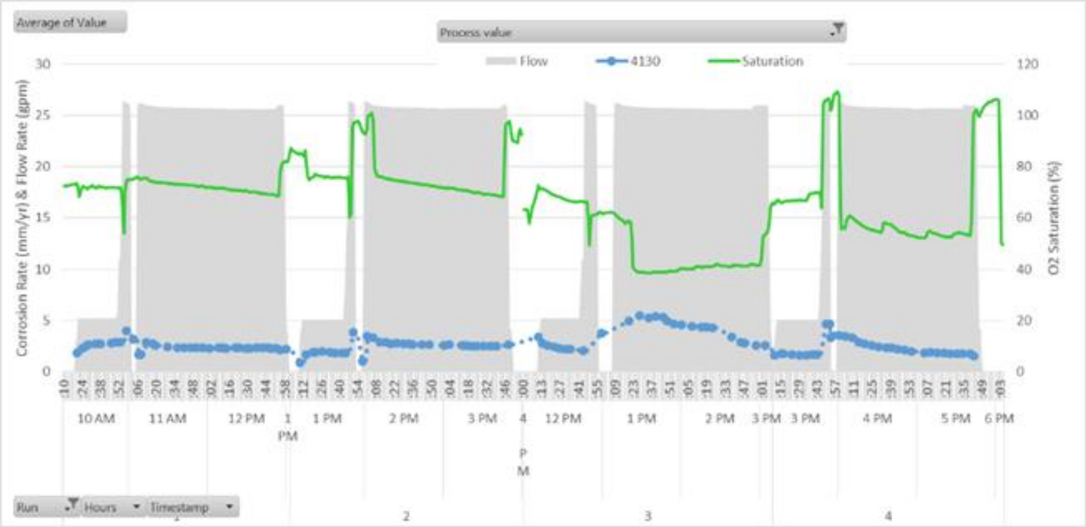
Test Summary

- Testing conducted on Monday, July 24, 2017 through Thursday, July 27, 2017
- Four days of testing divided into two simulated frac stages per day
- Each stage was approximately 3 hours and consisted of six phases
  ①pump down ②acid ③flush ④pad
  ⑤proppant ⑥final flush
- Flow loop was flushed each day and left full to keep sensors wet.

Test Plan B

- O_2 in Slurry Tank dropped unexpectedly
- Corrosion rates were significantly lower
- Corrosion data was compromised resulting in the loss of a baseline
- A "recycle" of the 60/40 test was needed
- "Fresh" produced water was acquired
- Brine test was run again on Oct 3-4
- O_2 Levels were consistent

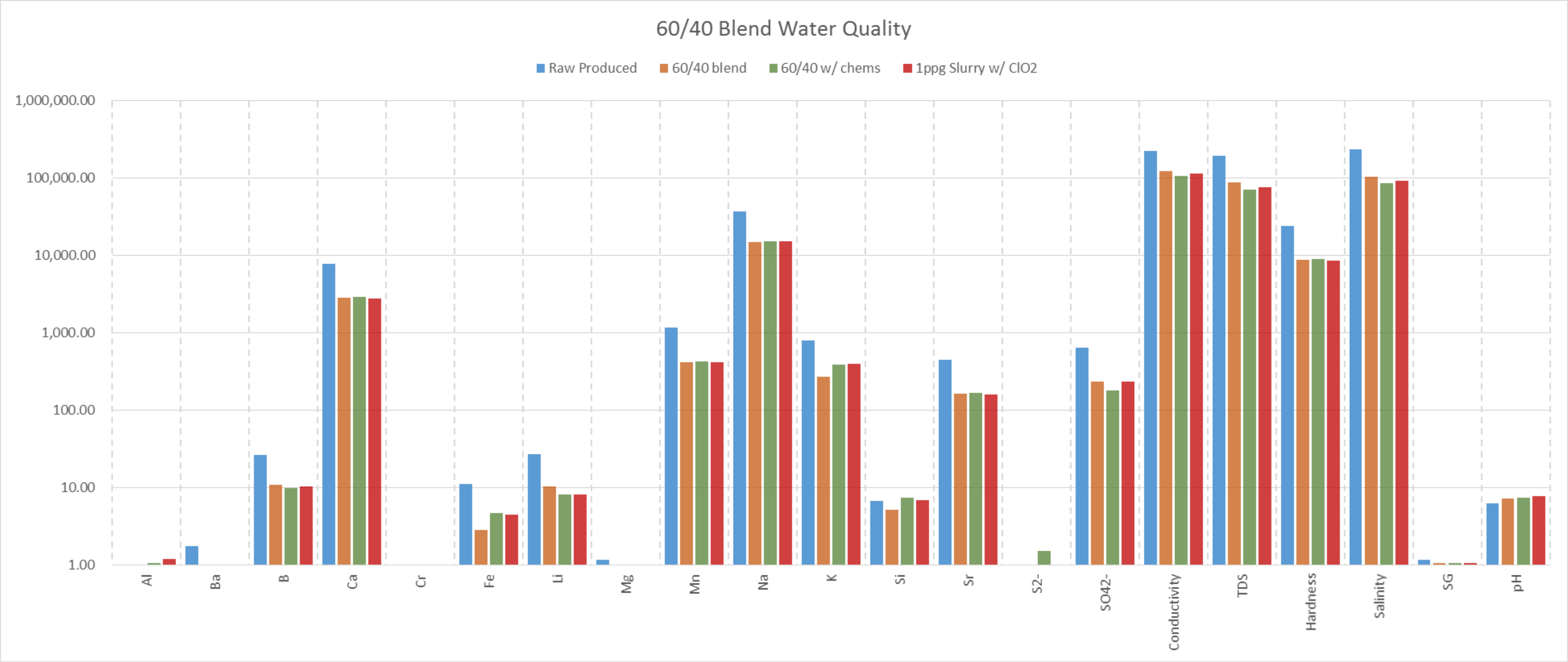




Fresh Water Quality

- Elements with concentrations < 1.0 are not shown

Produced Water Quality



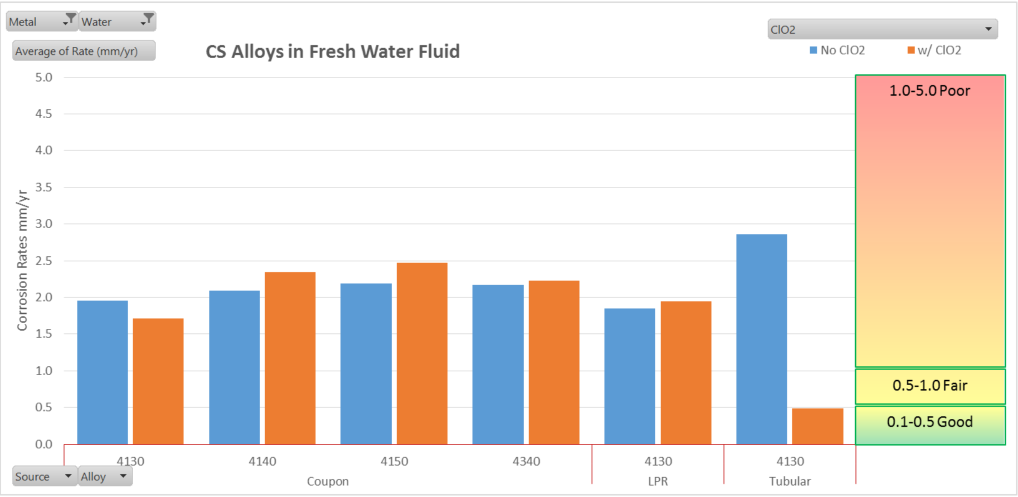
Results and Analysis

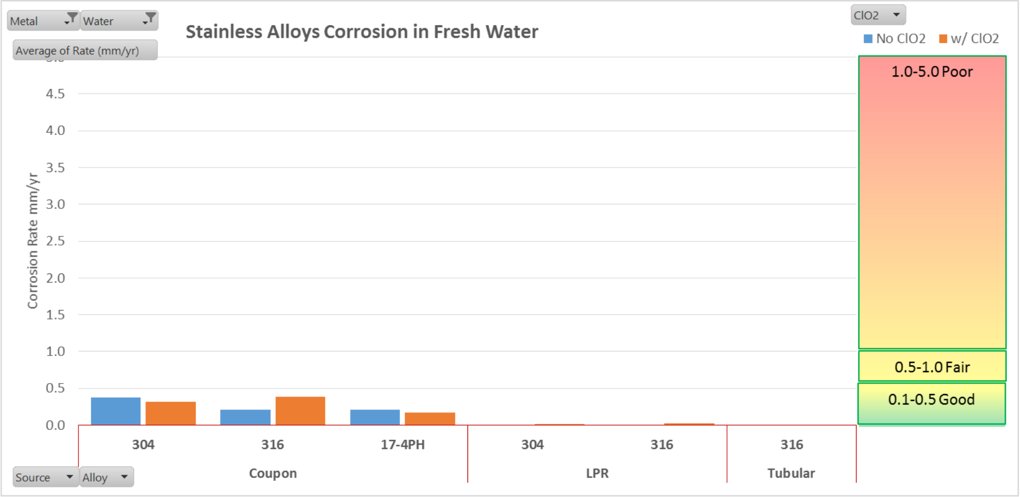
Results

Carbon Steel Alloys

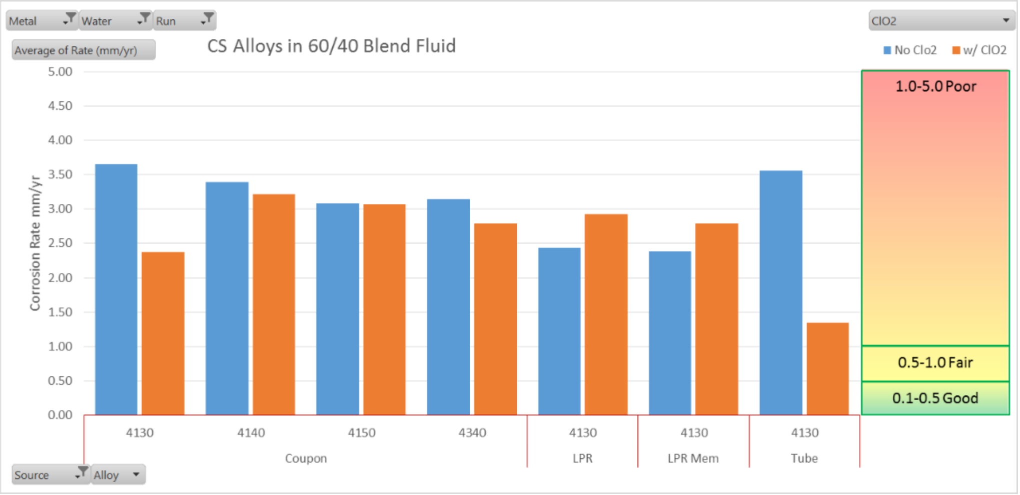
Stainless Steel Alloys

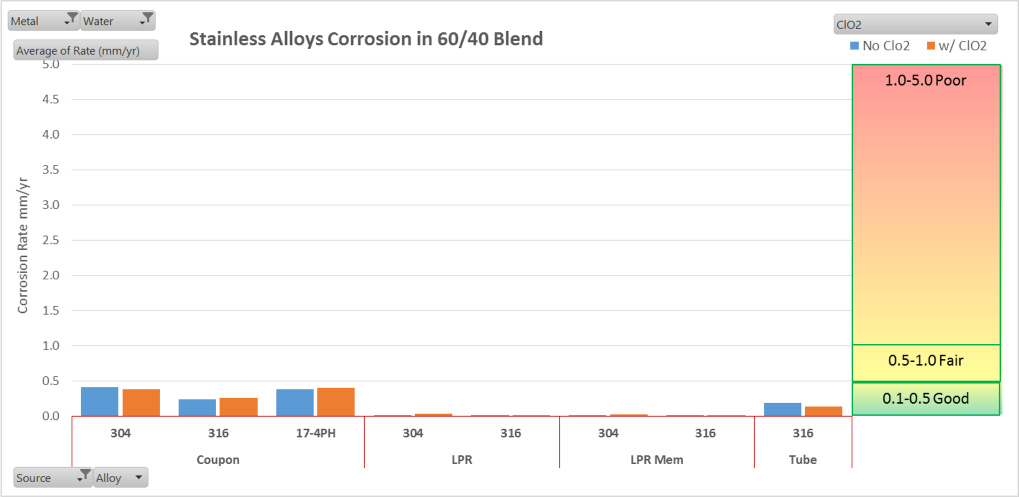
Fresh Water





60/40 Blend





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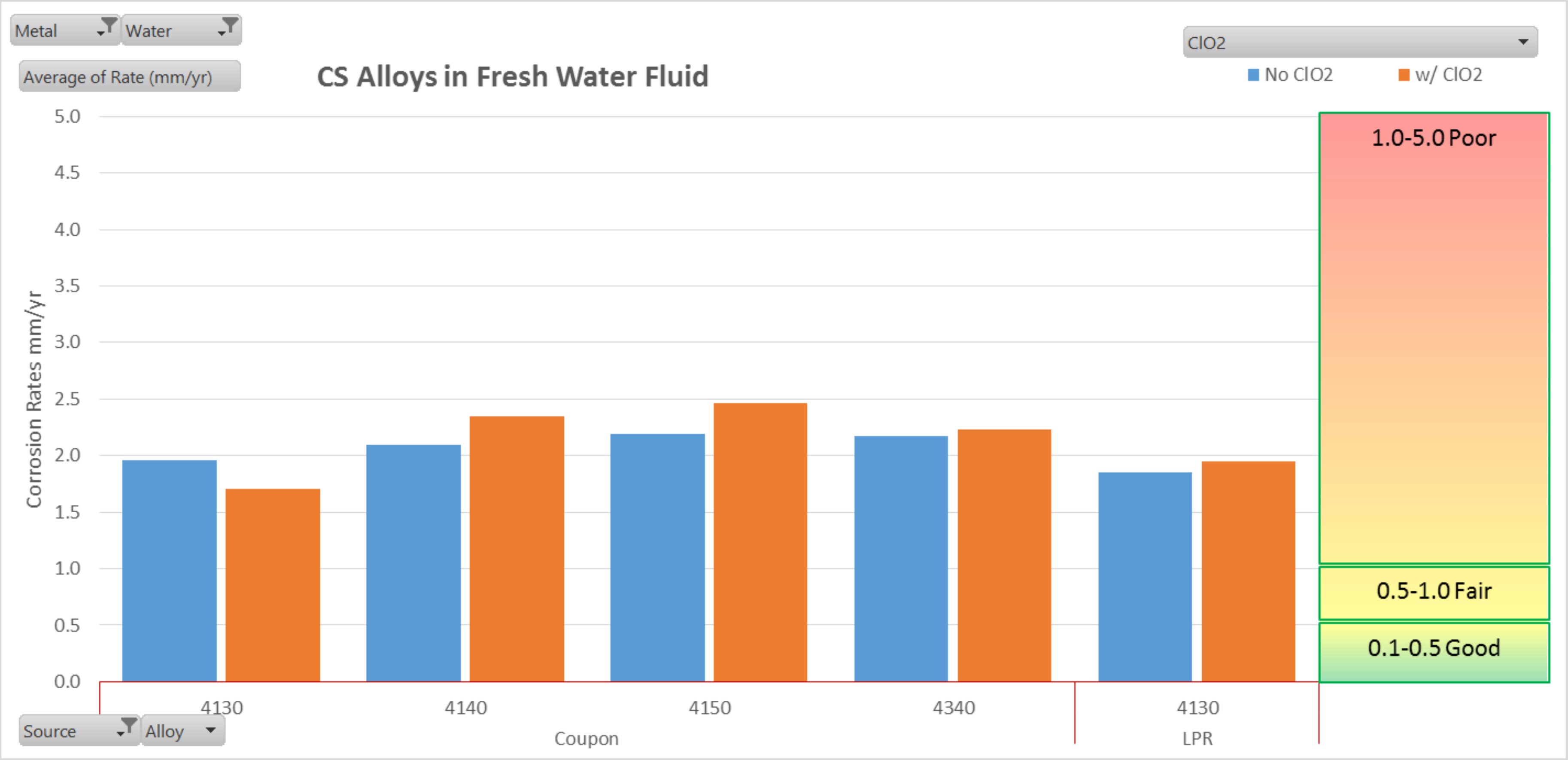
Corrosion ranges taken from Corrosion Engineering (1986) by Mars G. Fontana, McGraw-Hill Book Co., NY, ISBN: 0-07-021463-8

Carbon Steel Individual Coupons (Fresh Water)



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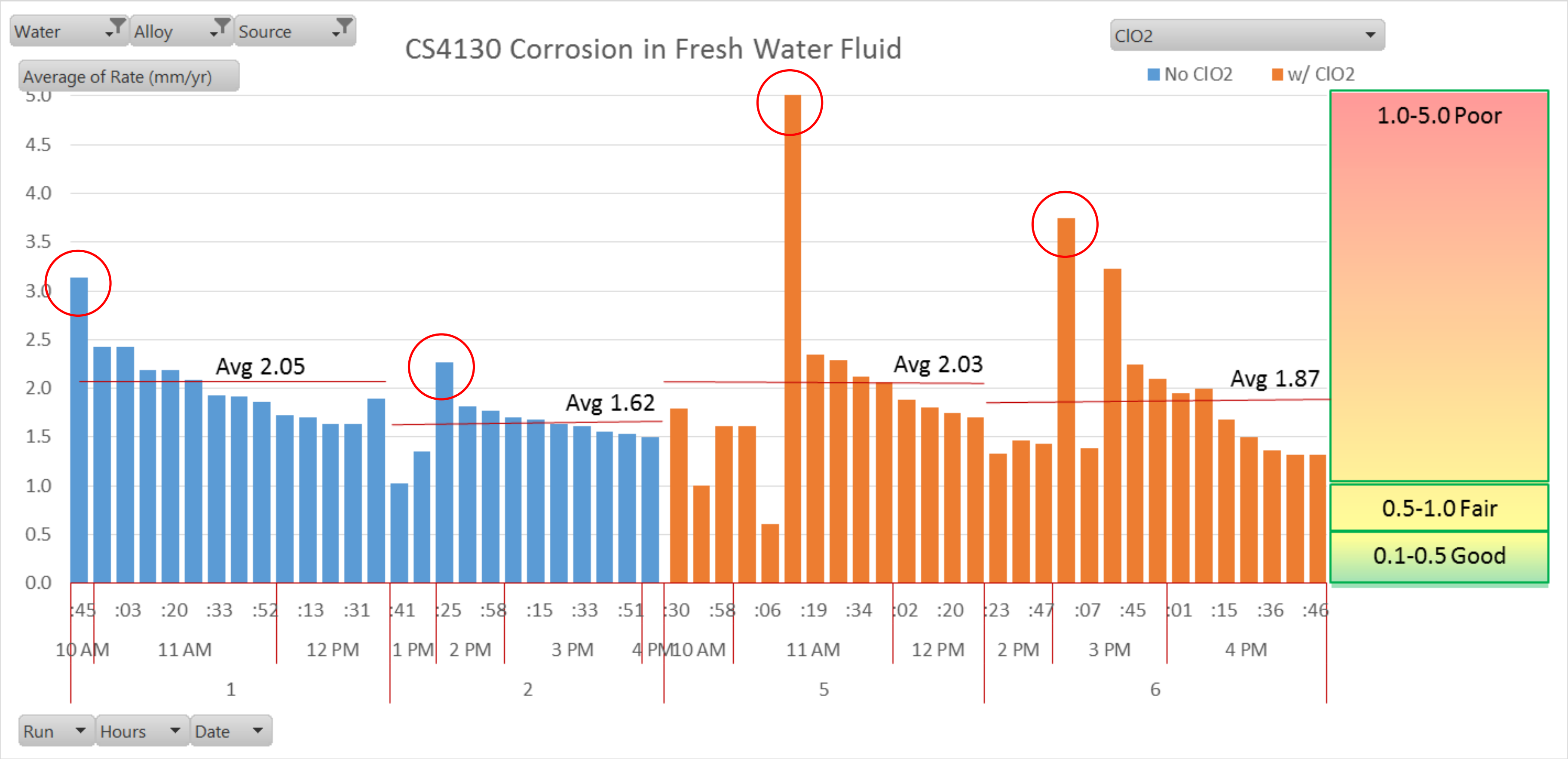
CS4130 Alloy (Fresh Water)

The spikes in corrosion are a reaction to the acid pad, but rates dropped back to a lower equilibrium each time.



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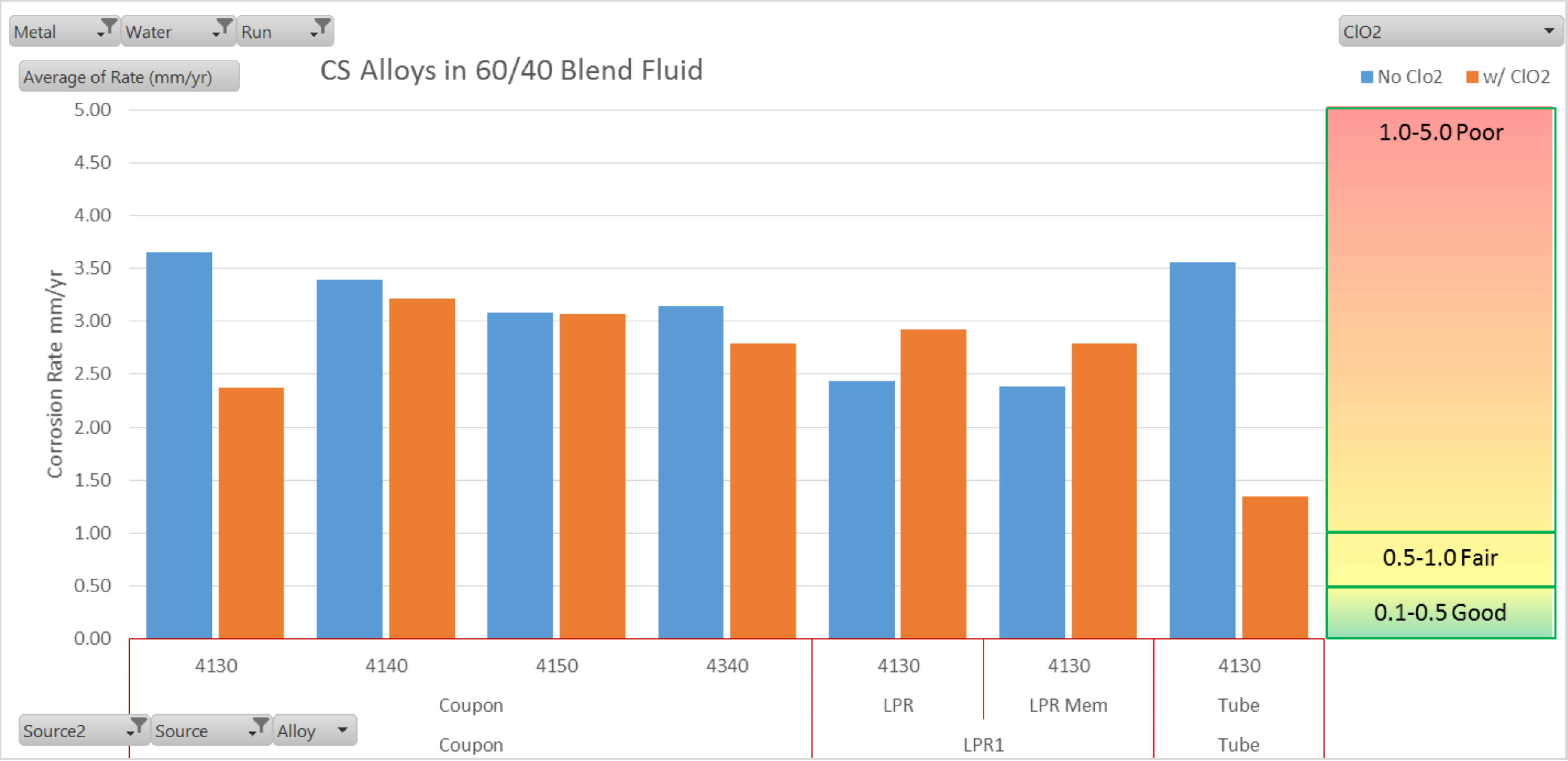
Carbon Steel Coupons Averages (A&B) (60/40)



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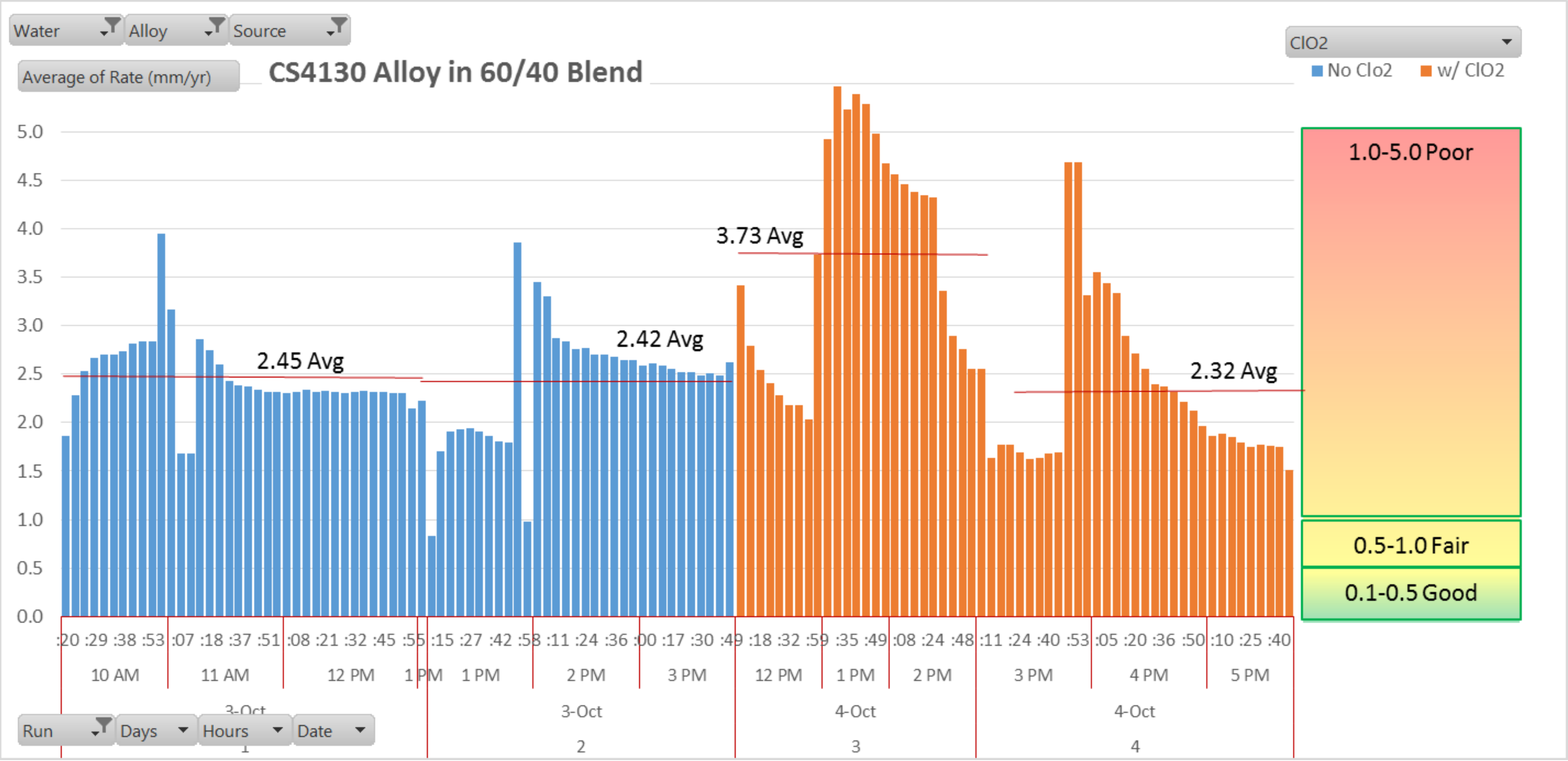
CS4130 Alloy in 60/40 Blend



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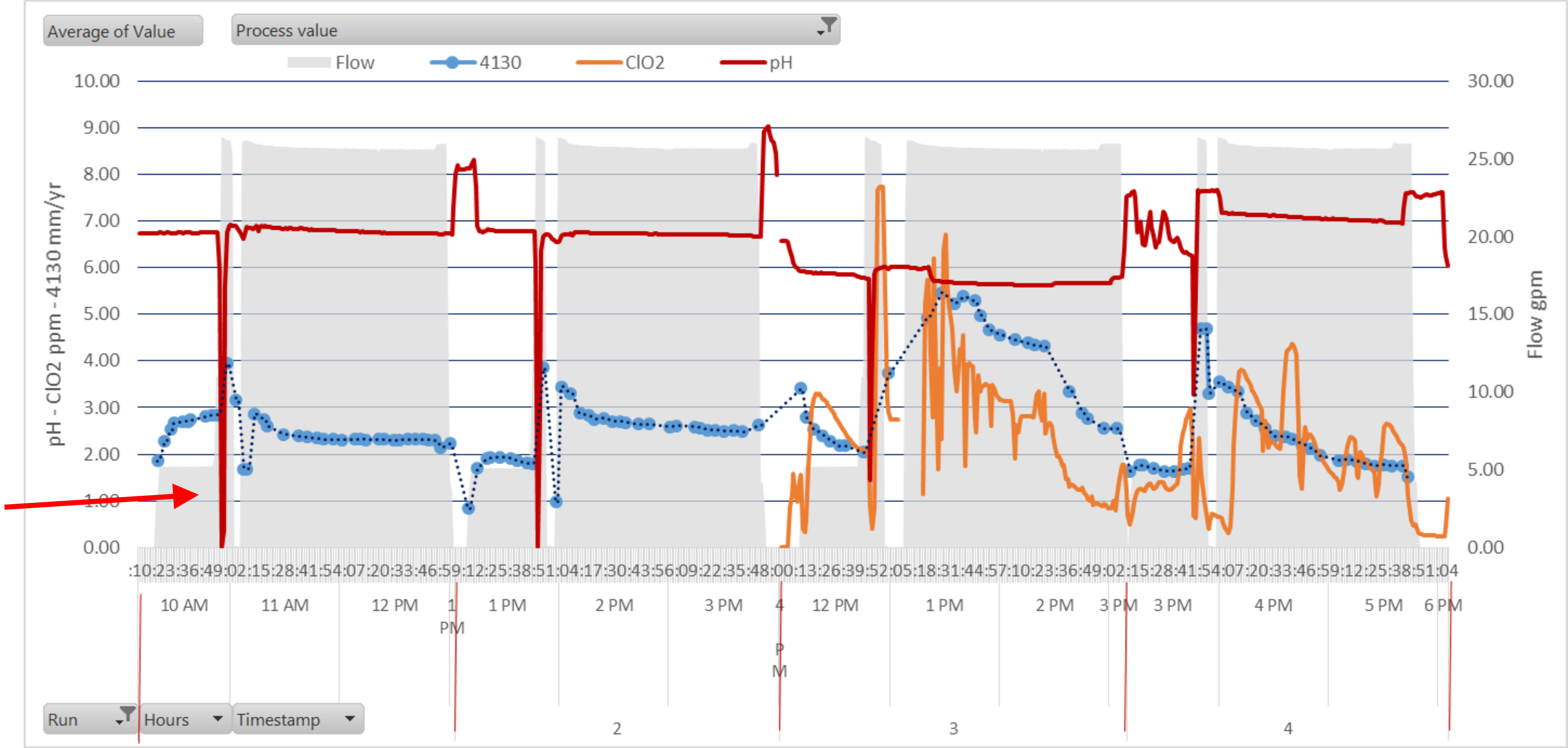
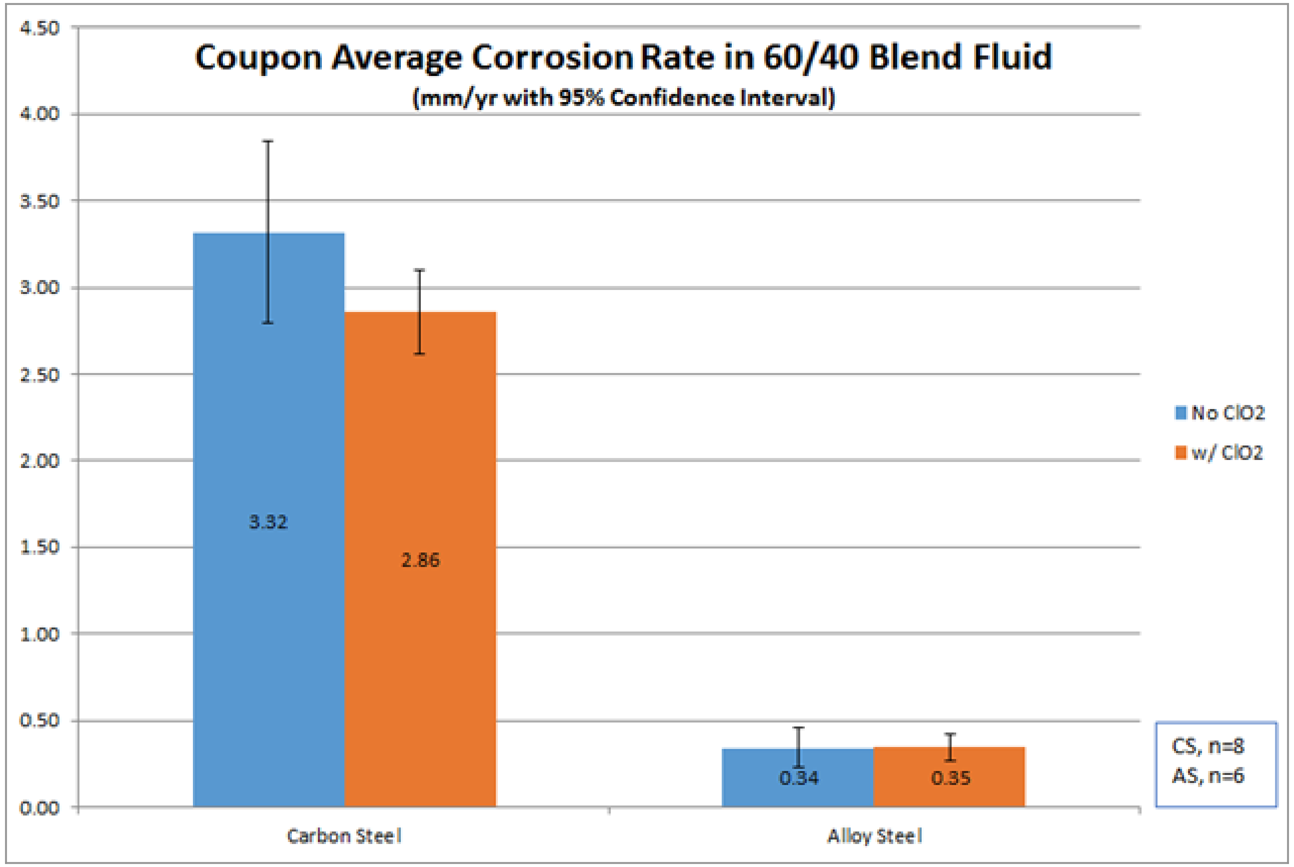
4130 Corrosion in 60/40 Blend w/ ClO2 Residuals & pH



Note the low pH spikes resulting from the acid pad residual flushing thru the system

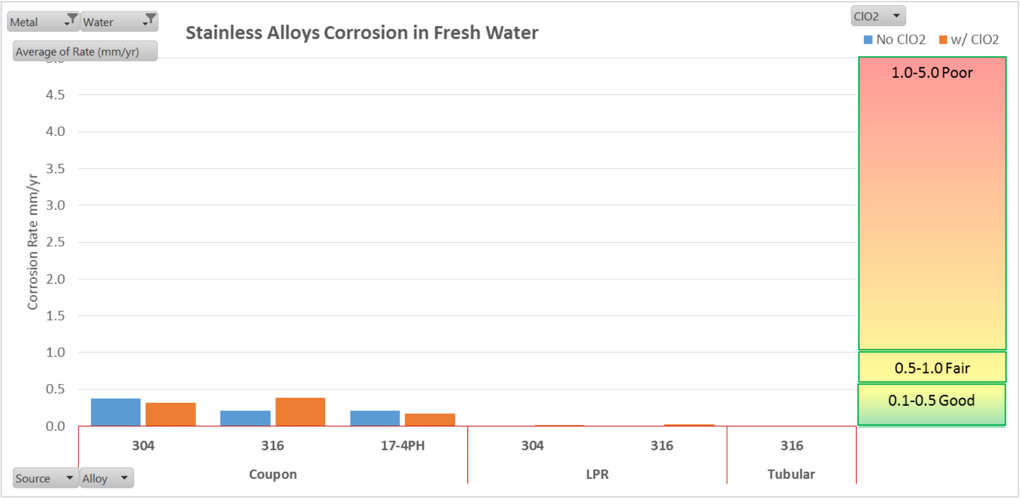
Carbon Steel Statistical Analysis

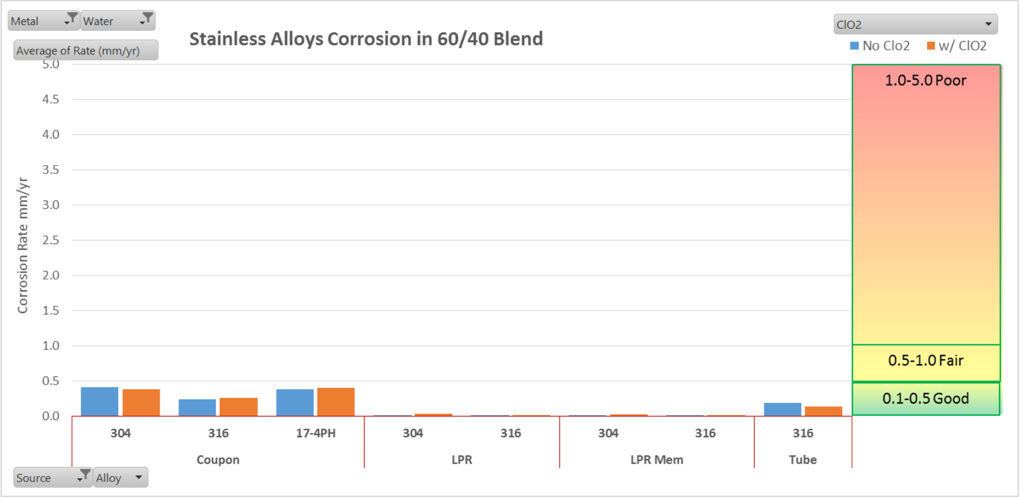
- Statistical analysis of the corrosion coupon data in the 60/40 blend shows no statistically significant difference with or without addition of ClO_2 in either group.
- This can be seen graphically in the overlap of confidence intervals.



Stainless Alloys

- Corrosion of the stainless alloys was consistently in the excellent to good range
- No statistically significant impact of the ClO_2 in either fresh nor brine water solutions
- The average of both observed and memory LPR data was <0.1 mm/yr while coupon corrosion rates were <0.29 mm/yr in fresh water and <0.35 mm/yr in the 60/40 blend





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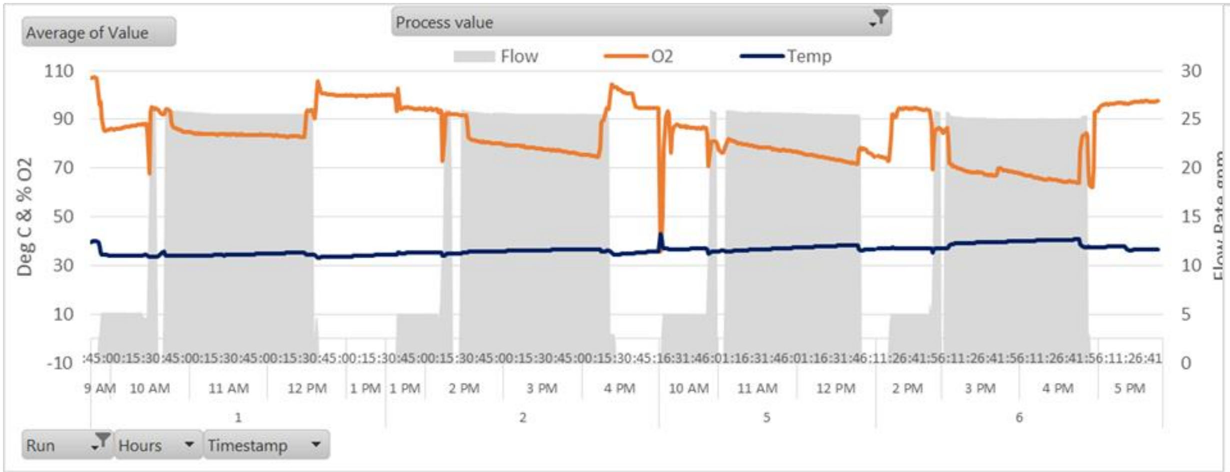
Conclusions

Conclusions – Water Chemistry

1. ClO_2 did not change water chemistry
2. ClO_2 did not increase O_2 saturation
3. Excess acid in poor quality ClO_2 effected carbon steel when pH < 5.8 and ClO_2 residuals > 3.0



Fresh Water O_2

Brine O_2

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Conclusions - Corrosivity

Fresh Water	Brine Water
The application of ClO_2 had very little effect on stainless alloys	The application of ClO_2 had very little effect on stainless alloys
Carbon steel corrosion rates showed some slight increase but less than 4% overall	Carbon steel (CS) corrosion rates were over 30% higher than fresh water
	CS exposed to low pH and high ClO_2 residuals appears more susceptible to corrosion
	Adding ClO_2 shows no detrimental impact over a statistically significant population of CS samples and test runs

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Acknowledgements

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- Mark Thompson
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- Terry Ballard
- Brian Bost

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- ERCO Worldwide

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  - Alan Burke
  - Scott Glynn
  - Bill Hulsman

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Questions?

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