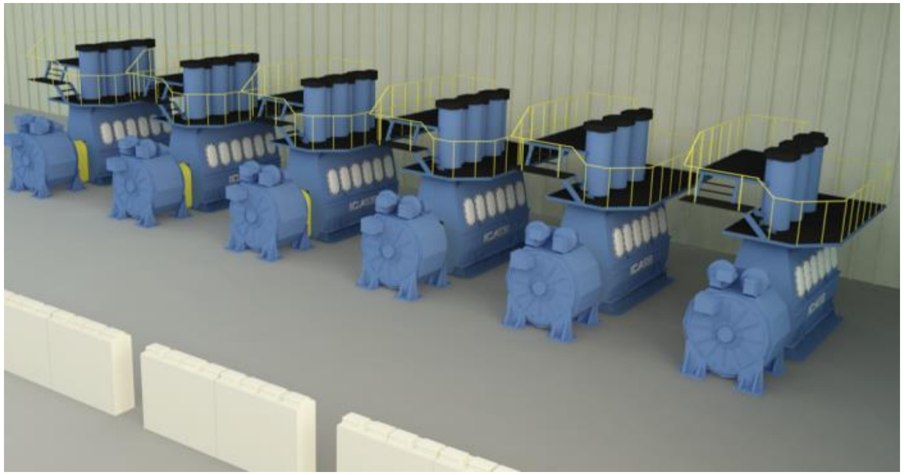
SustainX
SMARTER ENERGY STORAGE

ICAES



Lab Corrosion Tests
13 July 2012

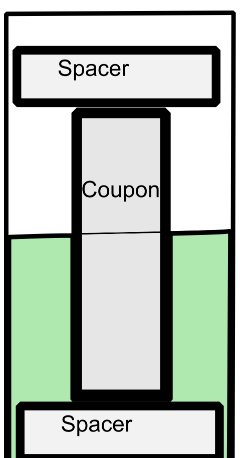
Sunapee Wetted Components
Corrosion
11 March 2014

The purpose of the pressure cycling test stand is to determine the effectiveness of anti-corrosive liquids in preventing corrosion on coupons made of pipeline carbon steel, API5L X70, while undergoing high levels of stress from large pressure changes, atmospheric to 3000 psi, while in a high O2 environment with a degassing liquid .

Coupons Positioning						
Low Pressure Spinning	Q-807 IS (5%) Biosoft (1%)	Q-807 IS (5%)	Q-807 WP (5%) Biosoft (1%)	Q-807 WP (5%)	TRAC100 (.25%)	Distilled H2O (100%)
High Pressure Spinning	Q-807 IS (5%) Biosoft (1%)	Q-807 IS (5%)	Q-807 WP (5%) Biosoft (1%)	Q-807 WP (5%)	TRAC100 (.25%)	Distilled H2O (100%)

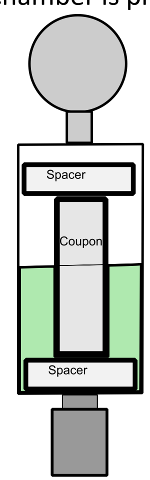
LP Chamber

The low pressure rotating part of the test stand will reuse the chambers and mounting brackets from the previous test stand. The chamber is made of acrylic and the carbon steel coupon is held in between two UHMW spacers.



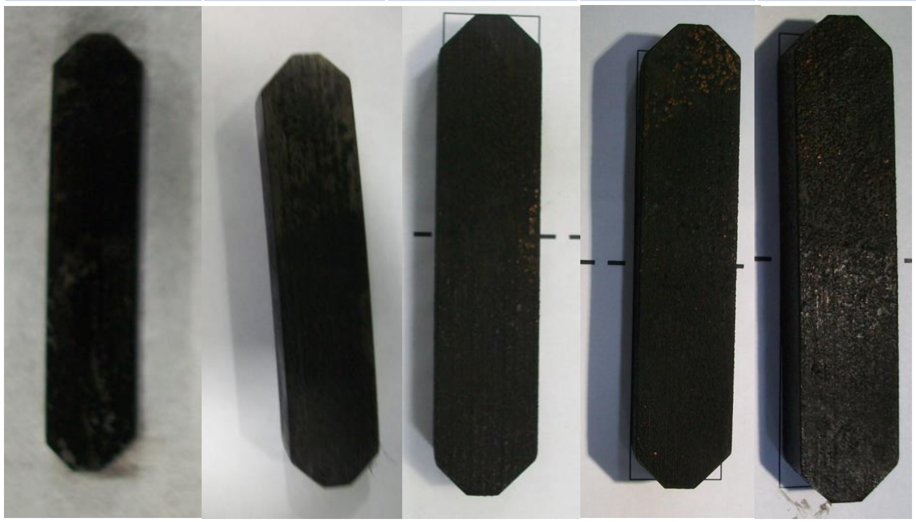
HP Chamber

The high pressure rotating part of the test stand will also reuse the high pressure chambers and mounting brackets from the previous test stand. The chamber is made of 316 stainless steel and the carbon steel coupon is held in between two plastic spacers. The chamber is pressurized to 2500 psi.



H_2O

LP: Atmospheric				
Week 1	Week 2	Week 3	Week 4	Week 5

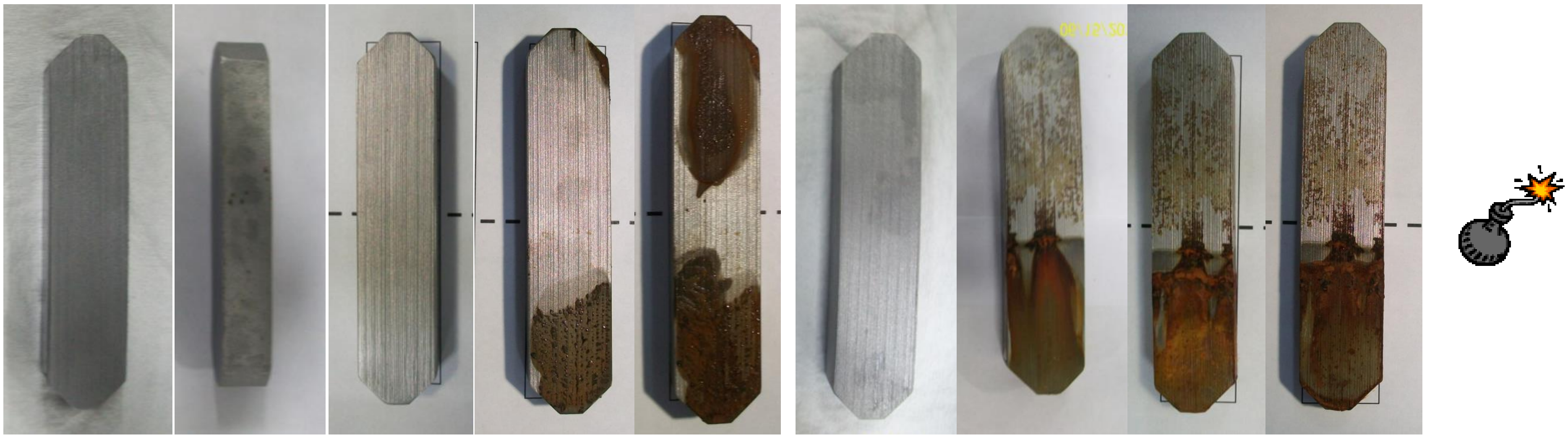


HP: 2500 PSI				
Week 1	Week 2	Week 3	Week 4	Week 5

- Results with plain water generally as expected
  - Black rust (Fe_3O_4, magnetite), low O_2 partial pressure
  - Red rust (Fe_2O_3, hematite); high O_2 partial pressure

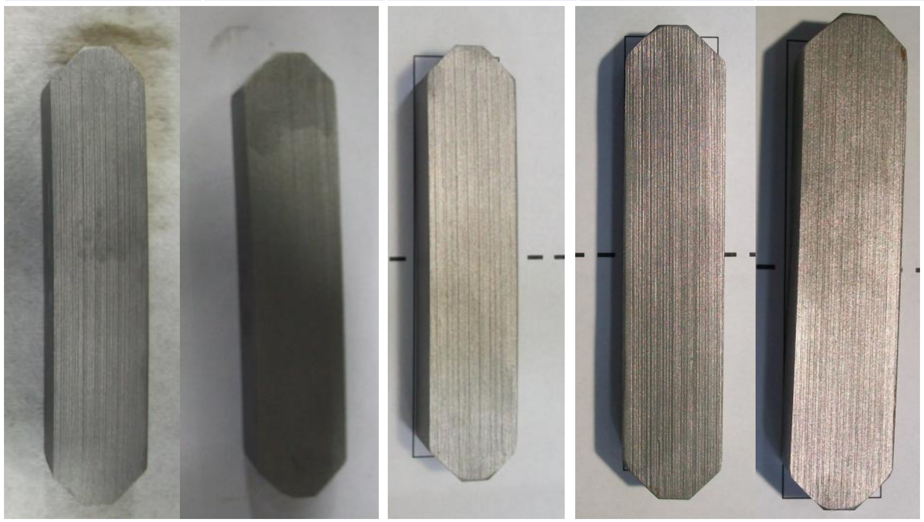
TRAC100 (0.25%)

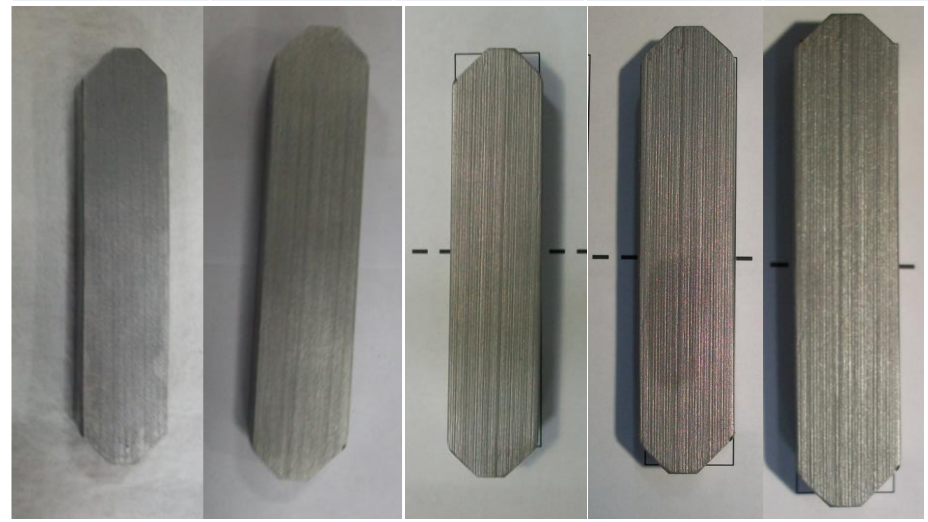
LP: Atmospheric					HP: 2500 PSI				
Week 1	Week 2	Week 3	Week 4	Week 5	Week 1	Week 2	Week 3	Week 4	Week 5



Q-807 WP (5%)

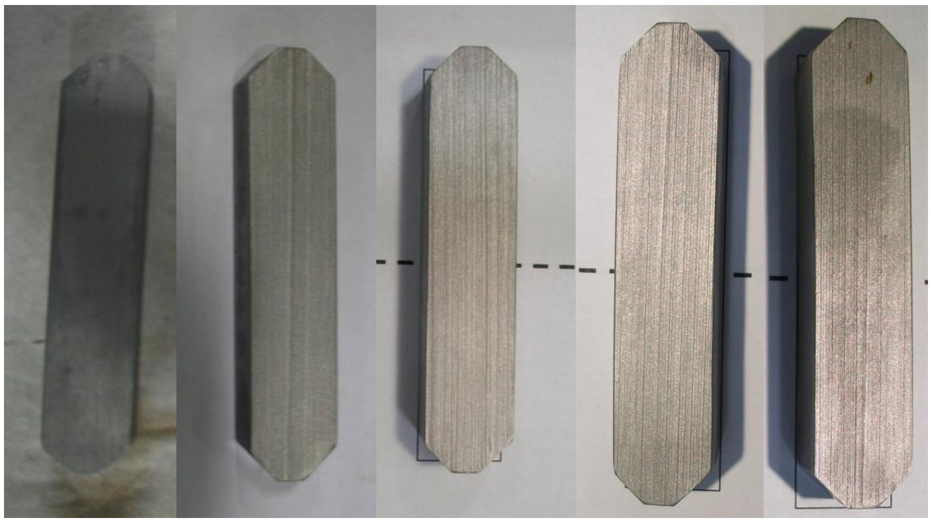
LP: Atmospheric					HP: 2500 PSI				
Week 1	Week 2	Week 3	Week 4	Week 5	Week 1	Week 2	Week 3	Week 4	Week 5



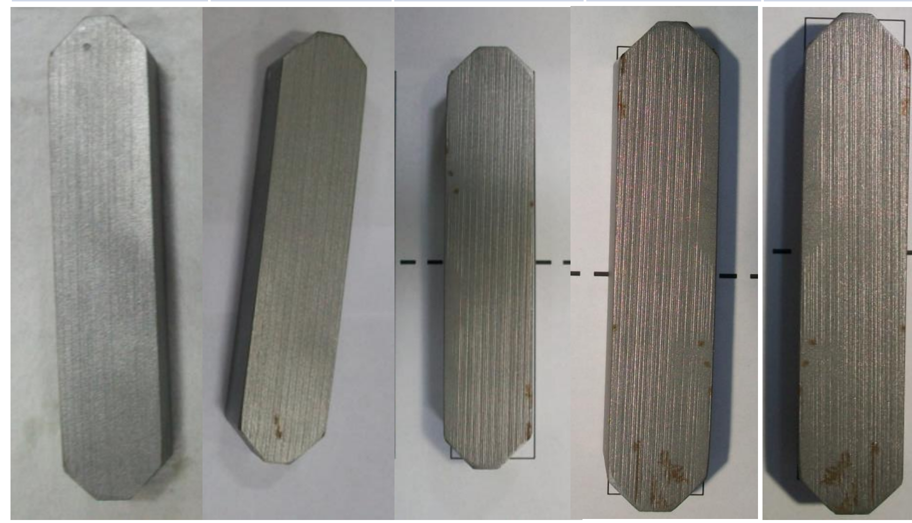


Q-807 WP (5%) with Biosoft (1%)

LP: Atmospheric				
Week 1	Week 2	Week 3	Week 4	Week 5

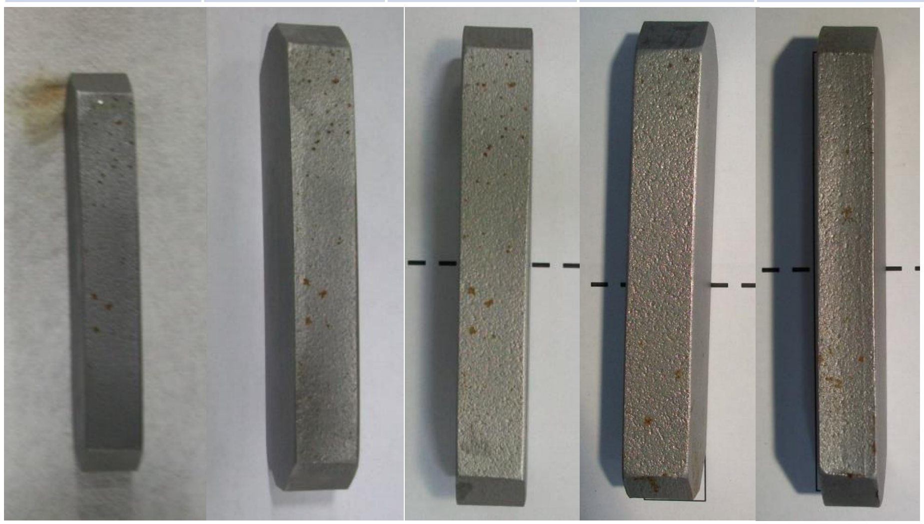


HP: 2500 PSI				
Week 1	Week 2	Week 3	Week 4	Week 5



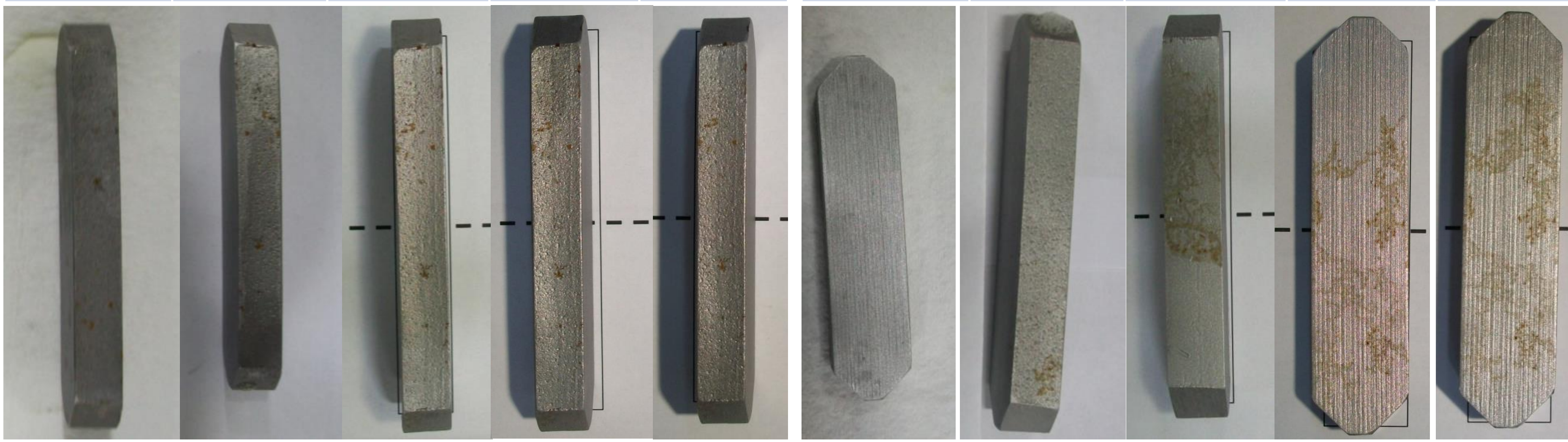
Q-807 IS (5%)

LP: Atmospheric					HP: 2500 PSI				
Week 1	Week 2	Week 3	Week 4	Week 5	Week 1	Week 2	Week 3	Week 4	Week 5



Q-807 IS (5%) with Biosoft (1%)

LP: Atmospheric					HP: 2500 PSI				
Week 1	Week 2	Week 3	Week 4	Week 5	Week 1	Week 2	Week 3	Week 4	Week 5



Overview

- SAE/AISI & ASTM Steel Numbering Systems
- Sunapee Corrosion Tour
    - Links to photo directories in the notes
  - Summary
  - LPM
  - LPC
  - MPV: Lower, Vertical & Upper
  - HPC
  - HPM
  - Storage
  - Filter housings
  - Process piping
  - Zinc plating
  - Ductile Iron
- Corrosion resistant alloying metals
- Carbon steels with Nickel
- Jamie's thoughts on Next System's Material Selection
- Ferrous Corrosion Inhibitors & Zinc/Aluminum
- Water Treatment & Corrosion Inhibitors
- Conclusions

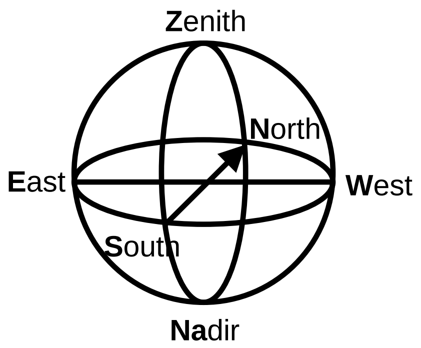


Photo Compass Rose

The arrow is into the page

Note: labels will differ depending on the photo orientation

Sunapee Corrosion Summary

- Corrosion has occurred but slowed or stopped in certain environments
  - LP Manifold, LPHs V4 side, potentially the HP circuits
- Corrosion has continued or accelerated in the MPV
- Corrosion has been a function of metal type, environment (pressure, liquid volume fraction), and flow
  - HP heads have very little corrosion compared to the MPV and HPM connected directly to them – same environments, different metals
    - The steel alloy highest in chromium, nickel and molybdenum fared best
  - MPV shows asymmetrical corrosion – same environment & metal, different local flows

SAE/AISI Steel Numbering System

- 1st digit indicates the main alloying element(s)
- 2nd digit indicates the secondary alloying element(s)
- Last two digits indicate the amount of carbon, in hundredths of a percent

- **Example AISI/SAE No. 1020**
  - the first digit indicates that this is plain carbon steel
  - the second digit indicates there are no alloying elements
  - the last two digits indicates that the steel contains approximately 0.20 percent carbon

- **Example AISI/SAE No. 4340**
  - the first two digits indicates a Nickel-Chromium-Molybdenum alloy steel
  - the last two digits indicates carbon content roughly 0.4 percent

LPH	10XX	Carbon steels	Plain carbon, Mn 1.00% max
	11XX		Resulfurized free machining
	12XX		Resulfurized / rephosphorized free machining
	15XX		Plain carbon, Mn 1.00-1.65%
	13XX	Manganese steel	Mn 1.75%
	23XX	Nickel steels	Ni 3.50%
	25XX		Ni 5.00%
	31XX	Nickel-chromium steels	Ni 1.25%, Cr 0.65-0.80%
	32XX		Ni 1.75%, Cr 1.07%
	33XX		Ni 3.50%, Cr 1.50-1.57%
	34XX		Ni 3.00%, Cr 0.77%
	40XX	Molybdenum steels	Mo 0.20-0.25%
	44XX		Mo 0.40-0.52%
Carts	41XX	Chromium-molybdenum steels	Cr 0.50-0.95%, Mo 0.12-0.30%
HPH	43XX	Nickel-chromium-molybdenum steels	Ni 1.82%, Cr 0.50-0.80%, Mo 0.25%
	47XX		Ni 1.05%, Cr 0.45%, Mo 0.20-0.35%
	46XX	Nickel-molybdenum steels	Ni 0.85-1.82%, Mo 0.20-0.25%
	48XX		Ni 3.50%, Mo 0.25%
	50XX	Chromium steels	Cr 0.27-0.65%
	51XX		Cr 0.80-1.05%
	50XXX		Cr 0.50%, C 1.00% min
	51XXX		Cr 1.02%, C 1.00% min
	52XXX		Cr 1.45%, C 1.00% min
	61XX	Chromium-vanadium steels	Cr 0.60-0.95%, V 0.10-0.15%
	72XX	Tungsten-chromium steels	W 1.75%, Cr 0.75%
	81XX	Nickel-chromium-molybdenum steels	Ni .30%, Cr 0.40%, Mo 0.12%
	86XX		Ni .55%, Cr 0.50%, Mo 0.20%
	87XX		Ni .55%, Cr 0.50%, Mo 0.25%
	88XX		Ni .55%, Cr 0.50%, Mo 0.35%
	92XX	Silicon-manganese steels	Si 1.40-2.00%, Mn 0.65-0.85%, Cr 0-0.65%
	93XX	Nickel-chromium-molybdenum steels	Ni 3.25%, Cr 1.20%, Mo 0.12%
	94XX		Ni 0.45%, Cr 0.40%, Mo 0.12%
	97XX		Ni 0.55%, Cr 0.20%, Mo 0.20%
	98XX		Ni 1.00%, Cr 0.80%, Mo 0.25%

ASTM System

- Designation: a letter followed by an arbitrary sequentially assigned number
- *A* for ferrous materials, examples
  - A106 Grade B
  - A105
  - A234 WPB
- A metric designated with an “M” after the number e.g. A582M

- Steel Industry Terms: Grade, Type, Class
  - Grade describes chemical composition
  - Type defines deoxidation process
  - Class indicates other characteristics, like strength or surface finish
- ASTM loosely follows industry standards and these rules:
  - As Grades increase alphabetically (A,B,C, etc.), it indicates higher tensile/yield strength; if unalloyed carbon steel, this means higher carbon content
  - Some Grade letters refer to pipe, tube or forgings
    - P – pipe, T – Tube, TP – tube or pipe, F - forging
  - Some Grades refer to SAE designations
    - E.g. *A312 grade TP304* → 304 stainless steel tubing or pipe

Low Pressure Manifold: LPM-510

1) July 3, 2013

2) Oct 10, 2013

3) Feb 10, 2014

4) March 5, 2014

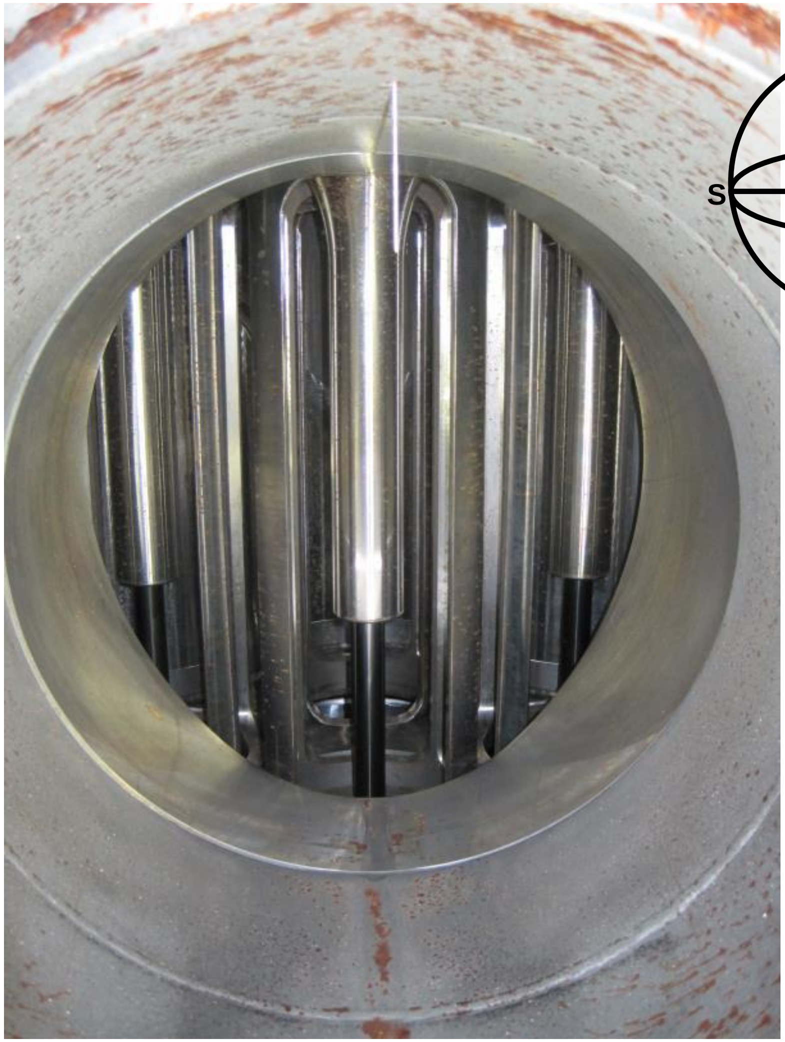
Low Pressure Manifold: LPM-510

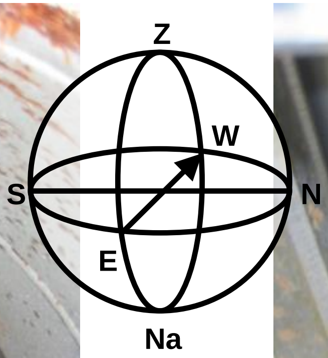
- After initial corrosion, corrosion appears to have stopped…
  - Liquid chemistry formed protective rust?
  - Summer months humidity caused corrosion, winter has stalled it?
    - Air intake has no process liquid – no protective chemistry
      - LP foam will change this – it has the potential to help (or hurt)

- July 3rd → Oct 10th : 99 days
- Oct 10th → Feb 10th : 123 days
- Feb 10th → Mar 5th: 23 days
- 245 days total

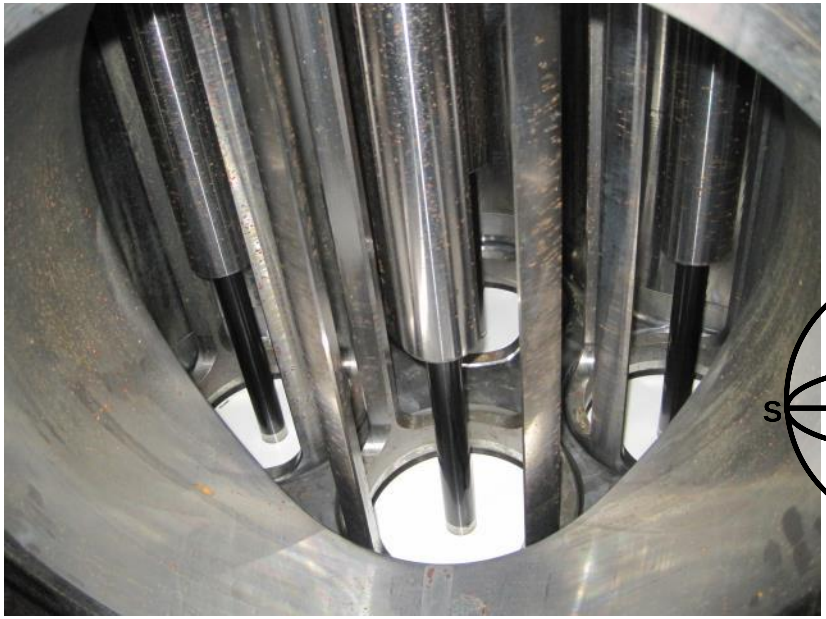
- Duct work: A36
- Flanges: A105

LPC 540, V4 side – 10 Oct 2013





LPC 540, V4 side – 5 March 2014



- 146 days later

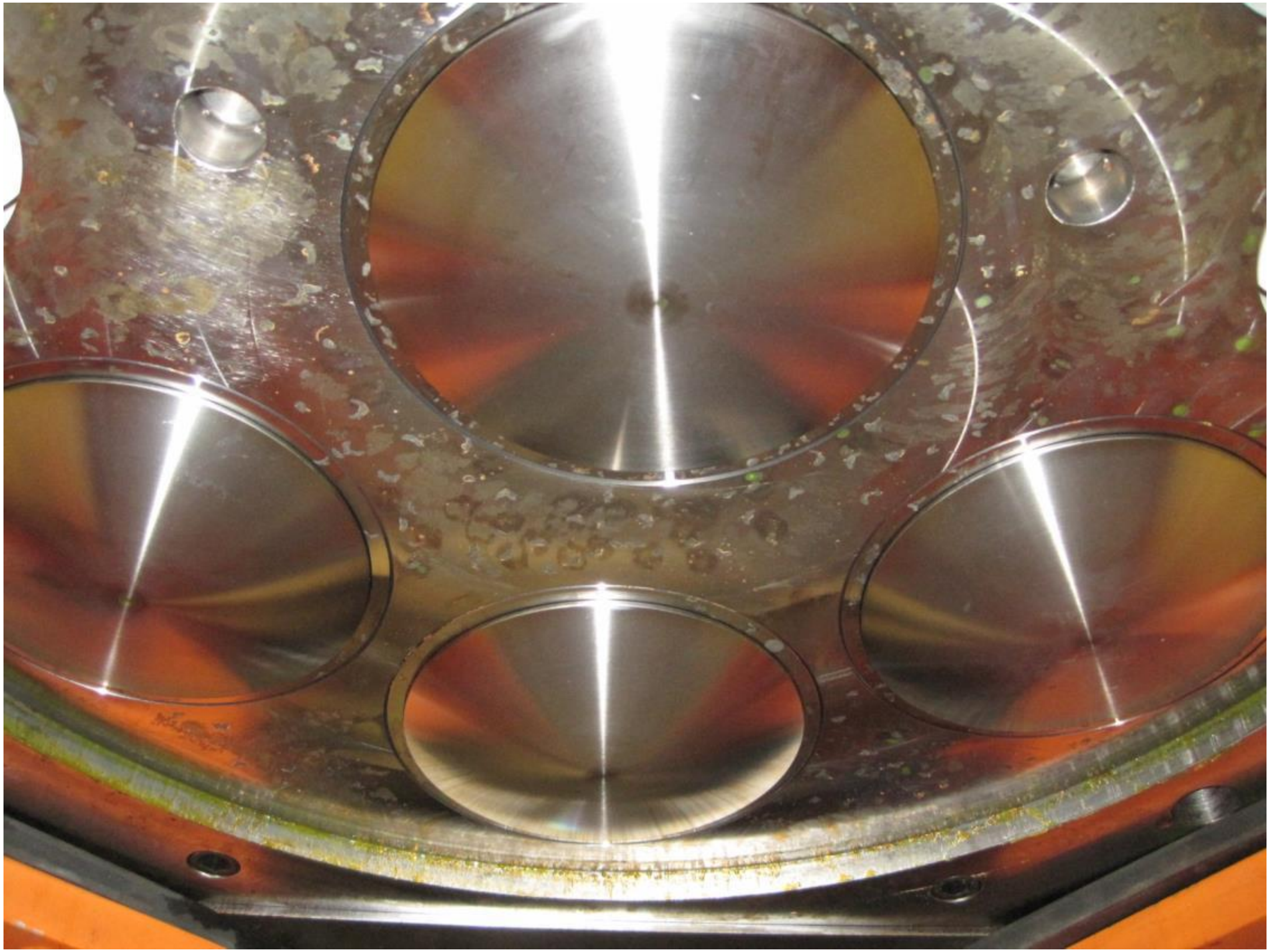
LPC 540, V4 side

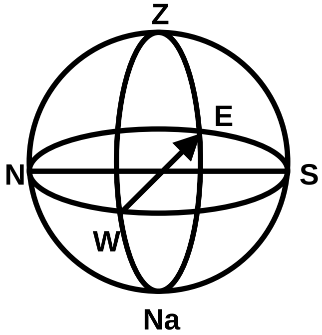
- No significant change in corrosion from Oct 2013 to March 2014
  - Consistent with LPM

- Cartridges (4140 steel): spots of rust, worse near ceiling
- Head (modified 1050 / A668 Class F steel)
  - Wall: few, small spots
  - Ceiling: more, larger spots
- Base plate (4340 steel): few, small spots

LPC-540 Underside – 5 March 2014

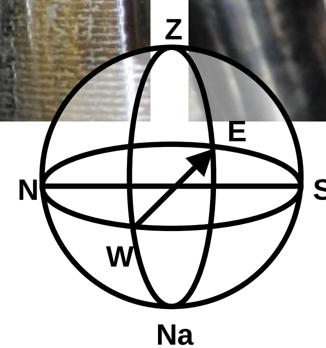
- Base plate: dried process liquid, some small spots of rust
- Valves clear



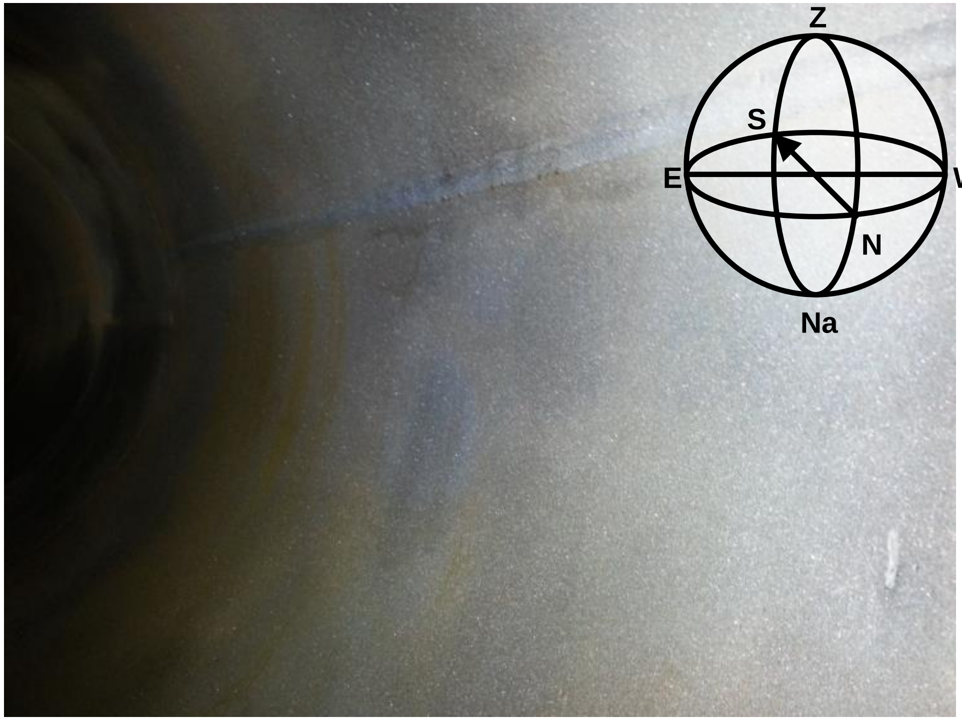


LPC 540, V3 – 5 March 2014

- More corrosion on base plate than on V4 side
  - Wetter, closed environment?
  - Or simply staining from rusty liquid running down walls
- Corrosion on head & cartridges is similar to, if not better than, V4 side



MPV Lower Leg – 3 July 2013

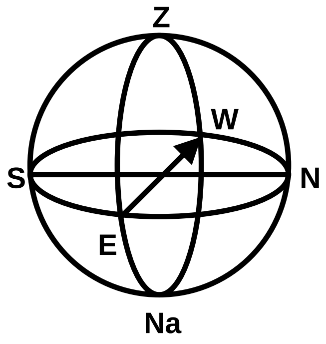


- MPV lower horizontal leg
- Pictured left: EvapoRust run-off, clean walls
- Pictured right: wall across from LPC 540
- Flanges - A105
- Tees – A234 WPB
- Pipe – A106 Gr. B

MPV Lower Leg

MPV Lower Horizontal Leg – LPC 540 port

- Significant corrosion from July 2013 to Feb 2014
- No apparent change in corrosion volume from Feb to March
  - Too short a period?
  - Limited up-and-running time during this period?
  - Corrosion rate slow down?
- Note asymmetric corrosion
  - Flow induced? Wet/foam/dry interfaces?
  - Local impurities in the metal?



Mid Pressure Vessel: Vertical Leg

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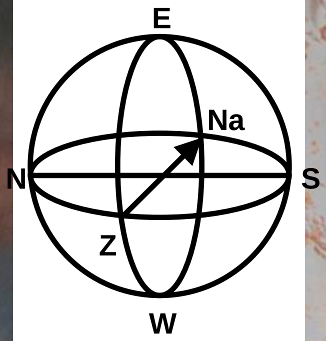
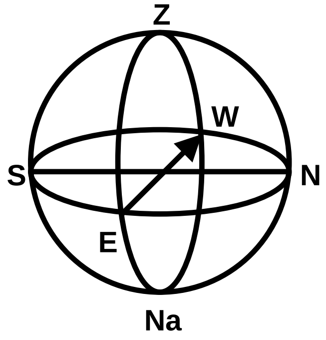


MPV Vertical Leg – 10 Feb 2014

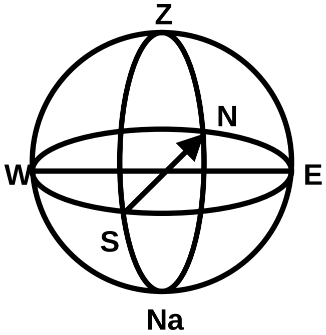
- Some corrosion July 2013 to Dec 2013
- Significant additional corrosion Dec 2013 to Feb 2014
  - Change in process liquid chemistry? Falling pH, additional iron ppm?



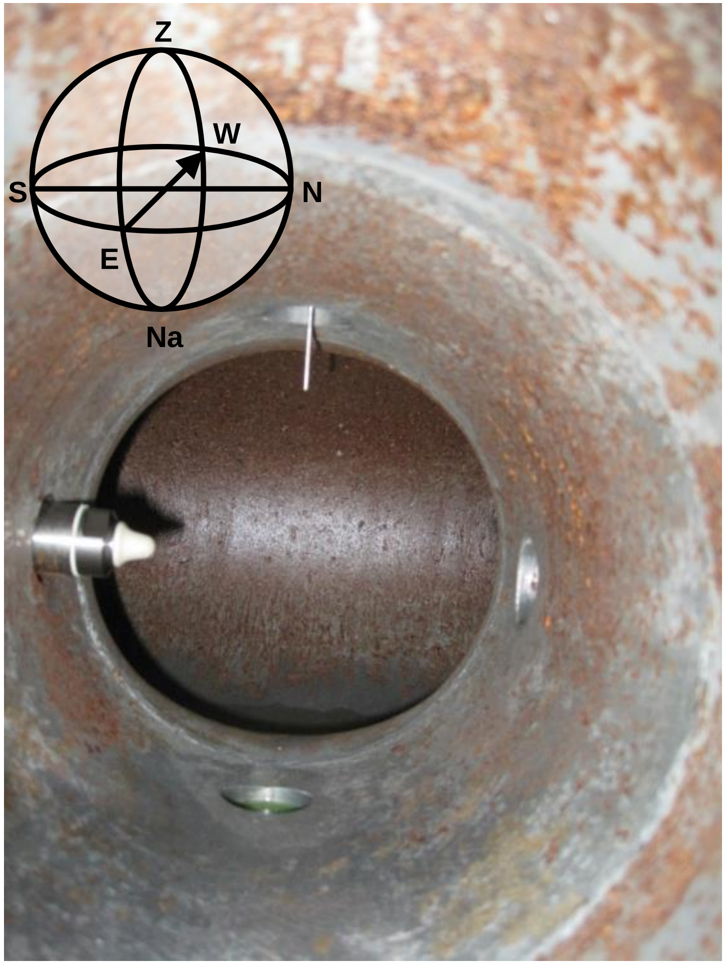
- Top of vertical MPV leg, just under flange
- This corrosion is more 3-dimensional than in other locations – nodules are tenacious, not easily brushed off
  - Dead leg? Condensing environment?

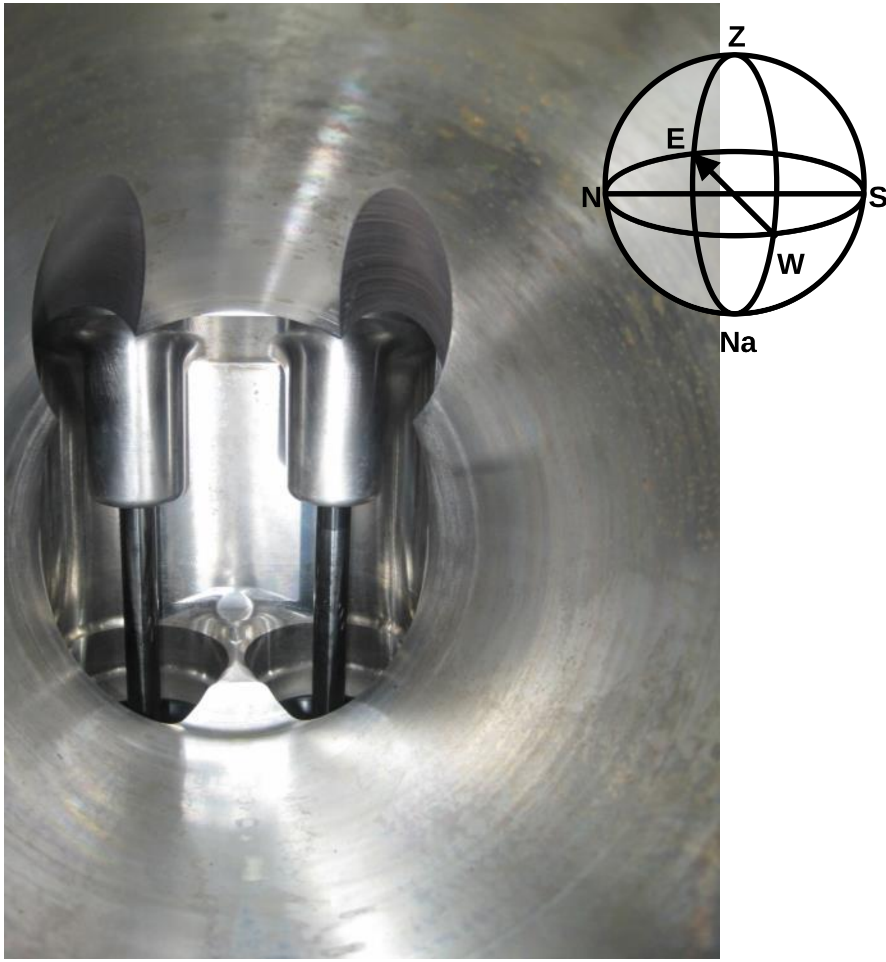
Upper MPV – 14 Nov 2013

- Top of MPV upper horizontal leg
- Note:
- Sensor weld (corroded) vs. pipe welds (not corroded)
- Wet/foam/dry interface corrosion?



HPC 560: MPV Port & Head – 14 Nov 2013

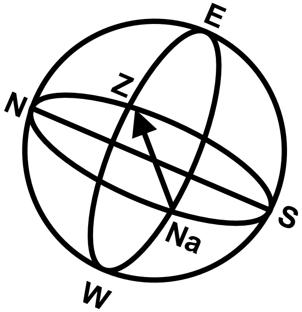




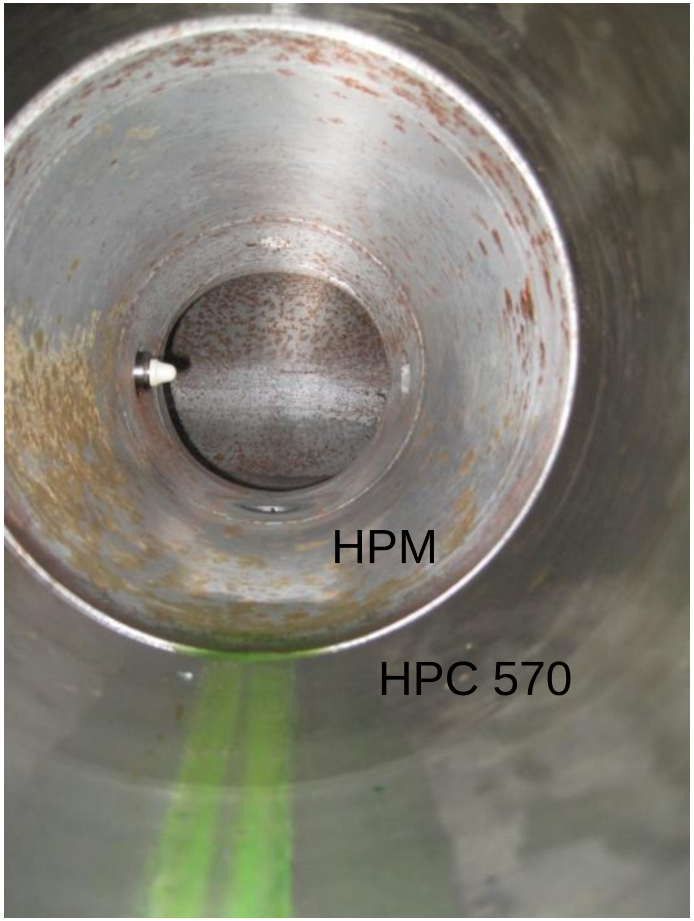
- Contrast the MPV (A234, A106 Grade B, A105 steel) to the HPC (4340 steel)
  - Same environment
  - MPV shows more corrosion – more rust coverage
  - HPCs show very little corrosion – not completely clear but significantly less

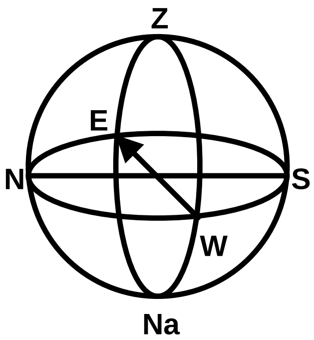
HPC-560 Head Underside – 14 Nov 2013

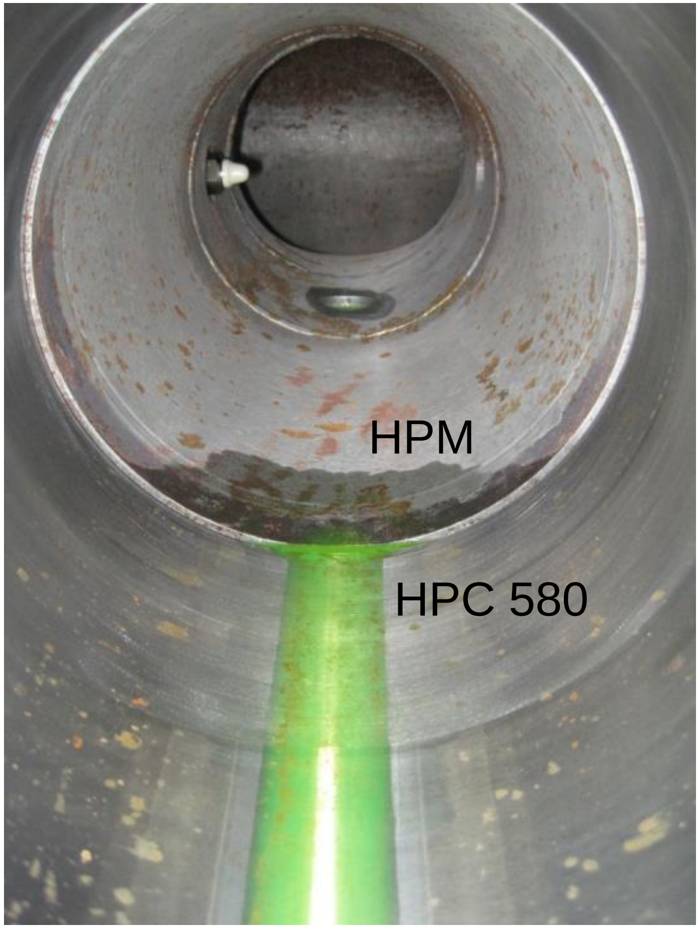
- 4340
- Essentially clear of corrosion



HPM & HPC – 14 Nov 2013



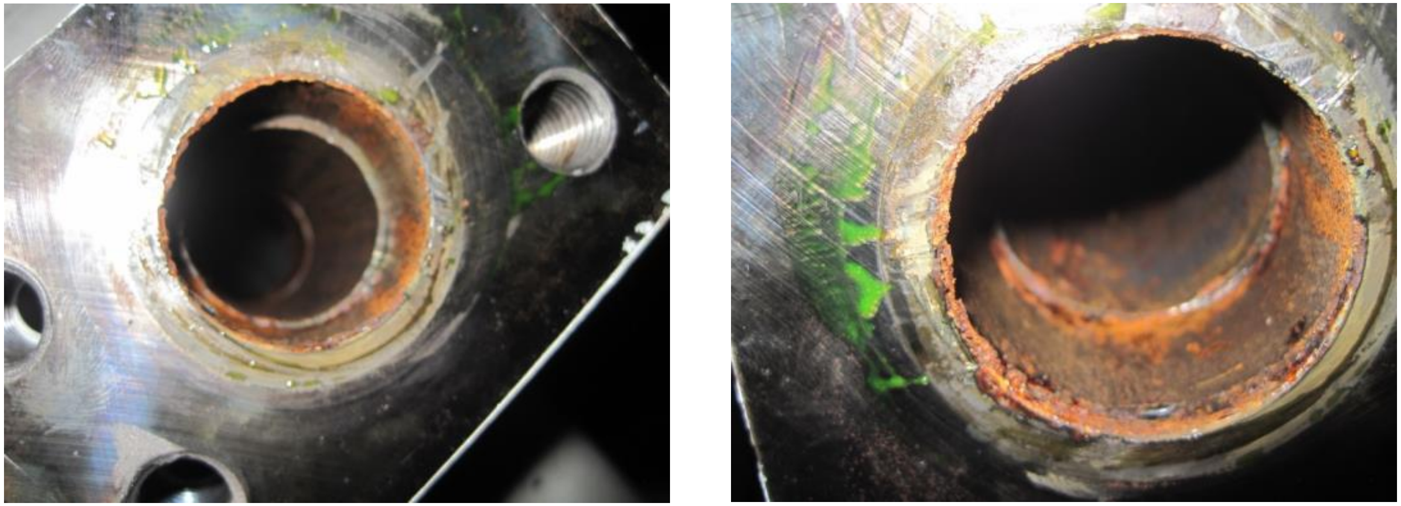




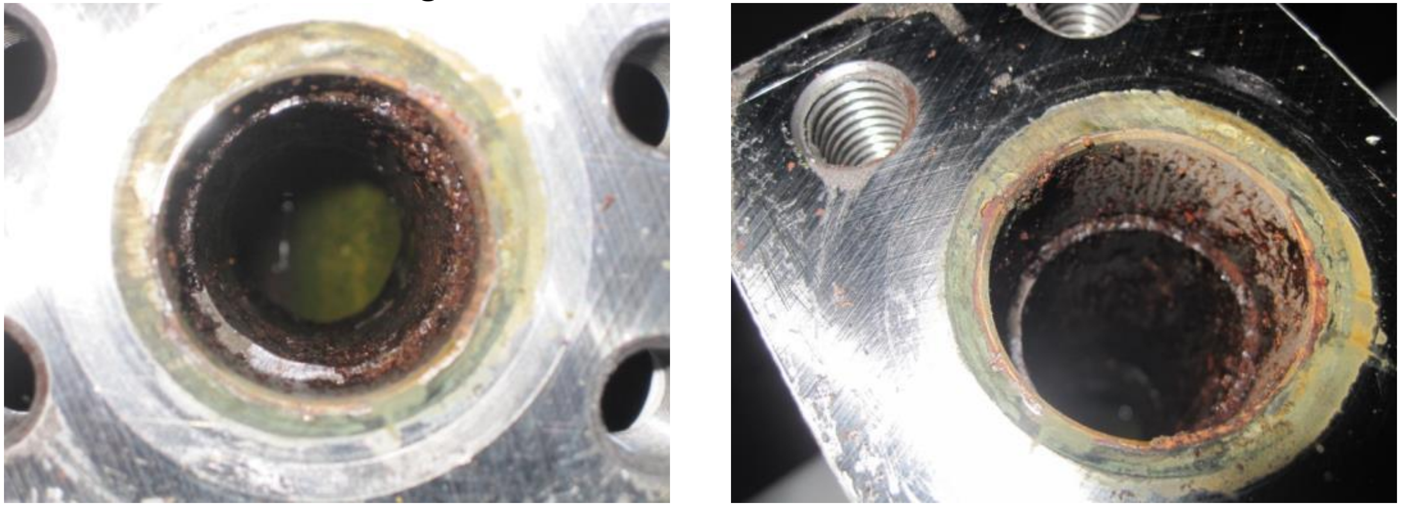
- Contrast the HPM (A234, A106 Grade B, A105 steel) to the HPC (4340 steel)
  - Same environment
  - HPM shows more corrosion – larger, more numerous rust spots
    - Top of header shows more corrosion
  - HPCs show very little corrosion – not completely clear but significantly less

HP Storage – 5 Dec 2013

HP Storage: distribution manifold, upper-end



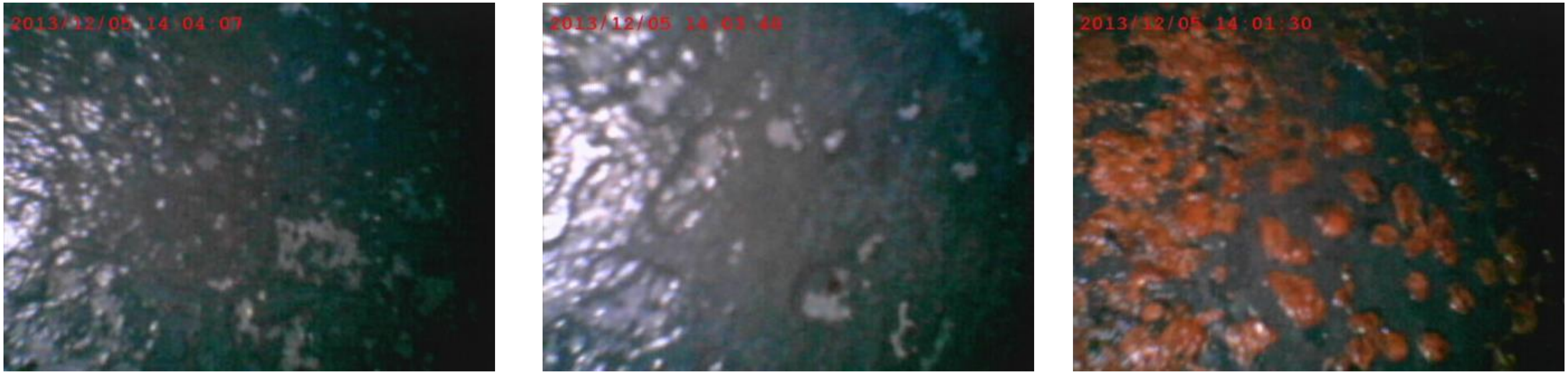
HP Storage: distribution manifold, lower-end



Sunapee in-service experience

HP Storage: vertical pressure vessel, interior, upper-end

HP Storage: vertical pressure vessel, interior, lower-end



Steel: SA372 Grade J, Class 70

HP FLT-620: 23 Oct 2013



- Tube: 1026 CRS (cold rolled steel)
- End cap: 1045 HRS (hot rolled steel)

Process Piping

591 Pipe Spool – 12/5/2013

591 Pump Piping – 12/5/2013

- Pipe spool: A106 Grade B
- Pump piping: Same

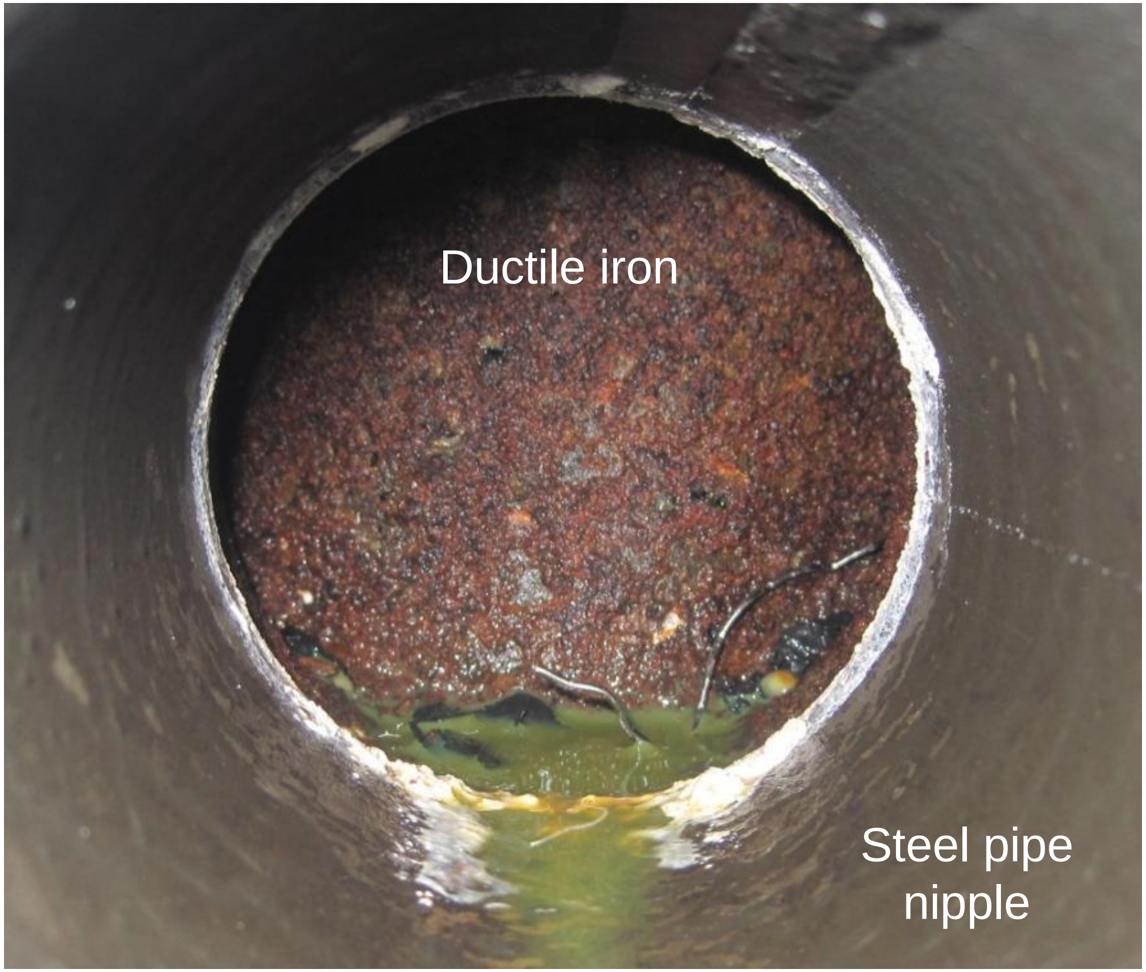
Zinc Corrosion

- Zinc coatings or platings are incompatible with Sunapee's process liquid
- Zinc coatings, like galvanized steel, corrode to "white rust" in
  - pH > 8.3
  - alkalinity > 300 ppm
- Sunapee's process liquid is
  - pH ~ 9-10
  - Alkalinity ~ 2200 ppm

Zinc plated fitting with "white rust" on a spray ring manifold. Zinc is incompatible with Sunapee's process liquid. – 6 Nov 2013

Ductile Iron

- Ductile iron appears to be the worst corroder in Sunapee
  - Nearly ~100% rust coverage
  - Fastest to rust
- LP & MP filter housing end caps (FLT-505, FLT-555), PMP-511 body



Metal Chemistry Round-Up

				Chemical Composition Specifications (limits, not necessarily actual values)											
				Carbon	Manganese	Phosphorous	Sulfur	Silicon	Chromium	Molybdenum	Nickel	Vanadium	Copper	Niobium	Magnesium
Equipment	**Corrosion**	**Material**	**Wt %**	**C**	**Mn**	**P**	**S**	**Si**	**Cr**	**Mo**	**Ni**	**V**	**Cu**	**Nb**	**Mg**
HP FLTs	Medium-Heavy	*CRS 1026*	Min %	0.22	0.6										
		cold rolled steel	Max %	0.28	0.9	0.04	0.05								
HP FLTs	Medium-Heavy	*HRS 1045*	Min %	0.42	0.6										
		hot rolled steel	Max %	0.5	0.9	0.04	0.05								
LPM	Medium	*A36*	Min %	0.25											
		mild/low carbon steel	Max %	0.29	1.03	0.04	0.05	0.28					0.2		
Piping, MPV, HPM	Medium-Heavy	*A106 Gr B*	Min %		0.29										
		Seamless carbon steel pipe	Max %	0.3	1.06	0.035	0.035	0.1	0.4	0.15	0.4	0.08			
Tees	Medium-Heavy	*A234 WPB*	Min %		0.29										
MPV, HPM		*Wrought carbon steel*	Max %	0.3	1.06	0.05	0.058	0.1	0.4	0.15	0.4	0.08	0.4		
Flanges	Medium-Heavy	*A105*	Min %		0.6			0.1							
LPM, MPV, HPM		*forged carbon steel*	Max %	0.35	1.05	0.035	0.04	0.35	0.3	0.12	0.4	0.08	0.4	0.02	
HPC head	Light	*4340*	Min %	0.37	0.6			0.15	0.7	0.2	1.65				
		alloy steel	Max %	0.43	0.8	0.035	0.04	0.3	0.9	0.3	2				
STG	Medium-Heavy	*SA372 Grade J, Class 70*	Min %	0.35	0.75			0.15	0.8	0.15					
		forged alloy steel	Max %	0.5	1.05	0.025	0.025	0.35	1.15	0.25					
LPC head	Light-medium	*Modified 1050 /*	Min %	0.48											
		modified A668 Class F	Max %	0.55	1.35	0.04	0.05								
Valve cartridges	Light-medium	*A519 4140 SR*	Min %	0.38	0.75			0.15	0.8	0.15					
		seamless steel tube	Max %	0.43	1	0.04	0.04	0.35	1.1	0.25					
LP, MP FLT caps	Heavy	*Ductile iron*	Min %	3.3	0.1	0.005	0.005	2.2							0.03
			Max %	3.4	0.5	0.04	0.02	2.8							0.05

Best: 4340 steel – contains ~1.8% nickel, otherwise similar to Storage's SA372
Average: manifold piping – contains less chromium, molybdenum and nickel
Worst: ductile iron – high carbon & silicon, no chromium, molybdenum or nickel

Corrosion Resistant Alloying Metals

- Chromium, nickel and molybdenum provide the corrosion resistance to stainless steel
  - Chromium >10.5% for stainless designation

- Examples
  - 304 stainless aka 18/8
    - 18% chromium, 8% nickel (0.6% molybdenum)
  - 316 stainless aka 18/10
    - 18% chromium, 10% nickel (3% molybdenum)
- These are Austenitic stainless steels, high corrosion resistance but at the cost of weaker mechanical properties & more $$$

- *In our process environment*, there are other stainless steels that may be as corrosion resistant as 300 series
  - The inhibitor could protect alloys typically only considered marginally corrosion resistant
  - Other options: Ferritic, Martensitic, Precipitation Hardened, 400 series, etc.

Example: Piping	**410 stainless**	**A106 Gr B**
Tensile strength (ksi)	60	60
Yield strength (ksi)	30	35

Steel – Nickel Alloys

- Nickel content appears to have imparted corrosion resistance in our process environment
- 4340 steel has nickel at 1.82% (1.65-2%)
  - A105, A106 Gr. B, A234 WPB: Ni≤ 0.4%, less Chrome & Moly
  - SA372 Gr. J, Class 70 virtually the same except no nickel

- Steel alloys with nickel >1.65%
  - 23XX, 25XX
  - 32XX, 33XX, 34XX
  - 48XX
  - 93XX
  - (How important are Chromium and Molybdenum though?)

Jamie's Scenario

- As of 6 March 2014
  - **LP Intake/Exhaust/Filtration** – 304SS
  - **LP Cylinder Head** – Ductile Iron (provided we can find an economical coating/surface treatment)
  - **MPV** – stainless clad carbon or coating/surface treatment
  - **HP Cylinder Head** – 4XXX series steel, possibly acceptable without any treatment
  - **HP Manifold** – stainless clad carbon or coating/surface treatment
  - **Process Piping** – stainless clad carbon, or carbon with reliance on corrosion inhibitor, or coating/surface treatment

Ferrous Corrosion Inhibitors & Zinc/Aluminum

- Zinc or aluminum corrosion resistant materials (paints, coatings, platings, etc.) have "self-healing" properties but are incompatible with ferrous corrosion inhibitors
  - Zinc & aluminum protect steel by being sacrificial to it
    - Protects steel electrochemically even if a coating is damaged
  - However, Zn & Al corrode/dissolve in pH above 8; ferrous materials are only inhibited above a pH of 9

- Mutually exclusive choice:
  - Ferrous corrosion inhibitors & only non-Zn/Al enhanced corrosion resistant materials

  Or
  - All Zn/Al enhanced corrosion resistant materials

- A. Bell's current thinking: ferrous inhibitors over Zn/Al materials
  - In the long term, Zn/Al will be depleted, the component would need to be re-coated.
  - Inhibitors can be controlled independent of the components

Water Treatment & Corrosion Inhibitors

- What if we rely solely on corrosion resistant materials?
  - Can we eliminate Water Treatment?

- Water Treatment is still required with or without corrosion inhibitors as we still have to control pH, conductivity, biological growth, (lubricity), etc.
  - Eliminating the corrosion inhibitor saves $$$ on inhibitor CapEx & OpEx, makes environmental compliance and waste liquid disposal easier…
  - But increases the corrosion risk and requires us to develop our own liquid package

Conclusions

- Given the experience with Sunapee so far
  - Corrosion inhibitors alone are insufficient to preventing corrosion in our environment to our requirements
    - Requirements: near-zero corrosion rate for filtration, abrasion and component lifetime reasons

- Corrosion resistant material selection should be the primary means of corrosion prevention
  - Alloy choice – high alloy carbon steel or stainless steels
  - Surface treatments
    - Heat & diffusion treatment e.g. nitriding
    - Coatings e.g. fusion bonded epoxy, thermal sprays
    - Platings e.g. galvanization, electroless nickel, Nedox

- Corrosion inhibitors should still be used, but in a secondary role
  - Boosts corrosion resistance of marginally resistant metals (potential material cost savings)
  - Act as insurance or redundancy for corrosion resistant material failure