Corrosion Testing in a Simulated High Temperature Geothermal Environment

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Motivation

Corrosion Challenges

- ***Geothermal wells and deep drilled geothermal wells producing superheated steam***
  - Often contain HCl; first condensate is very acidic
  - e.g. steam in IDDP-1

- Iceland Deep Drilling Project (IDDP)
  - Research and development project, aiming at deeper geothermal wells reaching into supercritical conditions
  - ***IDDP wells could produce 10x more power than regular HT wells***

Motivation

IDDP-1: hottest well in the world

- IDDP-1 pilot tests on-site
  - ***450°C and 140 bar at wellhead***
  - ***Steam contains HCl, HF, H_2S, CO_2***
  - ***pH ≈ 3***
  - ***Dissolved silica and silica particles***

- To evaluate the possibility of utilizing the ***superheated steam*** from the IDDP-1 well
  - **Wet-scrubbing of the steam**
  - **Erosion-Corrosion Testing** (T≈ 350°C, 12-13bar, 2-21 days)
  - **Heat Exchanger Experiment** (*T_{Inlet}= 330-370°C, T_{outlet} = 270°C, P ≈60 bar, 2-24 days)*
  - **Corrosion Testing in Flow line** (T≈ 350°C, P=12-13 bar, 113 days)

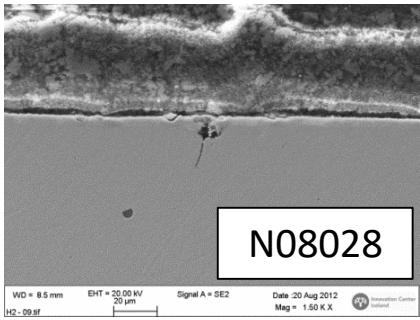
S.N. Karlsdottir, K.R. Ragnarsdottir, I.O. Thorbjornsson, A. Einarsson. *"Corrosion testing in superheated geothermal steam in Iceland,"* Geothermics, [53], 281-290, (2015).

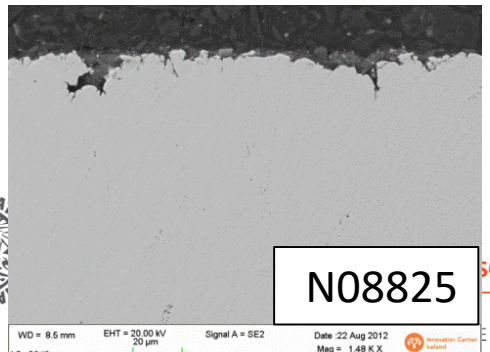
S.N. Karlsdottir, Thorbjornsson, I.O., Ragnarsdottir, K.R., Moller, A., Einarsson, A. "On-site erosion–corrosion testing in superheated geothermal steam." Geothermics, [51], 170-181, (2014).

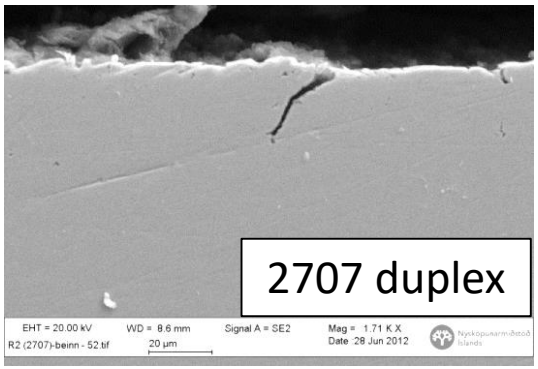
T. Hauksson, S. Markusson, K. Einarsson, S.N. Karlsdottir, A. Einarsson, A. Moller, T. Sigmarsson. *"Pilot testing of handling the fluids from the IDDP-1 exploratory geothermal well, Krafla, N.E. Iceland,"* Geothermics, [49] 76-82 (2014).

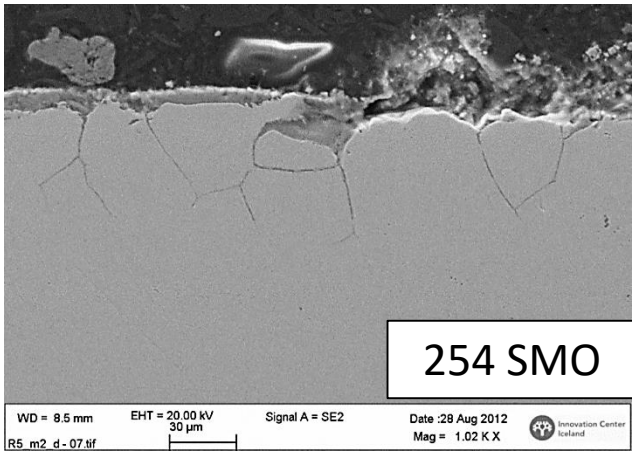
Results from IDDP-1 on-site tests

- **Very low corrosion rates** but small localized corrosion damages
  - narrow cracks and pits in even the most corrosion resistant alloys
- **Large amount of silica scaling** covered the test samples and clogged pipes
- Stress Corrosion Cracking (**SCC**) of **254 SMO** in heat-exchanger experiment
- **SCC** of low alloyed stainless steel (**304&316**)
- Overall best performance **Ni alloy 625** and **Titanium alloys**

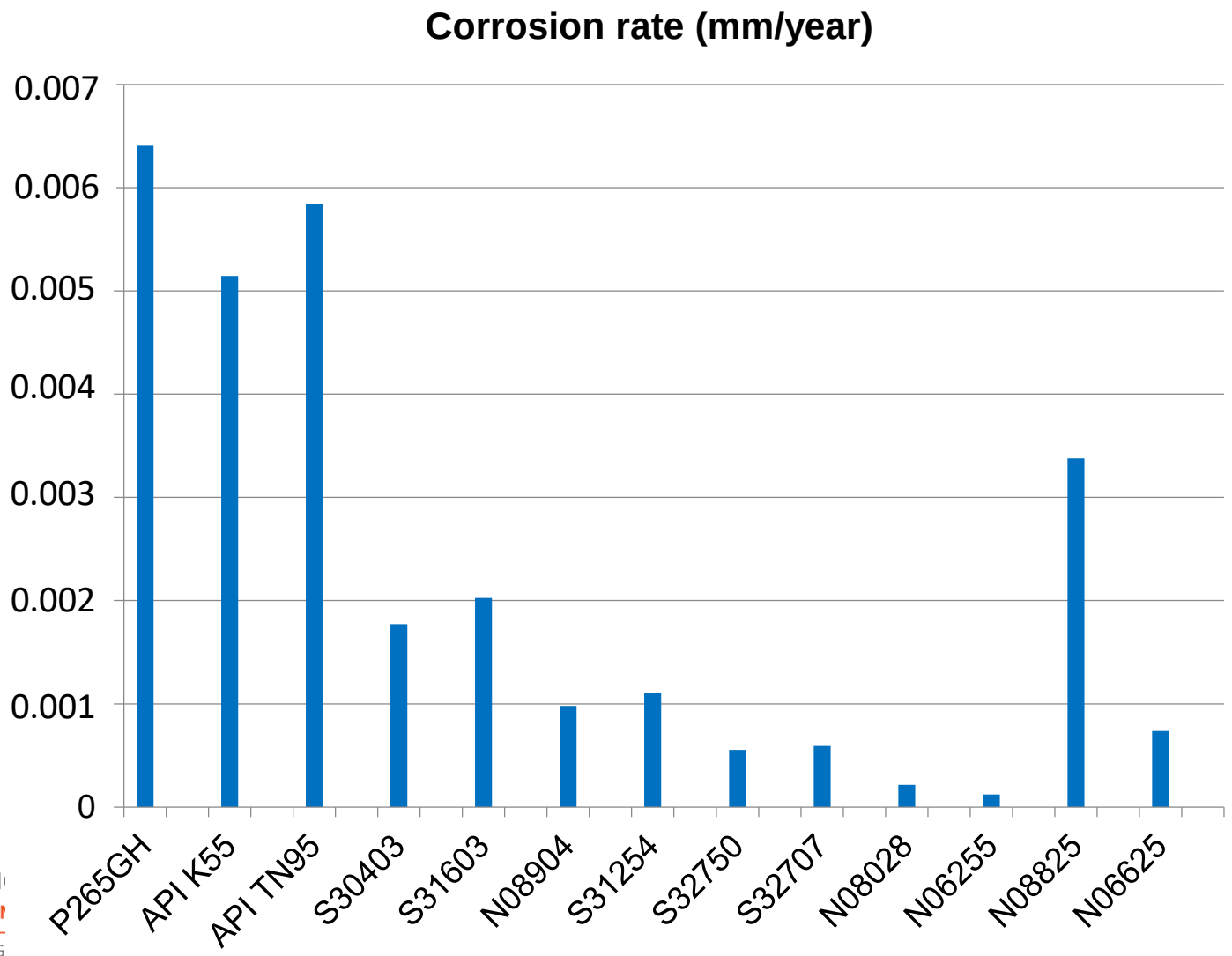








- Very low corrosion rates of materials tested
  - Combined effect of dry superheat and protection by silica



Objectives

- Setup laboratory testing facility to perform corrosion tests in a simulated high temperature deep geothermal well environment
- Expand on the lesson learned in the corrosion testing done on-site for IDDP-1
- Test the best candidates from IDDP-1 testing and high alloy materials in a high temperature acidic environment
- Compare alloy performance to lower temperature conditions with the same fluid chemistry

Experimental

Test Conditions & Fluid Chemistry

- T = 180°C and 350°C, P = 10 bar
- The fluid chemistry was based on conditions and the composition of the IDDP-1 steam and condensate
  - Steam contains HCl, H_2S, CO_2
  - Fluid pH ≈ 3
- Two solutions were used

$$Na_2CO_3 + 2HCl \rightarrow 2NaCl + CO_2$$
$$Na_2S + 2HCl \rightarrow 2NaCl + H_2S$$

CO_2 : 220 ppm
H_2S : 170 ppm

	Solution 1	Solution 2	Mixed Solution
Flow rate	0.5 ml/min	0.5 ml/min	1 ml/min
Na_2S (mmol/kg)	10	0	5
Na_2CO_3 (mmol/kg)	10	0	5
HCl (mmol/kg)	0	42	21
H_2O	Balance	Balance	Balance

Experimental Setup

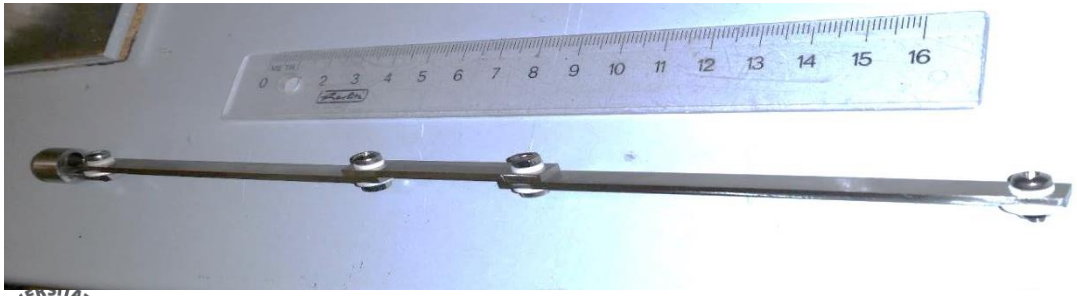
Equipment

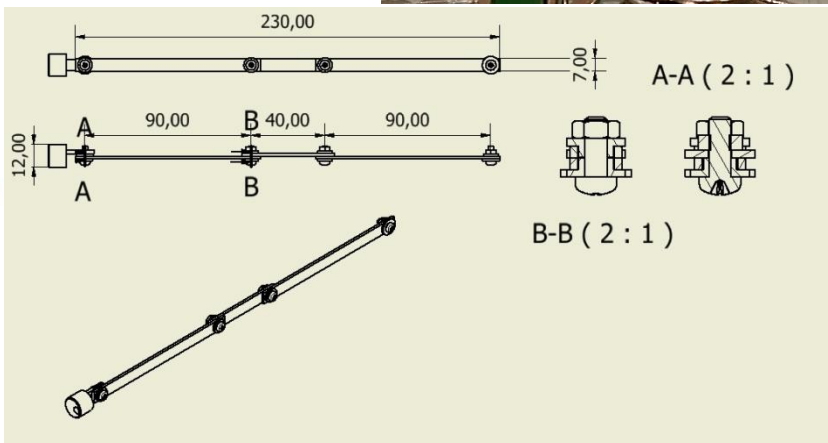
- Testing was done in 3 flow through reactors
- Backpressure valves maintained fixed pressure
- Digital heating elements to maintain temperature
- Piston pumps to circulate test solutions

Experimental Setup

Specimen design

- Custom samples were used due to small reactor size ID=11.7mm
- Ceramic isolation washers were not available and were machined from MACOR
- Sample size was 100x7 and 50x7, t = 2 or 1.5 mm





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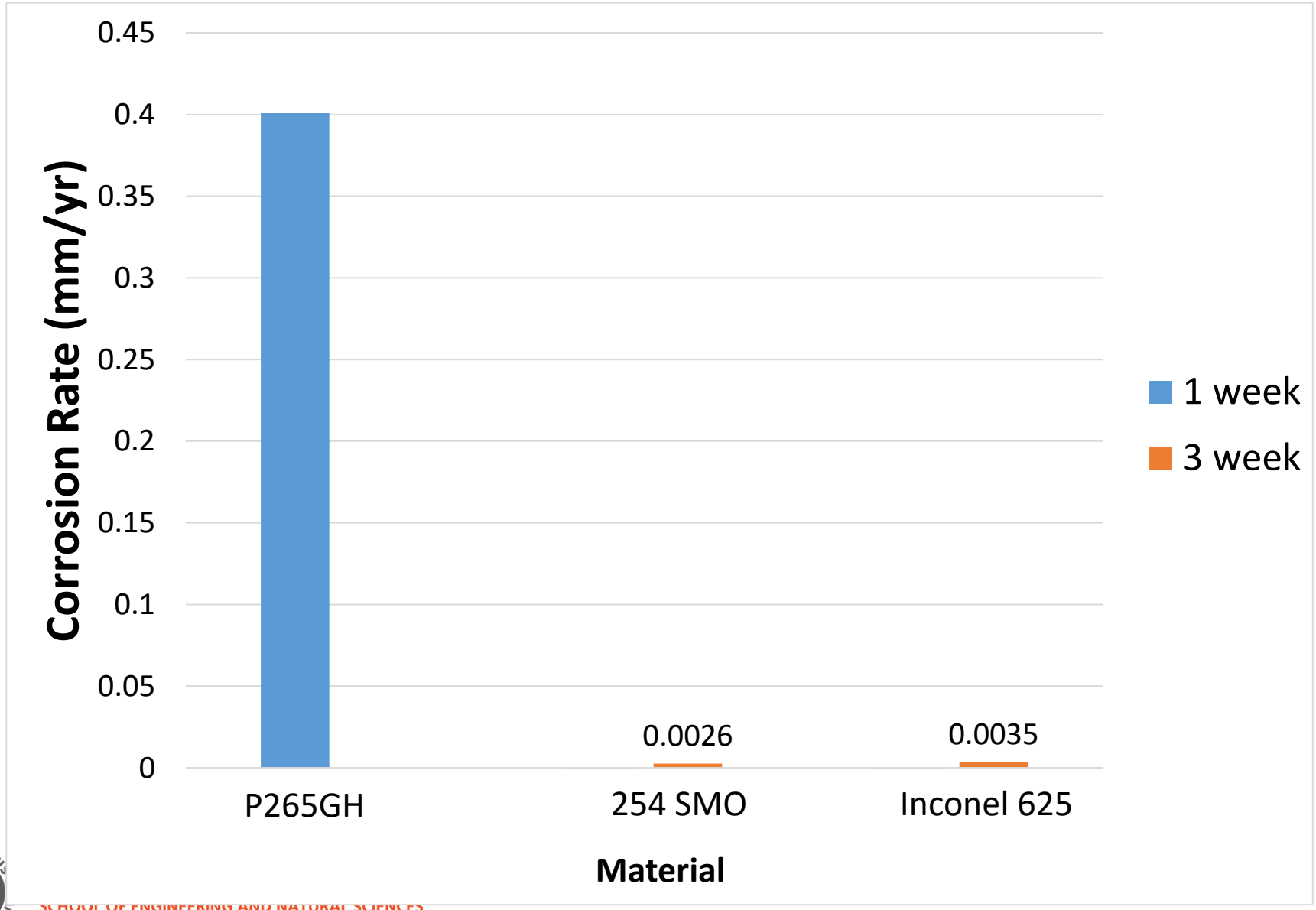
Material Selection

- Materials were selected based on previous testing and the severe conditions
- Carbon steel for comparison
  - P265GH
- High alloyed austenitic stainless steel
  - 254 SMO (S31254): 20% Cr, 18% Ni, and 6% Mo
- Nickel alloys:
  - Inconel Alloy 625 (N06255): 21.5% Cr, 9% Mo and 3-4% Nb
  - Hastelloy Alloy C276: 16% Cr, 16% Mo and 4% W

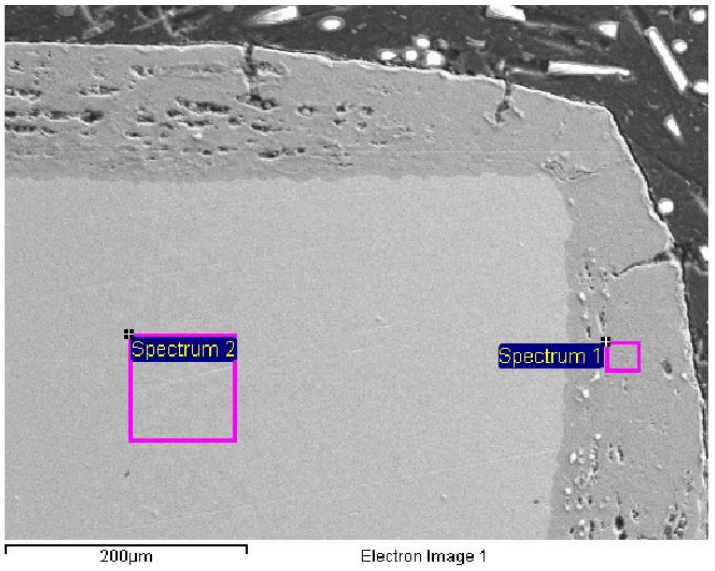
Results at 180°C

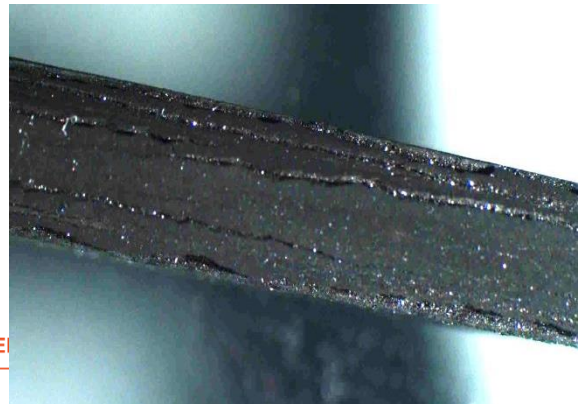


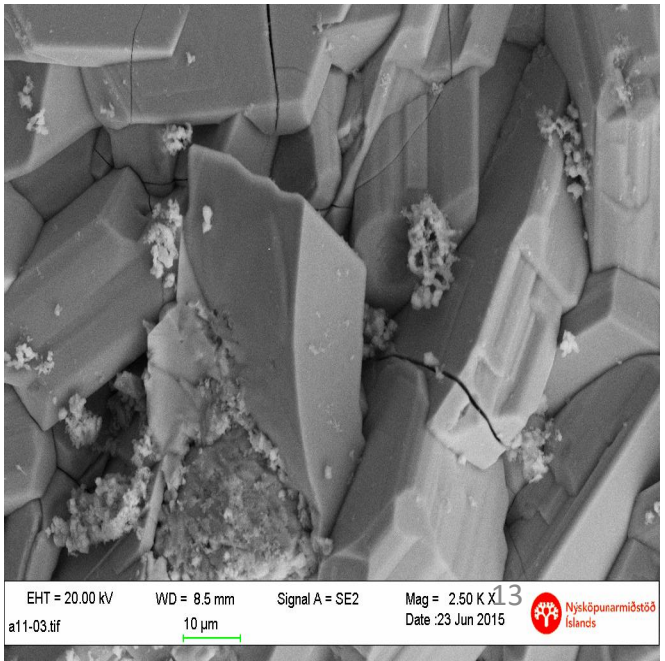
Results at 350°C

P265GH

- CR for 2 day test 13.5 mm/yr
- CR for 1 week test 10 mm/yr
- 3 week test aborted
- Unacceptable level of corrosion
- Mix of S and O corrosion products
- Parts of the samples had denser layer of corrosion product, more protective







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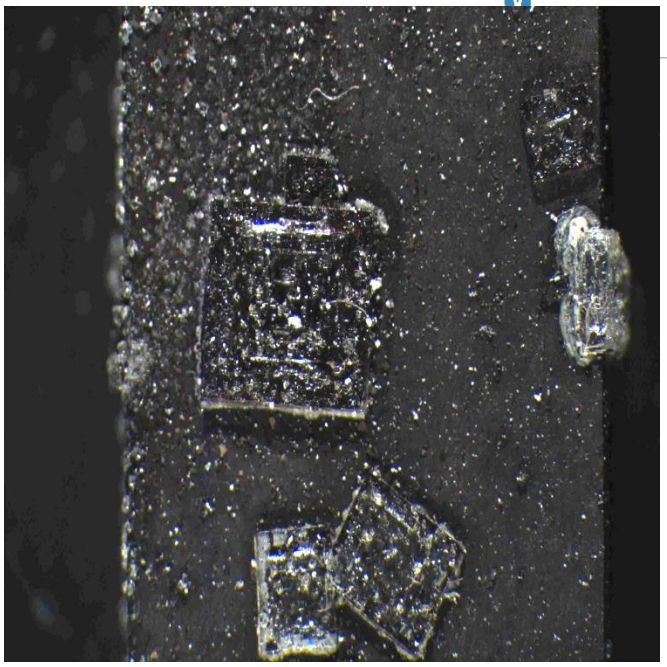
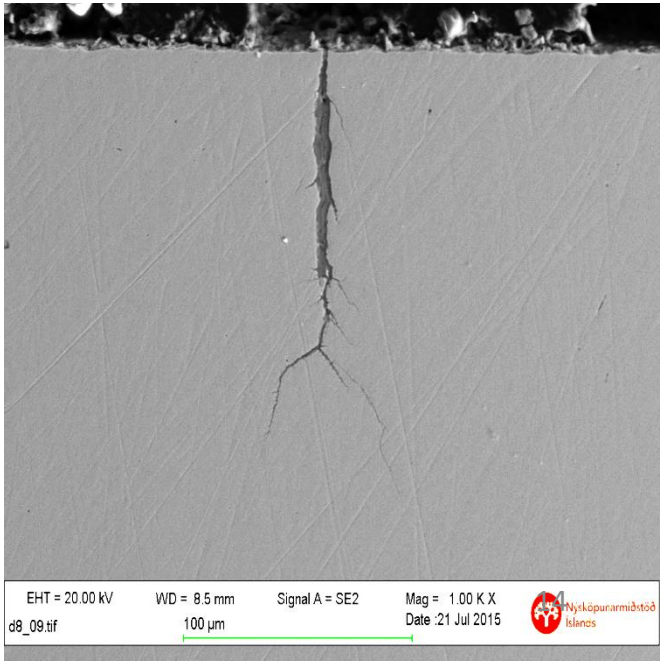
Results at 350°C

254 SMO

- CR for 1 week test 0.02 mm/yr
- CR for 3 week test 0.24 mm/yr
- Little damage on 1 week test
- NaCl crystals on samples for both tests
- Cracking seen after 3 weeks and acid corrosion damages

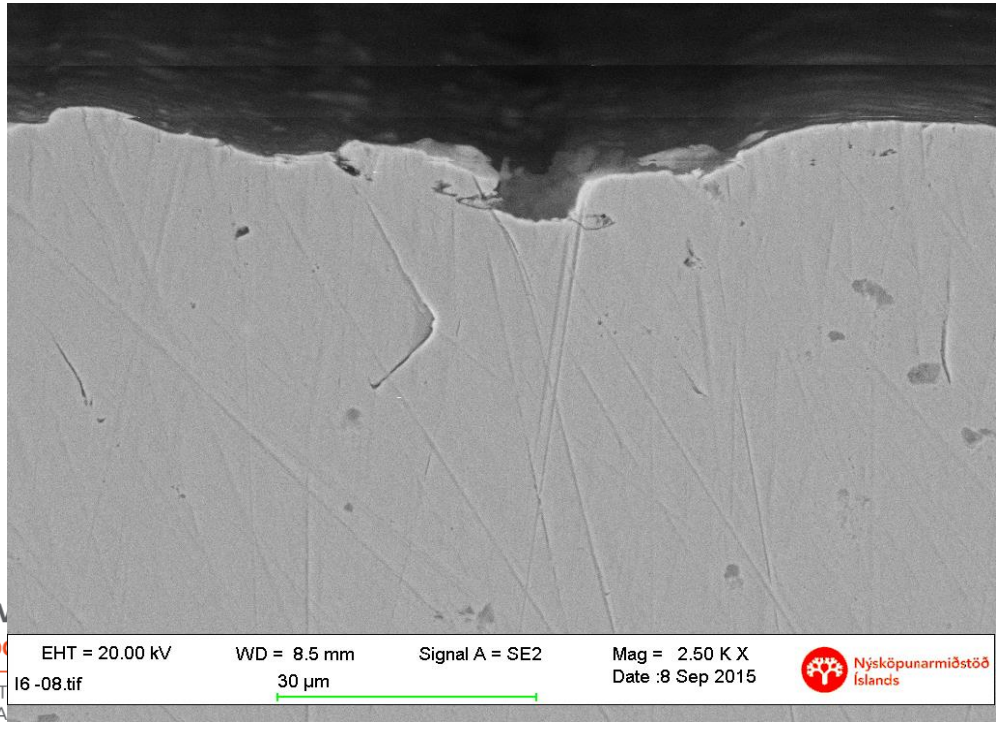


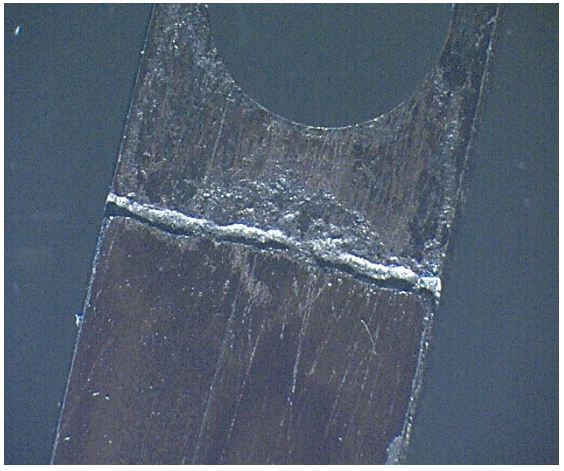


Results at 350°C

Inconel 625

- CR for 1 week test 0.026 mm/yr
- CR for 3 week test 0.15 mm/yr
- Deep pit across sample after 3 weeks

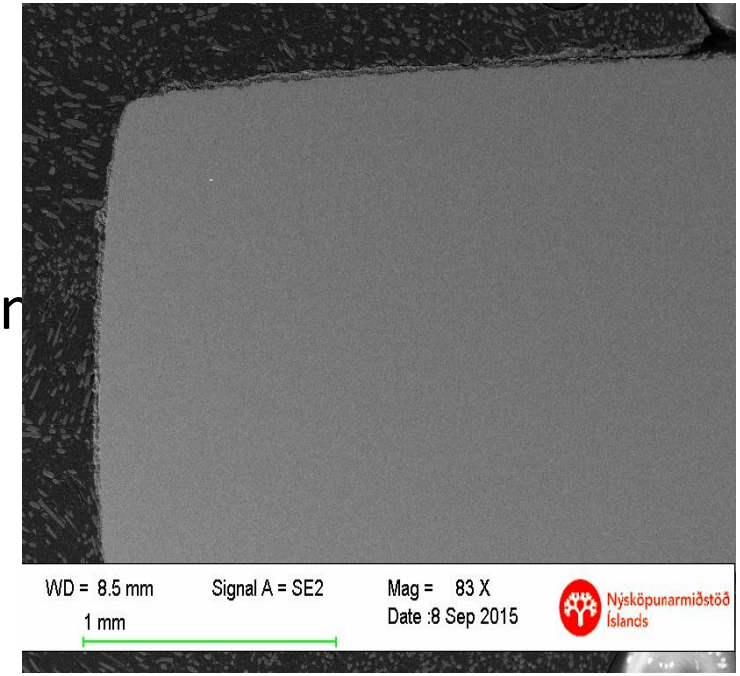




Results at 350°C

Hastelloy C276

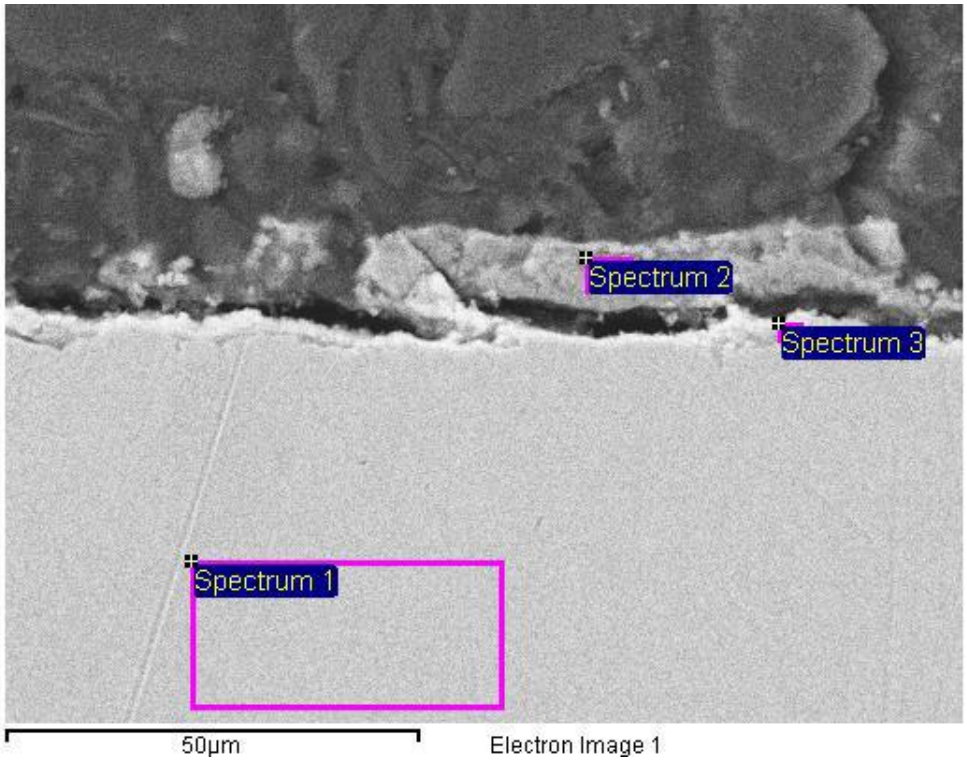
- CR for 1 week test 0.27 mm/yr
- CR for 3 week test 0.29 mm/yr
- Relatively high CR for such a corrosion resistant alloy
- Little localized damage
- Multi layered corrosion deposit



Results at 350°C

Hastelloy C276

1 week



Area	Fe wt %	O wt %	Na wt %	W wt %	Mo wt %	Ni wt %	Mg wt %	Al wt %	Cl wt %	Mn wt %	Ca wt %	Cr wt %
Spectrum 1	6.2	0	0	3.3	16.8	57.1	0	0	0	0.8	0	15.8
Spectrum 2	2.6	31.8	0	5.6	22.4	4.9	0.4	1.2	1.0	0	1.1	29.0
Spectrum 3	1.9	31.7	0	6.1	19.4	4.6	0.7	1.1	1.8	0	1.7	31.0

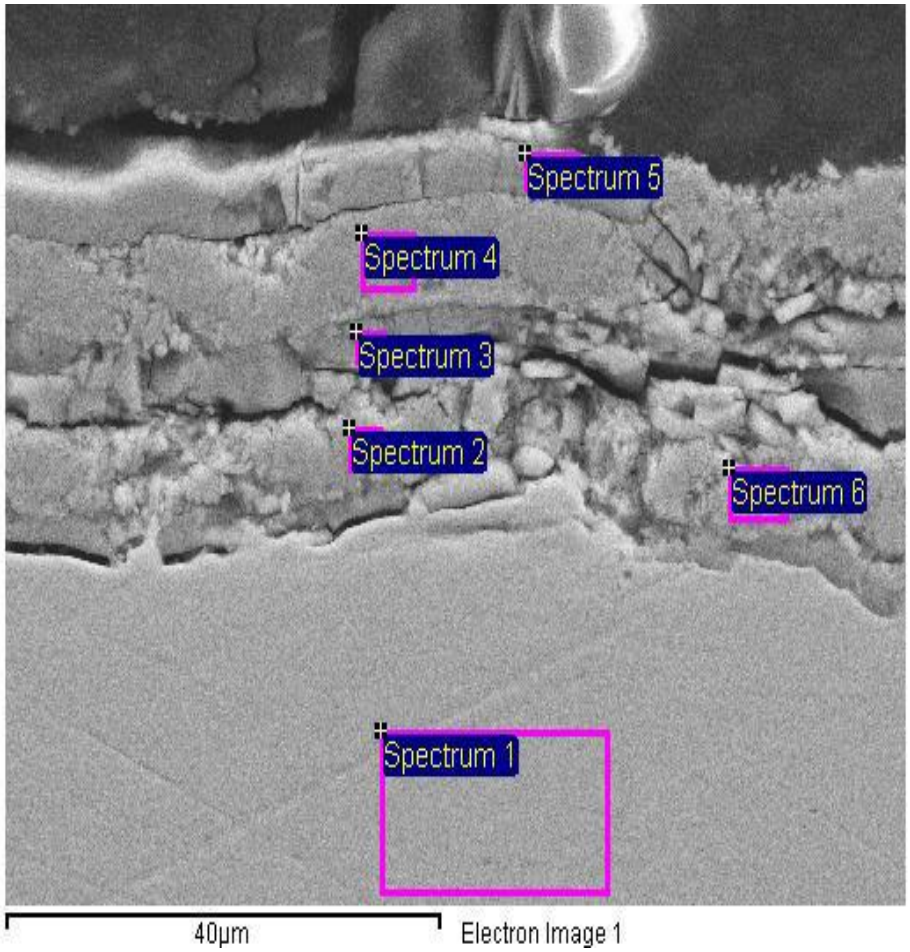
Results at 350°C

Hastelloy C276
3 weeks

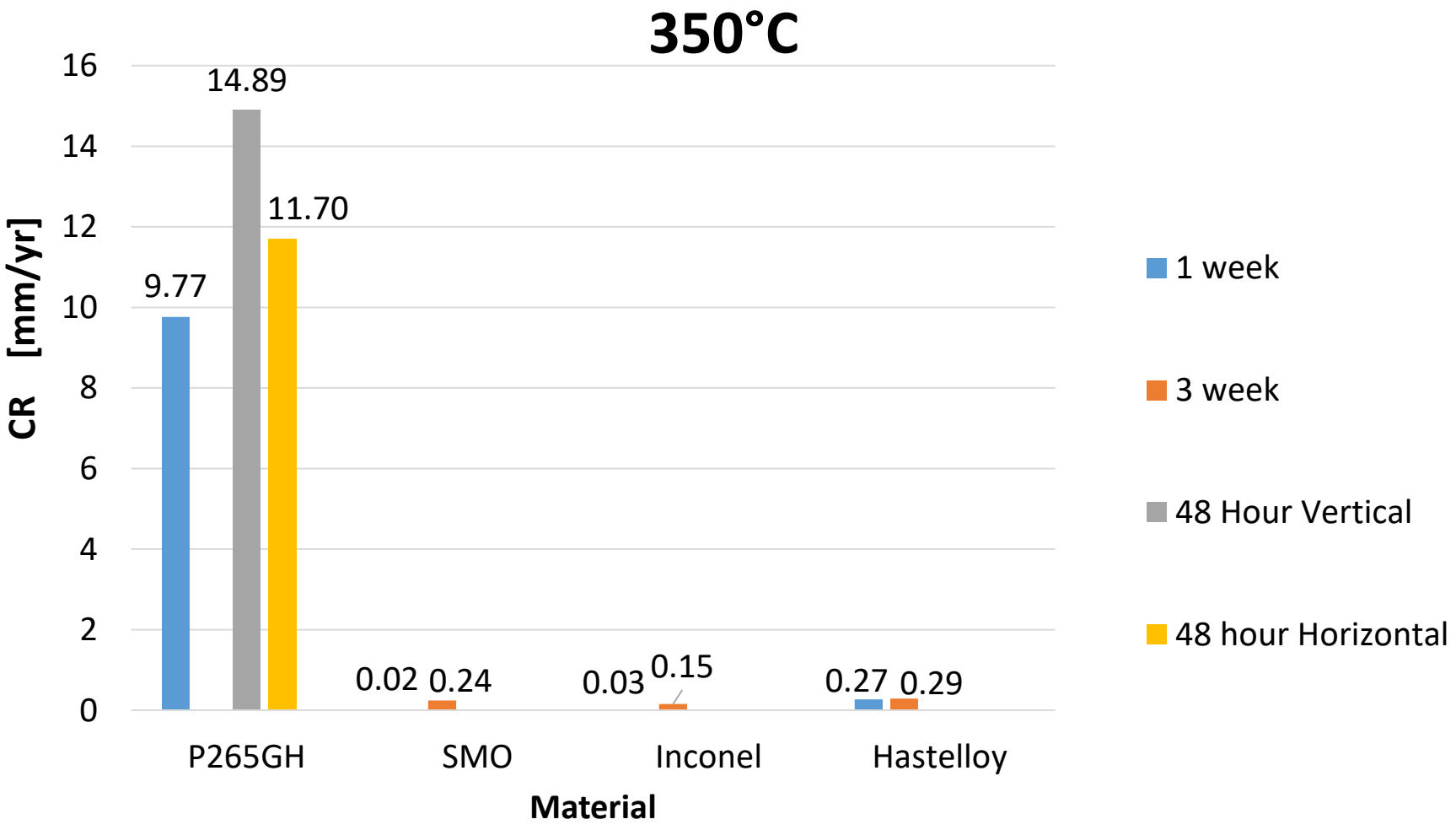
Area	Fe wt %	O wt %	S wt %	Na wt %	Ca wt %	W wt %	Si wt %
Spectrum 1	6.5	0	0	0	0	4.0	0
Spectrum 2	0.7	1.5	33.1	0	0	0	0
Spectrum 3	13.6	32.0	3.5	0.6	0.5	5.3	0
Spectrum 4	1.2	0	32.7	0	0	0	0
Spectrum 5	17.0	33.8	2.9	0	0.5	4.3	0.5
Spectrum 6	1.4	6.1	31.1	0	0	0	0

cont.

	Mo wt %	Ni wt %	Cr wt %	Mn wt %	Cl wt %	Al wt %	C wt %
Spectrum 1	16.5	56.3	15.8	0.9	0	0	0
Spectrum 2	6.6	56.8	1.4	0	0	0	0
Spectrum 3	6.9	3.1	33.3	0	0.8	0.5	0
Spectrum 4	15.2	49.9	1.1	0	0	0	0
Spectrum 5	4.8	3.3	31.5	0	0.7	0.7	0
Spectrum 6	10.1	47.0	2.5	0	0	0	1.7



Summary


350°C
CR [mm/yr]
16
14
12
10
8
6
4
2
0
14.89
11.70
9.77
0.02
0.24
0.03
0.15
0.27
0.29
P265GH
SMO
Inconel
Hastelloy
Material
1 week
3 week
48 Hour Vertical
48 hour Horizontal

Summary

- All materials show higher CR than expected at 350°C compared to IDDP-1 testing
- Only the carbon steel had high CR at 180°C as expected in an acidic wet environment
- Localized damage in 254 SMO and pitting and crevice corrosion of Inconel 625 after testing at 350°C
- CR of Inconel 625 somewhat lower than C-276 after 3 weeks at 350°C but no localized corrosion of C-276

Discussion

- CR higher than what was expected for superheated steam
- Most likely “wet” conditions formed in the 350°C testing
- Corrosion in acidic HTHP geothermal environments has had limited previous study
- No dedicated laboratory facility has existed for corrosion testing in simulated superheated geothermal steam

Discussion

Experimental issues

- Flow was interrupted on occasions due to blockages by corrosion products
- The Macor ceramic material used for isolation dissolved at the higher temperature
- Very possible that liquid droplets made it from the inlet to the surfaces of the lower sample
- Results should be considered a worst case scenario for well operation

Acknowledgements

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