Material characterization and testing of coatings for corrosion challenges in high-temperature geothermal power production

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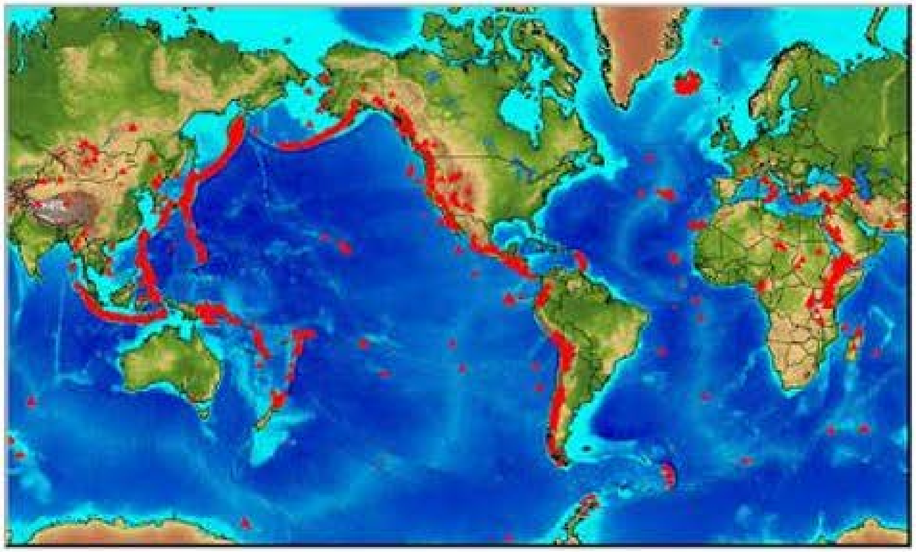
Outline

- Introduction to corrosion challenges in geothermal power production
- Geo-Coat Project
  - Materials & Approach
  - Corrosion testing in simulated HT geothermal environment
  - Post-exposure corrosion analysis
- Summary

Source of geothermal energy

- High temperature geothermal areas situated on geological hotspots

- Relatively short distance to retrieve energy from the geothermal reservoir



Global Map of Volcanoes. From the Global Volcanism Program website.

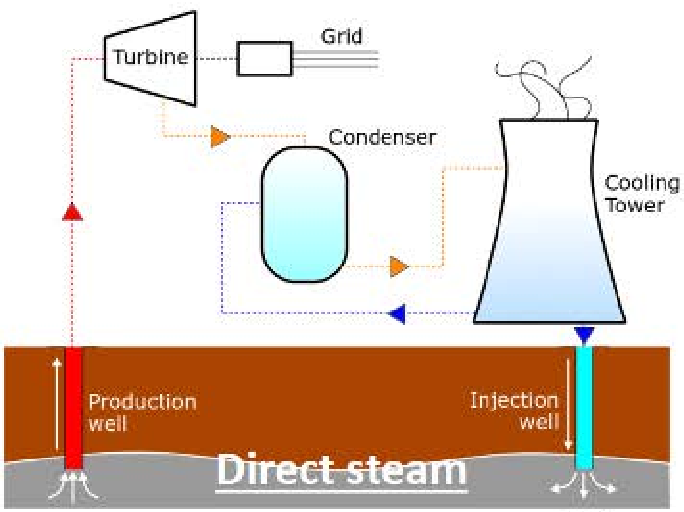
→ *Utilization of geothermal energy*

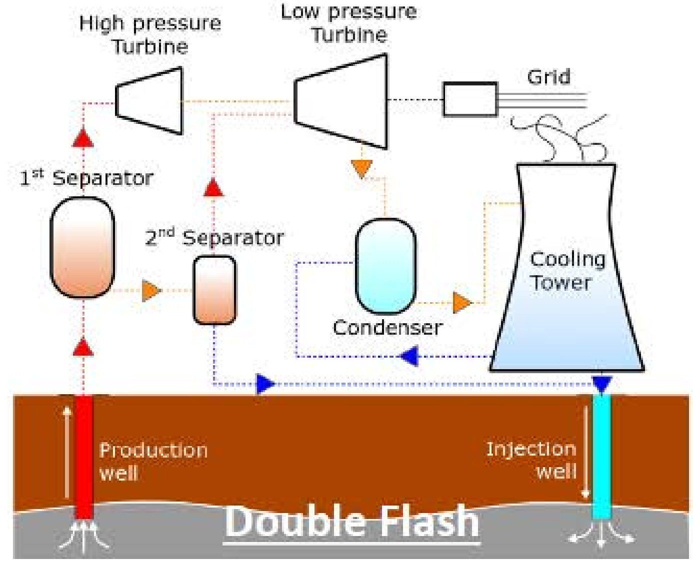
Geothermal energy utilization

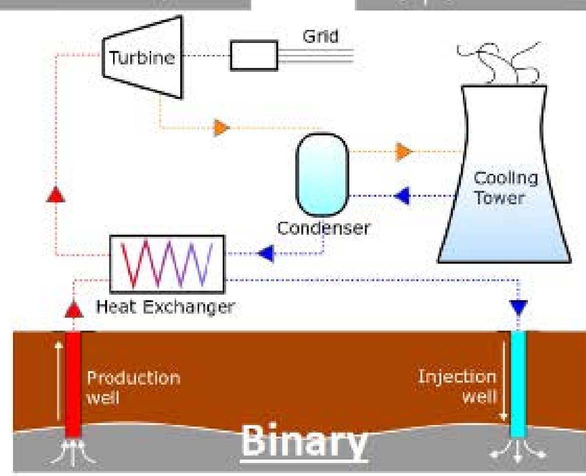
- High temperature geothermal wells
  - Electricity + hot water (space heating)

- in Iceland geothermal energy is 66% of primary energy
- 85% of all houses in Iceland are heated with geothermal energy

Geothermal Power Production





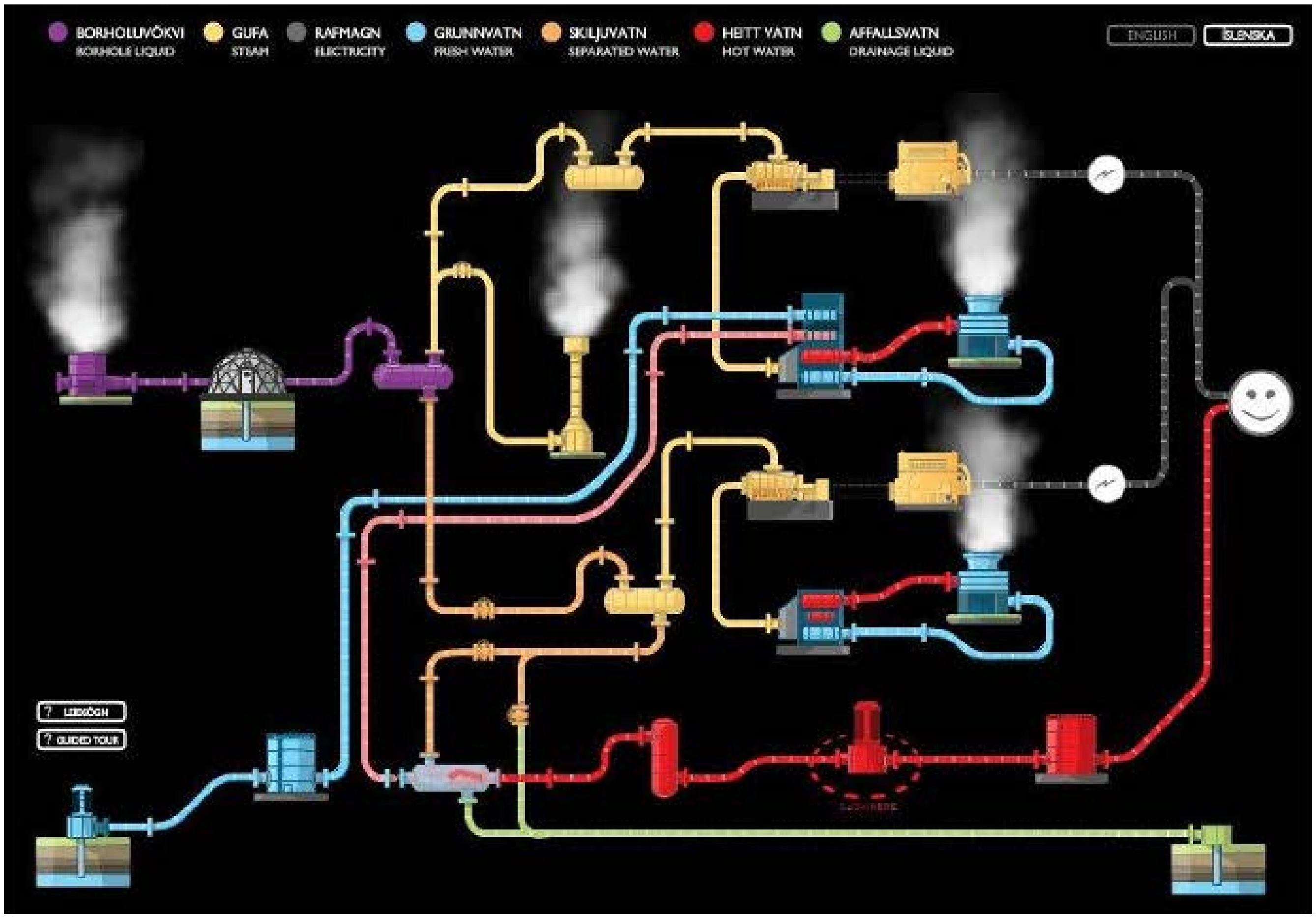


Others:

- Single Flash
- Hybrid
- EGS

[Courtesy of TWI]

Geothermal Power Production



https://www.datacenterdynamics.com/en/analysis/icelands-giant-geothermal-power-plants/

Corrosion in Geothermal Systems

- Materials in direct contact with geothermal fluid can be subjected to corrosion
- Corrosion aggressiveness of geothermal fluid depends on chemical composition and physical characteristics of the fluid and exploitation parameters
  - e.g. H_2S, CO_2, HCl, Cl^-
  - pH level, temperature, flow rate

Corrosion Challenges

- ***Geothermal Power Plants***
  - Gas lines & equipment in H_2S abatement systems (H_2S rich)
  - Turbine components (droplet formation, oxygen ingress)
  - Heat exchangers (condensation)
- **High Temperature Geothermal wells**
  - In casings and wellhead components

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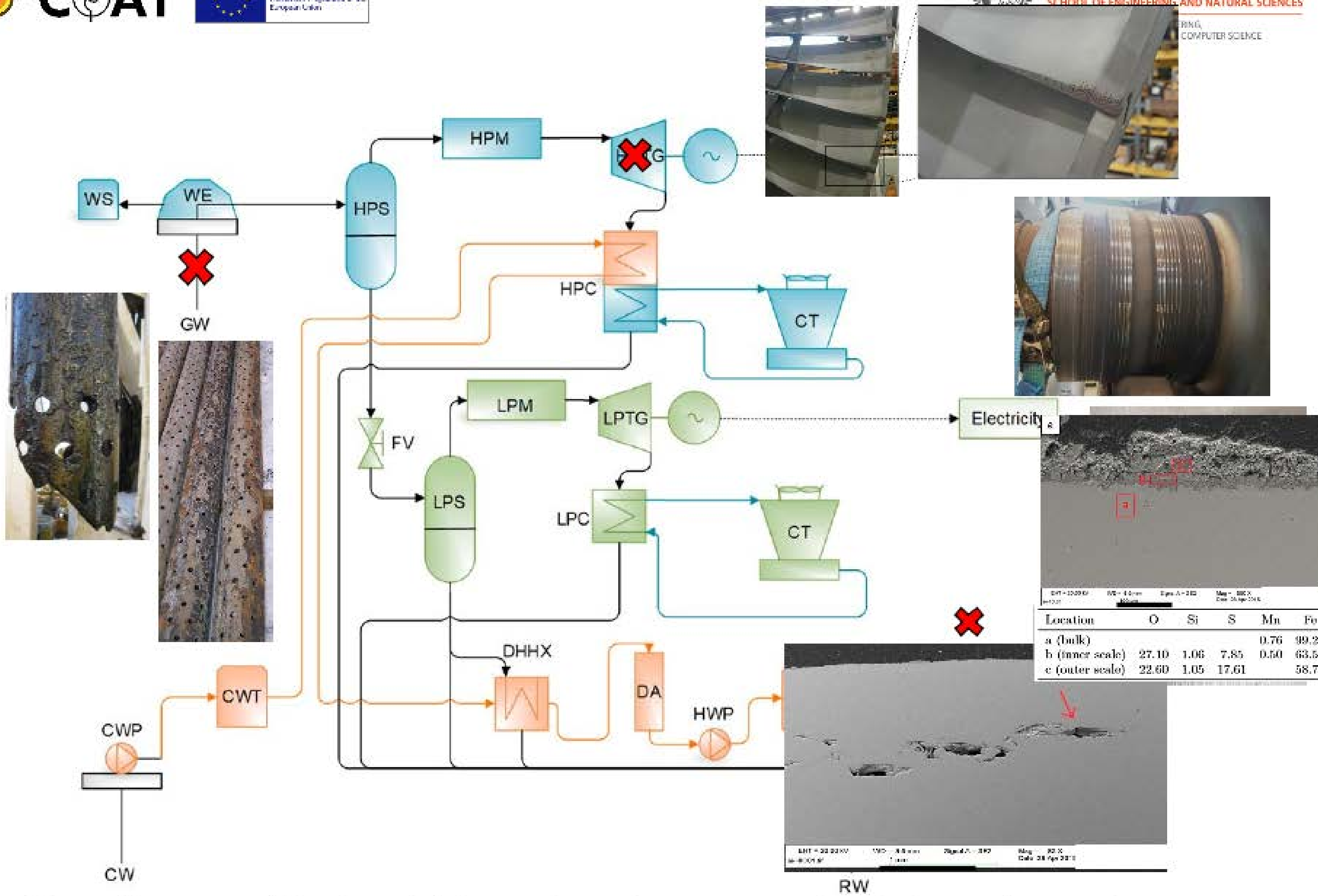

Location	O	Si	S	Mn	Fe
a (bulk)				0.76	99.24
b (inner scale)	27.10	1.06	7.85	0.50	63.50
c (outer scale)	22.60	1.05	17.61		58.75

Marta Ros Karlsdottir, Jukka Heinonen, Halldor Palsson and Olafur Petur Palsson, High-Temperature Geothermal Utilization in the Context of European Energy Policy—Implications and Limitations, Energies 2020, 13, 3187; doi:10.3390/en13123187
Helen Ó. Haraldsóttir, Corrosion Testing of Coatings for Turbine Components in Geothermal Environment, M.Sc. Thesis, 2018, University of Iceland, Reykjavik.
S.N. Karlsdottir, S.M. Hjaltason, K.R. Ragnarsdottir. "Corrosion behaviour of materials in hydrogen sulphide abatement system at Hellisheiði geothermal power plant", Geothermics, [70], 222-229 (2017).

Geo-Coat project

GEO-COAT

"Development of novel and effective corrosion resistant coatings for high-temperature geothermal applications"

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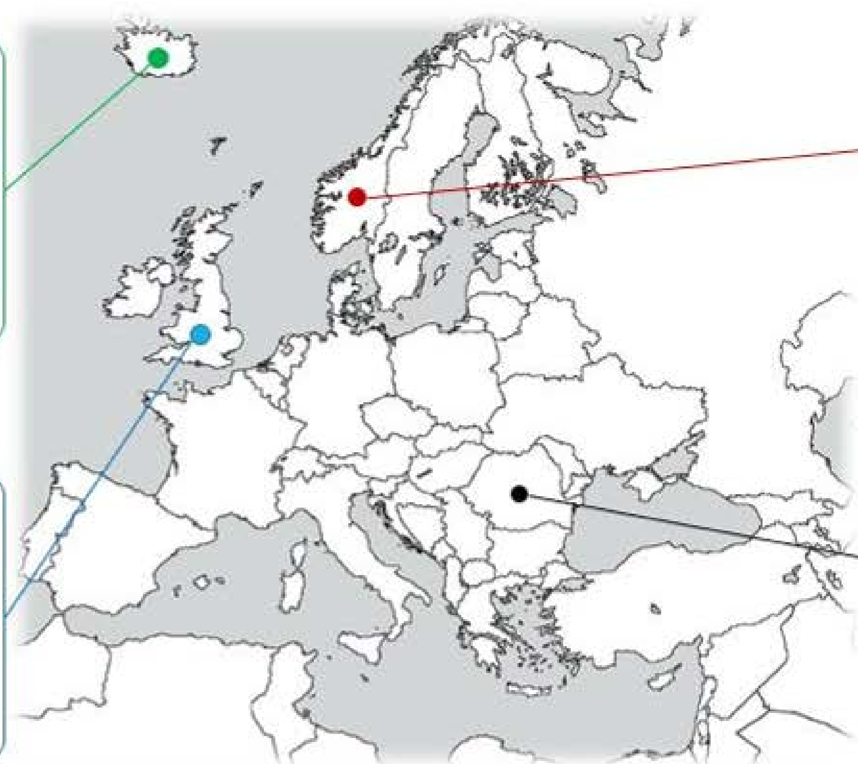

Norway

FLOWPHYS

Romania

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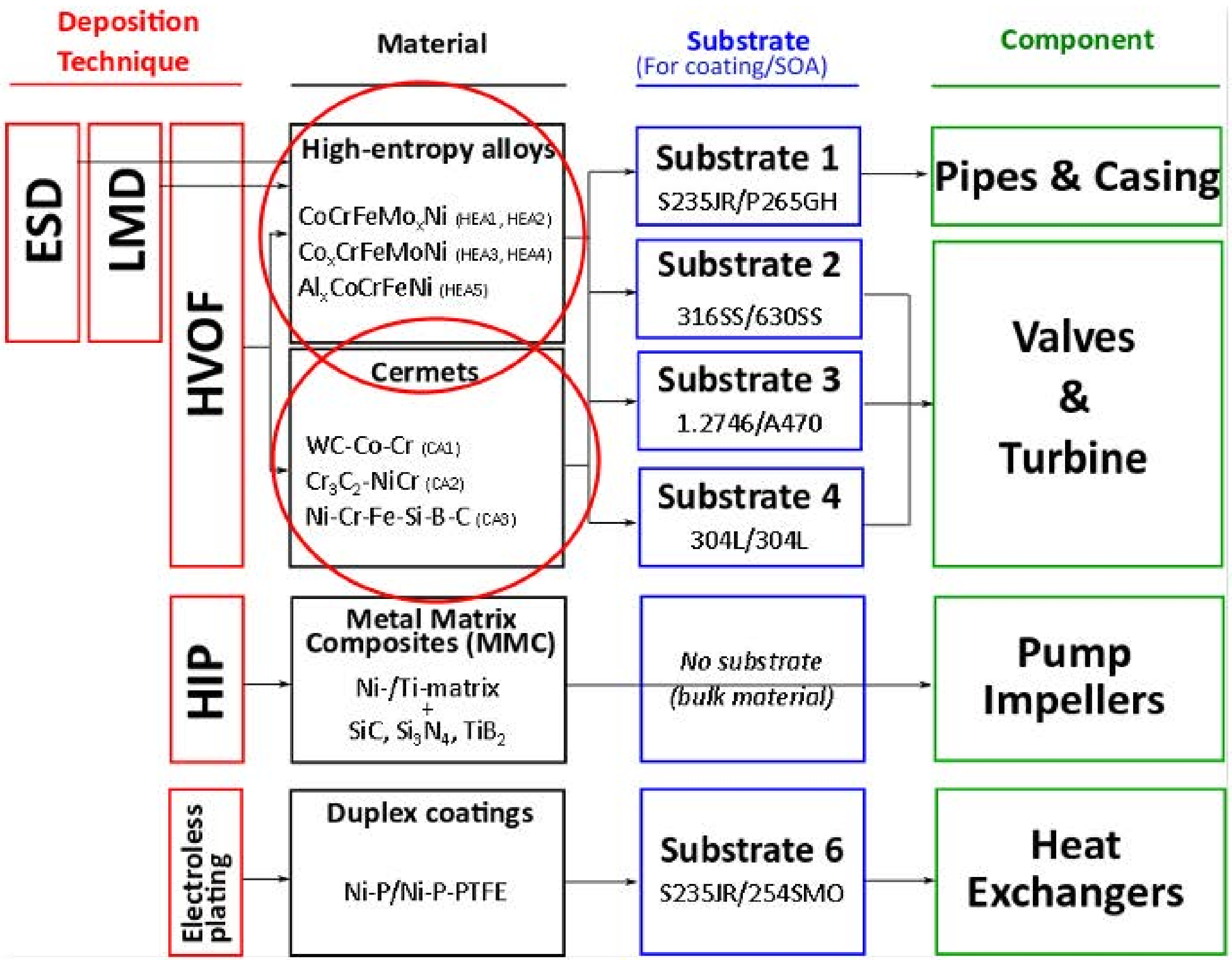
METAV CERCETARE-DEZVOLTARE
TEHNOID

Materials & Methods



High-Velocity Oxygen Fuel (HVOF) process *[Courtesy of TWI]*

Laser Metal Deposition (LMD) process *[Courtesy of TWI]*

Experimental Approach

- Down selection after laboratory tests @RT

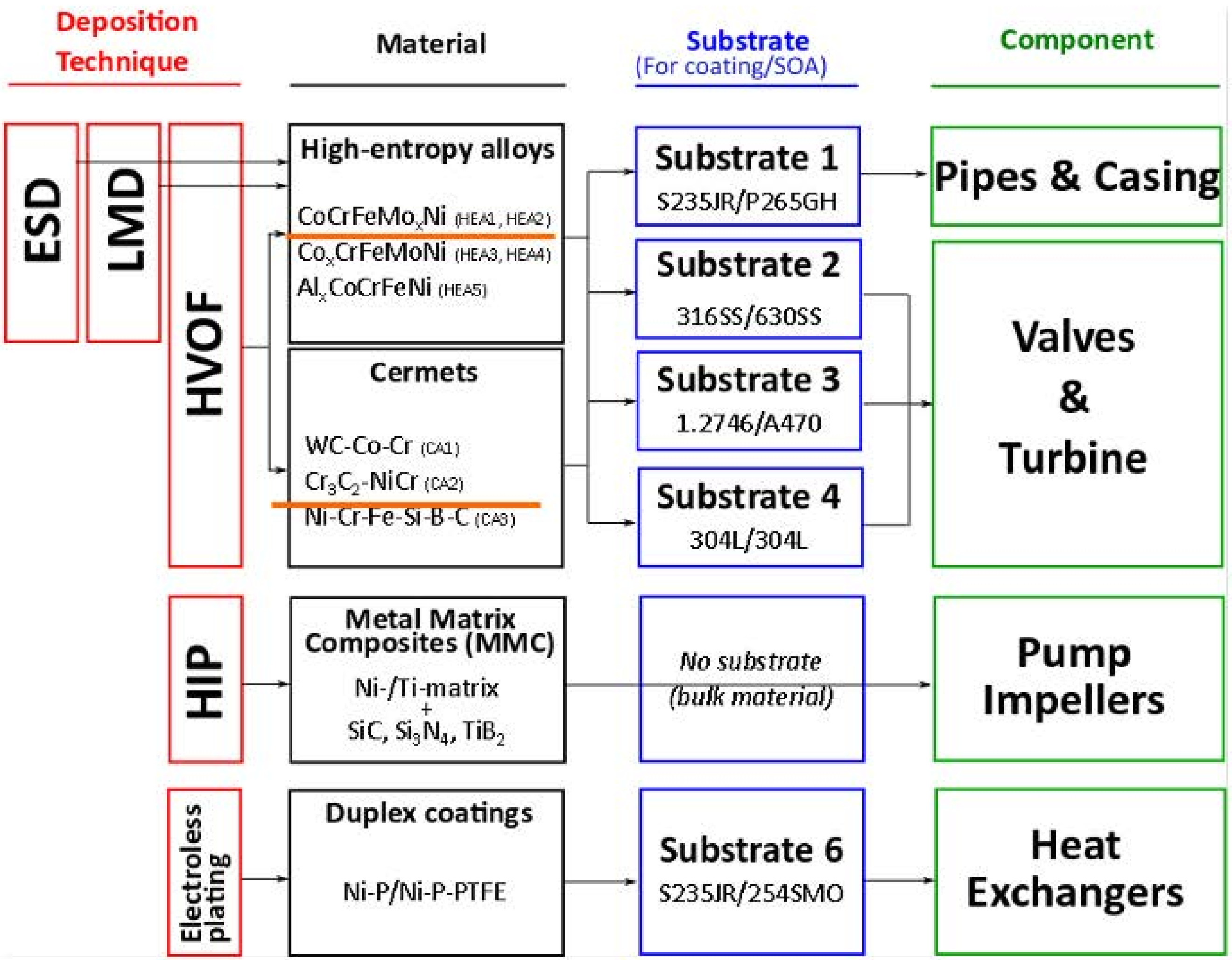
Laboratory tests at RT
- wear (PoD) and erosion-corrosion tests
- electrochemical tests in 3.5wt% NaCl

Corrosion testing in simulated high temperature geothermal environment

Long term in-situ testing of coatings

Verification by coating a component

Materials & Methods



High-Velocity Oxygen Fuel (HVOF) process
[Courtesy of TWI]

Laser Metal Deposition (LMD) process
[Courtesy of TWI]

Corrosion Testing in Simulated High Temperature Geothermal Environment

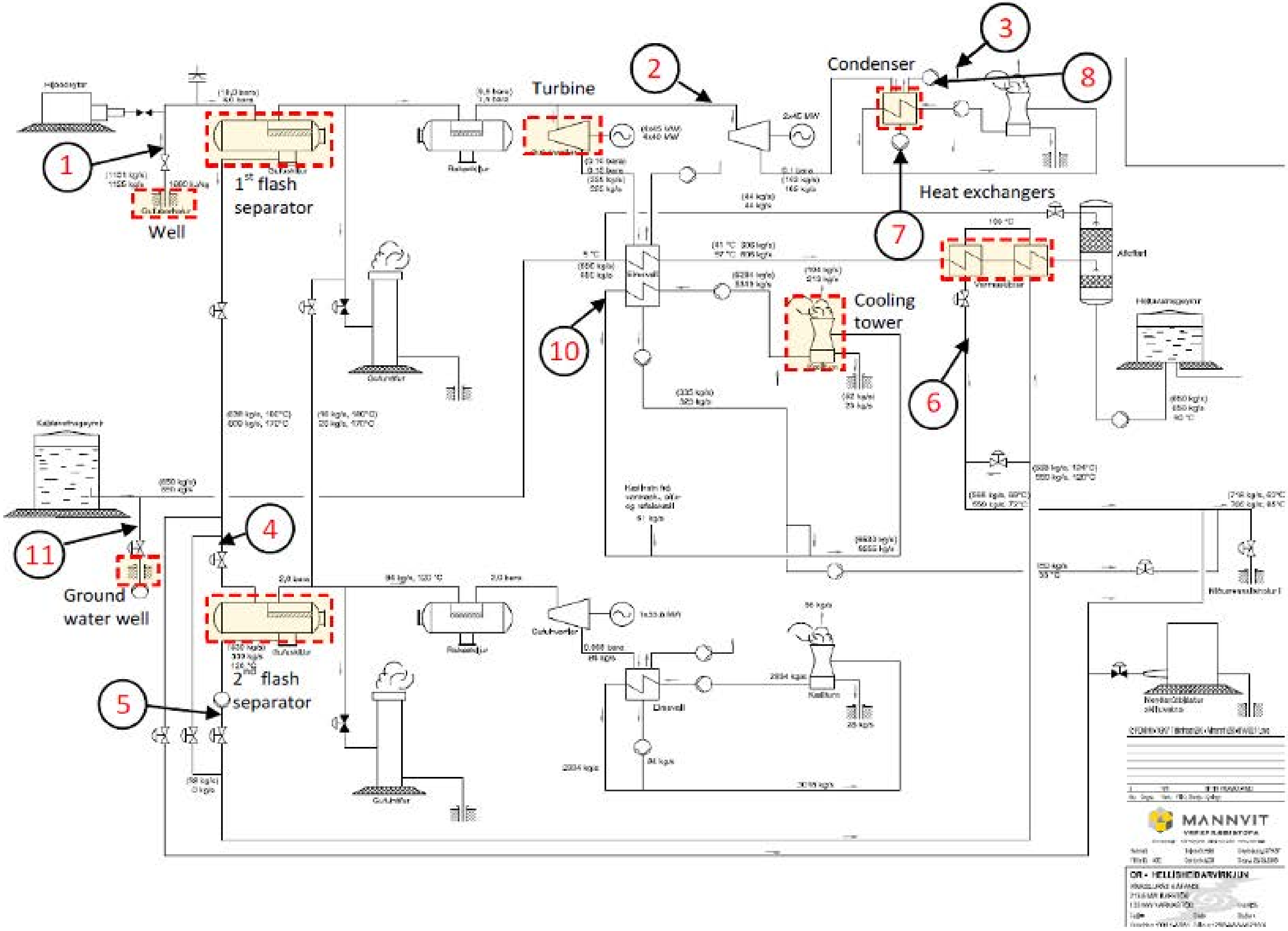
Hellisheiði Powerplant

Figure 1: Overview of Hellisheiði power plant. 1) Turbines 1-4, 2) turbine 11, 3) heat exchanger, 4) turbines 5 and 6, 5) main building for fluid distribution, 6) boiler, 7) low pressure separators, 8) moisture separators, 9) workshop, 10) cooling towers (photo: Gretar Ivarsson).

Figure 2: Overview of Nesjavellir power plant [1].

GeoCoat Deliverable Report D1.3: "Report on characterisation of geothermal fluid. " Sigrún Sif Sigurðardóttir et al.

Layout of Hellisheidi Power Plant



GeoCoat Deliverable Report D1.3: "Report on characterisation of geothermal fluid. " Sigrún Sif Sigurðardóttir et al., 2019.

Location	State	T [°C]	P [bar]	pH	CO_2 [mg/kg]	H_2S [mg/kg]	SiO_2 [mg/kg]	Na [mg/kg]	K [mg/kg]	Ca [mg/kg]	Cl [mg/kg]	SO_4 [mg/kg]	Se [mg/kg]
Wellhead	Water	176-209	16-77	7.12-8.67	4-29.1	7-105	204-1224	9.5-168.7	<4-36	0.32-0.46	5-205	1.5-13.4	0.82-46.9
	NCG	-	-	-	443-3807	410-1173	-	-	-	-	-	-	-
	Cond. steam	-	-	3.95-4.42	-	-	0.172-0.53	<0.1-0.13	<0.4	<0.1	0.08-1.8	0.3-1.6	<0.5-1.43
Steam into turbines	NCG	172-191	7.4-11.8	-	1268-3470	384-978	-	-	-	-	-	-	-
Gas from turbines	NCG	-	-	-	*37-66 [vol%]*	*12-34 [vol%]*	-	-	-	-	-	-	-
Separator water after 1st flash	Water	172-180	8.4-12	8.70-8.94	22-30	50-75	676-758	168-206	33-35	0.30-0.74	155-186	42705	n.a
Separator water after 2nd flash	Water	119	2-10	9.2	20	30	735	203	38	0.85	186	21.5	16
Separator water after heat exchangers	Water	10-85	10-12	8.83-9.2	19.8-23.7	30-82	735-764	159-206	31.6-35.5	0.27-0.78	118-186	18.1-24.4	7.6-15.3
Condensate	Water	40-60	1	5.1-6.9	2-20.9	1-98.3	<0.06-4.4	<0.1-1.78	<0.4	<0.1-0.86	<0.1-1	1-3.9	<0.5
Seal water	Water	40-60	1	n.a.	365-920	331-560	<0.06	<0.1	<0.4	<0.1	<0.1	7	0.535
Sulfix water	Water	15	7.5	n.a.	7100	4000	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.
Cooling water	Water	4	n.a.	7.3	25.7	0	24	6.3	0.9	4.56	5.8	1.4	<0.5
Typical ground-water	Water	-	-	7.72-8.3	-	-	24.1-34.9	6.2-14.8	0.88-1.67	4.8-9.5	7.0-13.2	2.2-10.5	<0.5

A combined overview of the range of the properties and chemical composition at the different sampling locations at Hellisheiði power plant

Table derived from GeoCoat Deliverable #1.3: Report on characterisation of geothermal fluid. Sigrún Sif Sigurðardóttir et al., 2019.

Corrosion testing in simulated geothermal environment

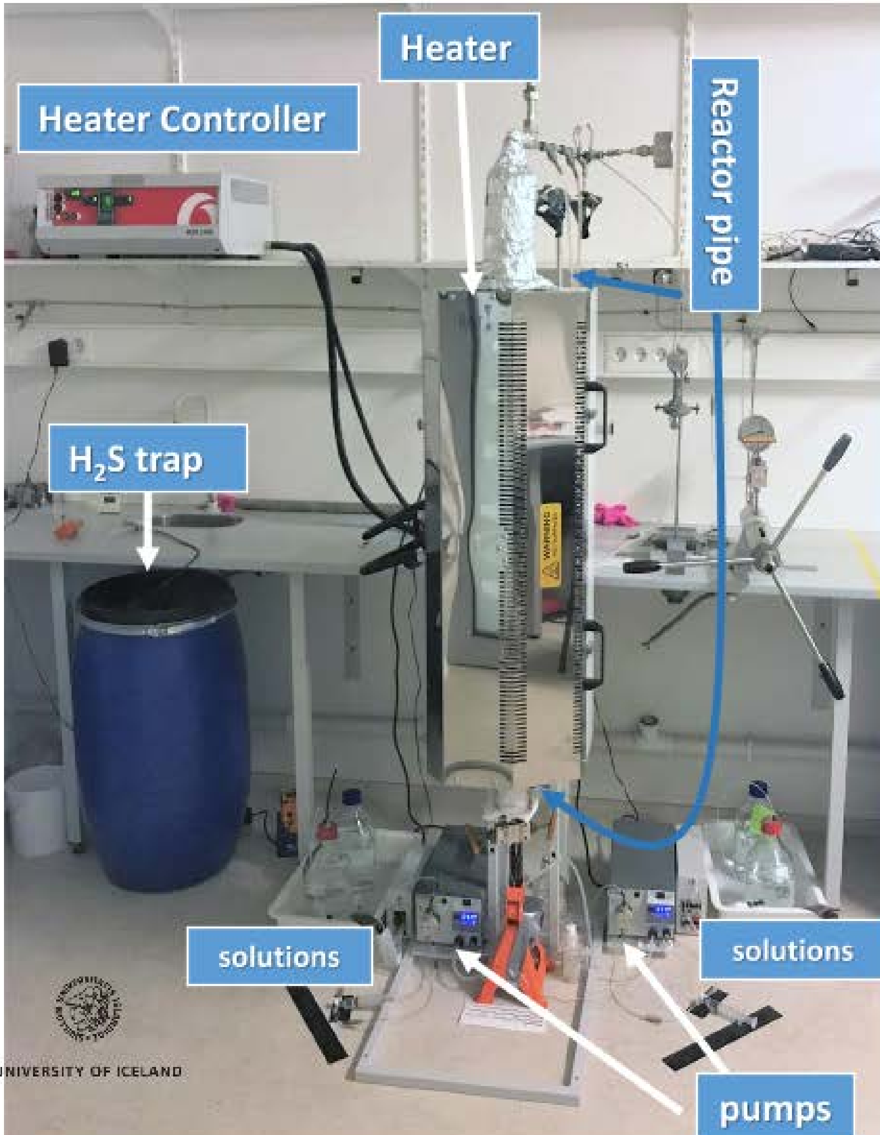
- UoI: Flow Through Reactor (FTR)
  - Continuous flow of solution for replenishment of H_2S and CO_2
  - Test time: 7 days (12 types of specimens)

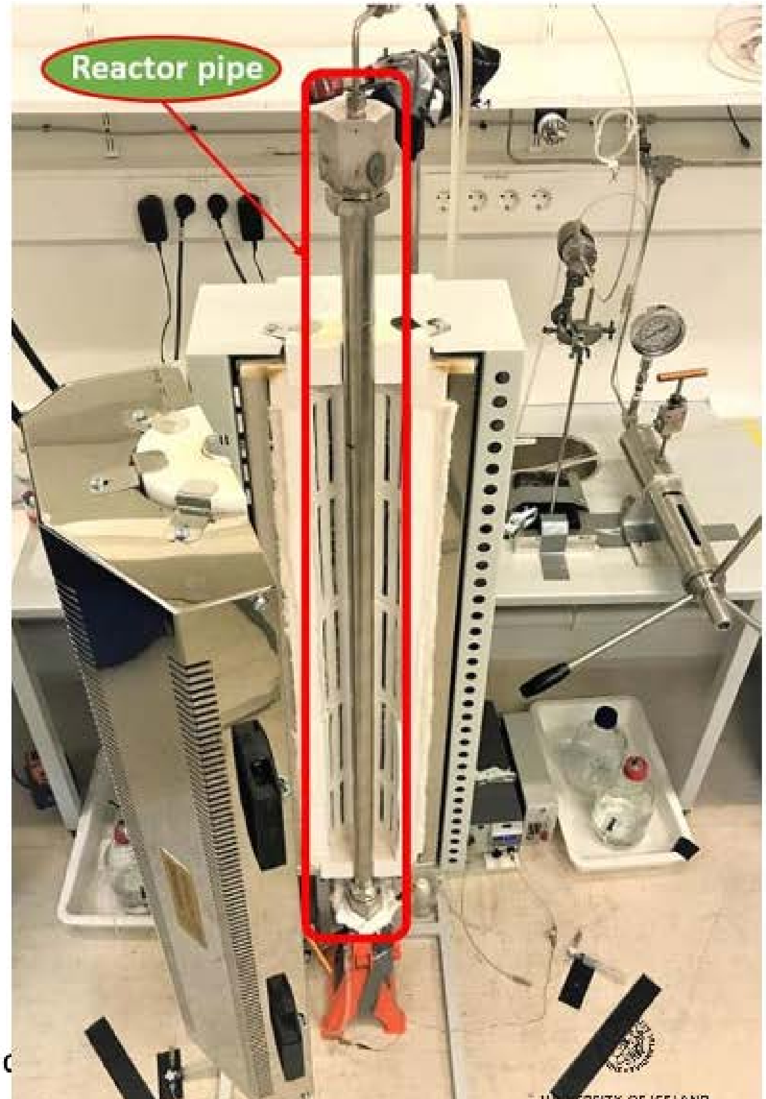
pH @RT	T [°C]	P [barG]	CO_2 [ppm]	H_2S [ppm]	Cl^- [ppm]
4	185	10.5	1012	170	1202

- TWI: Autoclave
  - Static conditions
  - Test time: 60 days (12 types of specimens)

pH @RT	T [°C]	P [barG]	CO_2 [ppm]	H_2S [ppm]	Cl [ppm]
4	120	50	7100	4000	205

High temperature corrosion testing in FTR

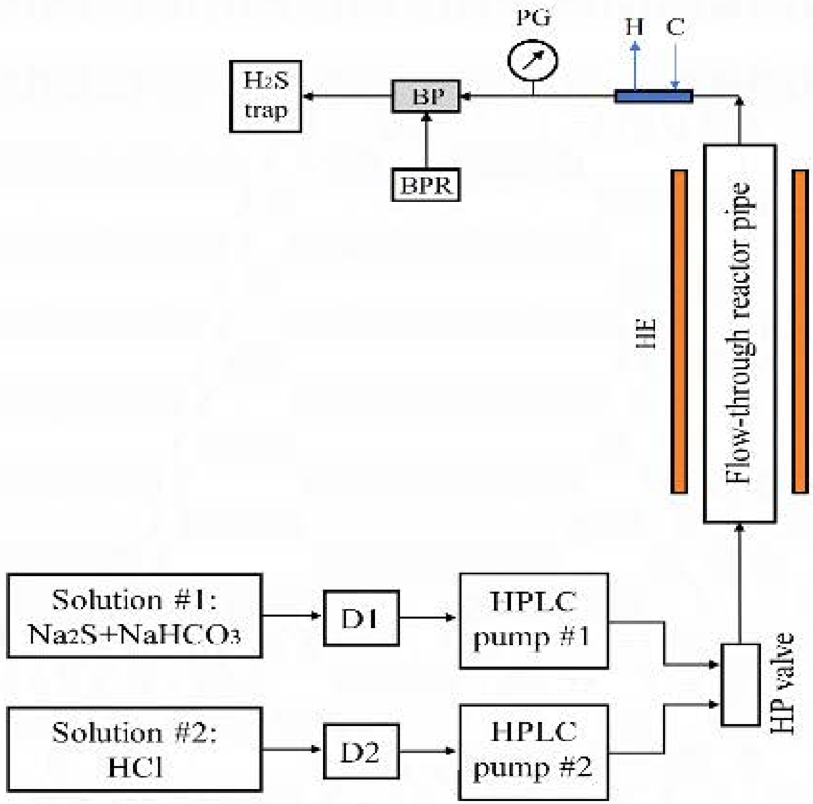


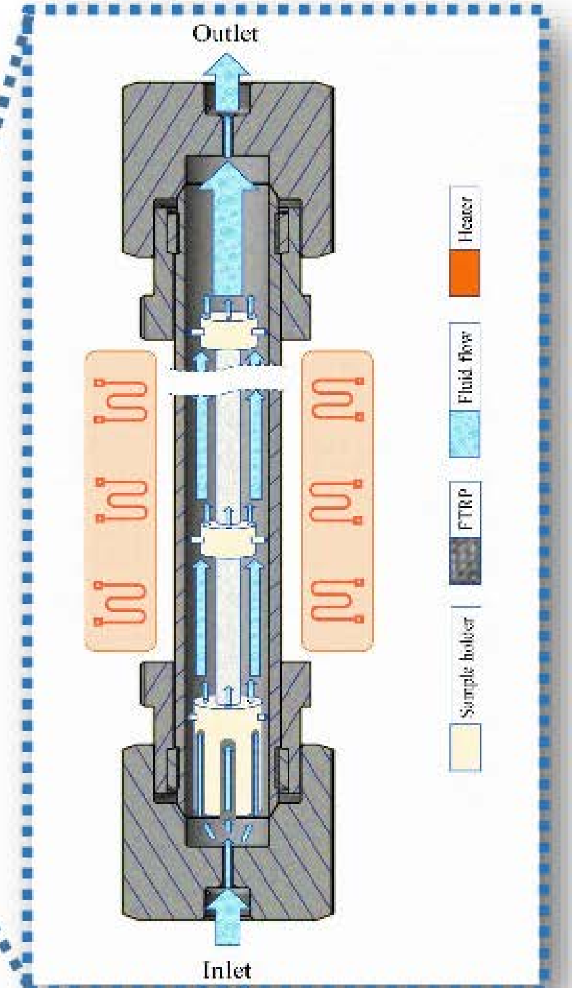


High temperature corrosion testing in FTR

$Na_2S + 2HCl \rightarrow H_2S_{(g)}\uparrow + 2NaCl$

$NaHCO_3 + HCl \rightarrow CO_{2(g)}\uparrow + NaCl + H_2O$





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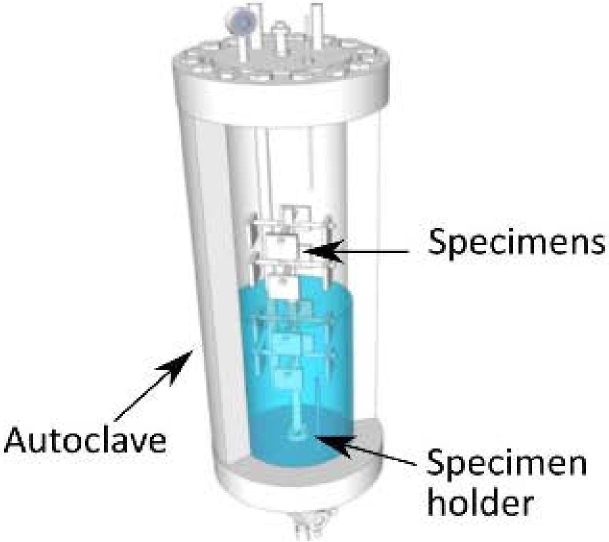
Corrosion testing in autoclave with high H_2S

[Courtesy of TWI]



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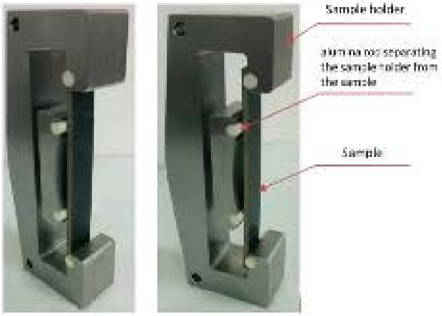


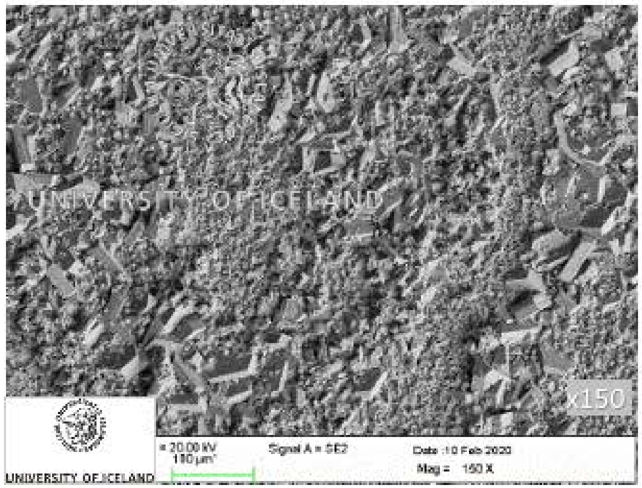
Corrosion testing in high temperature simulated geothermal environment

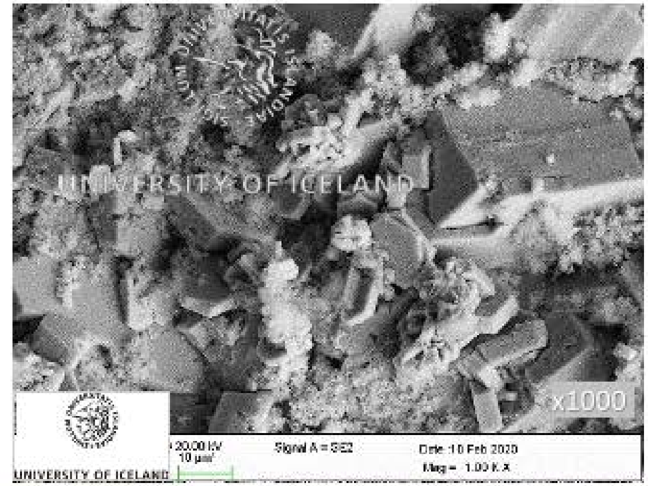
*Challenges in corrosion analysis of **coatings** in **high temperature** corrosion testing*

- What to look for?
- Weight loss method – CR ?

Microstructural and Chemical Composition Analyses

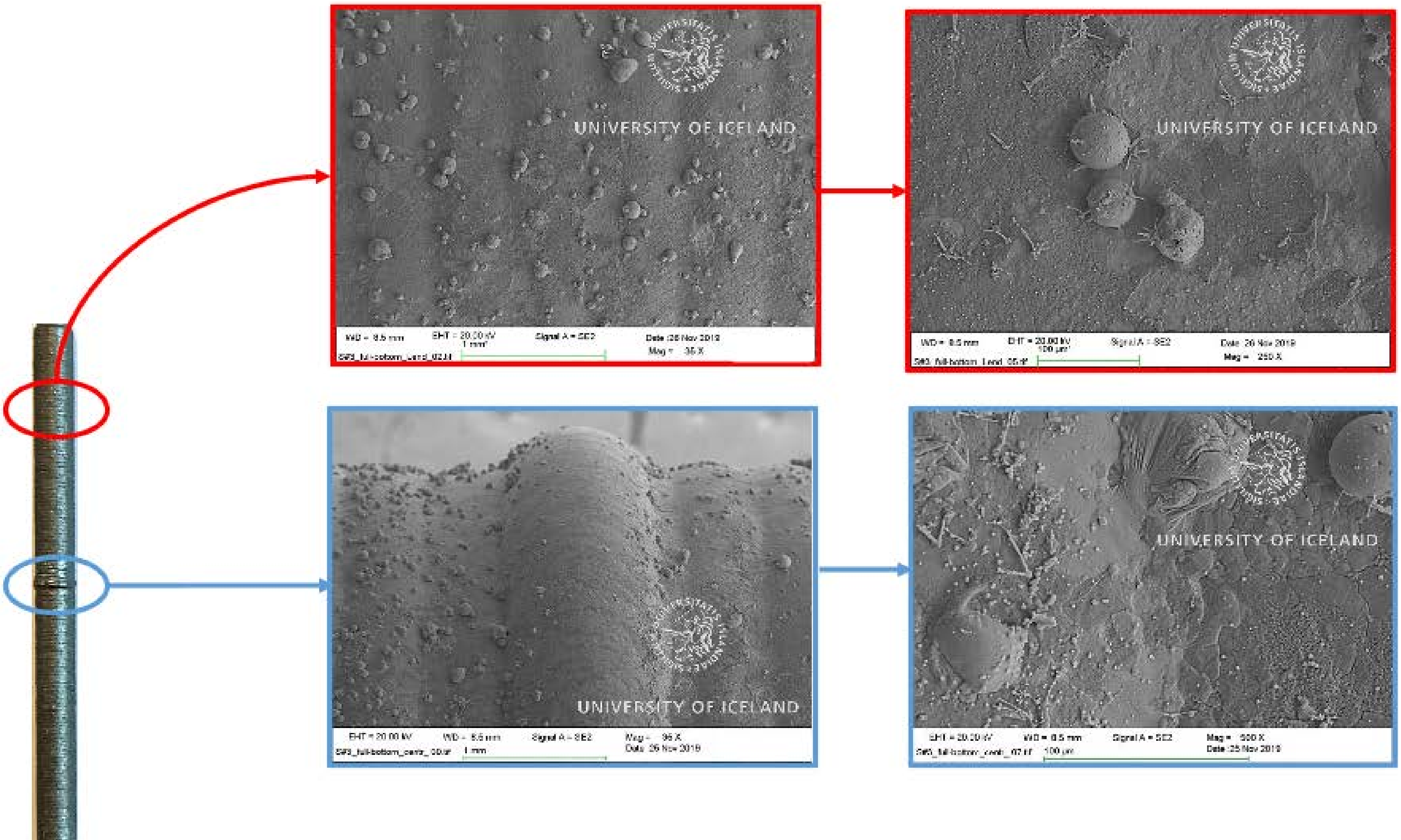
S3 (A470) Tested in simulated geothermal HT conditions





Substrate ID	Substrate	C	Mn	Si	P	S	Cu	Cr	Ni	Fe	Al	Mo	Nb	V
S3	A470 grade C	0.2 - 0.35	0.1	0.12	0.006	0.002	0.1	0.8 - 2.0	1.5 - 6.5	bal	0.01	0.9 - 2.0	0 - 0.07	0.1 - 0.4

HEA2 Tested in simulated geothermal HT conditions



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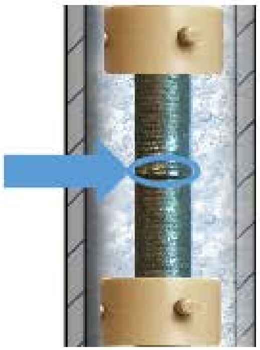
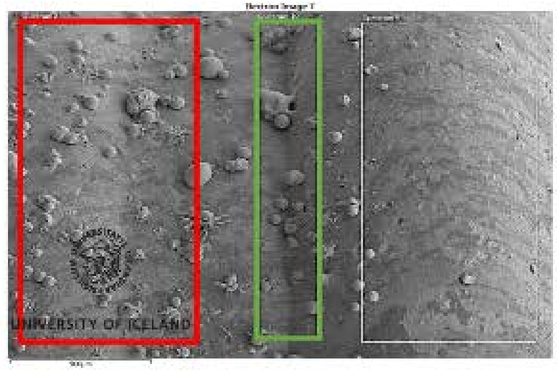
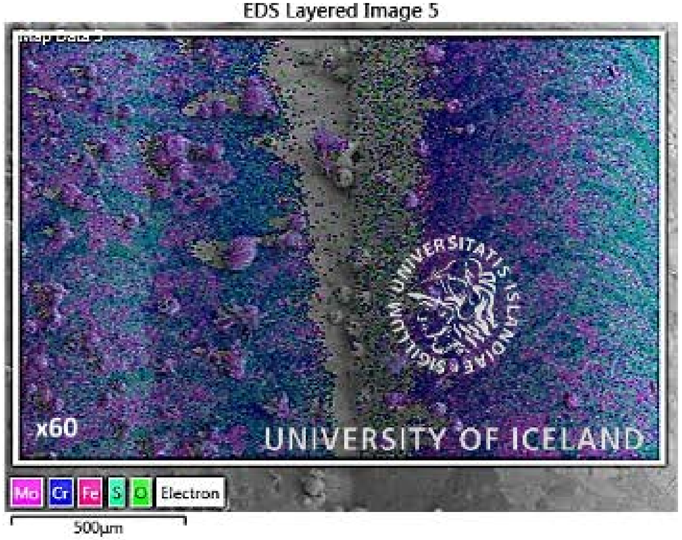
HEA2 Tested in simulated geothermal HT conditions







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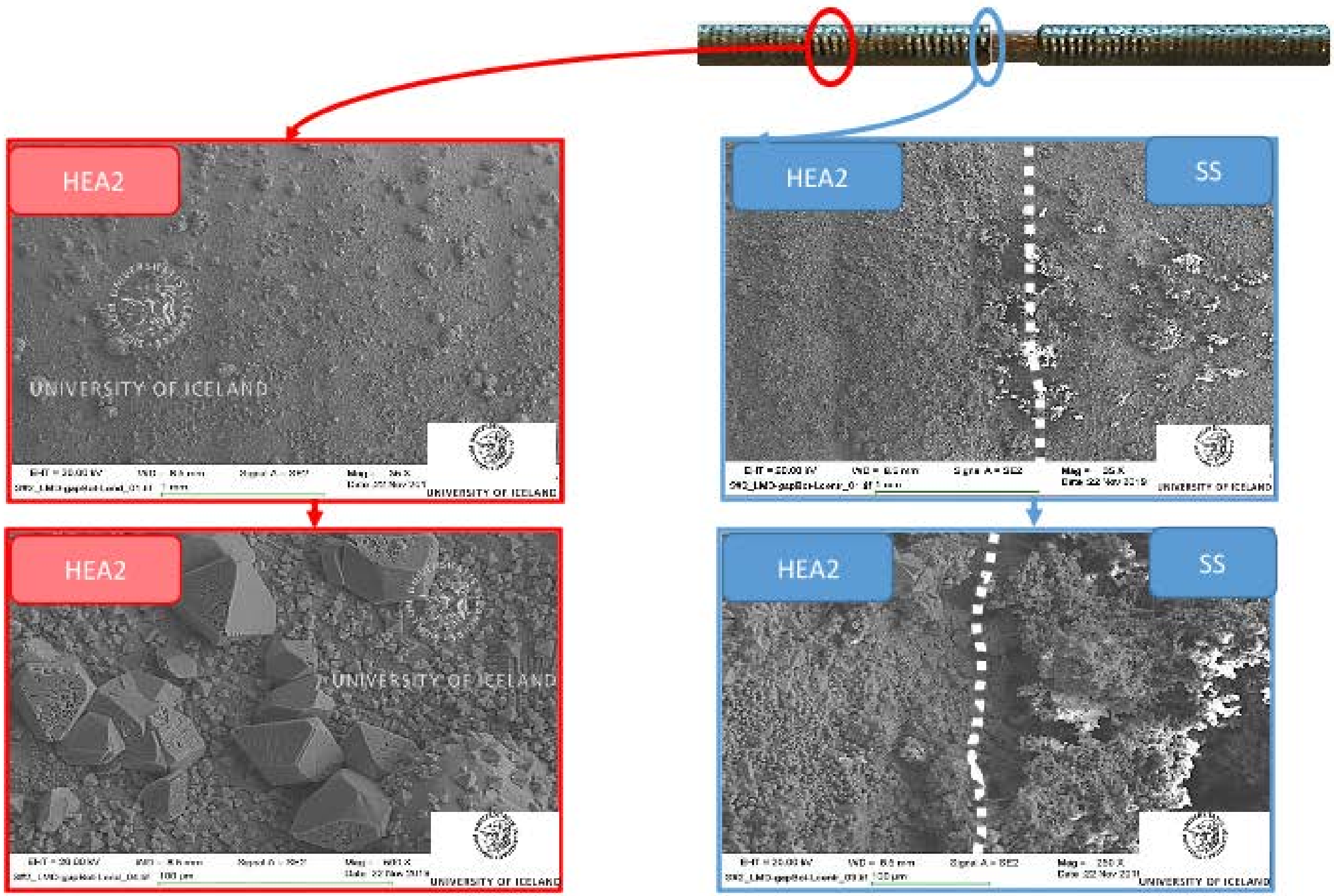
HEA2 coating w. gap tested in simulated geothermal HT conditions



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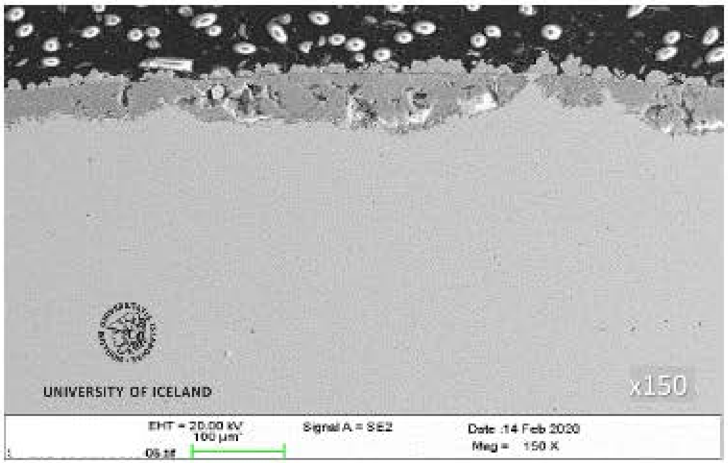
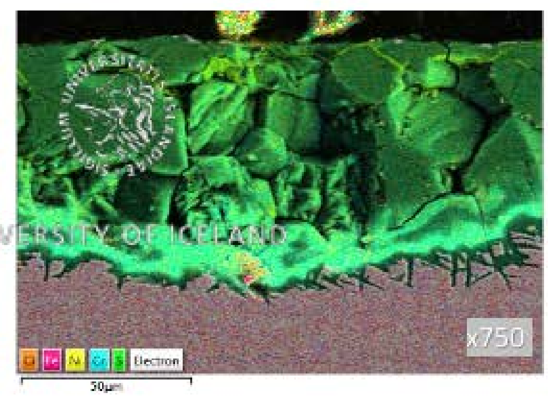
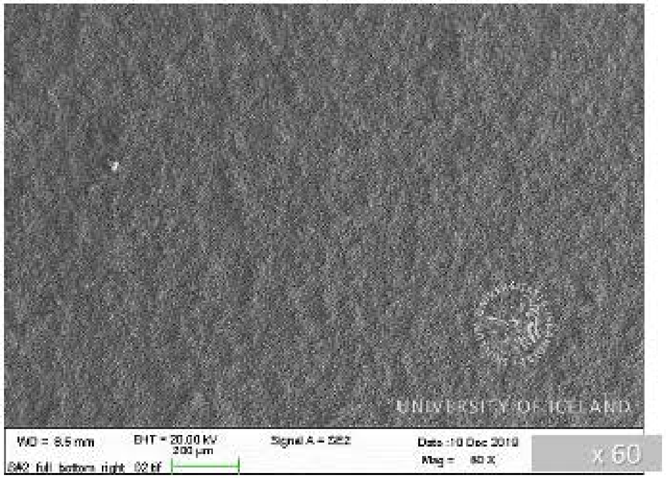
HEA2 coating w. gap tested in simulated geothermal HT conditions

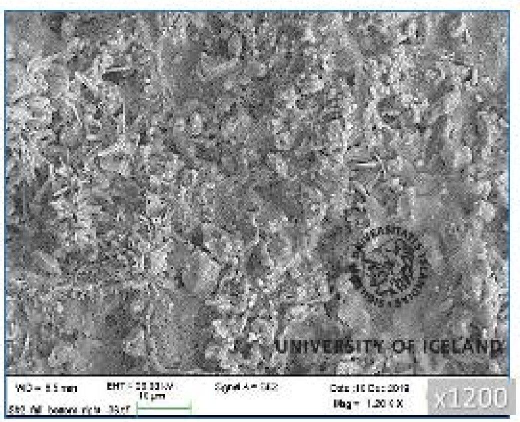
S2 - Cross-section in gap

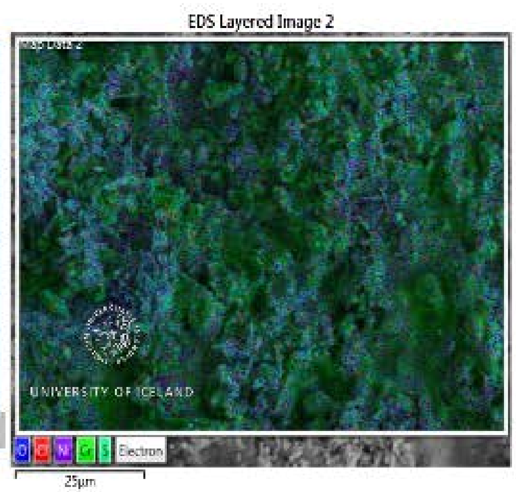


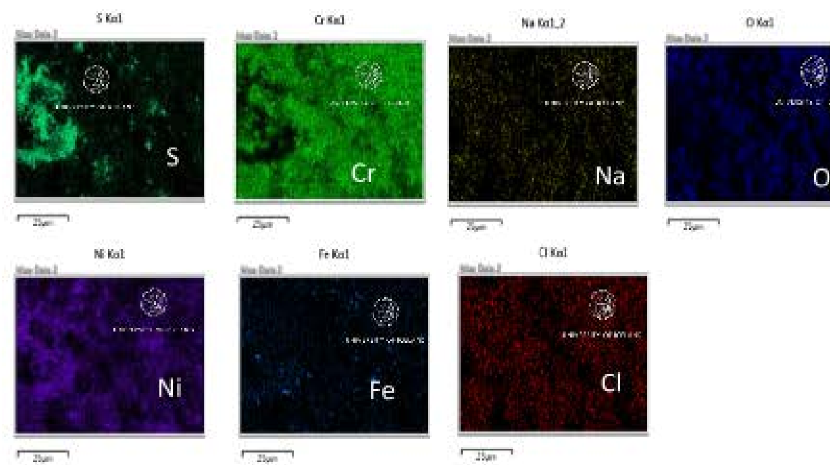


CA2 coating tested in simulated geothermal HT conditions



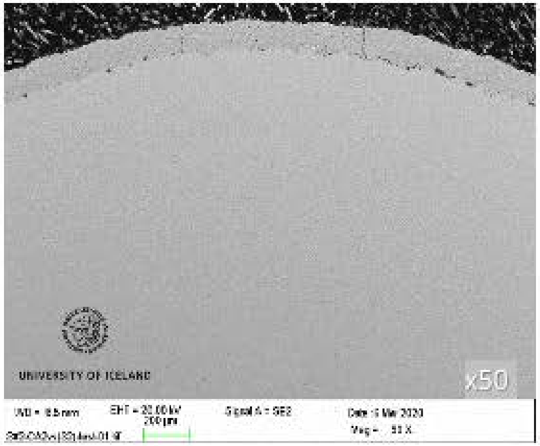


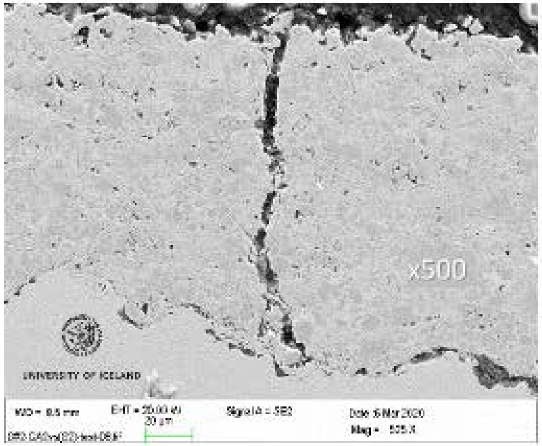


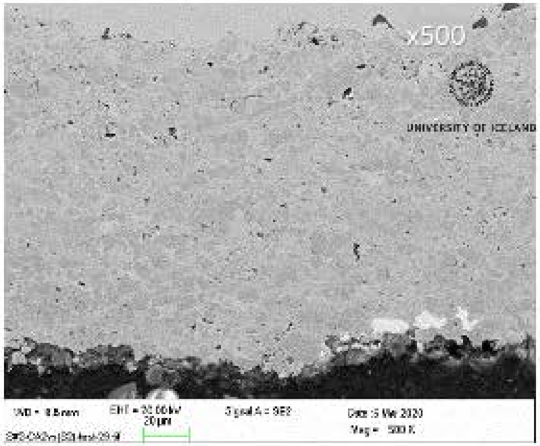


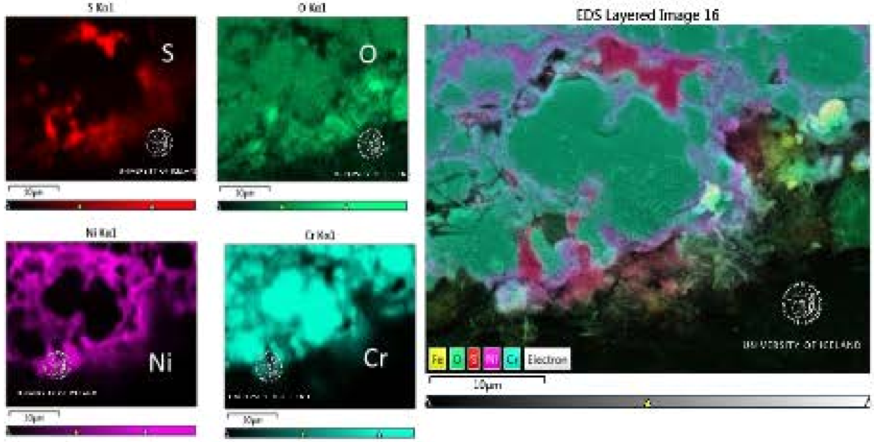
CA2 coating tested in simulated geothermal HT conditions

Cross-section









Summary

- Simulated geothermal environment established in laboratory with FTR corrosion tests equipment
  - Corrosion film comparable to what is found in in-situ conditions
- Promising results for HEA2 coating:
  - Good performance in HT simulated geothermal environment with H_2S & CO_2
  - Formation of passive film – Cr, O rich
  - No cracks or ingress of corrosive species
  - But evidence of increased corrosion effects in SS substrate for sample coated with gap
    - Galvanic effects – HEA2 more noble than SS 316

Summary

- For the cermet coating CA2:
  - More porous due to deposition technique
  - More brittle
  - Evidence of ingress of corrosive species (S, O)
  - But no rapid dissolution of coating

- First results from in-situ long-term test support results found in laboratory HT corrosion test in simulated geothermal environment

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Publications

- Gifty Oppong Boakye, Danyil Kovalov, Andri I. Thorhallsson, Vlad Motoiu, Sigrun N. Karlsdottir "Friction and Wear Behaviour of Surface Coatings for Geothermal Applications", Proceedings of World Geothermal Congress 2020, Reykjavík, Iceland (accepted).
- Danyil Kovalov, Jan Prikryl, Gifty Oppong Boakye, Andri I. Thorhallsson, Sigrun N. Karlsdottir, "Design and Operation of Testing Facility for Investigation of Novel Corrosion Resistant Coatings for High Temperature Geothermal Applications", Proceedings of World Geothermal Congress 2020, Reykjavík, Iceland (accepted).
- Danyil Kovalov, Jan Prikryl, Gifty Oppong Boakye, Andri I. Thorhallsson, Sigrun N. Karlsdottir, "High-Temperature Corrosion Testing Facility for Coating Materials in Simulated Geothermal Environment", GRC transactions", 2019, USA.
- Fanicchia, F., et al. "Effect of Microstructural Modifications on the Corrosion Resistance of CoCrFeMo0. 85Ni Compositionally Complex Alloy Coatings", Coatings, 9(11), 695, 2019.
- Buzaianu, A., et al. "Considerations regarding WC-cermets depositions by HVOF and ESD techniques used for reinforced steel components for geothermal turbines", IOP Conference Series: Materials Science and Engineering, Vol. 572. No. 1. IOP Publishing, 2019.
- Karlsdottir, S.N., et al. "Phase evolution and microstructure analysis of CoCrFeNiMo high-entropy alloy for electro-spark-deposited coatings for geothermal environment", Coatings, 9(6), 406, 2019.


Thank you for your attention
Questions?