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NACE Corrosion and Scaling Symposia Research Themes 2013 to 2019

Keith Lichti[1] and Sigrún Nanna Karlsdóttir[2,3]

[1]Quest Integrity NZL Limited, PO Box 38096, Lower Hutt, New Zealand

[2]Department of Industrial Engineering, Mechanical Engineering and Computer Science, University of Iceland, Hjarðarhagi 2-6, 107 Reykjavík, Iceland

[3]Gerosion Ltd., Árleynir 2-8, IS-112 Reykjavik, Iceland

K.Lichti@QuestIntegrity.com and snk@hi.is

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ABSTRACT

In 2013 a new initiative for dissemination of geothermal scaling and corrosion information was initiated within NACE International corrosion society. A Technology Exchange Group, TEG 182X - Geothermal System Corrosion, was formed with the purpose of promoting discussion of corrosion and scaling in geothermal energy systems – impact of production, process and reinjection conditions on materials and process efficiency. The primary means of achieving this goal has been by holding symposia within the NACE annual corrosion conference. Five symposia have been held to date and more are planned. This paper reviews the task group activities with particular emphasis on the recent corrosion and scaling research themes emerging from symposia papers.

1. INTRODUCTION

The NACE International corrosion society membership is open to all parties with an interest in material-environment interactions. The NACE definition of corrosion is:

- The deterioration of a material, usually a metal, that results from a chemical or electro-chemical reaction with its environment.

An important consequence of this definition is that any and all materials are included and the deterioration can be by any and all mechanisms. Naturally occurring geothermal environments have been utilized for direct use for millennia, adapted for cooking and bathing with the aid of locally sourced materials. The relatively recent energy production processes developed in the 20th century were facilitated through a combination of oil and gas technologies for exploration, drilling and well completion as well as thermal power steam turbine technologies for energy conversion. Energy processes and materials selection for these were based on a combination of existing technologies, targeted research and trial and error. The pioneering approach to geothermal fluid utilization continues to this day with R&D in new environments including volcanic and acid well environments and deep and high temperature near magma geothermal resources as well as for lower temperature space heating and small scale energy conversion. Conventional near neutral brine and steam produced geothermal energy systems are also benefiting from geochemistry and materials R&D with the application of scaling and corrosion inhibitors, duplex and triplex metal alloys, high entropy alloys as well as coatings.

Historical geothermal materials technology information is readily available in engineering journals and text books and conference proceedings. More recent conference presentations dealing with all aspects of geothermal technology including materials selection and use are tabulated in the IGA Geothermal Conference Database maintained by Stanford University. In 2013 NACE initiated a Technology Exchange Group (TEG)

- TEG 182X - Geothermal System Corrosion, Purpose: Promoting discussion of corrosion and scaling in geothermal energy systems – impact of production, process and reinjection conditions on materials and process efficiency.

This TEG focus on materials was initiated to bring together corrosion and metallurgy researchers of geothermal in the years between WGC conferences. The NACE Geothermal Scaling and Corrosion Symposium, one of many geothermal conferences and workshops held annually, has a specific focus to provide materials and scaling specialists with a forum for presentation and discussion of their most recent work activities.

Recent geochemistry and materials developments have been a key part of the TEG 182X technology exchange and this paper aims to summarize the emerging research themes.

The authors are the present Chair and Co-chair of TEG 182X.

2. EMERGING RESEARCH THEMES

The main themes emerging from the TEG 182X Symposia have been:

- Corrosion Products, Scaling, Scale Inhibition and Corrosion Inhibition.
- New Materials Development and Testing:
    - Coatings and High Entropy Alloys.
    - Materials for High Chloride Applications.
    - Performance of Stainless Steels.

- Materials and Processes for Deep Geothermal.
- Materials and Inhibitors for Acidic Geothermal.

Although these themes have inherent synergy it is useful to highlight the primary aims and objectives of the relevant researchers and operators who have contributed to the TEG 182X activities. The geothermal environments of interest for these themes range from conventional near neutral pH brine and steam to acidic fluids to high temperature superheated steam and supercritical brine. The extremes of geothermal have led to research and understanding of the limitations of existing materials and new materials solutions as well as the application of novel monitoring technologies.

2.1 Corrosion Products, Scaling, Scale Inhibition and Corrosion Inhibition

Silica Scaling: Emphasis of this work has been on problematic scales and monitoring. Mountain et al, 2013, described the deposition characteristics of aluminium silica scales at higher temperatures than amorphous silica. Thorolfsson, 2019, encountered a variety of scales in a geothermal power plant setting. Anhika and Regenspurg, 2013, demonstrated capability to monitor silica scaling using ultrasonics.

Scale and Corrosion Inhibition: Research on scale inhibitor selection (Guan, 2013) was a part of the first TEG 182X symposium and has continued throughout with recent emphasis on compatibility of scale vs corrosion inhibitors (Ferrer et al, 2018), calcite antiscalants for use at very high temperatures, (McCabe and Heath, 2019), environmentally friendly inhibitors for acid fluids (Ghaziof et al, 2018), CO_2 corrosion inhibitors for sweet geothermal brines at low temperature (Klapper et al, 2019) and inhibitors for acid cleaning of geothermal wells (Todd and Muller, 2019).

Iron Compound scaling: Deleterious iron sulfide scales were reported to form following acidification (Chen et al, 2018) and were identified as a contributing factor for hydrogen embrittlement (Folena and Gomes, 2018). Complex carbonates complimented by formation of magnetite contributed to corrosion control of carbon steel in CO_2 rich brines (Hua et al, 2019). Richter and Thorarinsdottir, 2013 argued that Icelandic geothermal waters used for central heating systems had inherent low corrosion in the non-aerated slightly alkali fluids.

Elemental Deposition of Cathodic Metals: The cathodic elemental metals form by reductive deposition on freely corroding carbon and low alloy steels in in mildly acidic geothermal brines, (Lichti and Brown, 2013). Elemental arsenic and antimony (Lichti and Brown, 2013), arsenic (Scheiber, 2016) and copper (Stoljarova et al, 2019) were reported for various geothermal equipment. Testing and corrosion control practices were outlined for pH modified fluids (Amend and Yee, 2013; Lichti and Brown, 2013; Lichti et al, 2016).

2.2 New Materials Development and Testing

2.1.1 Coatings and High Entropy Alloys

There was ongoing research to identify suitable coatings for geothermal applications and to develop new materials for both conventional and extreme geothermal environments.

Application of Conventional Materials: Success with improved cement mortars was demonstrated (Berndt, 2013) while Ni-P coatings readily corroded in H_2S containing environments (Lichti and Ghaziof, 2019). Explosive cladding gave acceptable performance in short term tests in conventional geothermal environment (Ragnarsdottir et al, 2018)

Novel Coatings: Polyaniline/silicon dioxide containing coating (Aristia et al, 2018; Aristia et al, 2019) and nanocomposite polybenzoxazine coatings (Espartero et al, 2019) were reported to show promise for geothermal brines.

Coatings for Turbine Applications: Electric arc sprayed titanium (Haraldsdottir et al, 2019), electric arc, HVOF and plasma jet coatings were tested in-situ in geothermal environment for erosion-corrosion to explore the options for new and repair turbine material applications (Ragnarsdottir et al, 2017).

High Entropy Alloys: Mechanically alloyed AlCrFeNiMn (Csaki et al, 2017) and CoCrFeNiMn (Csaki et al, 2018, Csaki et al, 2019) have been tested in a geothermal power station high temperature steam where CoCrFeNiMn showed better performance with corrosion rates well below 0.1 mm/year.

2.1.2 Materials for High Chloride Applications

Materials for Aggressive Chloride Containing Wells: Ti alloys and Ni-base alloys development for casing for Salton Sea applications having corrosive high salinity environments received continuing interest (MacDonald and Grauman, 2014, MacDonald and Grauman, 2018) and new alloy development has been outlined (MacDonald and Grauman, 2019). Good performance of pure metals Ta and Mo, and Co-based, Zr-based and Ti-based alloys in conventional steam was also reported (Lichti and Wong, 2014).

Deep formation water corrosion and scaling was reported for the Soults-sous-Forets project (Mundhenk et al, 2014) and the properties of the reservoir fluids were later modelled (Klapper et al, 2017).

2.1.3 Performance of Stainless Steels and Ni-Base Alloys

Stainless Steels and Ni-Based Alloys: The poor performance of carbon and low alloy steels in a number of new developments prompted laboratory and field testing of so-called Corrosion Resistant Alloys in laboratory and field applications. Results for low alloy stainless steels (Bäßler et al, 2013), duplex and superduplex stainless steels (Francis et al, 2013) and stainless steels and Ni-based alloys for Iceland applications (Karlsdottir et al, 2013, Karlsdottir et al 2016) and stainless steels for North German Basin applications (Regenspurg et al, 2013) were initially reported. There was a continuing effort to define the applicability of conventional stainless steels (Bäßler et al, 2014) and Ni-base alloys and ceramic (Bäßler, et al, 2014). Duplex alloys were again investigated for high salinity geothermal brines (Bäßler et al, 2016) (Wolf et al, 2016). The North German Basin materials testing continued to be reported (Klapper et al, 2016). The Ni-based alloy N06625 was tested for application in IDDP supercritical fluids (Thorhallsson et al, 2018). Pitting properties of stainless steels and Ni-base alloys in simulated geothermal environments were reported (Bogaerts and Winstons, 2017)

Drilling applications also required specialty alloys for high temperature and high pressure reservoirs (Klapper and Stevens, 2013). The Ni-base alloy N07718 was tested for applications for geothermal drilling (Klapper et al, 2016).

Performance of stainless steels in low temperature applications was investigated in aerated sulfide environments in H_2S removal systems (Karlsdottir et al, 2016) and in power station direct contact steam condensers (Wilson and Lichti, 2017).

2.3 Materials and Processes for Deep Geothermal

There is a growing experience of scaling and corrosion damage processes in deep geothermal applications that aim to utilize supercritical conditions as encountered in the IDDP projects in Iceland. Early work used a conventional approach to materials testing and the trial and error approach was well documented. Results obtained with wet scrubbing equipment at IDDP-1 were presented (Karlsdottir et al, 2013) and this was followed by descriptions for new methodologies for testing heat exchanger tube materials for IDDP-1 (Karlsdottir et al, 2014). Laboratory testing techniques for prescreening of candidate stainless steels were developed (Karlsdottir et al, 2017) and observed damage mechanisms with the deep well materials described; SSC of carbon steel injection string (Karlsdottir et al, 2019) and hydrogen damage of carbon steel in IDDP-1 (Karlsdottir et al, 2018). The second well supercritical geochemistry was predicted (Tjelta et al, 2019) while the materials screening for the second well development under laboratory conditions continued (Thorhallsson et al, 2019).

2.4 Materials and Inhibitors for Acidic Geothermal

Acids are variously encountered in geothermal under both dry steam and two-phase production and as deliberate addition for delayed silica polymerization. The latter to allow time for reinjection of flashed and heat exchange cooled brine (Lichti and Brown, 2013). Options for corrosion control when acids are encountered have featured in the TEG 182X presentations, materials selection for two-phase fluids; duplex alloys (Amend and Yee, 2013); stainless steels (Keserovic and Bäßler, 2013), super-austenitic materials (Sobetzki and Le Manchet, 2017) and environmentally friendly corrosion inhibitors (Ghaziof et al, 2018). On-line automated monitoring by waveguide ultrasonic for process control was espoused for dry steam applications (Farison, 2017).

3. GEOTHERMAL DAMAGE MECHANISMS

Geothermal fluids are natural environments that are "uncontrolled" with respect to the contaminants present downhole; however under production the processes selected for energy conversion can be altered or controlled to limit the risk of scaling and corrosion. Virtually all damage mechanisms can be encountered in geothermal environment and it is useful to summarize the damage mechanisms described in the TEG 182X symposia:

- Scaling in geothermal brines (Mountain et al, 2013, Lichti and Brown, 2013, Andhika and Regenspurg, 2013, Mundhenk et al, 2014)
- Scaling inhibition (Guan, 2013, McCabe and Heath, 2019, Todd and Muller, 2019)
- Heavy metal galvanic corrosion (Lichti and Brown, 2013, Amend and Yee, 2013, Lichti et al, 2016, Scheiber, 2016)
- Superheated steam and acid steam condensate corrosion (Karlsdottir et al, 2013, Karlsdottir et al, 2014, Thorhallsson et al, 2019)
- Surface corrosion of carbon steels (Richter and Thorarinsdottir, 2013, Keserovic and Bäßler, 2013)
- Surface corrosion of high entropy alloys in geothermal steam (Csaki et al, 2017, Csaki et al, 2018, Csaki, et al, 2019)
- Application of corrosion inhibitors (Ghaziof et al, 2017, Klapper et al, 2019))
- Aerated sulfide corrosion of stainless steels (Wilson and Lichti, 2017, Karlsdottir et al, 2016)
- Microbiol corrosion (Croese et al, 2019).
- Scaling and corrosion in power plants (Lichti et al, 2013, Thorolfsson, 2019)
- Pitting corrosion of duplex alloys, (Bäßler et al, 2013, Francis et al, 2013, Bäßler et al, 2014, Bäßler et al, 2016) austenitic stainless steels, (Bäßler et al, 2014) and Ni-base alloys (Bäßler et al, 2013, Bäßler et al, 2014, Mundhenk et al, 2014, Karlsdottir et al, 2014)
- SCC of austenitic stainless steels (Karlsdottir et al, 2014, Karlsdottir et al, 2016)
- SSC of duplex alloys (Francis et al, 2013) and carbon steel (Karlsdottir et al, 2019)
- Surface corrosion of cement mortar (Berndt, 2013) and of ceramic (Bäßler et al, 2014)
- Corrosion of titanium alloys (MacDonald and Grauman, 2014, Karlsdottir et al, 2014, MacDonald and Grauman, 2019), titanium alloys and other corrosion resistant metals (Lichti and Wong, 2014)
- Hydrogen embrittlement of carbon steel (Felona and Gomes, 2018, Karlsdottir et al, 2018)
- CO_2 corrosion (Hua et al, 2019)
- Corrosion fatigue (Klapper and Stevens, 2013, Wolf et al, 2016, Klapper et al, 2016)
- Corrosion control by coatings in geothermal brines (Aritia et al, 2018, Aristia et al, 2019, Espartero et al, 2019)
- Erosion corrosion of electric arc sprayed titanium and carbon steel (Haralddsottir et al, 2019) and erosion corrosion of thermal sprayed coatings (Ragnarsdottir et al, 2017).

4. SUMMARY

Many of the research themes outlined in this paper as presented at NACE Symposia since 2013 follow on from those described by Sanada et al. (2000) following an International Energy Association survey. The work of Sanada et al. (2000) was summarised in a single graphic as given in Figure 1. The main themes emerging from the TEG 182X Symposia build on this 2000 summary as outlined in Figure 2 for extremes of conventional geothermal environments, Figure 3 for aggressive geochemistry at high temperature and high pressure, Figure 4 for deep geothermal hot wet rock and corrosion and wear in energy plant and Figure 5 for above ground processes related to scaling and corrosion. The WGC provides a forum for researchers in materials and process selection to share their experiences in a once in four yearly forum. The NACE TEG 182X provides a similar opportunity for the discussion of current research themes in the intervening years.

5. ACKNOWLEDGEMENTS

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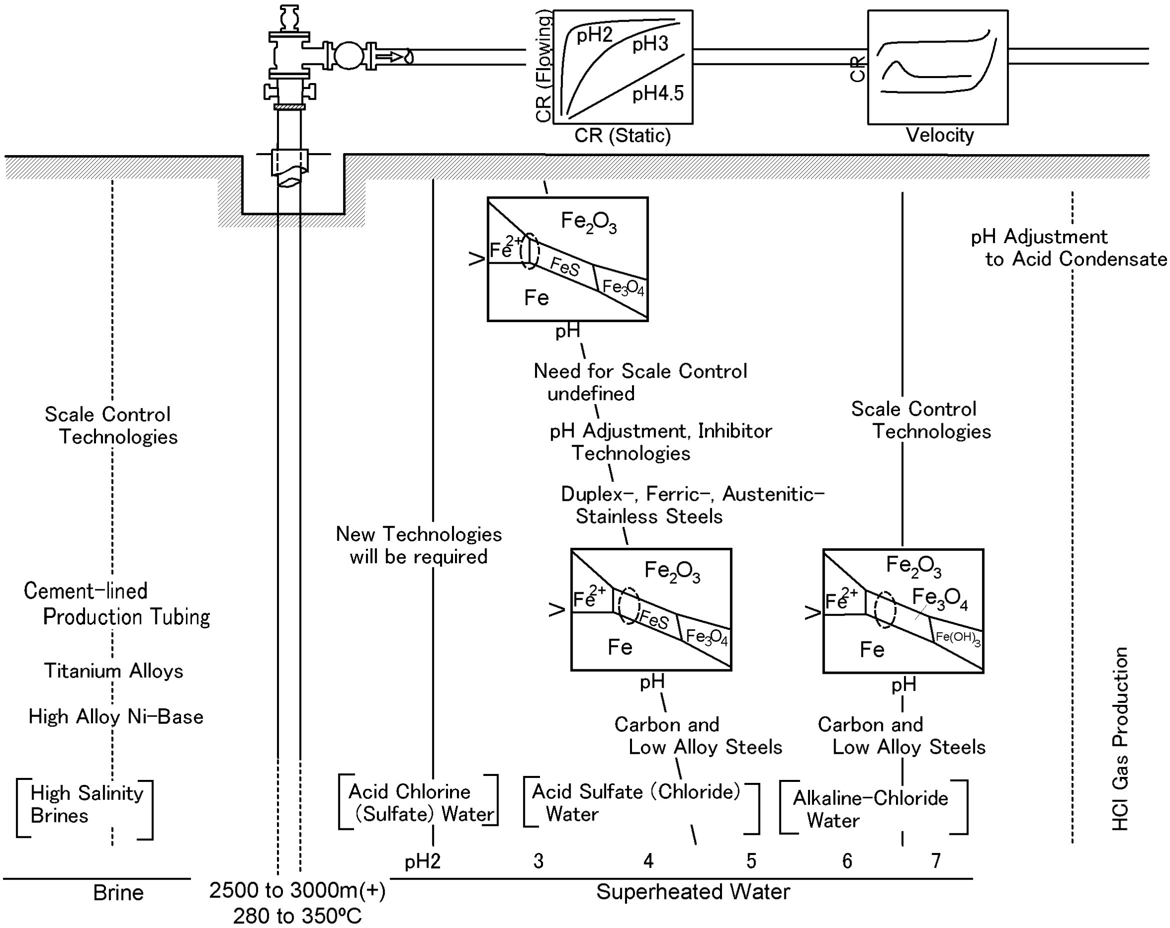

Figure 1: Research Themes for geothermal materials selection, corrosion and scaling from IEA surrey, Sanada et al. (2000).

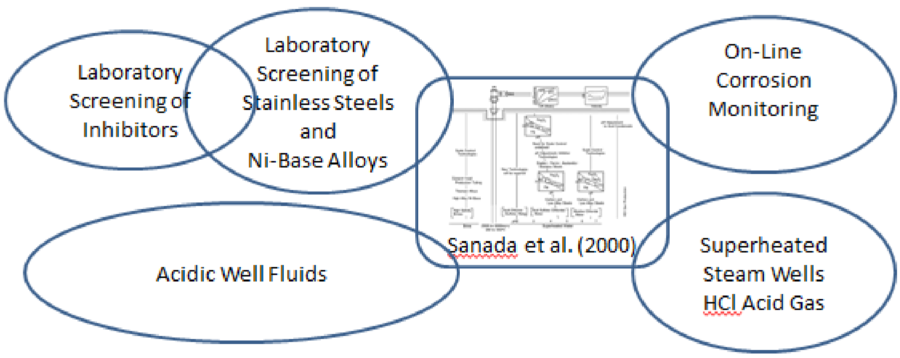

Figure 2: Research themes for extremes of conventional geothermal environments.

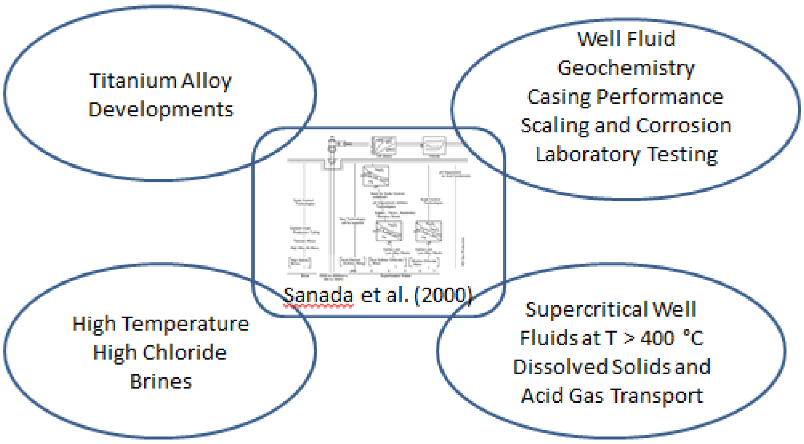

Figure 3: Research themes for aggressive geochemistry at high temperature and high pressure.

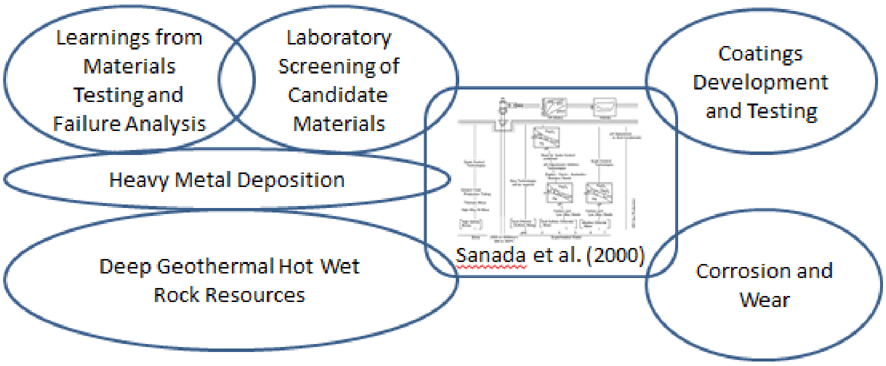

Figure 4: Research themes for deep geothermal hot wet rock and corrosion and wear in energy plant.

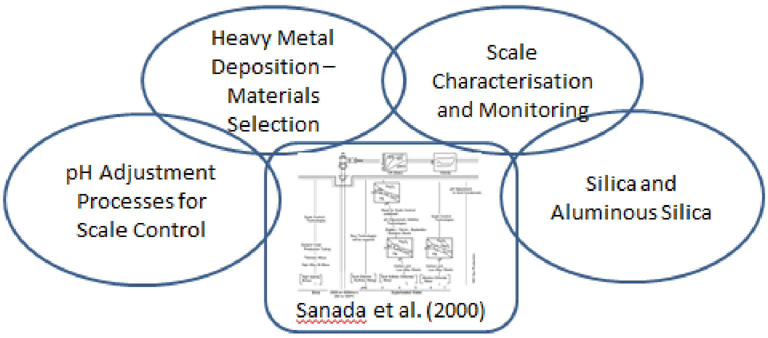

Figure 5: Research themes for above ground processes related to scaling and corrosion.

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