

Geothermal Energy Materials and Process Issues

Keith A. Lichti¹ and Norio Yanagisawa²

¹Quest Integrity (NZL) Limited, PO Box 38096, Lower Hutt 5045, New Zealand

²National Institute for Advanced Industrial Science and Technology (AIST), Institute for Geo-Resources and Environment, 1-1-3 Higashi, Tsukuba, Ibaraki 305-8567, Japan

K.Lichti@QuestIntegrity.com and n.yanagisawa@aist.go.jp

Keywords: Corrosion, scaling, materials, chemistry, pH adjustment, turbines, Japan, New Zealand.

ABSTRACT

This paper presents the results of a Japan New Energy Foundation sponsored collaboration between Quest Integrity (NZL) Ltd and National Institute for Advanced Industrial Science and Technology (AIST) Institute for Geo-Resources and Environment. New Zealand and Japan geothermal energy usage are compared and materials and process issues facing these two countries highlighted. Benefits that can be achieved from Risk Based Assessment and Risk Based Inspection of aging geothermal energy plant, from processes that improve efficiency and from industry groups such as the newly formed Geothermal Steam Turbine Users Group are discussed.

1. INTRODUCTION

The Japan New Energy Foundation (NEF) is charged with bringing international researchers together with Japan Institutes and private companies to promote green energy development projects since inception in 1980. The NEF was originally charged with progressing international exchange in the development of biomass renewable energy. Post-Fukushima Japan has a need for a broad range of renewable energy that will provide green energy alternatives to natural gas and coal. This will include not only biomass but wind, solar, and geothermal. The NEF have been expanding their activities to promote collaboration in these alternatives.

The 2013 NEF Programme included an exchange on geothermal corrosion and scaling between Quest Integrity (NZL) Ltd and National Institute for Advanced Industrial Science and Technology (AIST) Institute for Geo-Resources and Environment. This exchange aimed to expand understanding of materials-environmental issues with aging geothermal steam turbines, to alert geothermal users and equipment suppliers on the benefits of Risk Based Assessment (RBA) and Risk Based Inspection (RBI) and to share recent experiences with geothermal brine environments exhibiting heavy metal reductive deposition on carbon steel and galvanic corrosion.

An outcome of the exchange was the identification of challenges facing Japan and New Zealand materials and scaling specialists in the development of sustainable geothermal energy projects.

2. GEOTHERMAL MATERIALS R&D IN NEW ZEALAND AND JAPAN

2.1 New Zealand

Geothermal materials R&D began in New Zealand in the 1950s. The New Zealand government Department of Scientific and Industrial Research, Chemistry Division, Metals Section (founded in 1926) completed a series of tests aimed at selecting materials for the Wairakei geothermal power station development (low gas, 0.1 wt%, two-phase fluid). In the 1970s work was undertaken for the Ohaaki geothermal development (2.5 wt% gas, two phase) and from 1970 to 2000 this work expanded (see Lichti et al, 1985) and included higher gas fields such as Ngawha (25 wt% gas) and volcanic and acid well environments, the latter in collaboration with the AIST's Tohoku National Industrial Research Institute in Japan. The DSIR was reorganized into Crown Research Institutes in 1996 and the metallurgy and corrosion team charged with geothermal R&D became a part of Materials Performance Technologies (MPT) under Industrial Research Limited.

Quest Integrated (a company headquartered in Seattle, Washington) purchased Materials Performance Technology Solutions (formerly MPT) in 2006 forming a new group called Quest Reliability. In 2009 the company became a part of the Quest Integrity Group and geothermal materials R&D and consulting continued as a part of the company activities (Lichti, 2007). Quest Integrity Group became a part of Team Industrial Services in October 2010. More recent R&D focused on Risk Based Assessment of geothermal energy plant (Lichti et al, 2013), understanding heavy metal scaling and associated corrosion in power station processes using pH adjustment for control of silica polymerization (Soltis and Lichti, 2013, Lichti and Brown, 2013) and in steam turbine rotor life management.

2.2 Japan

In Japan, dry steam energy production began in 1966 at Matsukawa. The Tohoku National Industrial Research Institute (TNIRI) of AIST R&D activities began in the 1970s with a focus on erosion corrosion encountered in early two phase geothermal energy developments in Japan. Work by the TNIRI researchers has become the standard for predicting the risk of acid corrosion and erosion in many geothermal fields worldwide (Sanada et al, 1998). TNIRI made extensive progress in identifying opportunities for volcanic energy options and identified materials that might be used for energy plant in the late 1990s. The technology to economically utilize these resources is now being researched in countries such as Iceland. The AIST TNIRI geothermal corrosion team have largely disbanded as a result of retirements and changed emphasis in AIST during recent years. However the database of

materials selection and use for geothermal energy projects is well published in Japanese and English (Sanada et al, 1998). The base data for the published and unpublished work is held by AIST, TNIRI.

Recent AIST activities in scaling and corrosion have focused on scaling and corrosion in heat exchangers used on lower temperature hot springs fluids before being utilised for conventional tourism for example. This work, by Institute for Geo-Resources and Environment in collaboration with Hirosaki University and GERD, aims to understand energy process optimization while preventing scaling and corrosion in 70°C to 120°C waters. These lower temperature resources have significant potential for energy production by heating lower boiling point secondary fluids. Conventional refrigerants such as Hydro Fluoro Carbon (HFC), isopentane and ammonia are considered as options to produce high pressure gas that can be expanded through a turbine to produce electrical energy. (Yanagisawa et al, 2013)

3. STATUS OF GEOTHERMAL IN NEW ZEALAND AND JAPAN

New Zealand and Japan have many similarities in high temperature geothermal resources but significant differences in recent utilisation, Table 2.

The total capacity in New Zealand is currently 854 MWe (over 466 MWe being added since 2000) which is 13% of New Zealand electricity demand. A similar rate of development of generation capacity was seen in Japan until 2000 when 535 MWe was installed in Japan; however this has not progressed significantly, with only Hatchobaru Binary at 2 MWe being added in 2006. Geothermal capacity represents 0.2 % of Japan's energy needs. A significant difference between Japan and New Zealand use of geothermal is seen in the recent technologies utilised. New Zealand fields developed since 2006 are multiple flash, utilizing the separated brine waste heat energy to lower temperatures, 90°C to 120°C, through a process of pH adjustment to control the rate of silica polymerization until reinjection of the cooled brine can be achieved. On reinjection the brine is again heated in the reservoir and silica again becomes undersaturated. (Brown and Rock, 2010, Brown and Lichti, 2012)

Table 2: Major historical geothermal energy development projects in New Zealand and Japan.

New Zealand (New Zealand Geothermal Association)	Japan (Geothermal Research Society of Japan)
Wairakei (now 157MWe) Two-Phase Field	Dry Steam Fields
1958 First A Station Turbines Commissioned	Matsukawa (23.5 MWe) 1966
1964 B Station Turbines Commissioned	Otake (12.5 MWe) 1967
Wairakei Binary (14 MWe) 2005	
Broadlands-Ohaaki (45 MWe) 1989	Onuma (9.5 MWe) 1974
Pohipi Road (50 MWe) 1996	Onikobe (15 MWe) 1975
Rotokawa A (35 MWe) Binary 1998, 2003	Hatchobaru #1 & #2, binary (112 MWe) 1977, 1990, 2006
Mokai I (72 MWe), II (39 MWe), III (17 MWe) Binary, 1995, 2005, 2007	Kakkonda 1 & 2 (80 MWe) 1978, 1995
Ngawha (25 MWe) Binary Only 1998, 2008	Mori (50 MWe) 1982
Te Huka Binary (23 MWe) Binary Only 2010	Uenotai (28.8 MWe) 1994
Kawerau (132 MWe) 1997, 2008	Sumikawa (50 MWe) 1995
Nga Awa Purura (140 MWe) 2010	Yanaizu-Nishiyama (65 MWe) 1995
2013 Ngatamariki (82 MW) 2013 Binary	Yamagawa (30 MWe) 1995
Te Mihi (166 MW) 2013	Takigama (25 MWe) 1996
	Ogiri (30 MWe) 1996
	Hachijo-jima (3.3 MWe) 1999

The majority of the plants in Japan are of older design, using single flash technologies and reinjection of brine at silica saturation temperatures that are relatively high leading to reinjection of usable heat energy. The increased efficiency that can be achieved with multiple flash mixed pressure turbines or with a mix of steam turbines and binary plant that extract energy from the produced fluids to lower temperatures, is yet to be fully realized in Japan.

Japan aims to move to increased use of renewable energy, with geothermal being promoted to grow to 10% of energy needs by 2050 through improved developments of present and new resources, many of which are within National parks and near tourist spas. The low temperature reserves presently being studied by AIST, Hirosaki University and GERD, for example, have an estimated waste heat capacity of over 700 MWe with no additional well drilling required and no additional risk to the resource (Yanagisawa, 2012, 2013). These statistics highlight both potential for Japan geothermal development and constraints that need to be addressed.

4. GEOTHERMAL ENERGY MATERIALS AND PROCESS CHALLENGES

Improved efficiency has been achieved in many geothermal energy plants through the use of double and triple flash and mixed pressure turbines. At Wairakei in New Zealand for example, multiple flash was possible as the silica saturated waste waters were discharged to surface drains. Constraints on waste water surface discharge limited the development options for the Ohaaki geothermal power station where reinjection temperatures were kept above 155°C to allow downhole injection of silica saturated separated brine waters (Henley, 1981). Present practice in New Zealand is to acidify the waters to delay silica polymerization for a time that allows reinjection and the brines to be heated downhole where the silica solubility is increased (Brown and Rock, 2010). The use of double flash is not common in Japan (used only at Hatchobaru to date) and this is limiting efficiency of geothermal processes in existing facilities in Japan.

New geothermal power plants can be subjected to detail analysis for process selection for optimum efficiency and reliability. Options for improved efficiency of existing plant include additional heat exchange and binary plant (see for example, Sohel et al, 2009), replacement of aging turbines with new and improved turbine units, and more efficient processes (Kato, 2001, Sakuma et al, 2000, Matsuda, 2006, Fukuda et al, 2014).

Many aging geothermal energy plants in New Zealand have enviable base load operating histories with in excess of 90% run time. This record of performance is achieved by risk based assessment and risk based inspection programs that provide input to maintenance planning, allowing targeted repairs and replacements to be made in brief outage and overhaul periods. These methodologies are required to identify damage mechanisms and locations of greatest risk so that operators can manage their assets (Lichti et al, 2013).

Demand for renewable energy to be an integral part of future energy plans in Japan presents challenges for developers for utilisation of waste heat energy from low enthalpy geothermal brines as are used for spas and bathing and for novel methods of accessing high enthalpy resources located within parklands (Geothermal Research Society of Japan). Japan has completed deep well drilling to near magma without encountering good permeability (NEDO, 1996) and explored the potential for extraction of energy from deep-seated and near-volcanic geothermal systems (Ikeuchi, 1992). Japan / New Zealand / Philippines collaborative work in the Philippines explored the utilisation of acidic geothermal well fluids (Sanada et al, 2000, Villa et al 2000; Lichti et al, 2010). More recently, Icelandic researchers have encountered fumarole like production from deep wells in Iceland (Karlsdottir et al, 2013, 2014). These aggressive geothermal environments present challenges in materials and process selection for renewable geothermal energy.

4.1 Control of Silica Scaling for Increased Efficiency of Geothermal Energy Processes

The increased efficiency of New Zealand geothermal energy developments has been mainly through utilization of the waste heat in geothermal brines before the brines are reinjected. This utilisation requires the control of silica scaling. The brines are close to or in equilibrium with the downhole rock and the silica in the rock is dissolved as silicic acid. On cooling of the brine the dissolved silica is over saturated and begins to precipitate as long chain polymers (monomers combine to form dimers which grow to trimers and so on). These long chain polymers are quite large and can block pipelines and reinjection wells. Silica polymerization can be delayed for several hours by acidification or the solubility for silica can be increased by alkali addition. As acid is less costly than alkali, the addition of acid is the preferred solution (Gallup, 2011, Brown, 2011, Brown and Lichti, 2012, Lichti and Brown, 2013). Sulfuric acid is used and during the dilution phase severe acid corrosion can occur; concentrated and weak acids are less corrosive than moderate strength (Yusoff et al, 2012). In these instances tantalum has been used for critical components such as acid injection quills. Acidified brines have long been known to be corrosive to carbon steels (Sanada et al, 1998) but recent observations have noted presence of arsenic and antimony, for example in elemental form associated with localised corrosion sites under moderately acidic conditions (Amend and Yee, 2013, Soltis and Lichti, 2013). The process of heavy metal reduction was described by Gallop et al (1995) as follows:



Once the heavy metal, in elemental form, is deposited onto the surface of the carbon steel, localised galvanic corrosion is observed under the deposited heavy metal, see Figure 1 (Lichti and Brown, 2013). Under turbulent conditions erosion corrosion results (Amend and Lee, 2013). The process of iron oxidation and heavy metal reduction requires acidity (H^+), free electrons (e^-) and sufficient heavy metal in solution (for example SbO^+ or AsO^+), however the parameters that determine the likelihood of heavy metal formation and which heavy metal will preferentially form, have not yet been determined. The observation of heavy metals over localised corrosion is not new. Lichti and Brown (2013) describe an experiment with sulfuric acid addition to brine completed in 1983, where amorphous heavy metal deposition and under deposit corrosion was observed at pH 5. Lichti et al (2010) observed Pb, As and Zn formation with alkali addition to acid well fluids, the pH being adjusted from 3 to 4.5. Yanagisawa (2002) described formation of native Sb and metallic FeAs_2 from Kakkonda geothermal waters at pH 4 that later were no longer observed due to a pH change to 6 (near neutral). These results suggest acidity is required to obtain heavy metal precipitation.

A challenge for geothermal developers is to develop a mechanism for predicting the risk of heavy metal reductive deposition from the as-analysed brine chemistry. Understanding the effects of this same chemistry on the risk of galvanic corrosion of carbon steels presents a similar challenge (Amend and Lee, 2013, Lichti and Brown, 2013). Soltis and Lichti (2012) promoted a methodology to study antimony to carbon steel corrosion couples in the laboratory but were challenged to complete companion experiments using arsenic which is not readily available in solid form suitable for corrosion electrodes (Lichti et al, 2015).



Figure 1: Illustration of localised corrosion under reductively deposited heavy metal scale at pH 6 (left) and pH 5 (right) as described by Lichti and Brown, 2014.

4.2 Aging Turbines - Care and Maintenance

The success of geothermal energy is strongly dependent on the care and maintenance of the geothermal turbines. This is true not only for the aging turbines but also for new turbines that have engineering features that need to be maintained to ensure efficiency. The geothermal steam that is used directly in the turbines contains corrosive gases CO_2 , H_2S and NH_3 and, on occasion, H_3BO_3 and HCl gases. The turbine materials are critical to the life of the turbines. Research and experience has shown good performance from low alloy CrMo steels for rotors and 12% Cr alloys for blades and shrouds in the near neutral steam condensates that are normally encountered. The demand for improved efficiency and reliability has seen a number of recent changes in turbine design and materials selection, especially by the Japanese turbine manufacturers (Tanoguchi et al, 2013; Saito, 2010; Yamaguchi, 2010). These improvements are continuing especially for more aggressive fluids (Yan, private communication).

Older turbines, especially those using single flash, have demonstrated potential for continuing service. Many of these units used low strength materials and conservative designs that provide good resistance to Sulfide Stress Cracking and corrosion fatigue, for example the Wairakei steam turbines in operation for more than 60 years. Damage mechanisms encountered in geothermal steam turbines have been the subject of numerous investigations and turbine optimisations (see for example Morris and Carey, 2010).

Quest Integrity have initiated the formation of a Geothermal Steam Turbine Users Group (GSTUG) to promote sharing of knowledge and experience required to ensure long service life of aging turbines and turbine infrastructure. The first meeting of the GSTUG was held in November 2013 and the group formed officially in May 2014 with 4 inaugural members. The GSTUG industry group is managed by Quest Integrity on behalf of the members. The aims of the GSTUG are to:

- Understand damage mechanisms and expected lifetimes of geothermal steam turbines and associated components.
- Participate in joint research projects.
- Share experiences and exchange information.
- Share information on design upgrades.
- Research, develop and optimise inspection and refurbishment / replacement strategies.

A challenge for operators and turbine inspection engineers concerned with condition inspection of aging turbine assets is to identify the damage mechanisms of greatest risk and their likely locations, and to detect onset of damage before a failure is encountered so that repair strategies can be implemented to extend the life of the equipment. This requires continued vigilance, particularly for improved efficiency designs that utilise novel proprietary technologies.

4.3 Risk Based Assessment (RBA) and Risk Based Inspection (RBI)

Risk assessment is concerned with focusing limited resources during plant outage for inspection and maintenance on those areas of the plant having the greatest likelihood of corrosion or mechanical damage and the greatest impact should a failure occur:

$$\text{Risk} = \text{Likelihood of Failure} \times \text{Consequences of Failure} \quad (3)$$

By risk ranking components and equipment within energy plants, the inspection and maintenance activities at planned shutdowns will not miss critical items and time will not be wasted on non-critical items. The corrosion damage processes (Lichti, 2007)

leading to likelihood of failure in geothermal energy plant are not always well understood and experience in power plant operations and geothermal fluid chemistry is captured in plants having formal Risk Based Assessment (RBA) procedures to improve the plant reliability. RBA provides a formal means of capturing this growing knowledge and transferring this knowledge to other facilities. (Lichti et al, 2013)

RBA is commonplace in New Zealand geothermal steam fields and power plants. Japan geothermal power plants use planned maintenance procedures, for example Matsukawa, a dry steam field with potential for HCl gas production, requires annual inspection and maintenance due to pipeline corrosion problems.

A challenge for materials experts is to build confidence among geothermal plant operators regarding the benefits of RBA and RBI and to encourage development of a standard for identification of damage mechanisms and their likely locations in geothermal equipment (Lichti et al, 2013). Figure 2 illustrates the format for the proposed standard.

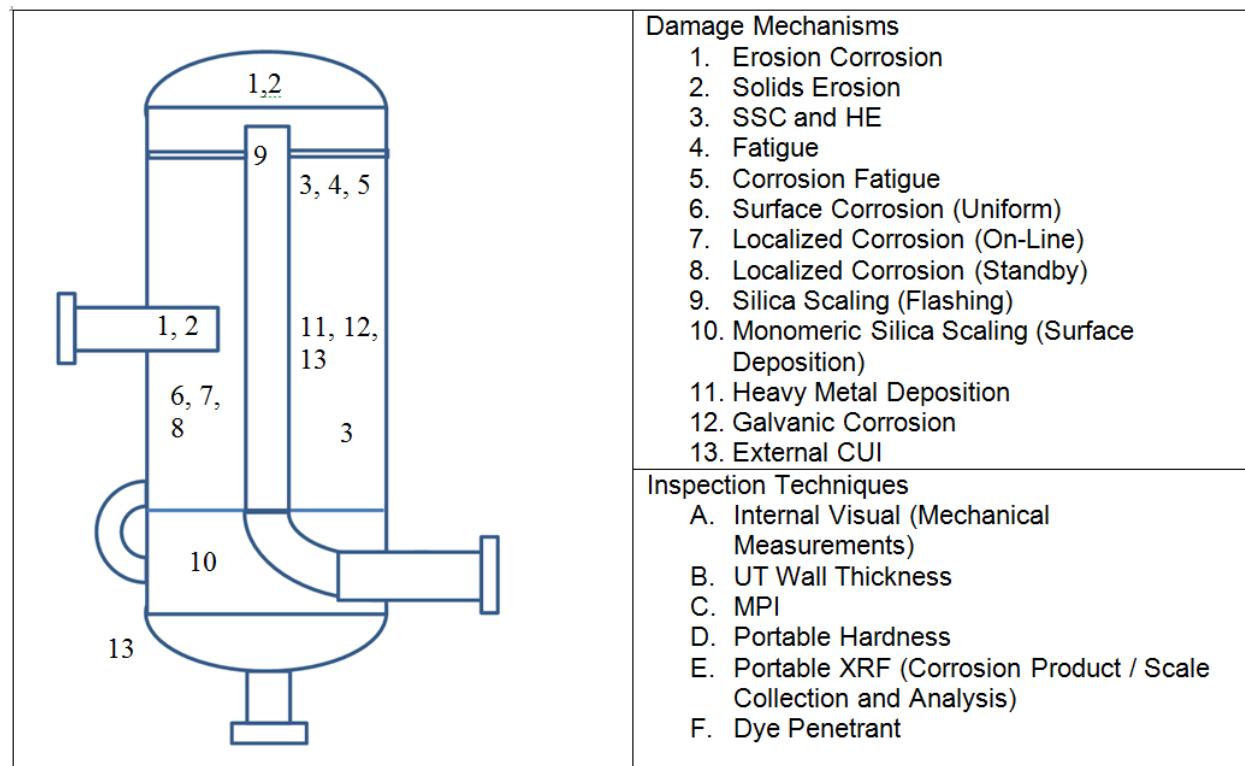


Figure 2: Illustration of proposed format for Risk Based Assessment geothermal equipment from Lichti et al, 2013.

4.4 Geothermal Materials Databases – Near Neutral, Acidic and Volcanic Environments

Japan and New Zealand have a history of independent and co-operative research spanning many years. The focus of Japanese research was on materials for acidic geothermal brines (Sanada et al, 1998) whereas New Zealand focused on near neutral geothermal resources. (Lichti et al, 1997) A joint research programme on materials for volcanic energy production was carried out on New Zealand's White Island characterizing corrosion processes in fumaroles, (Lichti et al, 1997, acid pools, (Lichti et al, 1998 and 1997) as well as atmospheric and soil environments. Sanada et al, 2000, summarized progress of an IEA task group that collected data from researchers around the world on acidic geothermal well environments, Figure 3. Technology for utilisation of acid well fluids was demonstrated viable in Costa Rica (Rivera et al, 2000) with improvements to the methodology used for injection control required to provide reliability. (Moya and Moro, 2010)

The database for utilisation of acid wellbore fluids is maintained by AIST, TNIRI in Japan. Since 2000, a significant development regarding the availability of geothermal conference proceedings papers dealing with all aspects of geothermal energy development is the geothermal database of papers maintained by Stanford University "<https://pangea.stanford.edu/ERE/db/IGAstandard/search.php>" with links to the Geothermal Resources Council e-Library and the OSTI Geothermal Collection, US Dept of Energy.

Although these public databases help with the preservation of the knowledge gained on materials selection and use in geothermal energy systems, there is an ongoing need for interpretation of the data for new applications and for continuing inter-country exchange of experience and results of on-going R&D to meet the needs of developers and users. Annual in-country geothermal conferences occasionally include some corrosion and scaling papers, but this is not always the case. The World Geothermal Congress is an exception as this congress always includes corrosion and scaling. Researchers also use corrosion and geochemistry journals, as well as related conferences to convey their results, such as the annual NACE Corrosion conference, however these often fail to reach the general geothermal community.

A challenge for materials researchers is to ensure that results of their research on materials for new and challenging geothermal developments reach the geothermal community. Equally, shared experiences among users can educate and train those engineers more concerned with preservation of existing plant than new developments. The GSTUG is one avenue for encouraging user exchange, increasing the opportunities for collaborative research and attendance of conferences and exchange visits. Another technology sharing initiative in a research conference environment has been the NACE Technology Exchange Group, TEG 182X, on Geothermal System Corrosion which aims to promote “Discussion of corrosion and scaling in geothermal energy systems – impact of production, process and reinjection conditions on materials and process efficiency”. Two meetings have been held in 2013 and 2014 with a total of 20 papers presented. The next meeting is planned for 2016.

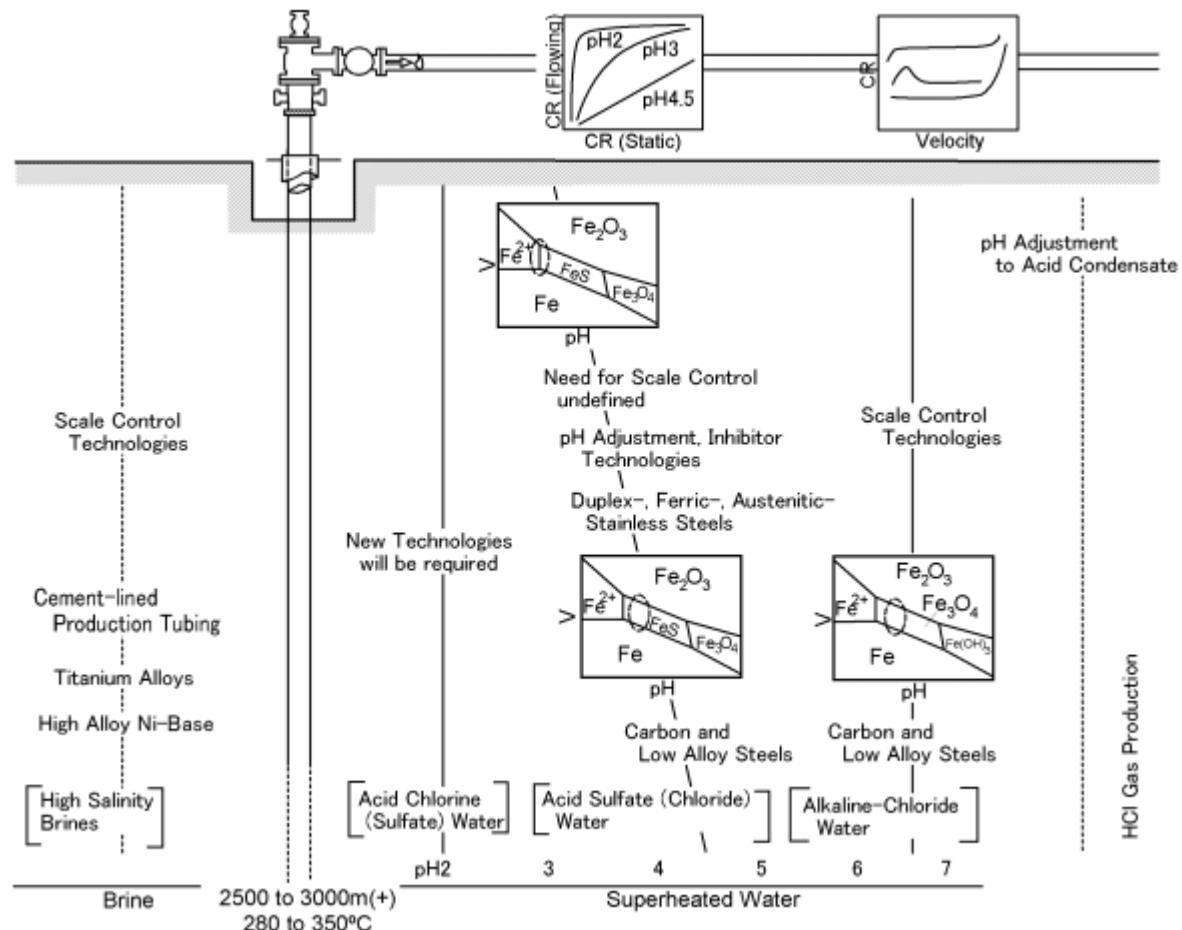


Figure 3: Summary of guidelines for corrosion control and materials selection for deep and acidic geothermal wells (Sanada et al, 2000).

5. SUMMARY

New Zealand and Japan have long histories of independent and joint geothermal corrosion and materials R&D. In New Zealand emphasis has been on near neutral pH two-phase fluids and separated steam, while in Japan the emphasis was on materials for acidic two-phase fluids. Joint projects have included the study of acidic geothermal well fluids (with the Philippines) and materials testing in anticipation of the utilisation of volcanic environments for energy production.

The New Energy Foundation sponsored collaboration between Quest Integrity (NZL) Ltd and the National Institute for Advanced Industrial Science and Technology (AIST) Institute for Geo-Resources and Environment on corrosion and scaling in geothermal energy power plants, has renewed and extended contact on materials and process R&D between New Zealand and Japan. Common interests on elemental heavy metal precipitation, improved efficiency of geothermal power plants and Risk Based Assessment have stimulated opportunities for renewing joint R&D activities that will again provide enhanced outcomes for the geothermal communities in both countries. The following challenges for the two countries have been identified:

- Materials selection for processes and equipment required for improved efficiency of geothermal energy plant.
- Risk Based Assessment and Risk Based Inspection of aging geothermal energy and power generation assets.
- Materials selection and process development for utilisation of more aggressive geothermal environments in a safe and reliable manner.

REFERENCES

Amend, B. and Yee, J.: Selective Application of Corrosion Resistant Alloys Mitigates Corrosion in pH-Modified Geothermal Fluids, NACE Corrosion (2013), Paper No C2013-0002416.

Brown, K. and Lichti, K.: Some Current Challenges in Production Geochemistry, Proceedings, The New Zealand Geothermal Workshop, Auckland New Zealand, (2012).

Brown, K.L.: Thermodynamics and Kinetics of Silica Scaling, Proceedings, International Workshop on Mineral Scaling 2011, Manila, Philippines, 25-27 May (2011).

Brown, K. and Rock, M.: Test rig Experiments for Silica Scaling Inhibition, Proceedings, World Geothermal Congress Bali, Indonesia, 25-29 April (2010).

N. Fukuda, F., Katsuki, N., Ogata, K., Saito, S., Hoshi, N. and Iwai, K.: Low Temperature Heat Recovery for Geothermal Binary Plant, Mitsubishi Heavy Industries Technical Review Vol. 51 No. 1, March, (2014).

Gallup, L., Featherstone, J. L., Reverente, J. P., and Messer, P. H.: Line Mine: A Process For Mitigating Injection Well Damage At The Salton Sea, California (USA) Geothermal Field, WGC, Italy, pp 2403-2408 (1995).

Gallup, D.L.: pH Modification Scale Control Technology, Proceedings International Workshop on Mineral Scaling 2011, Manila, Philippines, 25-27 May (2011).

Henley, R.W.: Chemistry and Silica Scaling Potential of Multiple Flash Geothermal Waters, Proceedings, New Zealand Geothermal Workshop, Auckland, New Zealand, (1981).

Karlsdottir, S.N., Ragnarsdottir, K., Thorbjornsson, I. and Sigmarsdottir, T.: Corrosion and Scaling in Wet Scrubbing Equipment of the Superheated Geothermal Well IDDP-1 in Iceland, "Proceedings" of the National Association of Corrosion Engineers Conference 2013 in Orlando Florida, paper no. 2556, (2013).

Karlsdottir, S.N., Thorbjornsson, I.O., Ragnarsdottir, K.R. and Einarsson, A.: Corrosion Testing of Heat Exchanger Tubes in Steam from the IDDP-1 Exploratory Geothermal Well in Krafla, Iceland, "Proceedings" of the National Association of Corrosion Engineers Conference 2014 in San Antonio, (2014).

Kato, Y.: Recent Technology of Geothermal Steam Turbines, Fuji Electric Reviews, Vol 47, No 4, (2001).

Ikeuchi, J.: Present status of Geothermal Material in Japan and its Future Prospects, Report of Tohoku National Industrial Research Institute, (1992), 89pp, in Japanese with English abstract.

Lichti, K.A.: Forgotten Phenomenon of Materials Selection and Use in Geothermal Energy Applications, Published in Materials Issues Governing the Performance of Advanced 21st Century Energy Systems, Wellington New Zealand, February-March 2006, Science Reviews (2007), Science Reviews 2000 Ltd, 243-255.

Lichti, K.A. and Brown, K.L.: Prediction and Monitoring of Scaling and Corrosion in pH Adjusted Geothermal Brine Solutions, NACE Corrosion (2013), Paper No C2013-0002544.

Lichti, K.A., Ko, M., Julian, R., and Lee, M.: The Application of Risk Based Assessment to Geothermal Energy Plant, NACE Corrosion (2013), Paper No C2013-0002538.

Lichti, K.A., White, S.P., Ko, M., Villa, Jr. R.R., Siega, F.L., Olivar, M.M.M., Salonga, N.D. Ogena, M.S., Garcia, S.E., Bunning, B.C., Sanada, N.: Acid Well Utilisation Study: Well MG-9D, Philippines, Proceedings World Geothermal Congress, Bali, Indonesia, April, (2010)

Lichti, K.A., Klumpers, A. and Sanada, N.: Utilisation of Acidic Geothermal Well Fluids Progress to 2002, Proceedings NZ Geothermal Workshop proceedings, (2003). Lichti, K A, Braham, B J, Engelberg D, Sanada, N, Kurata, Y, Nanjo, N, Ikeuchi, J and Christenson, B W, (1998) Corrosion Properties of a Volcanic Hot Spring, "Proceedings" 20th New Zealand Geothermal Workshop, Auckland, November.

Lichti, K.A., White, S.P., Sanada, N. (1998). Corrosion in Deep and Acidic Geothermal Wells. 19th PNOC-EDC Geo Conf, Manila, pp199-212.

Lichti, K A, Swann, S.S., White, S.P., Sanada, N., Kurata, Y., Nanjo, H., Ikeuchi, J. and Christenson. B.W. (1997) Corrosion in volcanic gases, "Proceedings" NEDO International Geothermal Symposium, Sendai, Japan, NEDO, pp 154-163.

Lichti, K.A., Swann, S.J., Sanada, N., Kurata, Y., Nanjo, H., Ikeuchi J. and Christenson, B.W. (1997) Corrosion In Volcanic Hot Springs, Geothermal Resources Council Transactions, Vol. 21, September/October, pp 299-307.

Matsuda, H.: Maintenance for Reliable Geothermal Turbine, GRC Transactions, Vol 30, (2006), pp 755-759.

Morris, C. and Carey, B.: Wairakei Power Station – New Zealand Plant Modifications Arising from Operational Deficiencies, Technology Advances and Life Extension Studies, "Proceedings" World Geothermal Congress 2010 Bali, Indonesia, 25-29 April, (2010).

Moya, P. and Mora, R.: Iron Meters for Production Wells at the Miravalles Geothermal Field "Proceedings" World Geothermal Congress 2010 Bali, Indonesia, 25-29 April, (2010).

Mountain, B.W., Björke, J.K. and Seward, T.M.: Amorphous Aluminous Silica Scales: Thermochemistry for Better Scale Prediction Models, NACE Corrosion (2013), Paper No C2013-0002246.

NEDO: Deep-Seated Geothermal Resources Survey, A compendium of Publications, October 1993 – February 1996, published by Geothermal Energy Development Department, New Energy and Industrial Technology Development Organization, (1996).

New Zealand Geothermal Association, website http://www.nzgeothermal.org.nz/elec_geo.html for “Geothermal Energy Power Plants in New Zealand”.

Rivera, E.S., Hartman Guido Sequeira, H.G and Ruiz, O.V.: Commercial Production Of Acid Wells At The Mirabelles Geothermal Field, Costa Rica, “Proceedings” World Geothermal Congress, Proceedings World Geothermal Congress, Kyushu, Tohoku, Japan, (2000) pp 1629-1634.

Sakuma, A., Takahashi, T., Watanabe, O. and. Fukuda, M.: Upgrading and Life Extension Technologies for Geothermal Steam Turbines, Proceedings, World geothermal Congress, Kyushu – Tohoku, Japan, May 28 – June 10, (2000).

Saito, S. Technologies for High performance and Reliability of Geothermal Power Plant, Proceedings, World geothermal Congress, Bali, Indonesia, 25-29 April, (2010), Paper 2602.

Sanada, N., Kurata, Y., Nanjo, H., Kim, H., Ikeuchi, J. and Lichti, K.: IEA Deep Geothermal Resources Subtask C: Materials, Progress with a Database for Materials Performance in Deep and Acidic Geothermal Wells, Proceedings World Geothermal Congress, Kyushu, Tohoku, Japan, (2000) pp 2411-2416.

Sanada, N., Kurata, Y., Nanjo, H. Ikeuchi, J. and Kimura, S.: Corrosion in Acidic geothermal Flows with High Velocity, Proceedings, 20th New Zealand Geothermal Workshop, Auckland, (1998), pp 121-126.

Sohel, M.I., Sellier, M., Brackney, L.J. and Krumdieck, S.: Efficiency Improvement for Geothermal Power Generation to meet Summer Peak Demand, Energy Policy, Volume 37, Issue 9, September, (2009), pp 3370-3376.

Soltis, J. and Lichti, K.A.: Galvanic Corrosion of Carbon Steel Coupled to Antimony, Corrosion Science 68 (2013), 162–167.

Stanford “<https://pangea.stanford.edu/ERE/db/IGAstandard/search.php>” website.

Tanoguchi, T., Saito S. and Iwai K.: Optimum Selection of Steam Turbine and Condenser for Geothermal Power Plant, GRC Transactions, Vol 37, (2013), 771-775.

The Geothermal Research Society of Japan, website <http://wwwsoc.nii.ac.jp/grsi/index-e.html> for “Geothermal Energy: Geothermal Power Plants in Japan”.

Villa, R..R., Siega, F.L., Olivar, M.M.M., Salonga, N.D., Ogena, M.S., Garcia, S.E., Buning, B.C., Lichti, K.A., White, S.P. and Sanada, N.: A demonstration of feasibility of acid well utilisation: The Philippines’ well MG-9D experience, Proceedings 2000 PNOC EDC Geothermal Conference, (2000).

Yamaguchi, N.: Variety of Steam Turbines in Svartsengi and Reykjanes Geothermal power plants, Proceedings, World geothermal Congress, Bali, Indonesia, 25-29 April, (2010), Paper 2645.

Yamaguchi, N.: Design of Wayang Windu Unit 2 Geothermal power Station, Proc World geothermal Congress, Bali, Indonesia, 25-29 April, (2010), Paper 2644.

Yanagisawa, N., Fujimoto, K. and Hishi, Y.: Scale Variation of the Production Wells from Deep Reservoir in Kakkonda Field, Proceedings, 27th Workshop on Geothermal Reservoir Engineering, Stanford University, Stanford, California, Jan 28-30, (2002), SGP-TR-171.

Yanagisawa, N., Sasaki, M., Sugita, H., Muraoka, H., Osato, K. and Sato M.: Scale and Corrosion of Kalian power Generation System Using Hot Spring Water, Proceedings, New Zealand Geothermal Workshop, 19-20 November, Auckland, New Zealand, (2012).

Yanigasawa, N., Muraoka, H., Sasaki, M., Sugita, H., Sato M. and Osato K.: Geochemical Property of geo-Pressured Reservoir for Binary System, Proceedings, New Zealand geothermal Workshop, November, Rotorua, (2013).

Yusoff, N., Ko, M., Lichti, K. and Julian R.: Sulfuric Acid Corrosion of Nickel Base Alloys and Tantalum at 225°C, Proceedings, 18th International Corrosion Congress, November, Perth Australia, (2011).