Advances in Geothermal Production Engineering in Recent Decades

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ABSTRACT

Geothermal energy is abundant, but only a very small fraction can currently be converted commercially to electricity and heating value with today's technology. Over the past two decades, the installed geothermal capacity worldwide has more than doubled. This increase in the use of geothermal energy has been a multi-disciplinary effort. Production engineering advances have played a significant part in making geothermal a competitive renewable energy resource. Some of these advances are highlighted. To unlock a significant fraction of this vast energy source additional major technological advances are needed. Considering successful past performance, production engineering will continue to play an integral part in further advancing the use of geothermal energy throughout the world.

Introduction

Over the past 20 - 25 years, worldwide output from geothermal sources has increased significantly. Seventy-five percent of the worldwide capacity increase is produced from about twenty sites with more than 100 MWe installed generating capacity. These geothermal power projects convert the energy contained in hot rock into electricity by using water to adsorb heat from the rock and transport it to the earth's surface, where it is converted to electrical energy through turbine-generators. Direct heating is used to offset the need for electricity production. It is estimated that more than 97% of current geothermal reservoir production is from magmatically driven reservoirs. Geothermal reservoirs may also develop outside regions of recent volcanic activity, where deeply penetrating faults allow groundwater to circulate to depths of several kilometers and become heated by the geothermal gradient (Bertani, 2005).

More than 90% of exploited fields are "liquid-dominated" under pre-exploitation conditions with reservoir pressures increasing with depth in response to liquid-phase density. "Vapor-dominated" systems, such as The Geysers in California, have vertical pressure gradients controlled by the density of steam. In the vapor-dominated systems, steam is cleaned and then passed directly into low pressure turbines. Typically, water from high-temperature (>240°C) reservoirs is partially flashed to steam. Heat is converted to mechanical energy by passing steam through low-pressure steam turbines. A small fraction of geothermal generation worldwide is generated using a heat exchanger and secondary working fluid to drive turbines. Direct heating accounts for significant total energy usage.

The purpose of this communication is to highlight some production engineering advances that have been made over about the past two decades. Technology development and execution have made it possible to exploit geothermal resources that might not have otherwise been accomplished. A major focus of production engineering in the geothermal energy industry has been to lower costs sufficient to allow geothermal energy to compete with other energy sources. This treatise is not intended to be an exhaustive discussion of the many engineering advances for production of geothermal resources. An attempt has been made to simply discuss some important developments centered on production engineering efforts to exploit geothermal resources with an aim to improve the economics of geothermal energy. This paper does not endorse of any specific companies who sell certain services or equipment that have increased production efficiencies or economics.

Enhanced Geothermal Systems

Starting about 25 years ago, experiments were conducted in Hot Dry Rock (HDR) in the USA, UK, France, Australia, Germany, Switzerland and Japan. The HRD concept has been to extract heat from rocks that are not naturally fractured and where permeability is generally low. Ongoing efforts are generally focused on mining heat from rocks by introducing water into the reservoir and then producing hot water or steam in doublet well configurations. Early on, HDR was not economically successful, but technological advances in recent years have pushed the concept toward commerciality. When this technology becomes commercial, the resource base of geothermal energy will increase dramatically worldwide. Variations of HDR that are being examined include hot wet rock (HWR) and enhanced geothermal systems (EGS). The thrust of these latter efforts also involves heat extraction from lower permeability geothermal systems (Takahashi and Hashida, 1992; McLarty et al., 2000).

The principal technology issues that are being addressed for HDR, HWR and EGS include decreasing drilling costs, controlling water losses, and improved fracture stimulation and mapping methods. Additionally, two other types of geothermal resource exploitation that have been investigated include the development of "geopressurized" reservoirs, where methane-rich fluids and co-produced with hot water or steam. "Geopressurized" reservoirs have yet to be commercially developed, but the US government supported production engineering studies in the Gulf Coast Region to simultaneously generate electricity from the geothermal fluids and to produce natural gas resources (Eaton, 1990). "Magma" resources have also seen some research and development in an effort to extract heat directly from cooling magma on active volcanoes (GRC, 1990).

"Vapor-Dominated" Geothermal Resources

It is generally agreed that the "vapor-dominated" resources are most easily produced since steam generation and conditioning are less prone to problems encountered in the "liquid-dominated" reservoirs and EGSs. Unfortunately, "vapor-dominated" resources are not as abundant and most of the fields that produce only steam have been discovered and exploited. Production engineering has made some significant advances to efficiently utilize dry stream extracted from these reservoirs. The implementation of strainers near wellheads has reduced formation solids from eroding turbines. Separator systems incorporating steam wash have also protected turbines from fouling with what is referred to as silica "spitballs." Various types of steam conditioners have reduced the tendency for volatile species in "vapor-dominated" steam resources to foul piping, turbines and condensers (O'Daly and Morelli, 1978). Foulants may include evaporated salts, boron, arsenic and mercury. Where steam is highly contaminated with non-condensible gases, several unique solutions have been developed to protect turbines. These generally consist of heat exchanging "dirty" steam with "clean" water to produce very pure steam (John Farison, personal communication, 1985).

Many geothermal plants use steam and turbine washing techniques to mitigate fouling and extend the time between turbine and generator overhauls. Steam washing usually consists of injecting water as a spray countercurrent to steam flow upstream of steam scrubbers. Turbine washing is a procedure to mildly "hydroblast" deposits off of turbine blades. A challenge to production engineers and chemists is to use wash water that does not harm the turbine. Waters containing dissolved oxygen should not be used in washing processes to avoid corrosion. Solids (dissolved or suspended) contents of wash waters also need to be minimized to prevent scaling and erosion, respectively. Cooling tower water, surface water, aquifer water and hotwell condensates are usually employed for steam and turbine washing. Careful application of these waters is required to maintain turbine integrity.

In some "vapor-dominated" geothermal systems hydrogen chloride gas may be produced. Innovations to control corrosion at the dew point of HCl have resulted in exploitation of certain wells that were considered too corrosive to produce. Metallurgies have been upgraded to mitigate corrosion at the dew point. The dew point of HCl has been sufficiently high that commercially available corrosion inhibitors have not been particularly useful in this application. Even the best nitrogen/amine based corrosion inhibitors are limited to ~200°C. Above this temperature, the inhibitors are often thermally deactivated. Caustic soda or other high pH solutions have been applied to these HCl producing wells successfully. Some caustic treatments are successfully applied downhole, while others are successful in controlling corrosion at the wing valves of wellheads (Hirtz et al., 1990). Another approach utilizes solid neutralizers at the dew point to convert acid to harmless salts (Hirtz et al., 2002).

Typically in these "vapor-dominated" systems, after about 30 years of production at fully developed commercial rates, much of the available heat still remains in the reservoir. This has presented an opportunity for secondary recovery projects such as the treated wastewater injection projects at The Geysers, California field. Production has depleted fluid mass from the reservoir much more efficiently than it depleted the available heat. Using sound production engineering principles, careful injection of treated waste water from local communities has curtailed the decline of The Geysers field and has been shown to significantly increase steam production at the field. This is an excellent example of solving several problems – local communities are able to dispose of excess wastewater and secondary heat recovery in a reservoir has been achieved to extend the production life of the field (Goddard and Goddard, 1991).

"Liquid-Dominated" Geothermal Resources

By far the most important technological innovations have been developed by production engineers and chemists to exploit these geothermal systems. The Salton Sea geothermal field in southern California is a major case history of advances in fluid production technology to generate electric power. This field, considered to be the largest in the world, exhibits brine chemistry that is corrosive and scale-forming. In order to commercially develop the field, difficult and significant corrosion and scaling problems had to be overcome. Corrosion at the field, due to hyper-saline brines containing traces of oxidizing metals, has been successfully controlled by materials engineers. High alloy well tubulars and production piping has mitigated corrosion. Judicious use of highly corrosion resistant alloys and cement-linings has allowed the field to be produced economically. Much of the current knowledge and implementation of corrosion controls came by trial and error.

A massive effort was required to monitor corrosion rates of a host of materials before mitigation was commercially achieved (Love et al., 1988).

The Salton Sea field has also been notorious for massive scale deposition. As the hyper-saline brine was flashed to produce steam, numerous scale types were precipitated. These included iron silicates, barite, fluorite, iron and silver antimonides, copper arsenide, heavy metal sulfides and several other exotic deposits. Production engineering and chemistry efforts led to the development of crystallizer-clarifier technology, where iron silicates were purposely precipitated in surface equipment as sludge to prevent fouling of pipelines, brine- and steam-handling equipment, and re-injection wells (Featherstone et al., 1979). Crystallizer-clarifier technology not only precipitated the iron silicate, but due to reaching iron silicate saturation at the boiling point of the brine (109°C), Ra-rich $BaSO_4$ and CaF_2 also deposited. A scale inhibition system was developed to inhibit crystalline scale growth without adversely affecting the precipitation of the nano-crystalline hisingerite scale [*i.e.,* $Fe_3{}^{2+}Si_2O_5(OH)_4 \cdot 2H_2O$] (Gallup and Featherstone, 1993).

Another technology that was applied initially at Salton Sea was brine acidification. This scale control technology was effective in mitigating hisingerite scaling, provided that the brine re-injection temperature was maintained above about 150°C. Acidifying brine at Salton Sea required carefully controlled pH adjustment to inhibit scale without exacerbating corrosion. The cost of acid was also a concern as was dissolution of the injection reservoir. However, by adjusting the brine pH just sufficient to mitigate hisingerite scaling, the process proved to be economical and not detrimental to corrosion or dissolution of the injection formation (Gallup, 1996).

Due to the hyper-saline brines encountered at the Salton Sea, steam conditioning was extremely important. However, engineers learned to remove brine carryover in steam to prevent fouling or corrosion of turbines and condensers. Efficient steam separators, steam wash systems, and demisters were employed to prevent turbine fouling, corrosion and erosion. The use of heat exchangers to generate "clean" steam from pure water using "dirty" steam has also been a valuable tool for mitigating turbine problems, *vide supra* (Cedillo and Yamasaki, 1981).

It has been proven that many of the innovations and learnings applied at the Salton Sea can be extrapolated to fields producing more benign brines. While crystallizer-clarifier technology has only been applied at Salton Sea, technologies such as pH modification, steam cleaning, crystalline scale inhibitors and materials selections are now used in many geothermal fields around the world. Crystallizer-clarifier technology also proved to allow the recovery of base and precious metals from the hyper-saline Salton Sea brines. Successful recovery of metals or minerals from geothermal brines is expected to be achieved in the future, not only at Salton Sea, but also other fields where certain metal or mineral recovery schemes can be implemented (Duyvesteyn, 1992).

Re-injection of brines, cooling tower waters and excess steam condensate has both advantages and disadvantages. The principal advantages are that the net withdrawal of mass from the system is greatly reduced. Reservoir pressure is supported, so that production well outputs can be maintained for a longer time. Additionally, re-injection is practiced to ensure that no environmental damage can occur from chemical species in the brine, such as As, B, NH_3, Hg, etc. Some fields located near coastlines were or are operated with discharge of fluids into the ocean or other waterways under significant environmental scrutiny (Kitz and Toreja, 2002). The principal disadvantage of re-injection is that the cool brine may flow directly to certain production wells before it has been in contact with hot rock long enough to reheat, causing a reduction in steam output from the production wells. This is a common problem and challenge for production engineers because a strong pressure difference builds up between injectors and producers. The fractured nature of the rocks in geothermal systems often allows an unpredictable, highly permeable path from injector to producer. This problem is usually mitigated by increasing the distance between injection and production wells. A technology that has been successfully employed in fields to understand communication between injectors and producers is stable tracers. These tracers may also be used to measure flow measurements in piping, to monitor brine separator and steam scrubber efficiencies, etc. (Rose et al., 2003).

Several geothermal fields are prone to calcite scaling in wellbores and some surface equipment. Again, production professionals have made great strides over the past two decades in applying inhibitors downhole to control $CaCO_3$ deposition. Simple to extravagant downhole assemblies have been developed to deliver the scale inhibitors just below the point of the onset of $CaCO_3$ formation. A variety of scale inhibitors have proven successful in treating high temperature brines. Electrical submersible pumps (ESPs) used extensively in the oil and gas industry have also proven to control carbonate scaling. The pumps maintain the brines in the well in the single, liquid phase. This prevents brine from flashing and CO_2 from exsolving. By maintaining the acid gas in the liquid phase, the brine pH is not allowed to increase such that carbonates remain undersaturated. Conversely, learnings from downhole scale inhibition in geothermal facilities are now being applied in the oil and gas industry for high temperature, high pressure wells in the North Sea, for example (Benoit, 1990).

Some advances have also been made in the use of "organic" inhibitors to control silica scales. These inhibitors are usually dispersants that keep the scales from adhering tightly to piping or equipment surfaces. The dispersants do not stop supersaturated amorphous silica or metal silicates in brine from polymerizing, but they make cleanout of piping and equipment much easier than when silica scales are tightly bound to surfaces. Fortuitously, it has been found that very low dosages of these silica inhibitors will mitigate hard scale deposits. If used at high dosages, these inhibitors become uneconomical and they coagulate silica such that deposition of even soft deposits can rapidly reduce brine flow. The use of "organic" silica inhibitors is a fruitful area for research, since a better understanding and implementation of control mechanisms would likely be simpler and cheaper that crystallizing silica or slowing the kinetics of silica polymerization with pH adjustments to brines. Further improvements in the application of these types of inhibitors are anticipated (Garcia and Mejorada, 2001).

A major advancement in the exploitation of "liquid-dominated" geothermal fields has been the application of heat recovery systems in many fields. Heat recovery systems, as defined herein, are typically binary plants. Hot water, sometimes using ESPs, is maintained under pressure. The heat from this single liquid phase is exchanged against a binary working fluid. This secondary working fluid is flashed in a special turbine to generate electricity. Some binary plants are used to as the sole source of electricity production. This is analogous to the "dirty" steam – "clean" steam system discussed above. An advantage of the binary systems used in this manner is the non-release of gases (primarily CO_2 and H_2S) to the environment. Other uses of binary plants are topping and bottoming cycles of flash plants. The topping and bottoming cycles can recover additional energy without the need to flash more brine. Whether a dual flash system or a binary system is used as a bottoming cycle, silica scaling must be addressed. In the dual or multiple flash processes, steam is generated while brine becomes more concentrated. If amorphous silica or metal silicate saturation is exceeded, scaling is exacerbated. Scale control methods will necessarily need to be employed, especially if brine is re-injected. Injection pipelines, injection wells and injection formations may be plugged or damaged if silica is precipitating therein. In the bottoming cycle, shell and tube heat exchangers are utilized; the shell side usually contains the binary working fluid. As a result, the small diameter tubes in the binary heat exchanger may become scaled, if the temperature of the brine is low enough to yield silica/silicate supersaturation (DiPippo, 1997; MlCak, 2002).

The binary-type heat exchanger cycle plants have additional advantages beyond generation of electricity or generating "clean" steam from "dirty" fluids. The heat exchange processes have proven to be useful in several locations worldwide for space heating. For example, geothermal hot water or brine can be used to heat "clean" water. The hot "clean" water is then used in radiators for space heating, deicing and agricultural applications (Bertani, 2005). If the geothermal fluid were used directly in these applications, "radiator" type piping will eventually foul or corrode as the fluid cools in these space heating-like applications. To reiterate, the "clean" heated fluid must be carefully chosen or pre-treated to prevent adverse reactions in the heat exchangers and "radiators."

In recent years, production engineers and chemists have obtained access to a variety of inorganic geochemical codes and flow models to improve operations. Scale prediction models are used to determine (a) when downhole scale inhibitors need to be applied, (b) flow patterns in wells and surface equipment, (c) flash temperature and pressure setting to control silica scaling, (d) the behavior of two-phase flow, (e) the most efficient and cost-effective brine handling schemes, etc. Considerable effort in application, development and improvements of physico-chemical, fluid flow and thermodynamic data has been expended to generate these codes and models. The result has been development and implementation of these tools by production and operation personnel to make geothermal energy competitive as a renewable energy resource (Klein, 1997). Without the research and development of these tools, many mistakes in design and application of technology to generate maximum energy from geothermal resources at a competitive price could have accrued.

This is not to infer that development of geothermal resources has proceeded without a few surprises along the journey. Exotic scale deposits, unusual corrosion behavior and other unexpected challenges in handling geothermal fluids have plagued some geothermal developments (Gallup, 2004). The resiliency of production engineers and associated personnel has overcome many of these obstacles through both careful technology development efforts and some trial and error learning exercises.

Conclusion

Production engineering, together with other disciplines, has increased geothermal energy production by more than two-fold over the past couple of decades. A number of technological advances have made this possible. Production engineering and closely associated disciplines have assisted in exploiting geothermal resources worldwide. A few selected engineering advances in the field have been highlighted; an exhaustive dialog of the many major and minor engineering advances for production of geothermal resources has not been attempted. Many important advances in production technologies will no doubt be developed in future decades. The sustainability of geothermal energy will require many developments in technology and production philosophies.

From an investor's standpoint, maximizing withdrawal of geothermal fluids over a 10 – 20 year period is a more attractive option than operating at a lower electrical or heating capacity for hundreds of years. Commercial developments usually ramp up production in the first few years, maintain it constant for a period of perhaps 15 – 20 years, and then allow a natural decline once the cost of makeup wells to maintain steam or heat supply cannot be economically justified. The question of whether geothermal is truly a sustainable energy source therefore depends on the extraction rate and utilization chosen for each resource. Challenges facing the production engineering community include such factors as:

- The most productive and accessible sites have been discovered and exploited in many countries. Some very attractive prospects are located in environmentally sensitive or scenic areas.
- Global economic cycles have discouraged investment in some attractive geothermal resources.
- Multilateral lending agency support and government incentives for geothermal development have been decreasing in recent years.
- Price fluctuations in fossil fuels and lobbying for other "renewable" energy sources (biofuels, wind, tidal, etc.) make it more difficult for geothermal power and heat to compete in the marketplace.

Geothermal is often at a commercial disadvantage to fossil fuels, because the effect of having to drill enough wells to supply full plant capacity at startup is the economic equivalent of purchasing most of the fuel required for the next twenty years in a fossil-fired plant, prior to bringing the plant on-line. However, a significant opportunity for geothermal development is emerging in decreased greenhouse gas emissions compared to fossil-fuel plants. The challenge to production engineering in the short term is to continue to lower the cost of production without compromising safety to remain competitive with other power sources.

In the medium term, a significant opportunity for production engineering exists in the development of technology to recover stranded heat in reservoirs after conventional development. In the long term, EGS probably holds the greatest promise and challenge. Cost effective heat mining technology will require coordinated efforts by governments and industry over the next few decades. Extracting a significant fraction of the available geothermal heat commercially presents a considerable challenge, but an eminently worthy one, as the world faces an increasing need for non-fossil, non-polluting energy in the decades to come (Williamson et al., 2001).

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References

Benoit, W.R., 1990. "Development of a Carbonate Scale Inhibition Program at Dixie Valley, Nevada." Geothermal Resources Council Transactions, v. 14, p. 1567-1573.

Bertani, R., 2005. "World Geothermal Power Generation in the Period, 2001-2005." Geothermics, v. 34, p. 651-690.

Cedillo, R., and R.N. Yamasaki, 1981. The Brawley 10 MWe Power Plant Unit 1. Geothermal Resources Council Transactions, v. 5, p. 397-399.

DiPippo, R., 1997. "High-Efficiency Geothermal Plant Designs." Geothermal Resources Council Transactions, v. 21, p. 393-398.

Duyvesteyn, W.P.C., 1992. "Recovery of Base Metals from Geothermal Brines." Proceedings International Conference on Industrial Uses of Geothermal Energy. Reykjavik, Iceland.

Eaton, B.E., 1990. "U.S. Gulf Coast Geopressured-Geothermal." Proceedings 12th NZ Geothermal Workshop, p. 273-279.

Featherstone, J.L., R.H. Van Note, and B.S. Pawlowski, 1979. A Cost Effective Treatment System for the Stabilization of spent Geothermal Brines. Geothermal Resources Council Transactions, v. 3, p. 201-204.

Gallup, D.L., 1996. "Brine pH Modification Scale Control Technology. Geothermal Resources Council Transactions, v. 20, p. 749-755.

Gallup, D.L., 2004. "Unusual Adherence of Manganese Silicate Scale to Metal Substrates." Geothermal Resources Council Transactions, v. 28, p. 529-532.

Gallup, D.L., and J.L. Featherstone, 1993. "Control of NORM Deposition from Salton Sea Geothermal Brines." Geothermal Resources Council Transactions, v. 17, p. 379-385.

Garcia, S.E., and A.V. Mejorada, 2001. "Geogard SX: A Silica Scale Inhibitor for Geothermal Brine." Geothermal Resources Council Transactions, v. 25, p. 15-21.

Goddard, C.B., and W.B. Goddard, 1991. "Use of Lake County Treated Municipal Wastewater for Geothermal Resource Replenishment." Geothermal Resources Council Transactions, v. 15, p. 141-147.

GRC, 1990. Special Issue on Magma Energy, Geothermal Resources Council Bulletin, v. 19, p. 268-275.

Hirtz, P., J. Miller, and E. Prabhu, 1990. "Operational Results of a Dry-Steam Resource Chloride Corrosion Mitigation System. Geothermal Resources Council Transactions, v. 14, p. 1667-1675.

Hirtz, P.N., M.L. Broaddus, and D.L. Gallup, 2002. "Dry Steam Scrubbing for Impurity Removal from Superheated Geothermal Steam. Geothermal Resources Council Transactions, v. 26, p. 751-754.

Kitz, K., and J. Toreja, 2002. Maintaining Steam Purity in Response to Changing Reservoir Conditions in Tiwi, Philippines. Geothermal Resources Council Transactions, v. 26, p. 763-768.

Klein, C., 1997. "Geothermal Chemistry Thermodynamics: The Watchworks Program for MS-Windows™." Geothermal Resources Council Transactions, v. 21, p. 555-557.

Love, W., C. Cron, and D. Holligan, 1988. "The Use of Beta-C Titanium for Downhole Production Casing in Geothermal Wells. Geothermal Resources Council Transactions, v. 12, p. 49-53.

McLarty, L., P. Grabowski, D. Entingh, and A. Roberston, 2000. "Enhanced Geothermal Systems R&D in the United States." Proceedings World Geothermal Congress 2000, p. 3793-3796.

Mlcak, H.A., 2002. "Kalina Cycle Concepts for Low Temperature Geothermal." Geothermal Resources Council Transactions, v. 26, p. 707-713.

O'Daly, W.L. and G. Morelli, 1978. "A Control System for Steam Gathering at the Geysers. Geothermal Resources Council Transactions, v. 2, p. 507-508.

Rose, P.E., M. Mella, and C. Kasteler, 2003. A New Tracer for Use in Liquid-Dominated High-Temperature Reservoirs. Geothermal Resources Council Transactions, v. 27, p. 403-406.

Takahashi, H., and T. Hashida, 1992. "New Project for Hot Wet Rock Geothermal Reservoir Design Concept." Proceedings 17th Stanford Workshop Geothermal Reservoir Engineering, p. 39-44.

Williamson, K.H., R.P. Gunderson, G. M. Hamblin, D. L. Gallup, and K. Kitz, 2001. "Geothermal Power Technology." Proceedings of the IEEE, v. 89, p. 1783-1792.