

THE HISTORY AND SIGNIFICANCE OF THE HAWAII GEOTHERMAL PROJECT

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ABSTRACT

The Hawaii Geothermal Project, since its initiation in 1972, has not only demonstrated that there is a viable geothermal resource present on the Kilauea East Rift Zone, it has also produced a wealth of information about the characteristics of the resource and the operational requirements that must be met to generate electrical power on a long term reliable basis. The HGP-A well demonstrated that a high-temperature hydrothermal system was present on the East Rift Zone; the HGP-A Wellhead Generator Facility showed that electrical power could be generated on a long-term basis from the geothermal reservoir with an availability factor of more than 90%; and research at the facility tested several types of systems for control of hydrogen sulfide and scale deposition. The results of the Hawaii Geothermal Project have helped resolve many uncertainties about the reservoir and will provide guidance to private and regulatory interests as a commercial geothermal development comes on line in Hawaii.

INTRODUCTION

The Hawaii Geothermal Project was initiated by the University of Hawaii College of Engineering in 1972 in an effort to determine the technical feasibility of extracting usable energy from the active volcanic systems on the Island of Hawaii. The project organizers' early recognition of the necessity for Hawaii and the nation to identify alternatives to fossil fuel fired electricity was strikingly confirmed by the oil shocks of the 1970's. During the eighteen years since it was first conceived, this project has made substantial progress toward addressing the many technical and engineering barriers to geothermal development in Hawaii: a productive well was drilled in 1976; a wellhead generator was installed in 1981; steam was produced continuously from the HGP-A well from 1981 until 1989; and the commercial production of electrical power was demonstrated with an availability factor of more than 90% from the first geothermal power facility in Hawaii. Many of the problems faced by the drilling, testing, and production of the HGP-A well and power station have been shown to have engineering solutions and,

even where the operation of the HGP-A facility was not completely successful, the results of its operation have helped identify necessary changes in operational and regulatory approaches that will be required to enable the production of geothermal electricity to make a significant contribution to the energy future of Hawaii. This paper will present a review of the accomplishments, and some of the failures, of the HGP-A project as it has developed and evolved during the last eighteen years.

EARLY EXPLORATION

In 1972 the University of Hawaii College of Engineering submitted a proposal to the National Science Foundation to undertake a long-term investigation of the feasibility of extracting usable energy from the volcanic systems on the island of Hawaii. The effort, which was to become the Hawaii Geothermal Project, focussed on both the identification of sources of magmatic heat and the engineering aspects of extraction of usable energy from that magma. A geological and geophysical exploration program was initiated in 1973; investigations initially surveyed much of the island of Hawaii but quickly focussed on the Kilauea East Rift Zone (ERZ) where the strongest evidence for a heat source was found. Surveys conducted on the ERZ included active and passive seismic and microseismic monitoring, resistivity soundings, self-potential surveys, surface mapping, and groundwater temperature and chemistry studies (Furumoto, 1978; Kauahikaua, 1981; Keller et al., 1977; Macdonald, 1973; Macdonald et al., 1977; Zablocki, 1977). The results of these investigations showed several anomalies on the rift but no clear definition of where drilling would have the greatest probability of success. A drilling target was ultimately chosen on the basis of the coincidence of an SP anomaly, elevated groundwater temperatures, and an apparent structural discontinuity on the lower ERZ. However, because surface rights could not be obtained at the primary drilling target, the proposed drill site was moved to an adjoining property that was located on the shoulder of the the SP anomaly originally chosen.

Identification of a drilling target completed the first phase of the Hawaii Geothermal Project;

subsequently, funding was obtained jointly from the Energy Research Development Agency and the National Science Foundation to enable the project to drill a deep research well. Drilling commenced in December 1975 using a Spencer Harris 7000 rotary rig with mud circulation in the hole to remove cuttings. As part of the scientific effort, drill cuttings were obtained at five-foot intervals in the well and spot coring was done at ten separate intervals downhole. Voids and cavities present in the subaerial basalts resulted in extremely difficult drilling conditions over the first 500 meters of the hole but, as the rock became less permeable at depth, drilling conditions improved. The well was completed to a depth of 1966 m with 24.4 cm production casing to a depth of 670 m and a 17.8 cm slotted liner from 670 m to bottom hole.

After the well was allowed to heat up down-hole surveys showed that temperatures in excess of 300°C were present. However, after the drilling mud was flushed from the hole, water pump-down tests showed that the formation permeability was quite low: approximately 1000 millidarcy feet. Nonetheless, the well was induced to flow briefly on July 2, 1976 and, on July 22, 1976, extended testing of the well showed that it was capable of sustained production of geothermal fluids. Subsequent flow and downhole testing indicated that, although mudcake baked on the walls of the hole was restricting flow, the well was capable of producing about 50,000 kg per hour of geothermal fluids composed of 60% steam and 40% liquid at a wellhead pressure of 620 kPa (Kihara et al., 1977). Temperature and pressure surveys and downhole fluid sampling indicated that the bottomhole temperature exceeded 350°C and that high-temperature production zones were present in the well at depths of about 1370 m and 1830 m and that a low-temperature zone was present at the casing shoe at 670 m (Kihara et al., 1978; Kroopnick et al., 1980).

During the extensive testing program for the well, damage occurred to the production casing that allowed fluid circulation from the high-temperature reservoir into a shallow discharge zone in the well casing. Circulation of high temperature fluids from the deep reservoir generated both high wellhead pressures and a substantial gas cap, and hence it was necessary to install a second string of production casing to halt up-hole circulation. A 17.8 cm production casing from the surface to 884 m halted shallow circulation and isolated the suspected cold water intrusion zone at the 670 m level.

The long-term testing program confirmed that the well was capable of supplying sufficient steam to power a 3 MWe electrical generator. However, the question of whether the reservoir was capable of sustained production on a commercial basis, remained unanswered. Similarly, the potential engineering problems associated with the high concentrations of silica in the brine and hydrogen sulfide in the steam phase remained to be addressed before commercial production of power

could be pursued. The directors of the Hawaii Geothermal Project therefore proposed a long-term test to demonstrate the feasibility of generating electrical power from the HGP-A well using a 3 MWe wellhead generator system. The project was jointly funded by the U.S. Department of Energy, the State of Hawaii, the County of Hawaii, and the Hawaiian Electric Company. After a final series of flow tests, a wellhead generator was designed and installed on the well in June, 1981. The design of the facility included a wellhead separator, a 3 MW turbine generator package, and a shell-and-tube vacuum condenser. Steam condensate was recycled to a forced draft cooling tower as make-up water; the non-condensable gases were removed from the condenser with steam ejectors and were treated in an incinerator/scrubber system. Waste fluids from the abatement system, the plant separator, and the cooling tower were disposed of by percolation. The facility also included a rock muffler and steam scrubbing system for discharge of steam to the atmosphere during turbine off-line conditions. In recognition of the fact that the facility was constructed in a volcanically active area, all major components were skid-mounted to allow rapid mobilization in the event of a lava flow hazard (Chen and Lopez, 1982).

The initial start-up of the facility began on June 10, 1981 and was followed by a lengthy shakedown period. A number of equipment and operational problems were encountered during start-up that resulted from inadequate designs or improper installation of equipment during facility construction. The most significant of these was the installation of oversized turbine control valves that required several attempts at modification before reliable operation was achieved. During these efforts, an incident of excessive turbine vibration resulted in damage to the rotor blades. The source of the turbine imbalance was attributed to two possible causes: accumulation of pipe scale solids on the rotor blades during the multiple short-lived turbine start-ups or, alternatively, that a water slug had entered the turbine during the episode. This question was never resolved to the satisfaction of all concerned. Start-up efforts were temporarily suspended in September 1981 to allow the rotor to be returned to the manufacturer for rebalancing and testing for blade cracks. The rotor was returned to Hawaii in November 1981; on December 11 flow from the well was re-established and power plant start-up operations were again attempted. After approximately two months of shake-down, the facility was able to generate power on an intermittent basis and by March, 1982, commercial sale of electrical power from the facility began.

After the initial start-up problems were overcome, the operation of the power plant was relatively smooth. After eighteen months of operation, the facility was shut down for a complete overhaul and evaluation of the plant equipment (Baughman et al., 1985). This effort (funded in part by the Electric Power Research Institute) showed that corrosion and deposition in the steam and condensate systems were minimal:

general corrosion of the mild steel steam lines was confined to a very thin coating of iron sulfide and no evidence of pitting was found; scale deposition in the steam lines was minimal with the only significant deposits being present at the turbine inlet nozzles; the turbine rotor blades showed minor corrosion, erosion, and small amounts of pitting (possibly from sulfide oxidation products during off-line conditions); the stainless steel condenser showed no evidence of corrosion or scale deposition on the surfaces exposed to steam.

The brine handling system, however, showed significantly more problems. Evaluation of the discharge line from the well showed less than a millimeter of silica scale deposition; however, as the brine system was traversed, deposition of silica became progressively more extensive. A mixed silica/rock dust layer approximately 0.5 cm thick was deposited on the separator surfaces exposed to brine; the brine discharge line was similarly coated with silica from the separator down to the brine discharge valve at the brine muffler. Silica deposition downstream of the discharge valve increased dramatically and showed rates that were ten to one hundred times that found in the brine piping.

The gas abatement system showed that relatively few maintenance problems were present as long as proper combustion was allowed to occur. However, during the operations of the incinerator scrubber system it was found that inadequate air feed to the combustion chamber could produce both excessive temperatures or, when combustion was incomplete, deposition of elemental sulfur in the gas scrubbing column.

Following the facility overhaul, the turbine generator was restarted, and, with the exception of periodic scheduled and emergency maintenance outages, the facility continued to produce power until December 11, 1989 when the turbine generator was shut down permanently and the well was closed-in until such time as another commercial facility could purchase steam from the well.

OPERATIONS EXPERIENCE

During its eight years of operation, the HGP-A Generator Facility encountered and overcame a number of operational and maintenance difficulties. Silica deposition was by far the most significant of these. The high rates of silica deposition found during the initial overhaul of HGP-A continued or, in some cases, increased in the brine handling system. Silica scaling within the brine discharge line fouled seats and stems of shut-off and control valves and bridged smaller diameter access or discharge ports on the line. After several attempts it was found that ball valves were best able to overcome the valve seat and stem fouling problems. No clear solution was found to the bridging problems that were ultimately dealt with by periodically drilling out the silica plugs. Throughout the operational life of the facility, silica

deposition in the brine lines required constant maintenance; when this was not forthcoming, system failures forced shut-down of the facility to correct the problems generated.

The much higher rate of silica deposition in the brine muffler system and the brine disposal ponds proved to be an even more intractable problem. Whereas during the first year of operation, the brine discharge was easily able to percolate into a disposal pond of approximately 40 m², the progressive increase in deposition of a stable silica gel from the waste brine ultimately required several thousand square meters of percolation ponds for the disposal of waste fluids. Although no satisfactory solution to silica deposition in the percolation ponds was applied to HGP-A, research conducted on the fluids showed that deposition rates were controlled by fluid pH and by the physical and chemical changes that occurred when the brine was allowed to boil. A pilot-scale system installed at the site to evaluate gas reinjection and silica control methods showed that deposition of silica from the brine could be virtually eliminated by injection of steam condensate and non-condensable gases into the line to drop temperatures to below boiling and to lower the fluid pH. The mixtures of brine and condensate produced less than 0.01% solids when mixed and no detectable precipitation of solids after several days retention at room temperature. Addition of non-condensable gases showed small amounts of sulfide precipitation, although still less than 0.01% solids, but an even greater stability with respect to silica precipitation (Thomas, in prep.).

The high concentrations of hydrogen sulfide in the steam from HGP-A required that virtually all emissions from the facility be treated for removal of this gas prior to release. The abatement system initially installed on the facility efficiently removed H₂S from the condenser off-gases, however the expense associated with an incinerator-scrubber system encouraged examination of alternative gas treatment systems. These included: treatment of the NC gas with chlorine; a liquid phase Clause-type process; a two-stage caustic scrubber system; and a gas reinjection system. Although the former two processes showed that the respective chemical reactions on which they were based worked, both suffered from design flaws that did not allow them to be installed as primary abatement systems. The two-stage scrubber system provided abatement efficiencies as high as the single stage unit but at a substantially reduced cost. This system was used for several years at the facility. The final process, gas reinjection, was tested only as a pilot system but showed that recombination of the non-condensable gases with the brine and steam condensate was, as noted above, not only feasible but also conferred substantial benefits on total facility operations due to the stabilizing effect of the pH change on the silica deposition process.

The potential nuisance impact of hydrogen sulfide emissions from the facility also required

that virtually any steam discharge be treated to reduce the sulfide concentrations to as low a level as possible. During off-line conditions, abatement of hydrogen sulfide was accomplished using caustic soda alone as well as a caustic/peroxide injection system. The abatement efficiency of the former system was found to be approximately equivalent to that of the latter (~95%) but at a much lower cost and without the hazards associated with transport and storage of peroxide. In spite of the high efficiencies of abatement, odor nuisance became a highly contentious issue during the operation of HGP-A and it has become clear that future power plant designs must incorporate systems to minimize the occurrence of steam releases to the greatest extent feasible.

Although many of the major operational problems associated with production of power from the geothermal resource from HGP-A were overcome, the facility did show a gradual decline in reliability and in power output. Some of this decline was clearly the result of the fact that the facility had a (DOE mandated) design life that reflected the anticipated two year duration of the testing program. However, the absence of a routine preventative maintenance program is considered to have been the major factor in the deterioration of the facility. Many of the major repair and maintenance exercises at the facility, and most of those that generated public controversy, were the result of minor problems that were allowed to develop into major upsets. This experience may prove to be the most valuable lesson to be derived from the operation of HGP-A: a strict preventative maintenance program is essential to long-term reliable operation of a geothermal facility on the Kilauea East Rift Zone.

RESERVOIR TESTING

A second major objective of the operation of the HGP-A Generator Facility was to determine whether a well drilled into this reservoir would maintain its productivity over an economically useful lifetime. Although production data alone would have been able to provide output decline information, it was also found that the chemical monitoring program, which was initially intended to provide environmental and operations data, could also provide insight into the response of the reservoir to long term production. The production data showed that the well discharge declined at a rate of approximately 2.2% per year. Because of maintenance difficulties with the fluid flow monitoring equipment, this estimate is considered to be a maximum value and is based both on electrical output figures (which would also include loss of efficiency of the plant equipment) and intermittent flow measurements made over the operating life of the power plant.

Fluid chemistry monitoring also provided significant insights into the reservoir response to fluid production and greatly assisted in the development of a model of the reservoir. Among these was the discovery that a major source of

fluids in the high-temperature reservoir was from meteoric recharge. Long-term production of fluids from the HGP-A well showed, however, that seawater could infiltrate into the system in response to pressure draw-down. The fluid chemistry also showed that the inflow of seawater into the system may be a self-limiting process due to the rapid deposition of secondary minerals produced by high-temperature seawater basalt reactions. It can be inferred from this that future exploration in parts of the geothermal system that are likely to be saturated with seawater are also likely to have lower permeability than the interior, freshwater-saturated parts of the system. Finally, the chemical results indicate that production from the HGP-A well was derived from two levels: a lower temperature aquifer that produced steam and brine and a deeper one that may produce predominantly steam. These findings were further substantiated by later wells drilled in the vicinity of HGP-A that also produced predominantly steam from deeper production levels (Thomas, 1987).

Comparison of the chemical composition of the deep hydrothermal fluids from HGP-A with that of shallow groundwater in the lower East Rift Zone showed that this geothermal system is highly dynamic with a high through-put of meteoric and saline water. Estimates of geothermal fluid discharge, based on the chemical compositions of HGP-A fluids and shallow groundwater, indicate that several million gallons a day of geothermal fluids are released into shallow groundwater aquifers along the rift zone. The heat flux associated with this discharge amounts to approximately 1400 MW of thermal energy on a continuous basis.

The process and environmental chemistry data obtained from the long-term test of HGP-A indicate that, with the obvious exception of H_2S , the fluids have relatively low concentrations of the environmentally sensitive elements or compounds. Ammonia and boron, which are sources of many operational difficulties at the Geysers geothermal field, are either at undetectably low levels (ammonia) or at such low concentrations that they have no impact on operations (boron). The salinity of the fluids at HGP-A were approximately half that of seawater and hence the geothermal discharge was too saline for secondary uses such as irrigation. However, other elements, such as the trace transition metals (mercury, lead, arsenic, aluminum), were found to be at concentrations that allowed the fluids to be considered non-hazardous.

SIGNIFICANCE OF THE HGP-A PROGRAM

The impact that the Hawaii Geothermal Project will ultimately have on Hawaii's energy future is, at the present time, difficult to assess. When we compare the state of our knowledge at the time the HGP program was begun with our current understanding of both the geothermal reservoir and geothermal production technology after eight years of continuous production, it is clear that the impact of the information gathered during this

project will continue to be felt far into the future. When the HGP-A well was drilled, the acknowledged wisdom of that time was that high temperatures were unlikely to be present in the rift zone due to the high permeability of the surface rocks. When low permeability formations were found at depth, it was suggested that inadequate fluid flow would develop to sustain a geothermal facility. When sustained production of fluids from the well was established, it was questioned whether the difficulties inherent in fluid production from a water dominated resource could be effectively overcome in a geothermal electric power plant. The HGP-A well demonstrated that temperatures were present in the Kilauea East Rift Zone that were as hot as had been found in any geothermal system in the world. Sustained production from the well, for four hours in the first test and for eight years in the last, have demonstrated that economically producible reservoirs are present in the rift zone. The HGP-A Wellhead Generator Facility was the first geothermal generating station in Hawaii and was planned as a two-year demonstration project; it produced power for nearly eight years with an availability factor in excess of 90%. These facts by themselves, convincingly demonstrate that the geothermal system discovered by the HGP-A well is amenable to production of electrical power.

Even in areas where the HGP-A project was not a complete success, it is clear that the industry and the people of Hawaii will benefit. Due to financial and design constraints, it was not possible to maintain state-of-the-art hydrogen sulfide abatement systems through the life of the plant. The controversy generated by even the occasional nuisance odor of the HGP-A operations has clearly sensitized both the industry and the governmental permitting agencies to the fact that substantial efforts will have to be expended by the industry to minimize emissions from future, commercial-scale geothermal facilities. Handling of the geothermal brines was again not entirely successful at the HGP-A facility. Nonetheless, the difficulties inherent in transporting and disposing of these fluids is now apparent to any who hope to develop geothermal resources in Hawaii. Although we were not able to eliminate all the problems presented by the geothermal reservoir on the Kilauea East Rift Zone, we were able to identify many of the possible solutions to these problems during the operational life of the HGP-A Generator Facility.

Finally, when one considers the full range of possible outcomes that might have occurred throughout the evolution of the Hawaii Geothermal Project, it is clear that this program will be a key event in the development of the geothermal industry in Hawaii. Possibly one of the most telling of these possible outcomes is the successful production of steam from HGP-A. As noted above, the first choice for the proposed site of HGP-A was unavailable to the project and an alternate site was chosen nearby. Several years after the successful completion of the HGP-A well, exploratory drilling was conducted on the

site originally chosen for HGP-A by the Hawaii Geothermal Project site selection committee. When the site was drilled, it produced a hot dry hole on the first attempt and a low temperature one on the second, and last, attempt.

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