

A Geochemical Case History of the HGP-A Well 1976-1982

Donald M. Thomas

Hawaii Institute of Geophysics, Honolulu, Hawaii 96822

ABSTRACT

The Hawaii Geothermal Project Well-A, located on the Island of Hawaii, was completed in 1976 to a depth of 1966 meters. The bottomhole temperature, under shut-in conditions, is 360°C and at full discharge is capable of producing about 45,500 kg/hr of a mixed fluid composed of 48% steam and 52% liquid. The major element chemistry of the fluids suggests that recharge to the reservoir is largely fresh meteoric water with no more than 10% to 15% of the recharge being from sea water. Extensive water-rock equilibration has occurred; however neither Na-K-Ca nor silica geothermometry calculations have been able to yield reasonable reservoir temperatures. Isotopic data suggest that the circulation rate and residence times of fluids in the reservoir are on the order of a few thousand years. Helium isotopic data also indicate that the heat source for this reservoir is very young or very large.

INTRODUCTION

The Hawaii Geothermal Project Well-A (HGP-A) is located on the lower East Rift Zone of Kilauea Volcano on the Island of Hawaii and was completed in April of 1976. The well penetrates to a depth of 1966 m and has a bottomhole temperature under shut-in conditions of approximately 360°C.

The first flow test of HGP-A occurred on July 2, 1976 and, after it was determined that the well could maintain spontaneous flow for more than a few hours, an extensive well testing program was initiated to determine the sustainable flow rate, wellbore permeability and fluid chemistry. Flow testing of the well indicated that it was able to produce a total flow of approximately 40,000 kg/hr, of which about 48% was steam, and thus was capable of producing commercial quantities of steam. On this basis, a 3MW wellhead electrical generator facility (jointly sponsored by the U.S. Department of Energy, the State of Hawaii, the County of Hawaii and Hawaiian Electric Company) was installed on the well to demonstrate the technical feasibility of power production from this resource and thus to stimulate the development of a commercial geothermal industry in Hawaii. Initial start-up operations for this facility began in June 1981

and the power plant began producing electrical power on a continuous basis in March 1982. The present generating capacity of the facility is approximately 2.8 MWe.

WELL TESTING

Testing of HGP-A can be divided into two phases: preliminary testing conducted primarily to determine the basic engineering and geoscientific parameters of the well and developmental testing to define the production and process chemistry requirements for the design and construction of a generator facility.

RESERVOIR ENGINEERING ANALYSIS

Reservoir testing of the well initially consisted of pumpdown tests and short duration flow tests followed by pressure and temperature recovery analyses. Results of this work suggested that the wellbore had suffered some skin damage from mud caking during drilling and completion operations and that the reservoir permeability was low (about 1 millidarcy) (Yuen, et. al., 1978). The sustainable production rate from the well tended to increase with each flow test and stabilized at about 41,000 kg/hr at a wellhead pressure of 1100 kpa after an extended (40 day) flow test in 1977. Down hole temperature and pressure profiles obtained during and after production tests indicated that, during production, a mixed phase was present throughout the wellbore (steam flashing was occurring in the formation) and that at least three aquifers were providing fluid to the well. Production zones were located at depths of 1800 to 1860m, 1160 to 1250 m, and 670 to 700 m (Yuen et. al., 1978).

RESERVOIR CHEMISTRY

Fluid sampling and analysis have been conducted on an intermittent basis throughout testing and production from HGP-A. The early testing phase was intended to define the basic parameters of the reservoir penetrated by the well whereas more recent analysis has monitored changes in fluid chemistry arising from long term production.

CHLORIDE DATA

The chloride ion concentration in the HGP-A brines has been monitored very closely since the completion of the well as a means of determining the source fluids for the reservoir as well as for identifying changes in reservoir recharge (eg. cold water breakthrough into the production aquifers).

Table 1. Chemical Analysis of HGP-A Brines (mg/kg)

	Cl ⁻	Na	K	Mg	Ca	SiO ₂
11-8 -76	2190	1200	212	<0.5	81.9	
11-17-76	2520	1320	223	0.5	78.8	
1-29-77	2590	1260	225	0.5	78.2	
4-11-77	3050	1460	266	0.1	77.3	710
6-15-78	2420	1500	250	0.08	56.6	
1-14-80	2450	1440	216	0.1	33.2	
6-12-81	1593	806	154	0.02	18.5	1200
9-4 -81	3700	2190	250	0.1	72	800
12-22-81	3261	1745	281	0.04	58.3	1100
3-22-82	5050	2655	431	0.080	121.	
4-19-82	5293	2792	472	0.134	123.	799
5-17-82	5489	3066	508	0.060	124	802
6-14-82	5677	3200	513	0.070	149	818
7-12-82	6044	3300	536	0.073	157.	

During initial well testing the chloride concentration (Table 1) in the brines produced was found to be substantially lower than that in sea water (Kroopnick, et. al., 1978). This result was unexpected since the well penetrates to a depth substantially below that expected for the bottom of the Ghyben-Herzberg lens in this area. The initial interpretation of the low chloride concentrations was that drilling water was being cleared from the producing aquifers. However, more recent production from the well has indicated only a very gradual increase in the chloride concentrations in the geothermal fluids. Thus it is presently believed that the total dissolved solids content in the reservoir fluids under equilibrium conditions is on the order of 6000 mg/kg.

The low salinity of the reservoir fluids may be the result of isolation of the interior of the rift zone from ocean water intrusion by the impermeable dike system within the rift zone. High rates of meteoric recharge from the surface coupled with rapid mixing within the dike compartments could thus maintain a uniformly low salinity within the individual compartments.

Comparison of observed chloride concentrations in the brine versus time (Fig. 1) (all values have been corrected to 1200 kPa flash pressure) for three separate production periods suggests that the changes in chloride concentration with time follow a reproducible trend. Although it is possible that the gradual chloride increase is the result of increasing sea water influx into the reservoir, it is more likely that the change in chloride ion reflects migration of the flash front out into the formation thereby allowing the liquid phase to mine progressively more heat, and thus form more steam from the rock matrix between the flash front and the wellbore. This interpretation is substantiated to some degree by the change in steam quality observed during production; during the first 300 to 400 hours of

well flow, the steam quality increases substantially but the rate of increase gradually declines with time. It is suggested that the sudden breaks in the slope of the chloride concentration curve reflect the migration of the flash front into areas of the formation that have not been produced from before and therefore have a higher temperature.

General Brine Chemistry

The remainder of the dissolved solids in the HGP-A brines have been analyzed in an effort to further define the characteristics of the reservoir recharge fluids as well as attempt to calculate reservoir temperatures. The data acquired indicate that if sea water does make up a portion of the reservoir recharge it has, in most cases, been substantially altered by interaction with the reservoir rock. The ratios of the sodium and potassium ion concentrations to chloride ion are about 5% and 450% above the corresponding sea water ion ratios whereas the calcium ion ratio is depleted by about 65% and both magnesium and sulfate ion ratios are reduced by more than 99% relative to sea water. The mechanism for the modification of the ion ratios is largely through the alteration of potassium containing minerals (primarily plagioclase or interstitial glass) and the formation of chlorite and anhydrite for the removal of magnesium ion and calcium and sulfate ions respectively (Bischoff and Dickson, 1975). Both chlorite and anhydrite have been identified in the deeper cores from HGP-A; the former as an alteration product and the latter as a vein filling mineral (Stone, 1977). Even though the cation concentrations have been substantially altered by interactions with the reservoir rocks, attempts to calculate reservoir temperatures using the cation geothermometers have been uniformly unsuccessful. Depending on the assumptions made, calculated reservoir temperatures have ranged from 80°C to 120°C below the static (nonproducing) bottom-hole temperature in HGP-A. Calculations of the reservoir

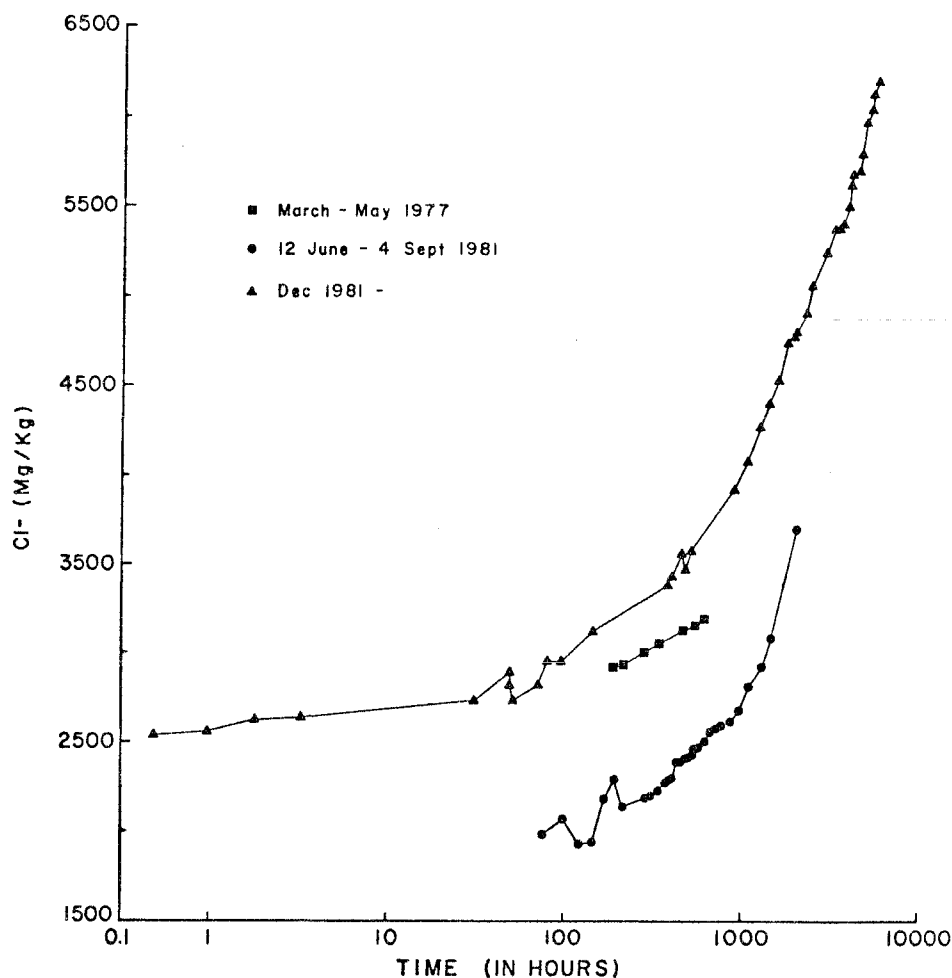


Fig. 1 Plot of Chloride Concentration versus time in HGP-A brines

temperatures using silica geothermometry have similarly been unsuccessful. Although the silica concentrations are high in the HGP-A brines, the calculated temperatures using the silica concentrations are well below the static bottom-hole temperature. Evaluation of silica concentrations during well start-up operations indicates that the concentrations peak a short time after production begins and then rapidly decline as the wellbore is cleared of fluids. This suggests that the dissolved silica in the brine phase is rapidly re-equilibrating to the much lower bottom-hole temperatures brought about by production of steam from the well.

The deposition of hydrothermal minerals in the formation or the wellbore during production is of major concern to the potential for long term production from this reservoir. If the above mechanism for silica concentration control is valid, it follows that silica must be depositing in the formation around the wellbore. Although silica scaling in the surface piping of the power plant has proceeded at a relatively slow rate, during the last twelve months it is highly probable that deposition is considerably more rapid in the reservoir. Comparison of the ratios of the individual cation concentrations to chloride ion can also indicate

whether deposition of other minerals is occurring. If, for example, calcium carbonate were being deposited, one would expect a gradually increasing Cl/Ca ratio in the brines produced. The chemical data obtained to the present time indicate that all of the cation to chloride ratios in the brines have been relatively constant and do not exhibit any distinct trends. The absence of a trend of this sort for the cation concentrations suggests that silica is the only mineral that is presently being deposited at an appreciable rate as a result of the flashing process.

The concentrations of the trace transition elements in the geothermal brines has been monitored on an intermittent basis in order to evaluate the potential environmental impacts of the geothermal fluids being produced. The presently available data (Table 2) indicate that the concentrations of many of these elements are well below those found in fluids from most other geothermal environments. The low transition element concentrations in the HGP-A fluids almost certainly arise from the low concentrations of these elements found in Hawaiian basalts.

Table 2. Trace element concentrations in the HGP-A brines

Date	Hg	Cd	Pb	Tl	As	Cu	Zn	B
6/16/77	0.41	<10	<1	≤1	<0.5	<10	≈35	-
6/13/81	≤1.0	<1	-	<1	50	<100	≈40	1.3
1/27/82	<0.5	-	-	-	<100	-	-	2

Table 3. Down-hole water chemistry for HGP-A

Date	Depth (meters)	Cl	Na	K	Mg	Ca
12/2 /76	690	910	500	77.5	1.9	21
12/2 /76	1310	920	480	85	0.7	17.3
12/3 /76	1770	980	500	223	0.6	22.6
2/14/77	690	4800	2160	248	14.7	465
2/14/77	1070	1030	600	82.5	0.4	39.3
2/14/77	1770	2330	1080	160	2.0	161
2/14/77	1920	1310	620	87.5	1.9	95.7

DOWNHOLE WATER CHEMISTRY

During early testing of the well a number of downhole profile water samples were obtained as a means of identifying and defining the production chemistry of the different aquifers in the well (Kroopnick, et. al., 1978a). The chemical data from these samples (Table 3) initially indicated a relatively uniform composition in the wellbore, suggesting that only one production zone was providing fluids to the well or that multiple zones were producing fluids of similar chemical composition. But, subsequent sampling profiles identified three different production zones (Fig. 2, Fig. 3) having distinctively different compositions. The upper production zone, at about a 670 m depth, had substantially higher chloride, magnesium, and calcium concentrations than the deeper aquifers. The ratios of magnesium and calcium ion concentrations to the chloride ion suggest that fluids from this aquifer had not been thermally altered to the same degree as the fluids entering the well at deeper levels. On this basis it was hypothesized that this aquifer was injecting low enthalpy fluids into the well during production; a recasing program necessitated by a leak in the surface casing subsequently sealed off this aquifer. The second production zone at a depth of 1158 m is also indicated to have a significantly higher salinity than the bottom hole. The loss of calcium and magnesium from the fluids in this aquifer suggests that higher enthalpy fluids are being produced at this depth. The data indicate that the third production zone at bottom hole has a lower salinity and total dissolved solids than those above it. The gradual development of these aquifers with time tends to substantiate the engineering analysis that the wellbore had suffered substantial

skin damage during drilling and completion operations; several flow tests were apparently necessary to clear the drilling mud and debris from the major production zones in the well.

NON CONDENSIBLE GAS COMPOSITIONS

The concentration and composition of non-condensable gases in the HGP-A steam phase have been determined on a frequent basis since the completion of the well. The earlier data (Table 4), acquired during short term flow tests, indicated quite variable compositions having total concentrations ranging from 750 mg/kg to 5900 mg/kg in the steam phase. Although some of the observed variability is undoubtedly the result of sampling and analytical errors, more recent analysis of the gas compositions during longer term flow tests indicates that the non-condensable gas concentrations and compositions change radically during the first few hundred hours of production and then gradually stabilize. The observed changes are probably due, in part, to the development and migration of the flash front into the reservoir however, other chemical processes are undoubtedly involved as well. Analysis of the non-condensable gases from the most recent production period indicates that the gas compositions have stabilized and are likely to remain at a concentration of about 2400 mg/l for the immediate future.

Analysis of the steam phase for other volatiles have not found ammonia at detectable levels whereas mercury, boron and arsenic are present only at trace levels.

ISOTOPIIC ANALYSES

Stable and radio-isotopic analyses have been performed on the geothermal fluids from HGP-A on

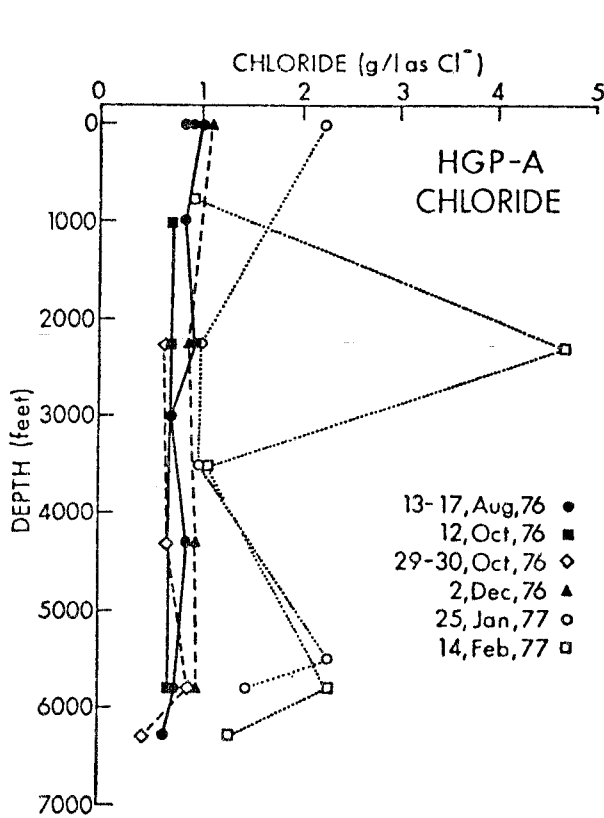


Fig. 2 Plot of Chloride Concentration versus depth for downhole profile samples.

an intermittent basis since flow testing of the well began both as a means of determining the reservoir recharge characteristics as well as to monitor environmental impacts of the well discharge. Radioisotopic analyses were done for tritium, carbon - 14, and radon isotopes in the geothermal fluids during the early testing phase as well as more recently. Tritium concentrations in the brine under extended flow (i.e. uncontaminated conditions) are at background levels (0.1 TU) indicating that the bulk of the recharge for the well is at least 30 years old. Brine samples analyzed from an earlier test, (Thomas, 1980) conducted approximately five months after a substantial quantity of surface water had been pumped into the well indicated that all of the water pumped into the reservoir ($\sim 8 \times 10^6$ kg) was discharged over a period of 12 to 14 days. This would suggest that the fluid circulation and residence times within the immediate vicinity of the wellbore are on the order of years.

Analysis of carbon-14 in carbon dioxide produced by the well during early testing yielded an apparent age of about 12,000 years (Thomas and Kroopnick, 1978). This value was considered to be a maximum age since magmatic carbon dioxide (having zero carbon-14 activity) is expected to make a significant (if not substantial) contribution to the carbon present in the well fluids. Thus it was originally hypothesized that carbonaceous materials used in the drilling process (bagasse, cotton seed hulls, etc.) was a

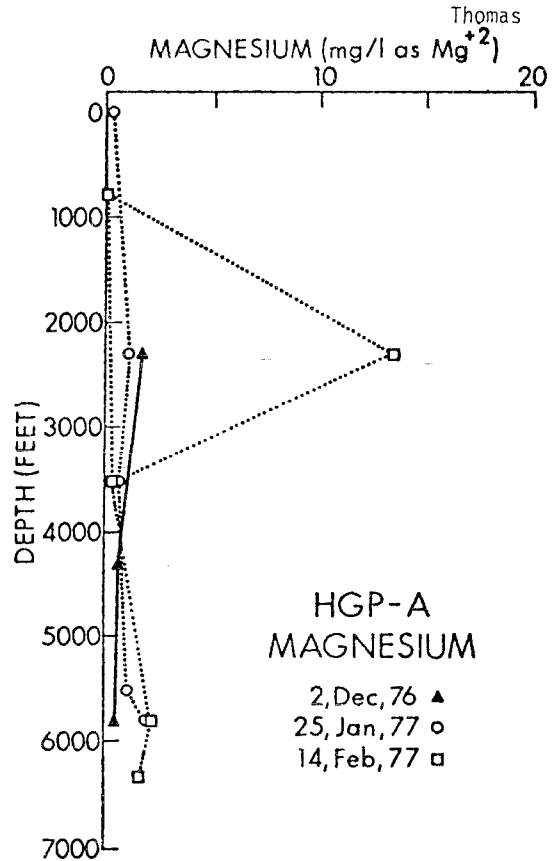


Fig. 3 Plot of Magnesium Ion Concentration versus depth for downhole profile samples.

Table 4. Non-Condensable Gas Compositions in HGP-A. (expressed in mg/kg of steam)

Date	CO ₂	H ₂ S	Ne	H ₂
2/ 9/77	4431	1435	131	46.3
5/ 8/77	2378	878	375	15.1
7/19/77	445	112.	116.	2.3
1/19/80	1000	750	168	11.0
5/31/82	1238	886	129	11.0

substantial contaminant in the carbon dioxide in the well discharge. More recent analyses, however, have confirmed the earlier data suggesting that the hydrologic circulation rate within this reservoir is substantially more rapid than that within larger continental reservoirs.

The concentrations of radon in the geothermal fluids have ranged from 1.16 nano curie per kilogram of steam condensate (nCi/kg) during early flow testing to approximately 3.7 nCi/kg during more recent longer-term production (Kruger, personal communication). The concentration of radon in the total well flow for the later samples is calculated to be about 1.65 nCi/kg. This compares with values averaging approximately 20 nCi/kg in the Geysers geothermal field. The lower radon concentrations found in Hawaii are considered to be largely due to the lower uranium concentrations present in Hawaiian basalts relative to the more silicic volcanic and sedimentary rocks found in continental environments.

A very limited number of stable isotopic analyses have been performed for carbon, oxygen, hydrogen, and helium in the HGP-A fluids. Carbon-13 isotopic values ranged from -1.97‰ to -3.6‰ versus PDB. These values are somewhat heavier than expected since the primary sources for the carbon present in these fluids would be biogenic carbon and magmatic carbon which are presumed to have ratios of approximately -20‰ and -7‰ respectively. Although isotopic fractionation processes are almost certainly controlling the C-13 ratios observed in the well discharge, the data are presently inadequate to attempt even a preliminary evaluation of the reactions governing the carbon isotopic ratios.

A limited number of hydrogen and oxygen isotopic analyses were conducted on fluids obtained during the early testing of HGP-A. The isotopic ratios determined for these samples ranged from -6.4‰ to -8.2‰ and from -3.6‰ to -4.6‰ relative to standard mean ocean water (SMOW) for deuterium and oxygen-18 isotopes respectively. These values suggest that the fluids analyzed were of local meteoric origin and that oxygen isotopic exchange with the reservoir rock had not occurred to an appreciable degree. On this basis, it is considered highly probable that these fluids were comprised largely of water pumped into the reservoir during the drilling and completion operations. Unfortunately no more recent analyses have been conducted for the hydrogen and oxygen isotopes from HGP-A.

Helium isotopic analyses for the fluids from HGP-A have yielded $^3\text{He}/^4\text{He}$ ratios of approximately 1.7×10^{-5} (Thomas and Kroopnick, 1978), nearly a factor of ten above atmospheric helium isotope ratios. These values are similar to those observed in fumarolic gases at the Kilauea summit, suggesting that there is a substantial component of magmatic helium present in the geothermal fluids. This, in turn, implies that the magma bodies from which the reservoir derives its helium (and its heat) are relatively young or are very large.

SUMMARY

In summary, the geochemical data obtained from HGP-A suggest the following tentative conclusions regarding the Puna geothermal resource:

1. The total dissolved solids content of the fluids produced by HGP-A is well below that of seawater indicating that parts of the reservoir have minimal direct communication with the normal Ghyben-Herzberg lens adjacent to the rift sone. This, implies that there is strong compartmentalization within the reservoir.
2. The total dissolved solids content of the fluids produced by the well is likely to increase as the flash front migrates out into the formation. The rate of increase in the dissolved solids content of the fluids over the production life of the well is expected to be relatively constant until such time as the flash front stabilizes.
3. Steam production occurring in the formation is inducing silica deposition within the production aquifers.
4. The toxic transition element concentrations in the fluids from HGP-A or other geothermal wells in the reservoir are likely to remain relatively low compared to continental geothermal systems.
5. The non-condensable gas concentration in the well fluids will probably remain at a nearly constant level for the immediate future.
6. The circulation rate and residence time of fluids within the reservoir produced by HGP-A are greater than 30 years but almost certainly less than a few thousand years.
7. Helium isotopic data suggest that the heat source for the well is a relatively young and/or large magma body still out-gassing its primordial rare gases.

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