HAWAII GEOTHERMAL PROJECT

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PHASE III - WELL TESTING AND ANALYSIS

PROGRESS REPORT FOR THE
SECOND QUARTER OF FEDERAL FY77

April 1, 1977

1093 8-1

SUPPORT FOR PHASE III PROVIDED BY:

Energy Research and Development Administration
State of Hawaii

SUPPORT FOR PHASES I AND II PROVIDED BY:

Energy Research and Development Administration
National Science Foundation
State and County of Hawaii
Hawaiian Electric Company
Water Resources International, Inc.

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Reservoir Engineering

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*I used the
program Directors
because they showed
up on screen as
having been used
before with this
same project but
different quarters.*

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HAWAII GEOTHERMAL PROJECT
PHASE III QUARTERLY PROGRESS REPORT
January 1 through March 31, 1977

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HAWAII GEOTHERMAL PROJECT

ACTIVITY OF THE MANAGEMENT-COORDINATION PROGRAM

January 1 through March 31, 1977

During the second quarter of FY 77 the major activities of the HGP Management Program continued to be: a) Coordination and administrative support to the research and well testing programs; b) Informational and promotional efforts at both the local and national levels to help assure adequate visibility and support for the project; and c) Planning and negotiating for future development of both the well and the reservoir.

Principal Investigator for the HGP and Director of the Management Program is John W. Shupe, Dean of Engineering, assisted by Administrative Officer Diane Sakai. Charles E. Helsley, Director of the Hawaii Institute of Geophysics, is Co-P.I. and Coordinator for all geosciences activity. Paul C. Yuen, Associate Dean of Engineering, is Director of the well testing and reservoir engineering programs. Both Drs. Helsley and Yuen have direct technical supervision and budgetary authority for their respective programs, and have prepared their sections of this quarterly report independently.

Dr. Helsley has provided a rather succinct summary of geosciences activity during the second quarter. Progress continues in all areas on the analysis and synthesis of data, which is to be completed by the end of this fiscal year. Water samples have been collected and analyzed, and apparently the well is beginning to stabilize in its chemistry. An extensive refraction survey involving one ship and three seismic systems was conducted in the Puna area, and exceptionally high velocities were obtained -- as yet unexplained. Hopefully, this information will assist in the evaluation of reservoir boundaries.

Dr. Yuen and his reservoir engineering group have provided a great deal of well testing data, and have presented some preliminary evaluations. HGP-A is a very hot well, with static temperatures exceeding 350°C. However, the formation is fairly tight, with the transmissivity or permeability-thickness factor running between 1000 and 1500 md-ft. The fluid is only slightly brackish, with salinity that of a ten percent seawater mix.

The well probably has experienced skin damage due to the drilling mud, with initial discharge less than half the potential flow rate. This is substantiated by successive flow tests, which show increasing discharge rates for each test.

Significant quantities of mud and cuttings have been emitted during flashing -- all suggesting that the well is "healing". Throttled flow tests for HGP-A show a steam flow rate of around 60 Klb/hr, with a wellhead pressure of 165 psig, resulting in a power output of 4.0 MWe.

After flow stabilizes in the well, the principal producing region appears to be at bottomhole, with some flashing occurring in the formation, and two-phase saturated flow continuing throughout the wellbore. Based upon well-testing data, the reservoir appears to be rather extensive and exceeds 0.8 cubic miles. No reservoir limits have been encountered as yet during the relatively brief testing periods. This is substantiated by microseismic measurements, which identify an elliptical reservoir with major dimensions of 2 by 3 kilometers.

Switching from results to budget, Table I presents a summary of the amounts awarded and expended by the HGP through the second quarter of FY 77. The total amount from ERDA of \$300,248 represents a \$50,000 advance from the transition period, a \$220,248 grant approved in November, and a supplemental award of \$30,000 approved in December. Although only \$195,000 of this \$300,248 had been released to the project by ERDA-SAN as of January 1, 1977, the remainder of these funds was received during this current quarter. The State of Hawaii has provided \$66,405 in FY 77 to assist with the well testing program. With almost two-thirds of the funds already encumbered after the first two quarters, it is obvious that the well testing and support programs must operate at a reduced level of activity for the remainder of FY 77.

In fulfilling the coordination and liaison function of his responsibilities during this quarter, the Director of the Management Program has:

- Taken two trips to the Big Island to observe and advise on the project and to confer with County officials.
- Attended the 18th Meeting of the ERDA-DGE Geothermal Coordinating Group in China Lake, California, to discuss immediate and long-range aspects of the HGP with the Group, including two representatives of ERDA's Geothermal Division.
- Presented a report on the HGP and other natural energy resources at the Western Region Conference of the National Association of Counties in Reno, Nevada.
- Conducted a meeting of the HGP Hawaii Advisory Committee -- sixteen key representatives of government, industry, the scientific community, and citizens groups, whose support is essential to development of geothermal power in Hawaii.

TABLE I
FISCAL SUMMARY OF THE HAWAII GEOTHERMAL PROJECT FOR FY 77
March 31, 1977

<u>PROGRAM</u>	<u>AWARDED AMOUNT THROUGH 9/30/77</u>		<u>ESTIMATED COMMITTED EXPEN- DITURES THROUGH 3/31/77</u>		<u>ESTIMATED BALANCE AS OF 3/31/77</u>	
	<u>Federal funds</u>	<u>State funds</u>	<u>Federal funds</u>	<u>State funds</u>	<u>Federal funds</u>	<u>State funds</u>
Management	\$ 25,000		\$ 14,054		\$10,946	
Geosciences Tasks 2.1-2.7 & 4.1	141,975		93,934		48,041	
Reservoir Engineering and Well Testing Tasks 3.1-3.3	133,273	\$66,405	99,930	\$31,072	33,343	\$35,333
TOTAL	\$300,248	\$66,405	\$207,918	\$31,072	\$92,330	\$35,333

- Given written and oral testimony on the development of geothermal energy in Hawaii at four sessions of energy and finance committees of the Hawaii State Legislature.
- Conferred on geothermal power with over forty individuals from a half-dozen countries representing business, government, and the scientific community.

However, the bulk of the management effort this quarter has been directed toward establishing a consortium for undertaking the next development phase of the project and for pulling together a proposal to ERDA to provide major funding for this endeavor. The University does not wish to become a major developer of geothermal power, but does have a role to play in the future identification and utilization of geothermal resources throughout the island chain, particularly at the site of HGP-A.

This organizational effort has resulted in the creation of the HGP-A Development Group, consisting of: 1) The State of Hawaii, represented by Hideto Kono, State Energy Resources Coordinator; 2) The County of Hawaii, represented by Clarence Garcia, Director of the Department of Research and Development; 3) The Hawaii Electric Light Company (HELCO), represented by Frank Montgomery, Vice President for Engineering of the Hawaiian Electric Company (HECO) -- which is HELCO's parent organization; and 4) The University of Hawaii, represented by John Shupe, HGP Director. Hideto Kono will serve as Executive Director of the Development Group, while John Shupe is authorized to negotiate for the Group with ERDA.

TRW, Inc. was granted a \$38,500 contract by the State to assist in the preparation of a proposal for a wellhead generator and supporting research and testing facility for HGP-A. Work is nearing completion on this proposal. It will be submitted to ERDA by the HGP-A Development Group on April 6, 1977, and requests support to assist in establishing a "Geothermal Electric and Nonelectric Research Facility Utilizing the HGP-A Well on the Island of Hawaii." Different types of wellhead generators are considered, along with alternate possibilities for reinjection and research capability. Depending upon which options ERDA is interested in funding, the project could run from \$3.1 to \$6.4 million, with some local matching support from the State and County. The utility has agreed to purchase the power from the project, with anticipated revenue running around \$260,000 a year. This would provide sufficient annual support to operate and maintain the facility.

Additional discussions with the landowner have resulted in designating the field associated with HGP-A as the Kapoho Geothermal Field, after the Kapoho Land and Development Company, which provided access to the drill site. Commercial enterprises continue to evidence interest both in developmental drilling in the Kapoho Field and in the utilization of electricity resulting from this geothermal resource. A cooperative program for getting electricity on line as soon as possible would reinforce the interest and confidence of private investors in geothermal energy for Hawaii and have a positive impact on the rapid introduction of geothermal power to the State.

ACTIVITY OF THE GEOSCIENCES PROGRAM

January 1 through March 31, 1977

Charles Helsley

The Geosciences tasks with the exception of the seismic subtask have primarily concerned themselves with continued data analysis and synthesis in the past quarter. Our goal is to have completed the analysis and synthesis of all of the previous work by the end of the grant period. The geochemical subtask is actively continuing with water chemistry as more water samples are collected during the production tests. The well appears to have stabilized in its chemistry now and perhaps we can begin to incorporate the water chemistry into the overall synthesis.

The seismic subtask carried out an extensive seismic refraction survey in the Puna area in January. This work involved the University ship NOII as well as three seismic systems. Self-contained seismic systems borrowed from the University of Texas at Dallas were deployed at seven sites in the region, and three self-contained ocean-bottom seismic systems were borrowed from the HIG marine geophysics group and deployed in the region as well. In addition, a telemetry array was placed in the vicinity of the well and consisted of seven elements spread over an area of several kilometers in radius. Three other portable systems were deployed during each sequence of shots fired at sea.

The experiment consisted of two subparts: one a refraction experiment in the general direction of the rift and one more or less transverse to the rift. Shots were fired off Cape Kumukahi for the experiment parallel to the rift and offshore of Pohoiki for the portion of the experiment transverse to the rift itself. The data acquired during this experiment have now been played back and are in the process of analysis. The seismic array in the vicinity of the well and the portable stations belonging to the geothermal project had approximately 97 percent recovery of data, while the portable self-contained units recovered useful data on six of the ten instruments.

In the traverse parallel to the rift, a general velocity of 8.2 km/sec was observed. This anomalously high velocity suggests that the rocks below the rift zone have a high density at all levels below approximately 2 kilometers. The exceptionally high velocity of 8.2 km/sec is as yet not explained.

The transverse line again shows high velocity, but not as high as the line parallel to the rift zone. The velocity at the point of intersection appears to be approximately 7.4 km/sec.

At the present time, analysis of the seismic data is still going on with major emphasis being focused on a detailed outlining of the rift zone on the basis of velocity anomalies. Hopefully, this greater understanding of the seismic velocities in the vicinity of the Puna rift will assist in reevaluating microearthquake data and help in focusing our attention on the dimensions of the reservoir responsible for the steam found in the HGP-A well.

Task 3.1

NUMERICAL MODELLING

Ping Cheng and Kah Hie Lau

The existing computer codes developed for the Hawaii Geothermal Project have been modified for the simulation of the Kapoho Geothermal Field. The new model assumes that (1) the aquifer can be recharged or discharged from the top through a permeable upper boundary, and (2) the aquifer is comprised of three layers with the middle layer being the least permeable, and the upper and lower layers being high and moderate in permeability. The heating of the groundwater in the aquifer is provided by the dike complex from the sides and magma chamber from below. To simplify the mathematical problem, the aquifer is idealized as a rectangular region filled with a homogeneous porous medium. As shown by Cheng and Teckchandani⁽¹⁾, the governing equations can be reduced to a Poisson equation for stream function ψ and a non-linear convection-diffusion equation for temperature θ . Since the three layers have different permeabilities (k_1, k_2, k_3), diffusivities ($\alpha_1, \alpha_2, \alpha_3$) and consequently Rayleigh numbers (Ra_1, Ra_2, Ra_3), the governing equations must be applied separately to the three layers. The boundary conditions at the interfaces are such that temperatures and stream functions are continuous and that flow rates are the same, which are shown in Fig. 1.

Numerical solutions for the problem are obtained on the basis of the finite difference method. The Poisson's equation for stream function ψ is solved by the direct odd-even reduction method which is much faster than the iterative method used in the previous computer programs. The finite difference equations for temperature θ are obtained on the basis of Arakawa's explicit scheme which has the advantage of being able to eliminate aliasing errors arising from the advection terms.

Two numerical computations were carried out for natural convection in a geothermal reservoir with an aspect (length/depth) ratio of 2. In the first case Rayleigh numbers for the three layers are 300, 120, and 750 respectively. The convection pattern is similar to those of Fig. 2 where a double-cellular flow motion is shown. From a plot of isotherms, it appears that the temperature of the groundwater in the central region of the aquifer is hotter than that at the sides. Thus the vertical impermeable boundaries act as heat sinks instead of heat sources. The multi-cellular flow appears to be the preferred mode as the system approaches steady state. Vertical normalized temperature profiles θ at

Figure 1. Boundary Conditions for the Simulation of the Puna Geothermal Field

-10-

Figure 2. Sketch of Vertical Convective Pattern Near Puna Geothermal Field

various distances away from the sides are plotted in Fig. 3. The similarity between the temperature profile of the HGP-A well as shown in Fig. 4 to that of Fig. 3 enhances the credibility of the present model.

Numerical solutions have been carried out for the second case with Rayleigh numbers 300, 50, and 750 for the three layers. Because of flow restriction due to the less permeable middle layer, steady state is reached after a longer time. Comparison of vertical temperature profiles in the two cases shows that the first case appears to be closer to the temperature profile of the HGP-A well.

References

1. Cheng, P. and Teckchandani, L., "Transient Heating and Withdrawal of Fluids in Geothermal Reservoirs." Presented at the Symposium on the Nature and Physical Properties of the Earth's Crust, Vail, Colorado, August 2-5, 1976.

Depth

1.0

0.8

0.6

0.4

0.2

0

$x=0.25$

$x=0.125$

$x=0.5$

$x=0.75$

$x=1.0$

θ , Normalized Temperature

0

0.2

0.4

0.6

0.8

1.0

Tasks 3.2 and 3.3

WELL TEST AND RESERVOIR ENGINEERING

P. Yuen, B. Chen, D. Kihara, P. Takahashi, A. Seki

The HGP-A wellhead assembly has been modified to reduce the noise level, and a new wellhead platform has been built which meets OSHA standards. HGP-A has been flash discharged from January 26 to February 11, 1977 and data obtained for throttled flow conditions by inserting orifices of varied sizes in the discharge line. A second pressure buildup test was run after the well was shut-in. Pressure and temperature profiles have been obtained during discharge and quiescent periods. Reservoir analyses have been made using pressure buildup and drawdown data.

A. Wellhead Modifications and Discharge Tests

Because of numerous complaints about the noise from residents in the Puna area and because of the need for additional safety conditions, several modifications have been made to the wellhead equipment to improve its operation and to reduce the high noise levels produced. A specially-built muffler has been installed in place of the 24-inch horizontal discharge line. The muffler, of standard design, is 6 feet long and made up to two annular regions, the inner one filled with cinders for absorption of noise while the outer region is empty. To reduce the noise generated by the low-frequency vibration of the separator stacks, circular stiffeners have been welded at two heights on each vertical stack.

The stilling basin for measuring the height of water flowing over the weir was moved to a more convenient location for personnel monitoring. To facilitate the insertion and removal of the temperature and pressure probes during discharge tests, a six-foot spool was added above the vertical valve. A steel platform with stairway (which meets OSHA requirements) and a pulley and winch for manipulating the recovery tube have been installed in place of the temporary wooden platform, which was deteriorating.

During the time that the wellhead equipment was being modified, the water column level in the well was monitored with the results presented in Figure 1. On January 24, 1977, the 36th day after shut-in, the water level was at ground level. This curve is similar to that obtained following the November discharge test. Two temperature profiles were taken during this buildup period and are shown in Figure 2. The temperatures in the wellbore had essentially returned to their pre-flash values measured on December 8, 1976.

FIG. 1. WATER LEVEL RECOVERY AFTER WELL SHUT-IN

FIG. 2. TEMPERATURE PROFILES AFTER DECEMBER 12-19 DISCHARGE TEST

Equipment modifications were completed on January 25, 1977, and discharge tests began on January 26 following a warm-up period during which the well was allowed to flow through the 2-inch bleed line. Initially, the well was allowed to surge for one-hour periods in an attempt to remedy suspected skin damage. During the three surges, rock chips and drilling mud were ejected with the well fluid.

Following this period of surging, the well was allowed to discharge with the control valve wide open. A comparison of the characteristics of the flows during the early stages in the three discharge tests is shown in Table 1. There has been a steady increase in flow rate and wellhead pressure with each successive test.

A series of throttled flow tests to determine HGP-A output parameters under throttled flow conditions was then conducted. Throttling was accomplished by placing orifice plates of various sizes in the 8-inch portion of the discharge line. The results are summarized in Table 2 and shown graphically in Figures 3 and 4. There is a substantial increase in wellhead pressure from 51 to 375 psig as the flow is reduced from 100% (101 Klb/hr) to 75% (76 Klb/hr) of wide open flow.

The electrical power output possible from these flow conditions was calculated, assuming a turbine-generator conversion efficiency of 75% as the steam expands from wellhead pressure to a back pressure of 4 inches of mercury. There is a broad power output maximum of 3.9 to 4.0 MW(e) over the range of wellhead pressures from 100 to 350 psig. This range will allow a wide latitude in the design of a wellhead generator system. While more power can be extracted per pound of higher pressure steam, this advantage must be balanced against the more expensive equipment (pipes, valves, separator) that higher pressure systems require.

Temperature and pressure profiles in the wellbore taken during the throttled flow tests are shown in Figures 5 and 6. As in previous flow tests, these profiles indicate that the fluid in the wellbore is at saturation conditions with a mixture of water and steam flowing up to the wellhead.

Temperature recovery of the well after shut-in is depicted in Fig. 7. This figure shows temperature profiles (a) while the well is discharging at 76 Klb/hr one day prior to shut-in, (b) 8 days after shut-in, and (c) 14 days after shut-in.

TABLE 1

COMPARISON OF DISCHARGE TESTS AT 7 HOURS AND 25 HOURS AFTER INITIATION OF FLOW

	<u>AFTER 7 HOURS</u>			<u>AFTER 25 HOURS</u>		
	NOVEMBER	DECEMBER	JANUARY	NOVEMBER	DECEMBER	JANUARY
WELLHEAD PRESSURE (PSIG)	55	66	72	47	53	59
WELLHEAD TEMPERATURE (°C)	150	157	160	146	150	151
LIP PRESSURE (PSIG)	11.1	10	17	7.9	10.1	12.5
WEIR HEIGHT (INCHES)	3-1/2	4-3/4	4-5/8	3-1/2	4	4-1/8
WEIR TEMPERATURE (°F)	203	207	208	203	205	205
MASS FLOW RATE (KLB/HR)	97.3	120.0	139.7	87.9	103.4	114.3
WATER FLOW RATE (KLB/HR)	24	52	48	24	34	36
STEAM FLOW RATE (KLB/HR)	73.2	68.3	91.7	63.8	70.0	78.0
STEAM QUALITY (%)	75	57	65	73	68	68
ENTHALPY (BTU/LB)	912	725	805	888	833	845
THERMAL POWER (MW)	26.0	25.5	33.0	22.9	25.2	28.3

Table 2

PRELIMINARY THROTTLED FLOW DATA

<u>ORIFICE SIZE (INCHES)</u>	<u>TOTAL MASS FLOW RATE (KLB/HR)</u>	<u>STEAM FLOW RATE (KLB/HR)</u>	<u>STEAM QUALITY (%)</u>	<u>WELLHEAD PRESSURE (PSIG)</u>	<u>WELLHEAD TEMP. (°C)</u>	<u>POSSIBLE ELECTRICAL POWER OUTPUT (MWE)</u>
8	101	70	69	51	146	3.5
6	99	70	71	54	149	3.6
4	93	66	72	100	170	3.9
3	89	62	69	165	189	4.0
2-1/2	84	58	69	237	205	4.0
2	81	54	66	293	215	3.9
1-3/4	76	50	67	375	226	3.8

Figure 3

FLOW RATES DURING THROTTLED FLOW TEST

1/26/77 - 2/10/77

Figure 4

POSSIBLE ELECTRICAL POWER OUTPUT DURING THROTTLED FLOW TEST
1/26/77 - 2/10/77

Figure 5. Temperature Profiles During Flashing

Figure 6. Pressure Profiles During Flashing

Figure 7. Temperature Recovery After January Flow Test

There is a substantial problem associated with the deposition of scale, primarily from dissolved silica. As an example, the muffler that was installed prior to this test uses an annular region filled with cinders as a sound-absorbing agent. However, after only 16 days of flow the scale deposited was sufficient to cement the cinders together so that cinder replacement is difficult and requires extensive chipping of the bound cinders.

The noise from the discharging fluid remains a serious problem. During earlier discharge tests, nearby residents have complained vigorously of the "jet roar" which was heard as far as six miles away from the well site. Sound level readings ranged from the mid-90's to the low-100's on the dBa scale within the fenced area, even with the silencer/separator installed.

In an attempt to reduce the offending noise level, modifications were made to the wellhead equipment by adding a cinder-filled muffler along the discharge line and stiffening the stacks. These changes reduced the sound level by about 3 to 8 decibels. Restricting the fluid flow with orifice plates also reduced the noise level. The 1 3/4" orifice plate produced sound levels of about 80-96 dBa, which is a reduction of about 5-15 decibels. Table 3 lists dBa noise level readings at various positions about the well site. Figure 8 is a sketch showing the locations where the readings were taken.

B. Pressure Drawdown and Buildup Tests

While data sufficient to assess a producible geothermal field can be obtained only from a number of properly-spaced wells, some limited reservoir information can be obtained from a single geothermal well by utilizing the theory developed for oil and gas fields. However, caution is needed in using these results because of several reasons, including the fact that the theory is basically one for single-phase flow and HGP-A produces two-phase flow. A summary of the basic theory and references is given in HGP Engineering Technical Memorandum No. 2, Geothermal Reservoir and Well Test Analysis: A Literature Survey, 1974, by B. H. Chen.

During the two-week flash discharge test in November, pressure drawdown test data were collected, and after the one-week test in December and the two-week test in January-February, pressure buildup test data were collected by dropping pressure probes to bottomhole. Results from the analyses of these three tests are given below.

1. Pressure Drawdown Analysis

Wellhead pressure vs. time plotted on log-log scales for type-curve matching and on semi-log scales for a pressure drawdown analysis are shown

Table 3
Noise Level Readings on DBA Scale

Station	11/3 flashed 11/3 recorded 11/6 recorded	11/3 flashed 11/17 recorded	12/12 flashed 12/14 recorded	1/26 flashed 1/27 recorded	2/10/77 1 3/4" Orifice
1	100/98	98	99	96	92
2	104	102	104	100	92
3	98/106	95	96	93	85
4	98	96	100	96	87
5	98/98	94	94	89	80
6	96	92	95	90	81
7	98/97	96	97	91	82
8	99	97	98	93	85
9	98	97	99	94	88
10	98	96	99	96	89
11	101	98	100	96	90
12	107	103	106	100	93
13	110	108	110	103	96
14	107	102	104	100	93
15	106	102	106	102	96
16	104	101	105	101	93
17	110	105	108	101	96
18	106	102	106	99	93
19	103	102	104	99	95
20	103	99	100	96	90
21	104/101	99	101	98	92
22	100	98	99	96	87
23	100/99	97	98	94	87
24	99	97	98	95	88
25	106/101	99	101	95	90
26	103	99	101	98	93
27	110	104	109	103	97
28	110/107	103	107	102	96
29	96	94	96	91	86
30	108	104	106	101	96
31	106	104	108	100	94
32	97	95	-	-	
33	87/-	-	-	80	74

DATE WIND DIRECTION

11/3/76

11/6/76

11/17/76

12/14/76

1/27/77

2/10/77

Figure 8. Map Showing Sites for Noise Level Readings

in Figures 9 and 10, respectively. The initial pressure was obtained from Figure 11. While these data can be used in a pressure drawdown analysis to obtain information about the geothermal reservoir, some skepticism must be directed towards this analysis because of the following reasons:

1. The analysis is based on a constant production rate during the discharge, and this condition was not met during the November test. In order to apply the theory, a normalized pressure was obtained by dividing the measured pressure by the concomitant production rate.

2. There was some overpressure at the wellhead prior to the start of the test. Consequently, opening the valve took some effort and about 2 to 3 minutes were needed to open the valve completely. Thus there is an uncertainty of that amount in the determination of zero time.

3. The theory is for bottomhole pressure whereas the data in Figures 9 and 10 are for wellhead pressure. Thus the assumption must be made that wellhead pressure is proportional to downhole pressure and the proportionality factor remains constant throughout the test.

Within these restrictions and assumptions, some information can be obtained. To normalize the pressure with respect to production the pressure relation can be written as

$$\frac{P_i - P_{wf}}{q} = \frac{162.6\mu B}{kh} \left(\log_{10} t + \log_{10} \frac{k}{\phi\mu C_t r_w^2} - 3.23 + 0.87s \right)$$

where P_i = initial pressure, psi

P_{wf} = flowing pressure, psi

q = production rate, std bbl/day

μ = viscosity, cp

B = formation volume factor, res vol/std vol

k = permeability, md

h = formation thickness, feet

t = time, hr

ϕ = fractional porosity

C_t = total system effective isothermal compressibility, psi^{-1}

r_w = well radius, ft

s = skin effect factor

FIG. 9. LOG-LOG PLOT OF NOVEMBER DISCHARGE TEST DATA

FIG. 10. SEMI-LOG PLOT OF NOVEMBER DISCHARGE TEST DATA

FIG. 11. LINEAR PLOT OF INITIAL DATA FOR NOVEMBER
DISCHARGE TEST

The left side of equation (1) is a linear function of $\log_{10} t$ so that a plot of $\frac{p_i - p_{wf}}{q}$ vs. $\log_{10} t$ will yield a straight line with a slope, m , psi/bbl/day/cycle, where

$$|m| = \frac{162.6 \mu B}{kh} \quad (2)$$

and this equation can be used to calculate the permeability-thickness, kh .

Equation (1) can also be used to calculate the skin effect factor, s . Letting p_{1hr} be the value of p_{wf} for $t=1$ hour on the correct semi-log straight line, equation (1) can be rearranged to yield

$$s = 1.15 \left(\frac{\frac{p_i - p_{1hr}}{q}}{|m|} - \log_{10} \frac{k}{\phi \mu C_t r_w^2} + 3.23 \right) \quad (3)$$

By using (3), the pressure drop due to the skin effect can be calculated from

$$\frac{\Delta p_s}{q} = 0.87 |m| s \quad (4)$$

and the flow efficiency

$$FE = \frac{\frac{p_i - p_{wf} - \Delta p_s}{q}}{\frac{p_i - p_{wf}}{q}} \quad (5)$$

With the assumptions made previously, a log-log type-curve plot of $\frac{p_i - p_{wf}}{q}$ vs. t for the November test is shown in Figure 9. The two unit-slope lines shown verify the existence of wellbore storage effects. From the end of the second straight line, it appears that the semi-log straight line or the radial flow period started at about 10 hours after the test was begun.

Figure 10 is a semi-log graph of $\frac{p_i - p_{wf}}{q}$ vs. $\log_{10} t$. An analysis of the plotted data shows that the permeability thickness

$$kh = \frac{(162.6) (24 \text{ hr/day}) (0.09 \text{ cp}) (1.5 \text{ res bbl/std bbl})}{(350 \text{ lb/bbl}) (1.11 \times 10^{-3} \text{ psi/lb/hr/cycle})}$$

$$kh = 1356 \text{ md-ft}$$

and if the thickness of the producing layer is assumed to be $h = 1000$ ft., then the permeability

$$k = 1.4 \text{ md.}$$

The skin effect factor

$$s = 1.15 \left[\frac{5.23 \times 10^{-3}}{1.11 \times 10^{-3}} - \log_{10} \frac{1.4}{(0.03)(0.09)(8 \times 10^{-6}) \left(\frac{8.755}{24} \right)^2} + 3.23 \right] = -0.86$$

The small negative skin effect factor suggests that skin damage is not present. Therefore, the flow efficiency of the well is approximately 1, or the well is discharging as much as it is able to produce.

The minimum drainage area for the duration of the November flow test can be estimated to be

$$A = \frac{0.000264 (1.4)(3.36)}{(0.03)(0.09)(8 \times 10^{-6})(0.05)} = 1.15 \times 10^8 \text{ ft}^2$$

Thus the minimum volume reached during this discharge test was

$$Ah = 0.8 \text{ cu mile}$$

2. December Pressure Buildup Analysis

As with the pressure drawdown test, the pressure buildup test employs the standard methods used in petroleum and gas field analysis. The end of the December discharge test permitted a pressure buildup test. Bottom-hole pressures were taken by two Kuster KPG pressure elements and recorders in tandem to ensure that pressure data were acquired since considerable difficulty had been experienced with equipment malfunction because of the very high temperature.

Figure 12 is a log-log type-curve plot of $(P_{ws} - P_{wf})$ vs. t . It shows two distinct wellbore storage effects as in the pressure drawdown test; the top of the second wellbore storage effect is indicated by the arrow A. The rule of thumb used is that the onset of the radial flow period on the conventional semi-log straight line is $1 \frac{1}{2}$ log cycle beyond A, which is indicated by the arrow B. This time is approximately 70 hours after well shut-in. Figure 13 is a semi-log graph of $(P_{ws} - P_{wf})$ vs. $\log_{10} \frac{t + \Delta t}{\Delta t}$.

From the curves the permeability-thickness

$$kh = \frac{162.6 (87.700)(24)(0.09)(1.5)}{(350)(150)} = 880 \text{ md-ft}$$

FIG. 12. LOG-LOG PLOT OF DECEMBER PRESSURE BUILDUP TEST DATA

FIG. 13. SEMI-LOG PLOT OF DECEMBER PRESSURE
BUILDUP TEST DATA

Again if the height of the producing layer is assumed to be $h = 1000$ ft, then $k = 0.88$ md-ft.

The skin effect factor

$$s = 1.15 \left[\frac{1900 - 467}{130} - \log_{10} \frac{.88}{(0.03)(0.09)(8 \times 10^{-6}) \left(\frac{8.755}{24} \right)^2} + 3.23 \right]$$

$$= 4.30$$

The pressure drop across the skin

$$\Delta p_s = (0.87)(150)(4.30) = 561 \text{ psi}$$

and the flow efficiency

$$FE = \frac{2300 - 467 - 561}{2300 - 467} = 0.65$$

This result indicates the well is producing about 65% of the capability without damage.

3. January-February Pressure Buildup Analyses

Bottomhole pressure measurements made after HGP-A was shut-in on February 11, 1977 produced data and plots similar to that obtained for the December test. The onset of the conventional semi-log straight line was approximately 70 hours after well shut-in and the slope of the semi-log plot is 105 psi/cycle.

Using these values gives the total effective permeability thickness as

$$kh = \frac{162.6 (76,000) (24) (0.09) (1.5)}{(350) (105)} = 1089 \text{ md-ft}$$

If the effective height of the producing layer is assumed to be $h = 1000$ ft., then the effective permeability $k = 1.09$ md.

The skin effect factor

$$s = 1.15 \left[\frac{1910 - 774}{105} - \log_{10} \frac{1.089}{(0.03)(0.09)(8 \times 10^{-6}) \left(\frac{8.755}{24} \right)^2} + 3.23 \right] = 6.29$$

The pressure drop across the skin

$$\Delta p_s = (0.87) (105) (6.29) = 575 \text{ psi}$$

Close examination of the January-February discharge data shows that two consecutive straight-line approximations can be made to the Horner plot. Interpretation of this occurrence is that there are at least two different production layers in the wellbore with different kh values (Matthews and Russell, 1967). The same effect is also present in the December flash data, but until it was reproduced in the January-February test, little credence was given to it.

Since the reservoir has at least two producing layers, the traditional Matthews-Bros-Hazebroek method of extrapolating formation average pressure cannot be used and the Miller-Dyes-Hutchinson method (Miller, Dye and Hutchison, 1950; Perrine, 1956; Matthews and Russell, 1967) must be used to obtain the value of the formation average pressure. The value is

$$\bar{p} = 2174 \text{ psi with no influx of fluid over the drainage boundary}$$

$$\text{or } \bar{p} = 2214 \text{ psi with constant pressure at the drainage radius.}$$

With the above pressures, the flow efficiency values are

$$FE = \frac{2174 - 774 - 575}{2174 - 774} = 0.59 \quad \text{with no influx of fluid over the drainage boundary}$$

$$\text{or } FE = \frac{2214 - 774 - 575}{2214 - 774} = 0.60 \quad \text{with constant pressure at the drainage radius}$$

4. Recalculation of December Data

If the analysis of the December Horner plots is redone to account for two producing layers, the permeability thickness

$$kh = \frac{162.6 (87,700) (24) (0.09) (1.5)}{(350) (85)} = 1553 \text{ md-ft}$$

And if the effective thickness of the producing layer is assumed to be $h = 1000 \text{ ft.}$ then the effective permeability $k = 1.55 \text{ md.}$

The skin effect factor

$$s = 1.15 \left[\frac{2032-467}{85} - \log_{10} \frac{1.553}{(0.03)(0.09)(8 \times 10^{-6}) \left(\frac{8.755}{24} \right)^2} + 3.23 \right] = 14.8$$

The pressure drop across the skin

$$\Delta p_s = (0.87) (85) (14.8) = 1098 \text{ psi}$$

Employing the Miller-Dyes-Hutchinson method for calculating the average formation pressure results in formation average pressure values of

$$\bar{p} = 2206 \text{ psi with no influx of fluid over the drainage boundary}$$

or $\bar{p} = 2214$ psi with constant pressure at the drainage radius.

With these values, one can calculate the flow efficiency to be

$$FE = \frac{2206 - 467 - 1098}{2206 - 467} = 0.37 \quad \text{with no influx of fluid over the drainage boundary}$$

or $FE = \frac{2238 - 467 - 1098}{2238 - 467} = 0.38 \quad \text{with constant pressure at the drainage radius.}$

5. Discussion

Table 4 summarizes the preceding analyses of the pressure drawdown and buildup tests. The permeability-thickness figures from all analyses are similar, but the skin effects and flow efficiencies are different. The assumptions for a pressure drawdown analysis include the production of fluid at a constant rate, which is difficult to satisfy in practice. In order to apply the theory, the pressure data were normalized by dividing by the production rate, which can be questioned for its validity. On the other hand, the pressure buildup analysis has no similar, difficult assumption to satisfy in practice. Thus more reliable conclusions can be drawn from the pressure buildup tests and analyses.

In a preliminary way the analyses of the pressure buildup tests indicate that the reservoir is tight (low permeability of perhaps less than 1 millidarcy) and that the well suffers from significant skin damage, resulting in a discharge rate of only 38-60% of what it is capable. This latter tentative conclusion is supported by the data in Table 1, which shows that the flow rates have increased with each test. This may have been a result of the initial surge in each test, which either removed the baked-in mud and thus reduced the skin damage, or possibly induced stress-caused microfractures.

It also appears that there are at least two production layers with different kh values. While the theory does not permit a calculation of the two kh values, its use indicates that the effective kh probably lies between 1000 and 1500 md-feet.

C. Possible Wellbore Models

At least five models have been suggested to explain HGP-A's performance. These five, based on the wellbore as the thermodynamic boundary, with the physical condition of the incoming fluid being the descriptive term, are:

- 1) Steam plus "cold" water
- 2) Steam plus hot water at saturation
- 3) Superheated steam

Table 4
COMPARISON OF PRESSURE DRAWDOWN AND BUILDUP TESTS

	CONSTANT PRODUCTION <u>DRAWDOWN</u>	JAN-FEB BUILDUP <u>TWO-LAYER</u>	DECEMBER BUILDUP <u>TWO-LAYER</u>	DECEMBER BUILDUP <u>ONE-LAYER</u>
PERMEABILITY THICKNESS, KH, MD-FT.	1356	1089	1553	880
APPARENT SKIN FACTOR, S	- 0.86	6.3	14.8	4.3
PRESSURE DROP ACROSS SKIN, PSI	---	575	1098	561
FLOW EFFICIENCY	~ 1	0.60	0.38	0.65

4) Hot water

5) Combinations of above from separate production regions

Steam Plus "Cold" Water Model

This model is shown in schematic form in Fig. 14. Under static conditions, the underground system is heated as hot fluid enters the borehole at 5900 feet or deeper and leaves the borehole at 4200 feet and 2250 feet (just below the casing). The result of this closed-in fluid movement is an overall increase in borehole temperature as shown in the "After Pump Test" curve of Fig. 15. After the four-hour flash, temperatures increased further.

During discharge the major production region is below 5900 feet, although 4200 feet could be a secondary source of hot fluid. In this model, once the well begins discharging, the effective pressure in the borehole at 2250 feet drops below the hydrostatic pressure and "cold" water, possibly at about 60°C, also enters the well. Using well output data enables the following estimate of "cold" water flow to be made:

At wellhead

Total flow = 75,000 lb/hr

Enthalpy = 850 BTU/lb

At 2300 feet cold water enters the wellbore

y lb/hr at 60°C

Enthalpy = 108 BTU/lb

At 5900 feet (and 4200 feet) steam enters the wellbore

(75,000 - y) lb/hr at 250°C

Enthalpy = 1204 BTU/lb

Application of conservation of energy gives

$$108y + 1204 (75,000 - y) = 850 (75,000)$$

Or

$$y = 24,225 \text{ lb/hr}$$

Thus, if 100% steam is entering the borehole at depth, 24,225 lb/hr of 60°C water can be entering the borehole. It is interesting to note that the weir flow rate was relatively constant at 24,000 lb/hr throughout the entire two-week November discharge test. However, the December test resulted in water flow between 33,500 and 52,000 lb/hr.

Additional supporting evidence of "cold" water intrusion can be advanced by analyzing shifts in the temperature profile. Temperature profiles during and following the November flash test in the region from 2500 to 3500 feet give temperature-time plots which look like

Figure 14. Steam Plus "Cold" Water Model

Figure 15. Temperature-Depth Plot

The drop in temperature below the "equilibrium" temperature at those depths could be caused by cold water intruding at 2250 feet and convecting down to 3500 feet.

A pressure gradient analysis, however, suggests that if there is cold water contamination, it is not all entering at one level. For an 8" diameter pipe with

friction factor = 0.02

Reynolds Number = 2×10^5

steam entering borehole at bottom

cold water entering borehole at say 2300'

for the saturated vapor from 6450 feet to 2250 feet, the pressure gradient should be

$$\Delta p_1 = 0.92 \text{ kg/cm}^2/1000 \text{ ft}$$

and for the two-phase fluid from 2300 feet to the surface the pressure gradient should be

$$\Delta p_2 = 1.83 \text{ kg/cm}^2/1000 \text{ ft}$$

Thus, there should be a definite break in slope at 2250 feet in the pressure profile, as the slopes are different by a factor of two. Figure 4 shows four pressure profiles. Changes in slope are evident at 2250 feet. However, it is also possible that these breaks are caused by the change in cross sectional flow area since the casing and slotted liner overlap near 2250 feet.

2. Steam Plus Hot Water at Saturation

In this model the wellbore contains steam and water at saturation temperatures and pressures. If the incoming fluid is at 250°C, the steam quality necessary to result in conditions experienced at the wellhead are:

Test	Wellhead		Downhole
	Steam Quality	Enthalpy BTU/lb	Steam Quality
November			
at 24.5 hrs	69%	893	58%
at 336.5 hrs	64%	846	51%
December			
at 25 hrs	62%	833	50%
at 168 hrs	50%	778	42%

Flashing occurs in the reservoir rather than in the wellbore.

The temperature profile during flashing shows that there are no sharp changes in the temperature gradient near bottomhole. However, if there is no inward flow of fluid at bottomhole (of flashing mixture at the relatively low temperature of 250°C) then at bottomhole there would be fluid which would have "fallen" from above and which would be heated by the rock, which in the quiescent state is at about 300°C. The temperature at bottomhole should then approach 300°C, but this is not the measured temperature. The conclusion is that at least a portion of the wellbore fluid is entering at bottomhole. The temperature at bottomhole returns to its former temperature much more rapidly than does the temperature at, say, 6000 feet because the rock at 6000 feet is heated, initially, by heat transferred radially while the rock at bottomhole is heated from both the radial and axial directions (from below 6300').

3. Superheated Steam Model

Very early in the testing program before the well was even flashed, an apparent very low permeability of the underground system resulted in some outside expectation that initially a two-phase flow, if any flow were achieved at all, would result. But as fluid was drawn from portions of the reservoir increasingly distant from the wellbore, the fluid would be heated to superheat and eventually, a small amount of superheated steam would be produced.

HGP-A, although it did initially produce both steam and fluid in November, instead of increasing in enthalpy, as required for this model, actually continued to drop in enthalpy, from 1000 BTU/lb to 800 BTU/lb. Thus at the

present early stage of production, superheated steam alone is not the correct model for HGP-A. However, the possibility cannot be eliminated that in the future this will be the correct model for HGP-A.

4. Hot Water Model

In this model only hot water enters the borehole and flashing occurs in the well. If the fluid enthalpy at the surface is 600 BTU/lb or greater, as is the case for HGP-A, this model is not the proper one for HGP-A, especially if the maximum producing temperature is below 308°C. Also, pressure profiles obtained while the well was flashing did not show any liquid level in the well as would be expected in this model. If the James method of calculation is reasonably correct, and if the temperature measurements during flow can be accepted as reliable, then it is highly probable that some steam is entering the borehole.

5. Combinations of the Above Models

Since the liner is slotted from 2250 feet to 6450 feet, there probably is fluid from a number of regions entering the wellbore. Few data are available to determine the regions and the relative amounts of entering fluid. However, because of the varying permeability with depth, it is reasonable to expect that fluid is entering at several levels.

6. Summary

At this time, the available data appear to support a wellbore model consisting of a flow of steam and hot water at saturation temperatures and pressures. Fluid of 50% steam quality is produced at bottomhole with the steam quality increasing to 65% at wellhead pressures. Flashing is occurring in the reservoir as there is no detectable water level in the wellbore during flashing. There is probably very little contamination by water much colder than bottomhole temperature entering the wellbore although the pressure profiles are ambiguous about this point at around 2250 feet.

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APPENDIX A

OVERVIEW OF THE HAWAII GEOTHERMAL PROJECT

May 1973 through December 1976

The Hawaii Geothermal Project (HGP) was organized to focus the multi-disciplinary research resources of the University of Hawaii on the identification, generation, and utilization of geothermal energy on the Big Island of Hawaii. This island is both the largest and youngest in the island chain, and is still growing from recent activity of the Mauna Loa and Kilauea volcanoes. Therefore, it is the island with the greatest amount of heat at or near the earth's surface. Consequently, the Big Island was selected as the appropriate site for initial geothermal exploration, with subsequent surveys to proceed throughout the island chain.

The HGP came into being when the 1972 Hawaii State Legislature allocated \$200,000 for geothermal research, contingent on the University obtaining matching federal funds. This was well before the Middle East oil embargo and resulting energy crisis; so was a progressive step for a state legislature to take. From the beginning this has been a cooperative project involving all segments of government, the University, the electric utility, and the private sector. A budget summary of the total support of \$3,417,000 that has been received to date, showing sources of funding for each of the three major phases of the project, is listed on the next page.

Research got underway in the early summer of 1973, with separate programs established for Geophysics, Engineering, Environmental-Socioeconomics, and Experimental Drilling. The major emphasis of Phase I was on geophysical surveys, but support activity was begun in the other programs as well. It became evident in early 1974 that an exploratory drilling program would be required to verify the subsurface conditions predicted by the surveys. Initially it was the intent to proceed with multiple drilling of both deep and shallow wells, but subsequent fiscal restraints limited the exploratory drilling "program" to one deep well.

The Site Selection Committee for this well was chaired by the former Dr. Agatin T. Abbott, after whom the well was ultimately named -- HGP-A, for Abbott. The committee considered all geophysical, geological, and geochemical

BUDGET SUMMARY FOR HGP-A

Phase I -- Exploratory Surveys & Related Research (May 1973 through April 1975)

State of Hawaii	FY72	\$100,000	
County of Hawaii	FY72	100,000	
National Science Foundation (NSF)	FY73-74	469,000	
Energy Research & Development Administration (ERDA)	FY75	119,000	
Other public & private funds	FY72-75	<u>39,000</u>	
	Subtotal		\$ 827,000

Phase II -- Experimental Drilling, Initial Well Testing, & Related Research (May 1975 through June 1976)

ERDA	FY75-76	\$1,472,000	
State of Hawaii	FY74	500,000	
Water Resources International	FY76	60,000	
Hawaiian Electric Company	FY75	<u>45,000</u>	
	Subtotal		2,077,000

Phase III -- Well Testing and Analysis (July 1976 through September 1977)

ERDA	Transition Period	\$147,000	
ERDA	FY77	300,000	
State of Hawaii	FY77	<u>66,000</u>	
	Subtotal		<u>513,000</u>
	TOTAL		\$3,417,000

A breakdown of this funding by category is as follows:

ERDA Funding	\$2,038,000	
NSF Funding	<u>469,000</u>	
Total Federal Support		\$2,507,000
State & County Support		773,000
Private Funding		<u>137,000</u>
TOTAL		\$3,417,000

4/1/77

evidence and selected as the optimum site a location in the Puna District near the eastern rift of Kilauea Volcano. No State or County land suitable for drilling was available near the selected site, and after some negotiation with landowners in that area, permission was obtained from the Kapoho Land and Development Company to drill the well on a four-acre plot approximately three miles southeast of Pahoa. The elevation of this site is just under 600 feet above sea level.

Specifications for drilling were drawn up and invitations to bid were sent in early June 1975 to 28 drilling companies on the mainland, in Canada, and throughout the Pacific area. The only bid submitted was by Water Resources International Inc. of Honolulu and, following extensive negotiations, the drilling subcontract was let in late-November 1975. A New Zealand geothermal consulting firm, KRTA, was commissioned to provide technical assistance and supervision of the drilling operation.

Drilling of this experimental well commenced on December 10, 1975. The well was completed to a depth of 6450 feet on April 27, 1976. Cores of the subsurface strata were taken at approximately 700-foot intervals and cutting samples were obtained every five to ten feet throughout drilling. The well was logged twice with Gearhart-Owen equipment, which measured resistivity, self-potential, natural gamma ray and slow neutron count, and cement bond. Depth of logging was limited by high downhole temperatures.

Below 4000 feet the drilling mud began to heat up rapidly, and subsequent mud temperature measurements approached 600°F. This high temperature was sufficiently encouraging to justify installing a slotted liner, flushing out the mud, and conducting a well testing program. The total budget for site preparation, drilling, casing, and preliminary rig-assisted well testing came to just over \$1.5 million, as summarized on the following page.

Preliminary well testing proceeded through the summer of 1976. The well was first flashed to steam and permitted to flow briefly on July 2. The rate of discharge of steam was impressive but noisy -- resulting in DBA readings of 120, roughly equivalent to that of a 747 jet aircraft at take off. Steam was discharged continuously for four hours on July 22, verifying that some natural flow into the wellbore was taking place. The quality of the fluid from HGP-A was generally good -- surprisingly low in chloride content, but with significant amounts of silica.

Because of the extremely high noise level generated during discharge a silencer-separator was constructed before proceeding with a more comprehensive

BUDGET SUMMARY FOR HGP-A

Cost of Site Preparation, Drilling, and
Preliminary Rig-Assisted Well Testing

Site Preparation, Water Reservoir, and Cellar	\$ 45,496
Mobilization	120,192
Labor and Rig Time	733,830
Consumable Materials and Misc. Services	673,995
Electric Logging	16,486
Demobilization	<u>9,615</u>
SUBTOTAL	\$1,599,614
Less Credit for Returned Consumables	<u>96,143</u>
NET COST OF HGP-A	\$1,503,471
Less Rig Rental Allowance by WRI	<u>60,000</u>
TOTAL COST OF HGP-A TO THE PROJECT	\$1,443,471

testing program. A two-week flow test was performed -- from November 3 to 17 -- with wellhead temperature, pressure, and other scientific measurements recorded throughout. Subsequently, instrumentation and procedure were perfected for obtaining downhole temperature and pressure measurements while the well was discharging steam. Temperature and pressure profiles throughout the full 6450-foot well depth were obtained during a six-day flow test conducted in mid-December, followed by a determination of the pressure build-up after the well was shut-in.

Because the steam quality is so high, the silencer has been only partially successful, and objections to the noise level continued to be raised by families in the area. In late December and early January additional muffling and stiffening was built into the silencer, after which a series of throttled flow tests were conducted to provide better assessment both of the well and to obtain preliminary design data for a wellhead generator. The results of this and subsequent flow tests are presented in the body of this report.

In summary, HGP-A is one of the hottest geothermal wells in the world. The highest downhole temperature encountered has been 675°F, and there appears to be ample -- if not plentiful -- flow of high quality steam. The fact that high temperatures are encountered within 4000 feet of the surface holds excellent potential for commercial development of the Kapoho Geothermal Field. Preliminary testing indicates that although some natural flow into the wellbore occurs at depth, HGP-A is a relatively tight well -- whether due to low permeability of the reservoir, to skin damage in the vicinity of the wellbore, or both, it's premature to judge. Subsequent well testing and interpretation of current and future data will provide a better understanding both of the Kapoho Geothermal Field and of HGP-A, the well itself.